PACS Calibration Document

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Introduction

The purpose of this document is to compile all requirements on PACS calibration and, on a high level, the corresponding implementation and analysis procedures in a central file. While the document is the master plan for the in-flight calibration, it addresses also ground-based related issues in order to achieve a complete calibration scheme of the instrument. Therefore, it is also an applicable document for ground tests, beside other relevant documentation like the "PACS Test Plan" (PACS-ME-PL-012, RD2). This shall ensure that all necessary prerequisites for in-flight calibration are met, by identifying all calibration activities that can only be done on ground. Furthermore, it will help checking out and optimizing in-flight procedures to some degree already on ground.

The document will also provide an overview on resources, both with regard to implementation efforts as well as observing time estimates per requirement. The assessment of calibration needs and their frequency will provide feedback to AOT and Logic design. The outline of the calibration analysis will provide feedback to the IA design.

Reference Documents

RD1: PACS Calibration Documentation Overview, PICC-MA-LI-003

RD2: PACS Test Plan, PACS-ME-PL-012

RD3: PACS Instrument Requirements Document, PACS-ME-RS-005

RD4: PACS Performance Verification Phase Plan, PICC-MA-PL-001

RD5: PACS Routine Phase Calibration Plan, PICC-MA-PL-002

RD6: PACS Commissioning Phase Plan & Timeline, PACS-ME-PL-024

Structure of the Document

The major part of the document is organized in the form of requirements which make up individual subsections. As a long term goal a general calibration philosophy shall be developed out of this document. This includes the identification of priorities and cross-links between individual requirements.

Structure of the Requirement Description

Each requirement comprises the following items:

- Label & Title
- Objective
- Fulfilling or fulfilled by (identify cross links)
- Priority (3 classes)
  A: core part of calibration system
  B: necessary to achieve required accuracy
  C: extension of instrument knowledge
- When performed / frequency (including ground tests)
- Required accuracy (driver for CIP design)
- Inputs, prerequisites
- Sources
- Calibration Implementation Procedure (CIP, high level only)
- Estimated time needed (from CIP)
- Calibration Analysis Procedure (CAP, high level only)
- Output, products
- Status / Version (some configuration control, in addition use of Concurrent Version System (CVS))

In the output section, we refer to (RD1) for the overview of all reports generated with regard to this requirement during FM-ILT, FM-IST, and in-flight.

Grouping of Requirements

The requirements are grouped according to the following scheme:

1) Detector Systems
   - Bolometer Array Cameras
   - Photoconductor Array Cameras
2) Optical Components
   - Filters
   - Grating
   - Chopper
   - Imaging Optics
   - Internal Reference Sources
   - Telescope Pointing Quality
3) Full System Calibration Photometer
4) Full System Calibration Spectrometer
5) Optimized Observing Strategies for AOTs and Scientific Validation of AOTs
6) Cross-Calibration
7) Telescope
8) Space Weather effects
9) Interferences

Group 1) & 2) requirements cover those requirements where module level calibration makes up an essential contribution. These requirements are also driven by inputs needed for AOT logic, time estimator and Observer's Manual. Group 3) & 4) requirements cover the core inflight calibration. Due to their special nature, some requirements are put into separate sections. It is not the task of the PACS team to calibrate the Herschel telescope, on the other hand, detailed information on the telescope system, which has to come from other parties, is needed for the calibration of the PACS instrument. Therefore, from the PACS team side requirements concerning information on the telescope will be put into this section. The section Space Weather effects covers trends due to this factor, the section interferences is not an outline of EMC-type tests, but addressess calibration issues in case certain interferences should occur or remain in space.

Traceability with Instrument Performance Requirements

The following verification test matrix provides a cross-check for coverage of the instrument performance items, as specified in the Instrument Requirements Document PACS-ME-RS-005 (RD3), by PCD items. For better visibility this cross matrix is split into two parts. The instrument performance items are related to test blocks executed during ground tests, in particular FM–ILT. These test blocks address a number of individual PCD requirements. Most of these ground test measurements will be later repeated in-orbit.

Table 1 contains the PACS verification test matrix relating Instrument Requirements Document and PACS FM Test Plan. Table 2 provides then the list of PCD requirements addressed by the test blocks. The order of test blocks is subject to prerequisites and dependences of some calibration items on others which is addressed by the Test Plan.

Table 1: **PACS verification test matrix, cf. PACS-ME-PL-012, Issue 3, Appendix C**

Instrument Performance Requirement category	Verification by execution of FM-ILT test blocks
2 System Level Requirements	
2.1 Basic Instrument Mode	mutual requirement fulfilled by alternating photometry and spectroscopy test blocks
2.2 Photometry requirements	
2.2.1 Wavelength range and filter bands	filter transmission and detector absoptivity measurements on module level (no test during FM-ILT)
2.2.2 Field-of-view and pixel scale	OGSE characterisation II (photometer)
2.2.3 Image quality	OGSE characterisation II (photometer) Photometer Calibration Tests
2.2.4 Straylight	Photometer Calibration Tests (restricted assessment on ground)
2.2.5 Dynamic Range	Photometer Set-ups I
2.2.6 Observing Modes	AOT Tests Photometer
2.2.7 Post Detection Bandwidth	Photometer Set-ups III
2.2.8 Sensitivity	Photometer Set-ups II
2.2.9 Calibration and photometric accuracy	Photometer Calibration Tests
2.3 Spectroscopy Requirements	
2.3.1 Wavelength coverage and spectral resolution	Spectrometer Calibration Tests I
2.3.2 Field-of-view, pixel scale, and spectrometer implementation	OGSE characterisation III
2.3.3 Image quality	OGSE characterisation III Spectrometer Calibration Tests II
2.3.4 Stray Light	Spectrometer Calibration Tests II (restricted assessment)
2.3.5 Dynamic range	Spectrometer set-ups
2.3.6 Observing modes	AOT Tests Spectrometer
2.3.7 Post-Detection Bandwidth	Spectrometer set-ups AOT Tests Spectrometer
2.3.8 Sensitivity	Spectrometer set-ups AOT Tests Spectrometer
2.3.9 Calibration and spectroscopic accuracy	Spectrometer Calibration Tests II
2.4 Operational Requirements	
2.4.1 Maximum Uninterrupted Operating Interval	Data Processing End-to-end Tests
2.4.2 Availability of and switching between instrument modes	Data Processing End-to-end Tests AOT Tests Photometer AOT Tests Spectrometer switch between photometer and spectrometer test blocks
3. Subsystem Level Requirements	
3.1 Sensitivty Related Subsystem Requirements	PACS instrument model
3.1.1 Photometry	optical transmission measurements on subsystem level Photometer Set-ups II
3.1.2 Spectroscopy	optical transmission measurements on subsystem level Spectrometer Set-ups
3.2 Chopper	Control Loop Optimisation
3.3 Timing/Synchronisation Requirements	Photometer Set-ups I Spectrometer Set-ups

Table 2: **PCD requirements relation with FM-ILT test blocks**

	Control Loop Optimisation
2.3.1	Angular Calibration of the Focal Plane Chopper
2.3.2	Duty cycle of (chopper) waveforms
2.5.3	Time constants: heat-up and cool down times of PACS calibration sources
	Photometer set-ups I (basic settings)
1.1.0	VRL-VHBLIND exploration
	Photometer set-ups II (optimum settings)
1.1.1	Control optimum pixel bias settings
1.1.2	Nominal responsivity
1.1.5	Monitor detector temperature variations with time
1.1.12	Measure the bolometers noise equivalent power (NEP)
3.2.3	Calibrate the photometer's non-linearity
	Photometer set-ups III (time & temperature dependences, SPU tuning)
1.1.6	Calibrate the variation of pixel offset with detector temperature
1.1.8	Measure bolometer time constants after switch-on
1.1.11	Measure the low frequency noise
1.1.16	Measure the signal dependence on chopping frequency
	Spectrometer set-ups
1.2.1	Optimum detector bias settings
1.2.2	Optimum detector temperature settings
1.2.3	Dynamic range per selected integration capacitor
1.2.4	CRE check-out voltage
1.2.6	Detector dark current
1.2.7	Nominal responsivity
1.2.8	Signal dependence on chopper frequency
1.2.9	Detective Quantum Efficiency
1.2.10	Noise equivalent power
1.2.11	Linearity of CRE read-out
1.2.16	Time constant: switch-on spectrometer
1.2.17	Time constant: bias change spectrometer
1.2.18	Time constant: flux changes spectrometer
	OGSE Characterisation II (photometer)
2.3.3	Optimal positioning of chopper on internal reference sources
3.1.1	Photometer central pointing position
3.1.7	Background structure in the photometer FOV over the full chopper angle range
3.2.8	Measure the photometer full system flat-field
	OGSE Characterisation III (spectrometer)
2.3.3	Optimal positioning of chopper on internal reference sources
2.5.2	Spatial stability (isotropy and homgeneity) of PACS calibration sources
4.1.1	Spectrometer central pointing position and grating alignment
4.1.x	Full field-of-view maps
4.3.10	Flat-field spectrometer external sources
	IMT/IST Tests II (main)
1.2.23	Curing spectrometer (heater & flasher)
7.x	L0 tests

Table 2: **PCD requirements relation with FM-ILT test blocks, continued**

	Photometer Calibration Tests
1.1.11	Measure the low frequency noise
1.1.17	Measure the level of optical cross-talk
1.1.18	Measure the level of electrical cross-talk
3.1.3	Photometer field-of-view distortion
3.1.4	Photometer point spread function
3.1.5	Photometer ghosts
3.1.6	Photometer straylight
3.2.2	Monitor nominal responsivity variations with time
3.2.4	Establish the linearity of the full system
3.2.6	Noise and minimum detectable flux
	Spectrometer Calibration Tests I (spectral calibration)
4.2.1	Grating wavelength calibration
4.2.2	Grating instrumental profile
4.2.3	Spectral purity
4.2.4	Spectral ghosts
	Spectrometer Calibration Tests II (spatial & photometric calibration, curing)
1.2.23	Curing, spectrometer
2.3.3	Optimal positioning of chopper on internal reference sources
2.5.2	Spatial stability (isotropy and homgeneity) of PACS calibration sources
2.5.4	Emissivity of PACS calibration sources
4.1.3	Spectrometer point spread function
4.1.4	Spectrometer ghosts
4.3.1	Absolute flux calibration internal sources, spectrometer
4.3.2	Reproducibility internal sources
4.3.3	Absolute flux calibration external sources, spectrometer
4.3.4	Flux reproducibility external sources
4.3.5	Linearity with flux
4.3.8	Relative spectral response function

Calibration Plan

There is, with some freedom, a logical order how to arrange the measurements related to individual requirements. This is determined by:

1) Priority and prerequisites
2) Mutual dependence
3) Available calibration sources (at various test sites)
4) Calibration frequency (e.g. for reproducibility assessment)

Calibration Plan for ILT

An ideal test plan for the Flight Model Instrument Level Tests (FM-ILT) has been compiled in PACS-ME-PL-012, Issue 3/FM. From this the necessary time resources, the grouping, the interlink of calibration items, and the requirements for calibration stimulators can be taken. It provides the baseline for the calibration team structure and manpower planning. An impression on the overall logical flow can be obtained from the test plan overview contained in Appendix F of this document.

For ground tests special stimulators and calibration sources are utilized which are part of the Optical Ground Segement Equipment (OGSE). These comprise:

1) 2 OGSE internal BlackBodies (OGSE BB), extended emission with the possibility to chop inbetween the two by means of a wheel chopper
2) External BB (ext. BB) or hot plate in combination with a hole mask on a xy(z) stage simulating (movable) point sources
3) Water vapour cells in front of a hot plate producing absorption line spectra
4) Tunable FarInfared laser for monochromatic emission lines.

These optical stimuli are described in detail in the PACS Cryo Test Equipment and OGSE Specification document (PACS-ME-DS-002).

The actual/daily test plan may significantly deviate from this ideal test plan depending on availability of stimulators and warm electronic components, unexpected events generated by the test equipment, non-conformances of instrument components or unexpected results of test evaluation which need follow-up. Therefore, no attempt is made to present an up-to-date test plan in this document.

A special test item are irradiation tests. These will be performed on detector module level. See Test Plan and Procedure for Investigation of Glitch Event Rate during Proton Irradiation, PACS-ME-TP-009, the introduction to section 1.2 and reqs. 1.2.12 – 1.2.15, 1.2.18 – 1.2.20., 1.2.22 – 1.2.23 for more details.

Calibration Plan for Performance Verification Phase

The PACS calibration test plan for the Performance Verification Phase is described in PICC-MA-PL-001 (RD4). It provides a tabular overview of all calibration activities related to the Performance Verification Phase and the preceeding Commissioning Phase calibrations with reference to the requirement section of this document.

The main content items of the PV Plan are:

1) Objectives of the PV Phase

2) Collection of the Operational Framework and Assumptions w.r.t. Spacecraft Operation and PACS Operation, the latter with a link to the calibration relevant procedures

3) Overview on all types of PACS Celestial Standards, their relevant properties and their visibility w.r.t. the planning launch date. Standards covered are

   - Photometric standards (prime, secondary, faint)
   - Point source references for photometer and spectrometer
   - Wavelength calibration standards
   - Astrometric standards for pointing and spatial scale assessment
   - Blank/dark sky fields

4) Test Plan Overview with test philosophy, test levels, verification and traceability matrices

5) PACS Commissioning Phase and Performance Verification Phase detailed contents with tabular overview of all observations and the link to the generated Astronomical Observation Requests (AORs)

6) PV Phase timeline with the PV Operational Day (OD) assignment overview, the high level plan, guiding the filling of each OD with AORs according to the logical flow, interdependencies of measurement and visibility of key sources, and finally the timeline per OD.

Calibration Plan for Routine Phase

The PACS calibration test plan for the Routine Science Phase is described in PICC-MA-PL-002 [RD5].

The main content items of the PV Plan are:

1) Objectives of the Routine Phase calibration

2) Collection of the Operational Framework and Assumptions w.r.t. Spacecraft Operation and PACS Operation, the latter with a link to the calibration relevant procedures

3) Overview on PACS Celestial Standards for Routine Phase, their relevant properties and their visibility. Standards covered are

   - Photometric standards (prime, secondary, faint)
   - Wavelength calibration standards
   - PACS-S – HIFI cross-calibration sources
   - Blank/dark sky fields

4) Routine Phase calibration overview with calibration philosophy, time forecast per major calibration item and actually required times and total numbers of AORs (Astronomical Observation Requests) per major calibration proposal.

5) PACS Routine Science Phase detailed contents with tabular overview of all observations and the link to the generated Astronomical Observation Requests (AORs)

6) Routine Phase timeline with the Operational Day (OD) assignment overview, the trace matrix of which targets of a specific calibration observation are executed on which OD and finally the timeline per calibration cycle (with only the calibration AORs listed, which are interspersed with the non-listed science AORs).

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DOCUMENT CHANGE RECORD

Version	Date	Changes	Remarks
Draft 0	07-Dec-2001	–	New document.
Draft 1	20-Dec-2001	all	Sections 1–4 & 9 Inputs from 12/13-Dec meeting at MPE included.
Draft 2	18-Feb-2002	medium	Sections 1–4 & 9 missing requirements of first consolidated list included. Addition of some introductory remarks. Full CVS control. Input to IBDR.
Draft 3	23-Sep-2002	medium	Section 1.1 revised following first bolometer tests Sections 1.2, 2.3 & 2.5 upgrade
Draft 4	07-Feb-2003	medium	CQM high-priority reqs. defined at ICC#14 (sections 3.1, 3.2, 4.2, 4.3) upgrades in section 1.2, upgrades in section 6.1 (cross-cal).
Draft 5	02-Apr-2003	medium	CQM high-priority reqs. defined at ICC#15 (sections 3.1, 3.2, 4.2, 4.3) upgrades in sections 1.1, 2.3
Draft 6	18-Jun-2003	medium	CIPs & CAPs for more CQM high-priority reqs. (sections 3.2, 4.1, 4.2, 4.3) restructuring of Introduction section and inclusion of CQM test traceability matrixes and CQM measurement sequences upgrades in section 5 (AOT optimization) in line with AOT design brainstorming
Draft 7	30-Sep-2003	medium	CIPs & CAPs for more CQM reqs. (sections 1.2, 2.5, 3.1, 4.1) updates for irradiation tests of Ge:Ga at CRC-UCL (section 1.2) upgrade of CQM test traceability matrixes and CQM measurement sequences
Draft 8	05-Jan-2007	major	Upgrade of CIPs & CAPs for FM-ILT (sections 1.1, 1.2, 2.3, 2.5, 3.1, 4.1, 4.2, 4.3) references to CQM calibration reports revision of introduction
Draft 9	31-Oct-2007	major	1st upgrade for preparation of PV Phase Plan (sections 1.1, 2.2, 2.3, 2.5, 3.1, 3.2, 4.3, 9.2) update of section 5 introductions, small addenda to section 6 new sections 7.1, 7.2, 7.3, 7.4
Draft 10	14-Mar-2008	medium	Further upgrade for preparation of PV Phase Plan and pointing calibration: sections 1.1, 2.6, 3.1, 3.2, 4.1, 4.2, 4.3 First complete version of section 5.1 covering all PACS photometer AOT modes
Issue 1.0	07-Aug-2008	medium	Further upgrade for preparation of PV Phase Plan and pointing calibration: sections 3.1, 3.2, 4.1, 4.3 New requirement 4.2.5 (spectrometer wavelength calibration dependence on slit position) New requirement 3.1.7 (photometer FOV scans) Complete revision and extension of section 5.2 (spectrometer AOT validation) New chapter (10) on characterization of ground calibration facility First new requirements on OGSE chopper (10.1.1 – 10.1.3) added Update of Introduction to describe the PV Plan

DOCUMENT CHANGE RECORD

Version	Date	Changes	Remarks
Issue 1.05	14-Mar-2013	medium	Description of Routine Cal Plan in Introduction Details in chapter 8, space weather and addition of requirement 8.1.1, EDAC monitoring Revision and update of chapter 6, cross-calibration
Issue 1.10	November 28, 2014	medium	Links to PACS calibration reference documents included in Introduction Add PACS Calibration Document Overview to reference list Update req. 7.1.1 Revision and extension of chapter 10, OGSE Characterization Update reqs. 10.1.1, 10.1.2, 10.1.3 New section 10.2, OGSE Blackbodies New requirements 10.2.1, 10.2.2 New section 10.3, OGSE External Sources New requirements 10.3.1, 10.3.2, 10.3.3 Revised section title 9, Inter-instrument Interferences Revision section 9.2 with reqs. 9.1.2, 9.2.2, 9.2.3, 9.2.4 New requirements 9.1.1, 9.1.2, 9.1.3 (for photometer) Typo correction in section 8, Space Weather Effects Revision section 7.4, Focal Plane Geometry, with req. 7.4.1 Revision section 7.3, Straylight suppression Revision of reqs. 7.3.1, 7.3.2, 7.3.3, 7.3.4 Revison section 7.2; Thermal telescope background, with req. 7.2.1 (RD) reference update in reqs. 6.1.1, 6.1.2, 6.2.1, 6.2.2, 6.3.1

Contents

Chapter 1

Detector Systems

1.1 Bolometer Arrays

It is not the purpose of this introduction to describe the general principles of bolometers, but rather to mention some specific properties of the PACS bolometer arrays that are relevant in the calibration context, as well as some particularities of the instrument development that impact the relevancy of some requirements.

The photometer instrument has seen some drastic evolution from the QM to the FM, both in the hardware and in the way we use it. The PCD is a living document that has followed the instrument through these transformations (and will continue to do so) and we try in the following pages to be clear as to which version of the instrument the requirements, or parts of the requirement, refer to.

For instance, this section, Dectector system, was first intended to compile requirements dealing with the bolometer focal plane (BFP) units exclusively, while chapter 3 deals with requirement that involve the complete photometer instrument. It is clear that as soon as the BFPs are integrated in the instrument, this separation becomes less evident. Therefore the separation between this and chapter 3 can be sometimes arbitrary.

1.1.1 Baseline before CQM Model

Note that this subsection is completely obsolete, and is kept only for historical reasons. The PACS bolometer arrays are equipped with two rows of blind pixels. These pixels are identical to the other pixels of the array with two exceptions: (1) they are closed on top so that they cannot receive light directly, and (2) they also have a heater implanted. At the start of any observation, the heater of each blind pixel is set so that their output signal is at the same level as that of the pixels seeing the sky. Their offset drifts should therefore be the same. As the readout process consists of differentiating the sky signal with both the blind pixel signal and a reference voltage, the temperature drift should be removed. More precisely, the normal readout process is the following: we first subtract a common reference signal to both both blind and "sky" pixels' signals, and then make the difference between "sky" and blind pixels. Note that there is a possibility to cancel this differentiation and downlink the absolute signal from either the blind pixels, the sky pixels or the reference voltage. This facility will have to be used to investigate the drifts, and will be only accessible for calibration.

It is also worthwhile to mention that the blind pixels offer a way to directly derive the mean absorption efficiency of the detectors (i.e. the ratio of absorbed to infalling power), provided that the calibration sources are stable or that their power output can be accurately computed. Laboratory experiments have shown that the MOS circuits used to read the pixels (one per pixel) are very uniform over the arrays. Therefore any difference between the signal read on a pair of pixels is attributable to a difference in absorbed power between the two pixels. Thus when power falls on the "sky" pixels, the difference in readout voltages between "sky" and blind pixels (once the reference voltage has been removed) is due to the lack of power falling on the blind pixels. One can adjust the current injected in the blind pixels so that the readout voltage matches that of the "sky" pixels (on average). Once this is done, the product of the injected current and readout voltage on the blind pixels gives the mean power absorbed by the "sky" pixels. Dividing by the power that falls on the detector, for instance from the calibration sources, gives a way of measuring, or at least monitoring the detector absorption efficiency.

Another particular aspect to consider with the PACS bolometer arrays is their non-linearity: as the detection is basically a measure of the temperature, the larger the mean temperature, the smaller the increment of signal per increment of temperature. Over the whole operating range permitted by the bolometers, this non-linearity is very large. It will have to be calibrated to allow the measurement of very bright sources. However the main operating mode of the bolometer will be to measure relatively faint sources over the strong telescope and sky backgrounds. In that case it is expected that a linear approximation will be correct. Yet we will have to measure over which flux interval this approximation is correct.

Finally, one should remember that the time constants of the bolometer are rather short ($\sim$40 ms). They are thus too short to be measured in the normal operating mode of the detector (where frames are summed on-board). In order to be able to measure them, a special read-out process exits where all readouts from a subsample of the pixels are down-linked. This mode will only be accessible for calibration.

1.1.2 Changes resulting from the CQM ILT and FM module-level campaigns

During the first phase of CQM detector level tests, it appeared that the blind pixel concept was quite difficult to translate into an operational setup, because the original goal seemed to be hindered by the poor control of the current we could achieve in the blind pixel heaters. During the CQM ILT, blind pixels were not used and there will be no way of using them for FM. All considerations of using the blind pixels became obsolete since then.

Despite the fact that blind pixels cannot be used in the FM, a bias parameter called "VH_BLIND" still exists. This bias is now disconnected from the blind pixels, but is connected directly to the circuit in order to give a supplementary voltage reference or offset to the output signal. This is one of the key parameters to adjust the signal of all the pixels within the allowed electronic digital range and to avoid digital conversion saturation. This is the main goal of the "Control optimum pixel bias settings" requirement.

During this CQM ILT period, a so-called "PEL commuté" mode was proposed and tested, which allowed to lower the power consumption by a factor $\approx$10. Switching to this mode is simply done by setting some BOLC bias, and is now considered the default operational mode.

Another important change was introduced after the FM detector level tests in SAp. The so-called nominal mode (double differential correlated sampling, or DDCS, which uses two voltage references) showed a higher noise level than the direct mode (that is using only one voltage reference) at any frequency, and particularly, contrary to the expectation, the low frequency noise was not reduced by the second reference subtraction. Basically this suggests that the low frequency part of the noise spectrum originates from the bolometer itself and therefore can not be removed by subtracting a reference voltage located at a later stage of the electronics. Further analysis forced us then to adopt the direct mode as the nominal mode for FM in order to achieve the lowest noise level. However, this mode has not been tested enough at module level with respect to the electromagnetic interferences to ensure that it can really form the baseline for PACS science operations. The noise measurements during FM-ILT at Garching together with EMC measurements will be particularly important for this final decision.

Req. 1.1.0 VRL and VH_BLIND calibration

Objectives

To measure how the input signal (V_bolo) is carried out through the readout chain. This is a pre-requisite for all operations of the bolometers. Here the bias VRL is playing the part of the bolometer signal. We use the VDECX and CKRL biases to lock the readout circuit on the VRL bias (i.e. we ignore the signal coming from the bolometer, and the output signal will only contain the reference voltage signal). Using a set of VRL and VHBLIND values, we map the output signal as a function of VH_BLIND and VRL, thus building the (V_bolo, VH_BLIND, output signal) surface. These data will be necessary to compute the bias settings of VL, VH, VRL and VH_BLIND requested to adjust the readout electronics so that it can transmit the signal generated by the incoming flux.

This also allows to measure/monitor the gain and offset of the electronics.

Fulfilling or fulfilled by

Self-standing

Priority

A

When performed / frequency

At the beginning of any major test period or instrumental phase, i.e. when the instrument is switched on in an environment that has not been explored before, or after a significant hardware modification.

Required accuracy

As achievable by the about 2 minutes measurements in one parameter set.

Inputs, prerequisites

The VRL and VHBLIND parameter ranges are based on the tests performed at CEA Saclay.

Sources

None. Signals are entirely generated by the electronics.

Calibration Implementation Procedure (CIP)

These measurements have been performed since FM tests at CEA Saclay. This has allowed us to restrict the interesting parameter space to be explored to the following two sets of values:.

The first part is in low gain:

parameter	low gain bias set in volts
VH_BLIND	2.4, 2.2, 2.0, 1.8, 1.6
VRL	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6

The last part is in high gain:

parameter	high gain bias set in volts
VH_BLIND	1.8, 1.6
VRL	0.0, 0.1, 0.2, 0.3, 0.4

This implementation is valid for all phases, including PV phase.

Estimated time needed

In low gain we have 5×7 pairs of values and in high gain we have 2×5 pairs of values. Assuming 2 min per measurement gives a typical duration of 1.5 h.

Calibration Analysis Procedure (CAP)

The signals are converted into volts and some of the statistically significant values, such as the minimum, maximum, mean, average and median, are derived and some appropriate values are stored as a function of the two parameters VRL and VH_BLIND.

These data are then used as a 2D surface by interpolation in the determination of high gain biases (VH, VL, VRL and VH_BLIND) for operations (NEP measurements, optimal bias setting) in the double differential correlated sampling mode.

This is also a method to monitor the state of the electronics throughout the mission, with shortened versions of the test.

Output, products

(VRL, VH_BLIND, output signal) surface.

Status/version

Revised for draft 9 of the PCD (PV preparation version)

Req. 1.1.1 Control optimum pixel bias settings: [FM] Determination of basic bias settings to get signal within dynamic range

Objectives

To estimate the bolometer signal level (V_bolo) for the flux levels that the bolometers are exposed to, for a grid of polarization biases that we may want to use in operation. This is the first stage of the procedure that will identify the optimum biases and is mostly concerned with fitting the bolometer signals within the restricted readout electronics dynamical range.

Fulfilling or fulfilled by

Self-standing

Priority

A

When performed / frequency

At the beginning of any major test period or instrumental phase, i.e. when the instrument is switched on in an environment that has not been explored before, or after a significant hardware modification.

Required accuracy

Not applicable. The objective is to locate the level of the bolometer signal in low gain.

Inputs, prerequisites

FM filter transmission curves to compute the input fluxes from the OGSE black body sources, internal calibration sources, telescope and eventually astronomical sources.

measured or modelled emissivities of the OGSE black-body sources, calibration sources and telescope, or a calibration table that provides us with the flux of these sources in the different PACS bands.

-Ground phases: Science performance requirements to set the sensitivity objectives, prescriptions on the typical background and SED that the bolometers will be exposed to.

-In orbit: Assessment of the telescope temperature to compare the expected background to ground-based measurements. A pre-defined setting of the calibration sources temperatures such that their fluxes is known, and possibly comparable to the actual telescope flux.

Sources

- CQM : Calibrated black-bodies for ground-based tests (with or without chopper to modulate the signal).

- FM : Both of the OGSE black body sources are used, but without signal modulation. During FM-ILT, 7 flux levels (0 to 6 pW/pixel) on blue and 7 flux levels (0 to 6 pW/pixel) on red of OGSE BBs are needed.

- Orbit : The PACS internal calibration sources. In orbit we cannot play with the flux level, and there are no celestial calibrated extended (w.r.t the field of view) sources.

Calibration Implementation Procedure (CIP)

- CQM: *Note: this text refers to the CQM version of the requirement only. The requirement has seen major changes since then.* To determine the optimum biases, use a calibrated source and measure the noise level of the bolometers exposed to this source. Adjust the pixel biases so that the system gain is maximized while keeping the noise level within the specification. This includes also provision to make sure that no extra sources of noise are added. These biases should also allow for the existence of a relatively large linear operating range.

- FM: The gain is set to low, so that we can explore on one go a wide range of flux levels for a given Δ V = Vh - Vl without adjusting the VH_BLIND bias. The "direct mode" (see PACS photometer user's manual) is used for these measurements. The different values of VH_BLIND for different ΔV are provided by the results of the detector level tests at Saclay. The signal levels are measured without using the OGSE chopper wheel (static measurements). During measurements on one flux level, 24 different ΔV are explored. This flux level is delivered by one of the OGSE BBs, say BB1. The time for the 24 ΔV measurements is used to stabilize the next flux level delivered by the other OGSE BB, say BB2. This way the stabilisation time of the OGSE BBs is optimized. The same measurements are then repeated with the other blue filter and slightly different flux levels to sample still better the flux levels on the red detector. We also use ground-based calibrations to convert a polarization ($Vh - Vl$) into a pair of bias values (Vh, Vl).

- Orbit: We use the same philosophy except that now we can no longer choose the flux levels. We will therefore explore all flux levels available: 3 values for the red detector (CS1, CS2 and telescope) and six values for the blue detector (filter A+CS1, filter A+CS2, filter A+telescope, filter B+CS1, filter B+CS2, filter B+telescope). For each of these levels (red measurements are done simultaneously with the blue measurements) we observe a restricted version of the set of 24 polarization biases (Δ V = Vh - Vl) in staring mode.

Estimated time needed

In FM tests, the full measurement lasts 16 to 17 hours. The important aspect is to allow sufficient time for the system to relax after each bias change (and there are a lot of them). A typical measurement time for a given (flux+bias) configuration is 6 min.

Calibration Analysis Procedure (CAP)

- FM and Orbit: The signals are converted into volts and some of the statistically significant values, such as the minimum, maximum, mean, average and median, are analysed and some appropriate values are stored as a function of the ΔV and the flux.

The reduced signal values are used to compute the actual bolometer signal, V_bolo, using the (VRL, VH_BLIND, output signal) surface. Once the bolometer signal level is established for all input fluxes, the best values of VH_BLIND and VRL when the high gain is used in both "double differential correlated sampling mode" and "direct mode" can be determined, where the optimal here has to be understood as allowing an optimal fit in the BOLC dynamical range. In ILT we used to define this optimal position as the middle of the dynamical range. In space it will obviously be one of its edges so that more of the range is available for the sources' signal.

The computed bias voltages are then used to generate a CUS script for NEP measurements which require the high gain to sample correctly the noise through the digital conversion.

From these data, rough estimates of the responsivity can already be derived for each configuration, allowing to assess also the non-linearity (this is the so-called static response measurement, see test reports).

Output, products

The table of optimum pixel bias. Possibly a set of tables to account for different expected levels of background.

Status/version

Revised for draft 9 of the PCD (PV preparation version).

Revised again 04/02/08.

Req. 1.1.1bis Control optimum pixel bias settings: Determination of optimum bias settings for responsivity/NEP

Objectives

This requirement was added after FM tests at CEA Saclay. This is a logical step forward of the req.1.1.1 performed in low gain. The results of the req.1.1.1 in low gain allow us to compute a set of suitable basic biases (VL, VH, VRL, VH_BLIND) in high gain for a given input flux. This second part consists of measuring the response and the noise with 24 biases for a series of background flux levels, suited to the operational expectations (for FM tests, this is 14 fluxes, 7 for blue and 7 for red, in orbit this the telescope background and the calibration sources) in "direct mode" and in "double differential correlated sampling mode"(DDCS mode). The high gain is absolutely necessary to obtain a good sampling of the noise. The goal of these measurements is to determine the bias setting which gives the lowest NEP for a given flux level. The difficult part of the test is generating the small flux step needed for response measurement.

Fulfilling or fulfilled by

Self-standing. This requirement now completely fulfills requirement 1.1.12.

Priority

A

When performed / frequency

At the begining of any test campaign, but several days after req.1.1.1. low gain measurement, as these measurements neeed to be completely analyzed to compute the exact values of biases to set for the high gain run.

Required accuracy

Detector level tests show that 2 minutes of data per configuration provides enough accuracy. Including the time needed for stabilization after each bias change leads to 6 minutes per configuration.

Inputs, prerequisites

- FM filter transmission curves to compute the input fluxes from the OGSE black body sources, internal calibration sources, telescope and eventually astronomical sources.
- measured or modelled emissivities of the OGSE black-body sources, calibration sources and telescope, or a calibration table that provides us with the flux of these sources in the different PACS bands.
- Astronomical calibration sources (in orbit).
- The complete results of the low gain measurements (req.1.1.1)

Sources

- FM: Calibrated black-bodies for ground-based tests (with and without chopper to modulate the signal). During FM-ILT, 7 flux levels (0 to 6 pW/pixel) on blue and 7 flux levels (0 to 6 pW/pixel) on red of OGSE BBs are needed.

- Orbit: Contrary to the ground-based situation we operate mostly in a single regime, that where the background emission is dominated by the telescope. The sources we need then are astronomical calibration sources to measure the response.

Calibration Implementation Procedure (CIP)

- FM: The loops are in the following order:

```
Loop over fluxes:
  Loop over biases:
   measurements with OGSE chopper wheel rotating (0.25 Hz signal modulation)
   measurements with OGSE chopper wheel on the lowest of the BBs
```

These loops are executed first with the “direct mode” and then with the “DDCS mode”.

- Orbit: The only way to create a controled flux step for a pixel is to raster a point source on the array. If the telescope background is not too variable within the PACS field of view one can perform a raster of 8x4 positions (in order to place the point source at 4 different locations per matrix), while chopping a full field of view. This will create the flux step for the response measurement. If the telescope background is too variable within the field of view, the chopper is fixed at its optical zero and we simply perform the same raster a number of time to get statistics. For the noise measurement, a staring in an off position is sufficient. This has to be repeated for all the polarization bias values, in “direct” and “DDCS” mode.

In principle, we could be measuring the noise directly inside the raster. It is worthwhile but that does not give us access to the full power spectrum of the noise (because of the chopping). Thus each raster should be associated with a dedicated noise measurement, a simple staring with the chopper at 0 position.

Estimated time needed

2 entire cooler cycles on the ground, much shorter in space as we only explore the performance on the background level given by the telescope. The individual response measurement is much longer in space because we have to perform a raster, while on the ground we are simply chopping.

Calibration Analysis Procedure (CAP)

The data will be sorted out to measure the response and the noise at each configuration. Noise measurement are straightforward to process. For the response measurement one will need to perform point-source photometry. It is not important that the sources are really well calibrated as the measurement is made to identify the best setting, not necessarily the absolute value of the response.

The NEP derived from these 2 parameters is plotted against the bias showing the best bias to adopt at a given flux level. Again in orbit we have a very small number of flux levels, and no handle to modify them. The aim is mostly then to identify the best compromise so as to have a single setting for the blue and green filters.

Output, products

Complete set of response and noise measurements.

Status/version

Revised for draft 9 of the PCD (PV preparation phase)

Revised again - 04/02/08

Req. 1.1.2 Nominal responsivity

Objectives

Note: This requirement dates from pre-CQM versions. It is now completely superceded by the previous requirements.

The responsivity is the essential calibration factor between the measured output voltage of the readout circuit and the incident illumination power onto the detectors. The responsivity of the bolometers may be affected by cosmic particle hits, it may vary in time due to aging of the detector or modification of the operating temperature. It can also change because of a modification of the mean background level on the detector (the bolometers are non-linear detectors). The nominal responsivity value is determined for a given mean background level and range of observable fluxes.

Note that during the module tests (i.e. when the detectors are not yet included in the instrument), we will not be able to expose the bolometers to a radiation spectrum similar in SED to the one they will see in operations. Also during these tests, what will be measured is the responsivity of the detectors alone. This will be different from the responsivity of the full system (see corresponding requirement).

Fulfilling or fulfilled by

Self-standing.

Priority

A

When performed / frequency

- during individual detector tests
- during ILT
- during PV

Required accuracy

$<5\%$ (goal)

Inputs, prerequisites

- Relative system response to derive in-band power from source spectrum.
- Definition of the operating background level

Sources

- Ground: Black-body sources
- Flight: celestial standards
- Flight & Ground: Internal calibration sources. They are specified with a stability of ΔT/T$< 10^{-4}$, which should be enough for our purposes.

Calibration Implementation Procedure (CIP)

- CQM : In general this measurement is done by illuminating the detectors with a well determined in-band power and measure the output voltage. As the bolometers are operated differentially, here it will most likely consist of measuring a given power step over a background. And since the detectors are not linear, we will need to specify both the power step and the background level.

- **FM :** The test procedure is almost the same as in req.1.1.1 “Control optimum pixel bias settings”. The differences are : (1) use the high gain to sample correctly the noise, (2) do the static measurements for the noise measurements, (3) use also the chopper wheel to measure correctly the responsivity, (4) use both modes “bolometer - reference” and “bolometer only” to characterize the noise level for each mode.

Estimated time needed

Calibration Analysis Procedure (CAP)

- **FM :** Given the signal converted in volts and knowing the flux level of the OGSE blackbody, the responsivity is derived for each configuration. It is important to check the consistency by comparing these values with those from the low gain data.

Output, products

Nominal responsivity table, possibly given for various levels of the mean illumination since the detector is non-linear.

Status/version

Considered superceded by the previous requireement at draft 9 of the PCD (PV phase preparation).

Req. 1.1.3 Measure sensitivity variations inside the pixel

Objectives

To investigate the existence of sensitivity variations of a given pixel depending on the exact location where the peak of the flux falls. Although the size of the pixel with respect to the PSF should allow for an almost always nominal sampling, we cannot exclude these variations, especially for instance when the peak of the source falls very close to the pixel wall (since the wall's thickness is not negligible with respect to the pixel's width). These sensitivity variations, if they exists, modify the PSF, which in turn may have some impact on our photometric calibration.

Fulfilling or fulfilled by

At the full-system level, this will be fulfilled by the characterization of the detector PSF requirement (Req. 3.1.4 Photometer Point Spread Function).

Priority

B (could be C because it is hard to make).

When performed / frequency

In principle, this should start at the module level. However SAp does not foresee the availability of point sources in their local test equipment. In that case, this measurement will only be done at a later stage.

Required accuracy

$<$20% should be enough.

Inputs, prerequisites

none.

Sources

A point source delivering a constant power.

Calibration Implementation Procedure (CIP)

Perform rasters around a point source with sub-pixel or non-integer multiple of pixel step sizes. Note that due to the various pointing uncertainties during operations, we will probably have to solve simultaneously for the actual pointing and the sensitivity variation (this is in fact the PSF measurement CIP).

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

A map of the sensitivity variation inside a pixel (more a typical map than an average since we will not be able to make this measurement for all pixels).

Status/version

Revised for draft 3 of the PCD.

Req. 1.1.4 Monitor Nominal Responsivity Variations with Time

Objectives

Although Herschel does not have a fast orbit, we could expect a variation of the nominal responsivity (measured under constant illumination conditions) with such parameters as the time since last activation of the instrument, last recycling of the cooler, glitch rate, etc…

Fulfilling or fulfilled by

Self-Standing as photometric calibration measurements will probably not be done frequently enough to monitor that variation. However now that the FM detector modules have been integrated in the instrument, this requirement is fulfilled by req. 3.2.2.

In flight, this requirement is completely fulfilled by the calibration blocks that are present at the beginning of each observation.

Priority

B

When performed / frequency

At the module level tests, since after that we will not be able to adress the detector individually (it will be included in the instrument and thus we go to the full system section). Since we can expect to have variations in many of the test equipment subsystems, we will probably only get an indication of the possible responsivity variations at the detector level.

Required accuracy

$< 5\%$ (goal). This accuracy is driven by the final photometric accuracy we are aiming at.

Inputs, prerequisites

The nominal value of the responsivity.

Sources

Black-body sources. One could use the internal calibration sources as their specifications makes them stable enough for that purpose ($\Delta \mathrm{T}/\mathrm{T} < 10^{-4}$). However relying only on those implies that the detectors are already included in the complete instrument in which case we are dealing with a full-system requirement.

Calibration Implementation Procedure (CIP)

Repeat Nominal Responsivity measurements at predetermined points in time after *e.g.* switch-on, cooler recycling, …

Estimated time needed

Calibration Analysis Procedure (CAP)

In flight, and for regular observations, this is taken care of by the pipeline and the results should be available for trend analysis.

Output, products

Responsivity correction factors as a function of elapsed time since determined events (switch-on, solar storm, etc…).

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Revised again - 04/02/08

Req. 1.1.5 Monitor detector temperature variations with time

Objectives

After recycling, the temperature provided by the cooler will slowly increase (expected increase of temperature is 25 mK over the 46 hr of cooler operations). Furthermore activity in this instrument can dissipate heat. Since the detector temperature is not controlled, this can and will result in variations of the detector's temperature. In turn these variations of the temperature can produce a change in the offset and/or gain of each pixel. Since the whole instrument is temperature controlled, we do not expect that processes such as solar aspect angle will affect the temperature of the detector. We stress that this is mostly a "trend analysis" activity.

Fulfilling or fulfilled by

Temperature of the detector, as well as that of various sub-elements of the instrument is measured every 2 s and transmitted in the housekeeping data.

Priority

B

When performed / frequency

A soon as a focal plane is available.

Required accuracy

$\sim$1 mK since the total expected temperature drift over the 46 hr hold-time of the cooler is 25 mK.

Inputs, prerequisites

None.

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Trend analysis of the housekeeping data.

Estimated time needed

Monitoring activity.

Calibration Analysis Procedure (CAP)

Output, products

None apart from a specification on the reproducibility of the temperature drifts, or a statement that it is not, and alerts when the drifts are faster and/or of larger amplitude than expected.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.6 Calibrate the variation of pixel offset with detector temperature

Objectives

The variation of the detector temperature results in dramatic changes of the pixel offsets. Given that the two references used in the differential readout (VRL and VH_BLIND) are fixed, this offset variation is potientially present in the output signal.

We will want to study, and possibly calibrate, the variation of the pixel offset with temperature in order to be able to identify possible problems affecting individual pixels.

The difficulty of this requirement is that one cannot control the detector temperature.

Fulfilling or fulfilled by

Self-standing

Priority

B

When performed / frequency

Can start at module level tests, although we may only be able to get a first idea of the trend as (1) long measurements are always complex in ground-based test facility, and (2) there are many sources of perturbation on the ground.

Required accuracy

A few % on the drift amplitude over a timescale typical for a PACS observation.

Inputs, prerequisites

None.

Sources

Controlled illumination level to minimize all other sources of drifts. We could use the internal calibration sources since their stability specification appears adequate ($\Delta \mathrm{T}/\mathrm{T} < 10^{-4}$).

Calibration Implementation Procedure (CIP)

This will require switching the read-out mode of the bolometer to the direct mode so that the output signal is directly related to the bolometer signal.

- **FM :** We can use all small blocks of calibration data using CSs in “direct mode”. As this mode provides directly the offset, one can monitor its long term variation during the test campaign.
- **In Orbit:** We can also use the calibration blocks performed at the start of each observation. These will contain images on a constant input flux, possibly with a different detector temperature.

Estimated time needed

Most likely a long term activity as the drifts are slow. One could break down that measurement into smaller one conveniently placed in a longer period of time.

Calibration Analysis Procedure (CAP)

Output, products

Parameterized fits for the drifts, with assessment of uniformity over the bolometer matrices.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.7 Monitor cooler recycling frequency

Objectives

The internal cooler ensures that the bolometers operate at the required temperature. It has to be regularly recycled to function. The recycling frequency is basically related to the rate at which the detectors dissipate heat due to various processes and to the operational activities of the day. Measuring and monitoring of this frequency is essential (1) to define the typical length of a feasible astronomical observation, and (2) to make sure that the instrument is in a correct health situation. The nominal hold-time for the cooler is 46 hr, with a 2 hr recycling time, making for a 48 hr cycle. Aside from this recycling frequency, a number of parameters describing the process are also monitored

Fulfilling or fulfilled by

Self-standing.

Priority

A

When performed / frequency

A soon as a focal plane is ready. This is a monitoring activity that has to be performed on every cooler cycle.

Required accuracy

not applicable

Inputs, prerequisites

- The information needed will be present in the instrument housekeeping data. We need a system to access them efficiently.
- Documents describing the normal operations of the cooler (*e.g.* nominal hold time, . . .). The PhFPU user's manual is a good source for this information.
- Definitions of key "observational" parameters in the cooler recycling process and well as in its cold cycle (see CIP).

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

- Recycling process: We want to monitor the duration of the process as well as the value of some temperatures at key locations of the process. The starting point is defined as the time when the first command is sent (closure of the evaporator heat switch). The ending point is defined as the time when the evaporator temperature drops below 300 mK. The temperatures we want to monitor are: (1) the L0 mean temperature during the first 10 minutes of the process, (2) the peak pump temperature during the process, (3) then peak evaporator during the process, and (4) the evaporator temperature when the evaporator heat switch opens (i.e. drops below 13 K).

- Cold cycle: We want to know its duration. Its starting point is defined by the end point of the recycling process (i.e. we include the stabilization in the cold cycle). Its ending point is defined by the time at which the evaporator temperature reaches 320 mK, which triggers a warning.

All of the information is obtained from the housekeeping.

Estimated time needed

Not applicable, monitoring activity.

Calibration Analysis Procedure (CAP)

- **Recycling process:** Extract the housekeeping information for the recycling and manipulate it to obtain the data requested by the monitoring activity.
- **Cold cycle:** This requires some ingestion of housekeeping values in time ordered files/databases, independently of the actual operations during this cycle. The evaporator temperature is part of the essential housekeepings.

Output, products

Mostly a green light indicating that cooler operations are nominal, or an alert to investigate a potential problem.

Status/version

Revised for draft 9 of the PCD (PV phase version).

Req. 1.1.8 Measure bolometer time constants after switch-on

Objectives

During normal operations, the instrument will be regularly switched on and off (mostly to allow the cooler to recycle, and when HIFI is used). This process may generate long-term variations of such quantities as the bolometer gains, or offset drifts. The time constants for these variations will have to be measured in order to define the minimal time after switch-on at which operations can start, or correct for the drifts.

It is expected that the value of these time constants are such that 30 min after switch-on, the detector is in its nominal operating mode. The transtion time from switch-on to nominal mode can thus be absorbed within the cooler recycle procedure.

Note that in some cases, it may be difficult to trace drifts directly to the switch-on process as a number of other sources may lead to drifts in the detector properties.

Fulfilling or fulfilled by

Switch-on of the detector will always occur. Monitoring the detector during that time is also likely to occur at all times.

Priority

A. Needed at least to define when to start using the instrument after switch-on and to validate that the allocated cooler recycle time covers the establishment of a nominal regime for the detector.

When performed / frequency

Measurements can be done as soon as we have an operating model of a focal plane. They will have to be repeated each time a new model of the instrument becomes available, and of course after launch. Possibly they should be repeated regularly to monitor the health of the instrument.

Required accuracy

One of the accuracy driver is the one we achieve on the nominal responsivity. Another driver is the one we achieve on the calibration of offset drifts with respect to detector temperature.

Inputs, prerequisites

None.

Sources

We need sources of constant flux to monitor the detector noise and responsivity. This can be the internal calibrators as they are stable enough, or a reference section of the sky. There is one caveat to the use of internal calibrators: after their own switch-on, they have a time constant of $\sim$15 min. If they are switched off, or if the detector switch-on is too close to the internal calibrators one, then they cannot be used for this requirement.

Calibration Implementation Procedure (CIP)

Switch on the instrument while chopping between two reference, preferably extended, sources of light.

Estimated time needed

1/2 hr to 1 hr to completely follow the settling of the detector to its nominal settings.

Calibration Analysis Procedure (CAP)

Straightforward, the establishment of the signal is fitted to obtain its time constant.

Output, products

Either provision of minimal operating time after switch-on or correction tables for the gain and possibly the offset as a function of time since switch-on.

Status/version

Revised for draft 9 of the PCD (PV phase version).

Req. 1.1.9 Measure time constants after cosmic ray impact

Objectives

The expected cosmic ray hit rate is currently estimated at 1 impact per pixel every 10 minutes (TBC). Though this is not very large, we will have to investigate the effect of these impacts on the detector and in particular see how long the detector (or more likely a pixel) takes to relax to its nominal state after a glitch. Current computations indicate that the time constants for the relaxation are very fast (typically 10-20 ms). Measuring them will require operating the instrument in the so-called buffer transmission mode, where no coaddition of frame is done and only a fraction of the recorded data is downlinked.

Fulfilling or fulfilled by

Self-standing since it requires a dedicated operating mode for the instrument.

Priority

A. It is of priority A to check that the time constants are indeed very short and that the hit-rate is as expected. It is of priority B to actually measure the time constants since currently we probably do not need to correct for glitches, but will simply remove or mask the affected readouts.

When performed / frequency

Prior characterization on the ground is preferrable, although it may be hard to implement during the ground-based calibrations. A detector similar to the PACS detector has been exposed to an accelerator beam, the complete instrument has not.

Required accuracy

$<$10-20% on the time constant should be sufficient.

Inputs, prerequisites

none.

Sources

Light sources are not the most important aspect of this requirement. However it is preferable to make this measurement while observing a source of constant illumination to minimize all possible variation sources. The internal calibration sources are perfectly suitable for that.

Calibration Implementation Procedure (CIP)

Observe a source of constant illumination, switch the detector downlink mode to the buffer transmission mode and wait for particles to hit the detector.

Estimated time needed

Integrate until sufficient glitch statistics have been accumulated (depends on the actual glitch rate).

Calibration Analysis Procedure (CAP)

Locate the particle impacts. Categorize them (those that affect single pixels, those that affect the whole array, positive impacts, negative impacts). For all these categories, fit the decaying signal with exponentials to extract time constants. Obtain statistical information on the glitch rate, deposited energy, etc.

Output, products

- The range of values for the pixel time constants (as they may differ from pixel to pixel and we may not be able to measure them all).

- A prescription on how to handle glitched data (discard or correct).
- An estimation of the noise component due to glitch impacts.

Status/version

Reviseed for draft 9 of the PCD (PV phase preparation).

Req. 1.1.10 Measure time constants after a flux change

Objectives

Although the bolometers are fast detectors, flux changes, such as those induced by chopping, are not immediately followed by a corresponding change in the read-out value. We will need to measure the value of these time constants to estimate the highest possible chopping frequency as well as the fastest scan speed, or more generally the impact of this finite time constant on the gain in chopped observations and on the spatial structures in scanned observations. We will also investigate whether the time constants are identical for an increasing or a decreasing flux change (i.e. do we observe the same kind of memory effects that photoconductors exhibit). Finally the dependence of these constants on the amplitude of the flux step will be characterized.

Currently these time constants are estimated to be $\sim$40 ms. This is too fast to be measured in the normal operating mode of the photometer where frames are coadded on board so we will need to operate in the buffer transmission mode where all frames are downlinked but only for a fraction of the recorded time sequence.

Fulfilling or fulfilled by

Self-standing since it requires a special operating mode for the detectors. Note that due to the CIP, this requirement now completely fulfills requirement 1.1.16.

Priority

A. We need to know these constants to correctly design the observing templates, i.e. this forms part of the instrument bias optimization.

When performed / frequency

As soon as detectors are available as this is a key element in the design of the observing templates. Will have to be monitored regularly, including in-flight to detect possible changes in these time constants. One should also remember that bolometer time constants depend on the polarization level of the bolometers (the higher the bias, the smaller the time constant).

Required accuracy

$<$10-20% on the time constant value should provide enough information.

Inputs, prerequisites

none

Sources

At least two different levels of illumination. More would be better to investigate the dependance of these time constants on the flux level. A fraction of this requirement can be performed with the internal sources only (using for instance the two blue filters to create more than one flux step).

Calibration Implementation Procedure (CIP)

- **Ground-based:** Set the OGSE sources to two different flux levels (typically separated by less than 1 pW/pix). Chopping is preferentially performed with the OGSE chopper as this allows it to be asynchronous with the detector readout (and leads to a better sampling of the time response). However fast chopping is only possible with the internal chopper (we chop between one calibration source and the neighboring open field of view) which is always synchronous with the readout process.

  For a selected range of bolometer polarizations (VH$-$VL), for a selected range of flux steps, we explore the effect on the recorded signal of increasing the chopping frequency.

- **Orbit:** We no longer have the possibility to choose the flux step, and we have to use the internal chopper. We can make two different flux steps by chopping between the open field of view and either CS1 or CS2 (for the blue side this can be multiplied by two by the filters).

All these measurements have to be done in buffer transmission mode and in the two readout modes ("direct" and "DDCS") if they are still considered for operations.

Estimated time needed

Quite long (i.e. 10-20 hr) if we want to investigate different flux levels and also considering that in buffer transmission mode we essentially get no data for most of the observing time.

Calibration Analysis Procedure (CAP)

A simple method consist in recording the signal amplitude as a function of chopping frequency. This allows the derivation of the time constant. A more complex method uses the asynchronous chopping to reconstruct the modulated signal at high sampling rate and studies its convolution with the bolometer low-pass filter as a function of chopping frequency.

Asymetries in the upward-downward transitions have to be explored. One should take care that the intrisic modulated signal may not be symetric.

Output, products

Mostly prescription on the observing templates.

Status/version

Revised for Draft 9 of the PCD (PV phase preparation).

Req. 1.1.11 Measure the low frequency noise

Objectives

The low frequency component of the noise is important to measure because it has impact on the ultimate sensisitivity that can be reached with PACS and also on the design of the observing templates (*e.g.* it defines the longest chopper plateau available). Its behavior also needs to be characterized as this has impacts on the data reduction strategy. This requirement now covers a measurement of the complete noise spectrum rather than strictly its low frequency part.

Note added for the FM: We need to measure in both “direct mode” and “DDCS mode”, since this measurement lead us to reconsider “direct mode” during the tests at CEA Saclay. The confirmation during ILT is needed to state that “direct mode” gives less noise than “DDCS mode” at any frequency and without any electromagnetic perturbation.

Fulfilling or fulfilled by

Experience shows that dedicated measurements provide better results.

Priority

A

When performed / frequency

As soon as a focal plane is available. To be repeated with all instrument models that have detectors in them as well as in-flight.

Required accuracy

Measurements smaller than 1 hr have a high risk of not providing enough data a low frequencies.

Inputs, prerequisites

None.

Sources

Stable source, preferably flat. The internal calibration sources can be used for that as their stability specification is strong enough. Due to the different emissivity of OGSE black body sources from that of the telescope and CSs, we need to set a different temperature for the blue detector and for the red detector.

Calibration Implementation Procedure (CIP)

Just measure a reasonable flux level from a source at least for a reasonable amount of time (good measurements last at least 3 hr). This most be done for the 2 readout modes and for 2 flux levels (blue and red).

Estimated time needed

$4 \times (\sim 8 \text{ hours}) \simeq 32$ hours

Calibration Analysis Procedure (CAP)

A large data file should be divided into several files of reasonable size (for the memory usage and for the longest duration in each file). After deriving a power spectral density (PSD) through FFT for each sub-time-intervall, all PSDs are averaged to improve the signal to noise ratio. We get a clean PSD per pixel.

Output, products

Prescription on the observing modes. Limit on the ultimate sensitivity.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.12 Measure the bolometers noise equivalent power (NEP)

Objectives

The Noise Equivalent Power (NEP) is a crucial piece of information that is used to estimate the science capacities of the instrument. The NEP will must be measured as early in the development of the instrument as possible to allow for efficient science planning and for the development of such tools as the time estimator. This NEP must also be determined under typical operation conditions. The NEP should be measured separately for the blind and the sky pixels to obtain the best handle on the different noise sources. One could also measure the noise level on the reference polarisation (output voltage from the bolometer), however, by doing so one risks adding additional noise on the line that sets this polarisation.

Post CQ note: The blind pixels are no longer used. No NEP measurements are to be performed on the blind pixels.

Fulfilling or fulfilled by

This requirement is now completely fulfilled by requirement 1.1.1bis.

Priority

A. Mandatory for science planning

When performed / frequency

Measured as soon as detectors become available, then for each instrument model containing detectors. Measured again regularly in-flight to check for possible degradations of the detector quality.

Required accuracy

Driven by the requirement on the achieved photometric accuracy.

Inputs, prerequisites

The following inputs are needed to properly prepare the CIP.

- The non-linear region of the detector response (PCD requirement 1.1.13).
- The time-constant after a flux change (PCD requirement 1.1.10).
- The 1/f noise (PCD requirement 1.1.11)

Sources

Two calibrated illumination sources that provide a constant (with time) level of input flux. Either the OGSE blackbodies or PACS internal calibrators are adequate for this purpose.

Calibration Implementation Procedure (CIP)

In a nutshell, one requires a well-calibrated illumination source, knowledge about the optical throughput of the instrument and detector efficiencies to estimate the NEP. When the optical throughput of the instrument is not well-known – as is expected to be the case for PACS OGSE –, the NEP is typically measured in laboratories by chopping the bolometer between a “cold” and a “hot” source. Provided the relative and absolute source fluxes are known, the differenced signal between the “hot” and “cold” source is used to calibrate the instrument and proceed with NEP estimation. Fortunately, two such sources are available with PACS (two grey-body calibration sources) and in the OGSE (two black body sources). Either pair of illuminators is sufficient for this experiment. For ground-based measurement, the OGSE setup is more practical while the internal calibrators are better suited for in-flight measurements.

To measure the NEP, one calibrator should be set to about 70 K (TBC), or close to ambient telescope temperature. The second blackbody should be set to 90 K (TBC). The chosen setting must provide flux levels that avoid the non-linear region of the detector’s dynamic range (input from PCD 1.1.13). The settings should be changed or tweaked to ensure this is the case. The bolometer is chopped between the two flux sources. The minimum integration time for each pointing is set by the time-constant after a flux change (input from PCD 1.1.10) and should be chosen to avoid non-linear part of the response and to allow the bolometer signal to stablize. The maximum integration time for each pointing should be such that 1/f noise does not become significant (input from Req. 1.1.11). The integration time per pointing which satisfies both these requirements thus determines the chopping frequency. Repeat the measurements for both blue filters.

The CIP described here is for a simple chopped observing, which is likely to be the most commonly employed observing mode. However, the achieved Signal-to-Noise Ratio (SNR), and hence the NEP, will likely change is the observing mode is changed. Thus, the measurements must be repeated for each of the other observing modes of PACS for the detector subsystem. The CAP for each observing mode (see below) will remain the same.

- **FM :** The first rough measurements of the NEP are done by req.1.1.1bis in the framework of searching for the bias that provides the best NEP. A more accurate result should be obtained from req.3.2.4 the linearity data and req.1.1.11 the low frequency noise data, assuming that the noise and the responsivity are stable from one cooler cycle to another.

Estimated time needed

Calibration Analysis Procedure (CAP)

The following expression can be derived from the definition of the NEP (see e.g. Rieke 1996):

$$\mathrm{NEP} = \frac{P_s(2T)^{1/2}}{S/N}$$

Where, P_s is the (calibrated) signal power incident on the detector, T is the integration time, and S/N is the measured signal-to-noise ratio of the detector.

The S/N actually achieved for a given P_s will likely depend on specific measurement strategies. This expression thus allows a relative NEP comparison between different PACS observing modes.

If the input signal is uncalibrated, then the (known) relative difference between the "hot" and "cold" calibrator must be used to calibrate the input signal.

Output, products

Values of the NEP for the different instrumental set-ups.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.13 Calibrate the detector non-linearity

Objectives

For large flux dynamics, the bolometer arrays are highly non-linear (the higher the flux level, the smaller the measured signal for a given input). We need to make sure this non-linearity is well calibrated although we will try to operate in regions of flux where a linear approximation is correct. This non-linearity calibration will have to be used when observing very bright sources (possibly planets) and even some of primary calibrators (Uranus inputs as much power on the array as the background).

Fulfilling or fulfilled by

As soon as the bolometers are integrated in the focal plane unit, there is no distinction between this requirement and requirement 3.2.3.

Self-standing, however since FM, a first rough estimate of the non linearity can be derived as a by-product of the req.1.1.1, when a set of very different flux levels (0 to 7 pW/pixel) are observed at low gain. The measurements at high gain in req.1.1.1bis provide a more accurate result on the non linearity. Given that in flight we can not fulfill these requirements at the same depth, it will become self-standing again.

This is unfortunately restricted to ground-based tests only, since in space we cannot play with the background flux. We thus have to rely again on a carefully selected series of celestial calibrators to explore the range of fluxes at which the detector becomes non linear.

Priority

A.

When performed / frequency

As soon as detectors become available.

Required accuracy

Driven by the photometric accuracy we wish to achieve.

Inputs, prerequisites

None

Sources

- **On the ground:** a set of sources with well-known fluxes covering a representative dynamical range, as well as a set of background levels covering a very wide dynamical range. This is rather easily achieved with the OGSE sources.

- **In space:** A simplifying point comes from the fact that, per filter, we only have one background value (imposed by the telescope). Thus we "only" have to identify a list of sources of increasing flux. Ground-based tests should be used to avoid selecting sources that are "too faint" for the non-linearity to manifest itself.

Calibration Implementation Procedure (CIP)

On the ground, the CIP is completely described in req. 1.1.1 and 1.1.1bis. In flight we will need to observe a series of sources covering a range of input fluxes. It is more than likely that saturation of the BOLC dynamical range will occur before non-linear effects can be detected. The best set-up for this measurement is thus to perform it fully in low gain.

To effectively separate the effect of non-linearity from the possible gain drift, one should monitor the gain using the calibration sources. The simplest is thus to program each source measurement as a point-source AOR since it includes a calibration block.

Estimated time needed

Individual measurements should last typically 5 minutes. This has to be multiplied by the number of sources on the flux scale. Then it has to be multiplied by the number of detector biases one wants to explore (not forgetting the stabilization time after bias change, or order 2-3 minutes).

Calibration Analysis Procedure (CAP)

On the ground, this is part of req. 1.1.1 and 1.1.1bis analysis. In orbit this will consist in making the photometry of the observed sources.

Output, products

For each pixel a relative linearisation curve. These curves are normalized to give 1 for the range of fluxes we will have selected as the operating range. Possibly the prescription that for a range of fluxes, the non-linearity can be neglected.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Revised again - 04/02/08

Req. 1.1.14 Establish the detector linearity

Objectives

Although the detector is globally non-linear, for small flux changes around a mean value, it can be considered as linear. In principle we will work under this linearity assumption. We will therefore verify that for the expected range of observed fluxes, the detector indeed behaves linearily.

Fulfilling or fulfilled by

In FM-ILT, the req.1.1.1 and req.1.1.1bis provide a measure of the non linearity. For completeness, a dedicated could be implemented for the linearity to explore more accurately a small flux differences, however the non-linearity is small enough that it is likely that the limited accuracy on the input flux control will completely mask the effect we are looking for.

In flight, this requirement could be fulfilled by req.1.1.13 provided we use a suitable list of calibrators and switch to high gain. For the sake of scheduling simplicity, it is probably better to separate the two measurements.

Priority

A. This is one of the basic assumption for the bolometer operations.

When performed / frequency

As soon as detectors and a controlled source of light become available. Will have to be repeated for each model of the instrument with detectors, as well as in-flight. Should be repeated regularly, more frequently than the non-linearity measurement.

Required accuracy

The accuracy here is driven by the final photometric accuracy required.

Inputs, prerequisites

The calibration of the bolometers' non linearity has been performed, and the range of operational backgrounds and fluxes has been selected.

Sources

Sources with well controlled fluxes falling in the interval defined as the operational one, over a background corresponding to the operational one.

- **FM :** OGSE BBs are used. One of BBs gives a background level and the other a source level. This latter goes from the background level till 0.5pW/pixel larger with 10 steps in logarithmic scale. The OGSE BBs temperature should be chosen independently for the blue and for the red detector.
- **Orbit:** a set of astronomical calibrators defining a flux scale representative of Herschel's science targets.

Calibration Implementation Procedure (CIP)

Measure, with identical observing set-up, a set of sources with different fluxes although all within the operational range, all over the operational background. If possible slightly change the background to search for maximal allowed background change. On the ground this can be achieved by chopping between a reference and an adjustable black-body.

- **FM :** These tests are done at "direct mode". The OGSE chopper wheel is rotating to provide 0.25 Hz signal modulation. The blue filter of 110 μm is set. Increase the temperature of one of the OGSE BBs step by step and make a data acquisition of 5 minutes at each step. Then set the OGSE BBs for the blue detector flux level and do the same procedure.

- Orbit: A series of point-source AOR measurements are performed on a list of sources of well-known flux in the PACS bands. These AORs include a calibration block that allows for gain drift monitoring.

All these measurements are performed in high gain.

Estimated time needed

7 hours during ILT. Possibly more in orbit as the sources will not all be in the same region of the sky.

Calibration Analysis Procedure (CAP)

- FM: Check that the measured signal differences scale linearly with the input flux step.

- Orbit: Perform source photometry and check that the measured signal scales linearly with the known source flux.

Output, products

Certification that the detector is linear within the operating range.

Status/version

Revised for Draft 9 of the PCD (PV phase preparation).

Revised again - 04/02/08

Req. 1.1.15 Establish the relative positions of the individual matrices.

Objectives

The detectors are made of 2 and 8 16×16 sub-matrices. In principle, CEA/LETI will align them with an accuracy better than 1/10$^{\mathrm{th}}$ of a pixel in both the line and column directions (typically $\pm 40\,\mu$m). At room temperature this relative positionning will be measured at CEA/SAp with an accuracy of 1 μm. A measurement at operating temperature will not be possible on the QM or FM.

These values are important to consider when reconstructing the images. In case we use an iterative process to reconstruct scan maps, the exact geometry of the detector array can become of quite high importance.

Fulfilling or fulfilled by

This requirement strictly covers the part that can be done at detector level, i.e. before assembly in the PhFPU. In the complete instrument, it will be impossible to distinguish measures this indepently from optical distorsion and this requirement becomes fulfilled by requirement 3.1.3.

Priority

B. The laboratory measurement will probably be a good enough approximation of the real alignment.

When performed / frequency

On the ground since the pixels are almost macroscopic but only at room temperature. We cannot exclude that individual matrix expand/contract/rotate differently with respect to one another. Measured again in-flight as part of the optical distortion.

Required accuracy

$<$ 1/10 of a pixel in order not to be the dominant source of uncertainty in the optical distortion determination.

Inputs, prerequisites

None.

Sources

None.

Calibration Implementation Procedure (CIP)

Measure the position of the matrices with the high-tech equivalent of a ruler.

Estimated time needed

Not applicable

Calibration Analysis Procedure (CAP)

None

Output, products

In-plane displacement and rotation for each sub-matrix with respect to the spacecraft axes.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.16 Measure the signal dependance on chopping frequency

Objectives

Since the detector responds to a flux change with certain time constants, it may be that for high chopping frequencies, we only explore a part of the actual detector response. This translates into an effective gain which is less than the nominal one. We therefore need to calibrate the possible variations of the gain as a function of the chopping frequency. Note that this requirement may lead to the definition of the maximum chopping frequency allowed.

Fulfilling or fulfilled by

This requirement is now completely fulfilled by requirement 1.1.10.

Priority

A. This is in the chain leading to the photometric calibration of the data produced by the bolometers.

When performed / frequency

As soon as detectors and a source of relatively controlled illumination become available. Then repeated for all instrument models with detectors. Finally perfomed regularly in-flight as a health-monitoring activity.

Required accuracy

Driven by the accuracy we wish to reach for the final photometry.

Inputs, prerequisites

Sources

A well calibrated source on top of a background, both constant with time.

Calibration Implementation Procedure (CIP)

Perform chopped measurement on the source with varying chopping frequency.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Either a table giving the gain corrections as a function of the chopping frequency or a prescription on the acceptable chopping frequencies for PACS.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.17 Measure the level of optical cross-talk in the detector

Objectives

Optical cross talk happens when light falling on a pixel actually manages to leak out (silicon, which makes up the pixel walls, is still quite transparent) and gets trapped in a neighborhing pixel. This will be hard to measure and distinguish from ghosts on the illuminated part of the array, as well as from the actual shape of the PSF.

Fulfilling or fulfilled by

Will probably have to be investigated in conjunction with ghosts. Measurements where a point source is scanned all over the array (typically requirement 3.1.3, photometer field of view distorsion).

Priority

B as it will be hard to distinguish it from ghosts and from the actual shape of the PSF.

When performed / frequency

Start at instrument level tests as we need a point source. SAp does not intend to include in its test facility a point source simulator.

Required accuracy

typically $< 5\%$ of the background level.

Inputs, prerequisites

None.

Sources

A bright point source to avoid uncertainties linked to small signal-to-noise ratios.

Calibration Implementation Procedure (CIP)

Observe a source at as many different locations on the array as possible.

Estimated time needed

This is typically counted in hours.

Calibration Analysis Procedure (CAP)

First reconstruct the expected position of the source at any time during the observation. Then search for signal variations outside of these expected locations that are simultaneous with actual source motions. Note that if these are detected on the same bolometer channel, there are likely due to electrical cross-talk.

Output, products

If possible a cross-talk matrix to be able to correct for it.

Status/version

Revised for Draft 9 of the PCD (PV phase version).

Req. 1.1.18 Measure the level of electrical cross-talk

Objectives

Since signal from different pixels is carried outside the cryostat in wires that are attached together, mutual influence between these wires could in principle exist. Furthermore, pixels are multiplexed along readout channels and this is know to create mutual influence between pixels that follow each other in the readout sequence. Measure the level of this effect.

Fulfilling or fulfilled by

In principle, the measurement is the same than that for straylight and ghosts measurement since is typically involves moving a source on the array to look for correlated signal on the matrix. Therefore the measurements requested for this study are partially made in requirement 3.1.3, although dedicated measurements are proposed (see CIP)

Priority

A. Electrical cross-talk is observed so we need to quantify it.

When performed / frequency

As soon that we have detectors and a movable point source. Repeated for every instrument model with detectors and in-flight.

Required accuracy

$< 1\%$ of the background which is still large compared to the astronomical sources.

Inputs, prerequisites

None.

Sources

A set of bright sources, or at least a structure with sharp edges

Calibration Implementation Procedure (CIP)

Scan a set of bright sources and look for “ghosts” appearing on pixels whose output is coupled to that of the most illuminated pixel.

Alternatively, one can use the sharp edge that exist between the calibration sources and the open field of view. These two edges are scanned back and forth on the array (we use both edges and both scan direction to eliminate all ambiguities that could be related to the unknown intrinsic shape of the flux transition). This only allows to identify electrical cross-talk in the channel direction of the detectors, the advantage being that the measurement is completely internal to PACS. Exploring the perpendicular direction requires external sources and many pointings.

The level of channel cross-talk is know to be related to the polarization of the detectors. Therefore the measurements should be repeated with different polarizations to identify the one minimizing the cross-talk.

Estimated time needed

Less that 1 hr if only the internal measurement is performed. Probably longer than that if one has to scan a source on the array.

Calibration Analysis Procedure (CAP)

Similar to the analysis of the optical cross-talk. Reconstruct the actual flux history and look for pixels that see this flux history simultaneously with others.

Output, products

At zero level, the polarization that minimize the effect and a map of the affected pixels. A more elaborated product is a cross-talk matrix to correct the read-out signal.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.19 Measure the detector global resistance

Objectives

The global resistance of the detector is our indicator to check that no pixel has gone into a short-circuit. When that happens the global resistance of the detector changes dramatically. The incriminated pixel also heats a lot which may be a danger for the rest of the instrument.

The global resistance is measured through the amount of current that goes to the detector (measured per matrix for the red channel and per couple of matrix for the blue channel) and the value is placed in the housekeeping data. It is the responsibility of the on-board software to monitor this value and accordingly switch-off the incriminated detector should it go beyond its nominal range.

Once a pixel goes into short-circuit, there is no way to recover it and the corresponding array has to be permanently shut down.

Fulfilling or fulfilled by

Monitored regularly on-board.

Priority

A. Basic safety measure.

When performed / frequency

starting at PV.

Required accuracy

10-20% (TBC).

Inputs, prerequisites

The nominal value for this current.

Sources

none.

Calibration Implementation Procedure (CIP)

monitor the housekeeping data.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

safety warning when necessary.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.20 Measure the level of correlated noise on the detector

Objectives

Correlated noise is noise, since it appears as random, unexpected time variations a pixel readout, but that appears simultaneously on all pixels of the array (or on series of pixels that are not optically or electrically connected). Correlated noise will not disappear when pixels are averaged. In a complex environment such as the PACS one, there are many source that could create correlated noise on the array. We need to measure the level of this noise component as it affects the ultimate sensitivity of the instrument.

Fulfilling or fulfilled by

self-standing, although the measurements required are covered by requirement 1.1.11.

Priority

It is of high priority to make sure that this noise component is very small compared to the other sources of noise. If this is true, then quantifying the level of correlated noise is not necessary.

When performed / frequency

As soon as detectors are available.

Required accuracy

This will depend on the level of other noise sources. Typically this level should be less than 10% of the high frequency noise.

Inputs, prerequisites

none

Calibration Implementation Procedure (CIP)

Correlated noise should in principle occur in any experiment if it is there. It is probably easier to search for it when observing a flat source as correlations may be hard to evidence, or be confused with cross-talk in complex fields. Low-frequency noise measurements are ideally suited for this investigation.

Estimated time needed

Not applicable

Calibration Analysis Procedure (CAP)

Perform correlation analysis of noise characterization data.

Output, products

Hopefully a prescription that this noise component is negligible.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.21 Self-calibrate the responsivity of the detectors

Objectives

With the blind pixels and the internal calibrators, there is a possibility to self-calibrate the detector. If we can trust the flux from the internal calibrators to be constant through time then one can use the heater on the blind pixels to search for the voltage required to match the power going through the blind pixels to that falling on the open pixels. This directly gives the conversion from volts to power of the detector.

To be suitable for absolute calibration of the detector, this experiment requires that the internal calibrators do not degrade through time. At the minimum however, it can serve as a health check on the detector+internal calibrators system.

Fulfilling or fulfilled by

Deprecated, blind pixels are no longer accessible in the FM version of the instrument, and this self-calibration feature can no longer be used.

Priority

C - This is more a “nice to have” rather than an absolute priority. It should however be tested as it provides a rather rapid way of deriving the absorption coefficient and of chcking the responsivity.

When performed / frequency

Once the instrument is assembled since we need to have the internal calibrators.

Required accuracy

Following the accuracy quoted in req. 1.1.2, this should be $<5\%$.

Inputs, prerequisites

The internal calibration sources should be well calibrated so that the power falling on the detector can be computed with a sufficient accuracy. The responsivity derived in req. 1.1.2 is used for the consistency check.

Calibration Implementation Procedure (CIP)

The “self-calibration method” allows to measure the absorption coefficient and the responsivity. For this purpose, the internal calibration sources are used with their corresponding chopper positions. The following procedure is iterated for 2 internal calibration sources of different temperature and optionally for 2 blue filters.

- ** Loop on different heater voltages **
- Set a voltage of the blind pixel heater
- Data acquisition
- ** End of loop **

The blind pixels are downlinked independently together with the active pixels. The voltage values in the loop must be chosen to obtain blind pixel output values going down or up through the average ouptput value of the active pixels.

- Knowing the source flux F received by a pixel, the absorption coefficient α is derived by $\alpha = E/F$, where E is the thermal energy provided by a blind pixel heater with its current I and its voltage V, so $E = VI$.
- Then the responsivity R is derived by $R = \alpha(v_2 - v_1)/(E_2 - E_1)$, where v is the output voltage of the bolometer and the indices indicate the 2 calibration sources of different temperature.

Estimated time needed

Calibration Analysis Procedure (CAP)

First the absorption coefficient is derived, which is then used to derive the responsivity. The result is compared with the value obtained in req. 1.1.2.

- The data must be reduced separately for the blind and active pixels.
- Find by interpolation the voltage V and the current I of the blind pixel heater which give the value of the active pixels illuminated by an internal calibrator.
- Compute the absorption coefficient α by $\alpha = VI/F$ where F is the flux falling on one active pixel.
- Compute the responsivity R by $R = \alpha(v_2 - v_1)/(V_2 I_2 - V_1 I_1)$
- Check if this result is consistent with the value obtained in req. 1.1.2.

Output, products

The detector responsivity.

Status/version

Revised for draft 9 of the PCD (PV phase preparation).

Req. 1.1.22 Measure the relative system response of the detectors

Objectives

In order to be able to make the appropriate color corrections to the large bands of the photometer, we need to characterize the relative system response of all its component. This requirement deals with the bolometer. The aim is to determine the absorption efficiency as a function of wavelength. The normalization of this response is arbitrary.

Fulfilling or fulfilled by

Self-standing. However this is only feasible on bolometer focal planes before they are integrated in the focal plane unit. After that stage, this requirement becomes indistinguishable from requirement 3.2.5 on the full system.

Priority

A. Measuring a global relative response of the full instrument may be hard to do, and we may have to build it from the individual elements.

When performed / frequency

At module level if possible otherwise it may be very hard to access the real bolometer relative system response.

Required accuracy

$<$10% rms

Inputs, prerequisites

none

Calibration Implementation Procedure (CIP)

The light of a 900 K source is sent into a Fourier Transform Spectrometer. In a first setup, the light coming out of the spectrometer is reflected on a mirror and is then recorded by a reference detector. We thus get a first interferogram corresponding to the spectrum of the 900 K source. We then perform a second measurement where the mirror before the detector is replaced by a PACS matrix. We record a new interferogram of the spectrum of the 900K source. The PACS matrix is not switched on during the measurement.

Estimated time needed

Calibration Analysis Procedure (CAP)

With a fourier transform we recover the two spectra. In the first case, the spectrum S_1 measured is that of the source multiplied by (1) the response of the FTS, (2) the response of the reference detector and (3) the reflectivity of the mirror (1 at all wavelengths of interest). In the second case, for spectrum S_2, (3) is now the reflectivity of the detector.

Given the instrumental setup, what is not reflected is absorbed so the relative subsystem response is ($1-S_2/S_1$).

Output, products

A table of normalized response as a function of wavelength.

Status/version

Added for version 3 of the PCD. Revised for version 9 of the PCD (PV phase preparation).

1.2 (Stressed) Ge:Ga Photoconductor Arrays

This Section describes calibration requirements for the spectrometer that deal with the characterisation of instrumental effects that are best or exclusively performed by on-ground tests at a modular or instrument level.

Most requirements deal either with

- the detectors or the CRE, or
- the effect of ionizing radiation

The first item covers requirements related to e.g. the linearity of the CRE, optimum settings for the detector bias and temperature, responsivity, responsivity, NEP, etc.

The second item covers the effect of ionizing radiation on the responsivity, dark current, noise properties, etc, as well as the feedback of ground-tests on the development and testing of de-glitching and ramp fitting numerical routines for the OBSW.

The effects of space radiation effects are an important effect to consider. A particle that hits a photoconductor deposits an amount of energy that depends on the type of particle, the detector material, and the length of the particle track.

The "ISO/FIRST Glitches Working Group, Final Report" (2001) describes how these effects have been handled in the reduction of ISO data, and makes recommendation for future missions, in particular FIRST/Herschel. Among their recommendations are: (1) that ground tests are mandatory to test the detector response and compare it to predicted ones ... and to confirm that deglitching and other algorithms for radiation background removal operate correctly, (2) detailed particle simulation analysis should be carried out before launch ... that should not only take into account protons, but also electrons, and secondary particles produced in the detectors and shield.

Information about the radiation environment in L2 can be found in the memo from J. Sorensen (2001) and the document by H. Evans (1997). It contains predictions, e.g. for the time integrated proton flux for a 4-year mission starting in 2007. From this, the average proton flux expected are 1400, 800, 150, 5 and 2 /cm^2/s at 0.1, 1, 10, 70 and 100 MeV.

With 11 mm shielding, typical for the Herschel satellite, protons below about 50 MeV are not expected to come through (Figure 9-1 in ECSS-E-10-04a). However, the detailed energy spectrum after shielding of solar protons is not available at this moment.

Equally, if not more, important are the effects of Galactic Cosmic Rays (GCR), which are dominated by protons. An example of the energy spectrum (including shielding by 10 mm Aluminium, but ignoring secondary particles) is shown in Dzitko (2001). The differential spectrum peaks at 500 MeV with a flux of 3×10^{-3} /cm^2/s/MeV, and 9×10^{-4} /cm^2/s/Mev at 100 MeV. Integrating over this differential spectrum leads to a GCR rate of about 4 /cm^2/s above 100 MeV.

Third, there are secondary particles and δ-rays which result from the interaction of the primary GCR with the shielding material. Details depend heavily on the shielding, but for ISOCAM the contribution of secondary particles and δ-rays to the total predicted glitch rate was equal to the one predicted from primary GCR (see Dzitko 2000).

Two test facilities have been discussed to perform radiation tests,

1) the Paul Scherrer Institute (PSI) (http://www.psi.ch/index_e.shtml),
   which has a cyclotron that can create the highest power in the world (590 MeV), and
2) the Cyclotron Research Centre at Louvain-la-Neuve (CRC-LLN) (http://www.cyc.ucl.ac.be/),
   which has a cyclotron build in the early-seventies that can accelerate protons to 80 MeV.

Test have actually been carried out at CRC-LLN during campaigns in March 2004, April 2005, October 2005, and are described in PACS-ME-TP-009 (issue 1.2, 10 March 2004; issue 2.2, 5 May 2005; issue 3.1, 2 October 2005; by Katterloher, Barl & Schubert).

Data analysis has been presented in:

– CQM Proton Irradiation Test Analysis,PICC-KL-TN-011, draft 2, P. Royer, 3 Jan. 2005
– UCL-CRC Proton tests of March 2004: glitch height distribution, PICC-KL-TN-012, M.A.T. Groenewegen (KUL)
– Analysis of the April 2005 proton test data, PICC-KL-TN-020, M.A.T. Groenewegen & P. Royer
– FM proton irradiation test. Flasher sequences, PICC-KL-TN-021, P. Royer, 8 Dec. 2005
– FM proton irradiation test. High & Low stress modules I: Glitch effects and curing, PICC-KL-TN-022, P. Royer, 11 Jan. 2006
– Analysis of the October 2005 proton test data on the low-stress module, PICC-KL-TN-024, M.A.T. Groenewegen

Literature:

H. Dzitko, 2000, Experimental Astronomy 10/2-3 (ISO Detector workshop), p. 279

H. Dzitko, 22 february 2001, SAp-PACS-HD-004, Evaluation of the cosmic ray effects on the PACS bolometers for the FIRST L2 environment

ECSS Space Environment Standard (ECSS E-10-04) http://www.estec.esa.nl/wmwww/wma/standards/ecss/ecss.html

H. Evans,4 March 1997, esa/estec/wma/he/FIRST/3, FIRST L2 radiation environment

Ana Heras, 21 August 2001, SAI/2001-013/Rp, ISO/FIRST Glitches Working Group, Final Report

J. Sorensen, 14 May 2001, 00-010/JS, FIRST L2 radiation environment

R. Katterloher, draft 5 September 2003, PACS-ME-TP-009, Test plan and procedure of glitch event rate and collected charge variation in the Ge-Ga detectors during proton irradiation at UCL-CRC

Req. 1.2.1 Optimum detector bias settings

Objectives

Responsivity and NEP of the photoconductors depend on the applied bias voltage. In the nominal range the responsivity rises steadily with the bias voltage. But increasing the electrical field inside the detector too much will lead to an avalanche of collisional ionisations triggering intrinsic spiking and eventually making the detector low ohmic and less sensitive. Hence there is a bias voltage range where the detector operates under stable conditions and the NEP shows a minimum. This optimum bias voltage range shall be determined for a typical operational photon level for spectroscopy mode, which is for most observations determined by the telescope background. However, it has to be considered whether observations of very bright sources which give photon fluxes far above the telescope background need special bias settings beside special CRE set-ups (highest integration capacities). Optimum bias settings are already determined during module level tests and are verified during ILT tests for the fully integrated modules.

With regard to the inflight operations there is the difference that the detectors are not operated under ionising radiation which leads to an additional increase in responsivity and earlier onset of spiking. Hence, it may be of advanatge to operate the detectors under lower bias voltage in space. Also the efficiency of curing and the time constants of responsivity drifts under ionising radiation can have an impact on the final bias settings in space. Measurements with ionising radiation, either protons or γ-rays can be performed only on module level, not with the ILT test facility.

Fulfilling or fulfilled by

Tests are combined with those for req. 1.2.2 “optimum detector temperature settings” in the case of the blue detector.
By switching between different bias voltages, req. 1.2.17 “time constant after a bias change” will be addressed.

Priority

A

When performed / frequency

- [1] As part of the ground module characterization. Here also the impact of ionising radiation can be simulated and optimum bias settings for in-flight can be recommended. See reqs. 1.2.13 - 1.2.15 for more details.
- [2] During ILT tests. For these types of test no simulation of ionising radiation is possible and only settings for laboratory environment can be established. These nominal values will serve as reference for the inflight performance.
- [3] In-flight during Commissioning Phase and Performance Verification Phase. Ground tests should provide hints for the in-flight strategy, whether detectors will be operated with reduced bias and how frequently there will be a curing. This has also an impact on the final Calibration Implementation Procedure strategy in-flight.

Required accuracy

The bias setting yielding a minimum NEP in the NEP vs. bias diagram for the majority of pixels should be selected. The NEP should be comparable with the expected $\mathrm{NEP_{BLIP}}$ from the PACS Instrument Model and Performance Prediction (3 - 4 $\times\ 10^{-17}\,\mathrm{W\,Hz^{-\frac{1}{2}}}$ for blue channel, 1 - 2 $\times\ 10^{-17}\,\mathrm{W\,Hz^{-\frac{1}{2}}}$ for red channel). Determining the optimum bias voltage with an accuracy of $\pm 3\,\mathrm{mV}$ is sufficient.

Inputs, prerequisites

1 Initial ranges for bias variation are provided by the module level tests.

2 Strategies how to cope with the ionising radiation provide requirements for the lowest bias voltage to test for reference with the inflight measurements.

3 For the determination of responsivity and NEP the flux on a pixel in the spectral band must be known.

4 It should be verified that the detector read noise NEP_{RO} is as specified (cf. req. 1.2.10).

Sources

1 Module level tests: laboratory BBs internal (cold) or external (hot) to cryostat.

2 ILT and IMT/IST tests: internal calibration sources (IMT/IST) and OGSE BBs (ILT).

3 In-flight: celestial standards, very bright sources for verification of bias settings up to the highest flux level.

Calibration Implementation Procedure (CIP)

For ILT:

- Perform differential measurements for typical spectroscopic observing conditions (i.e. $\Phi_B \approx 2 \times 10^{-14}$ W for blue array and $\Phi_B \approx 9 \times 10^{-15}$ W for red array and for the wavelength ranges specified below; PACS Instrument Model and Performance Prediction) for a range of detector bias seetings, and, for the blue array, for a range of temperature settings.
- The background conditions and the differential source signal are provided by the OGSE BBs 1 and 2. For the red detector array the corresponding OGSE BB temperature is 25 K, for the blue array it is around 32 K according to PICC-KL-TN-004, flux estimates in-orbit and OGSE. The differential source signal shall make up 10% of the total flux in the specified wavelength range below, i.e. the OGSE BBs are set to 25.3 K (BB1) and 24.7 K (BB2) for the red array measurement, and to 32.45 K (BB1) and 31.55 K (BB2) for the blue array measurement, respectively. The absolute OGSE temperature accuracy is $\pm$0.02 K at 20 K and $\pm$0.035 K at 50 K. The thermal stability of the sources is $\pm$1.25 mK at 20 K and $\pm$5 mK at 50 K. In order to achieve this, a stabilisation time of 45 min is needed. The target temperature is reached within 10 min. Since only a thermal stability of 0.03 – 0.05 K, corresponding to $\approx$0.5% of the background flux is needed, it is assumed that a stabilisation time of 20 min is sufficient for this test.
- Chopping is done with the OGSE chopper, the FPU chopper remains at its zero position. The OGSE chopper frequency is 0.5 Hz (the chopper wheel has a double on(1)-off(2) partition so that the effective flux modulation frequency is twice the specified one; 0.5 Hz is about the maximum frequency). The OGSE chopper should be synchronised with the detector read-outs.
- The grating should be configured close to maxima and flat parts of the RSRF. From CQM calibration this is 130 – 140 μm for the first order (red array) and 80 – 90 μm for the second order (blue array). From CQM calibration this corresponds to grating positions 794 300 ... 724 660, i.e. 760 000 for the red array, and 575 115 ... 409 210, i.e. 490 000 for the blue array (for FM-ILT the wavelength calibration is likely done after the bias optimisation).
- The bias voltage of the blue detector is varied between 80 mV and 290 mV in steps of 30 mV (8 settings), the optimum bias setting at module level is 200 mV.
  The bias voltage of the red detector is varied between 20 mV and 90 mV in steps of 10 mV (8 settings), the optimum bias setting at module level is 70 mV.
  Start with the bias variation for the red array followed by the nested temperature – bias loop for the blue array.
- The detector temperature of the blue array is varied between 2.1 and 2.9 K, in steps of 0.2 K (5 settings), the optimum detector temperature at module level is 2.5 K. The full bias scan of the blue detector is repeated for each temperature. Since the red detector is not temperature controlled but coupled to the Helium bath via a cooling strap, no temperature optimization is performed for this detector. When resetting the detector temperature allow for 60 s stabilisation time, check that the temperature is confirmed repeatedly in the HK.
- The CRE settings are $\frac{1}{2}$ s reset interval and the integration capacity of 0.1 pF. The assumption is that there is one ramp per chopper plateau.
- The 16 sample submean SPU mode is selected.

- When switching the bias no waiting time for stabilisation is applied. Rather a longer measurement in order to monitor the stabilisation of the signals is performed. The measurement time per configuration is 3 min.

Estimated time needed

Red detector:

OGSE BB stabilization 0.3 h
8 bias settings with 180 s each (no stabilisation time) = 24 min = 0.4 h
total time: 0.7 h

Blue detector:

OGSE BB stabilization 0.3 h
5 temperature settings with 60 s stabilisation time = 5 min = 0.085 h
5×8 bias settings with 180 s each (no stabilisation time) = 120 min = 2 h
total time: 2.4 h

Grand total $\sim$ 3.1 h

Calibration Analysis Procedure (CAP)

- Detector and bias HK has to be monitored on-line.
- For each pixel:
  For each bias and temperature setting and each chopper plateau determine the signal and noise from the 8 submean voltages by a straight line fit. For refined analysis, the first and last submean of the $\frac{1}{2}$ s ramp may be discarded to mask out effects by the chopper wheel transitions.
- Check for any significant trend of the signal with time due to the bias change. This should be done both for the absolute signals of both chopper plateaux and the differential signals. If there is any, determine the time constant (assume exponential time behaviour). Check if the time constant shows some relation with the relative bias jump.
- Average all signals on BB1 and all signals on BB2 which are not affected by any stabilisation (which are $\pm$10% within the final signal determined from the last 20 signals) and determine the differential signal.
- Determine the responsivity according to the prescription in req. 1.2.7. The incoming differential flux for the blue array is 2×10^{-15} W, for the red array 9×10^{-16} W. The flux prediction is based on PICC-KL-TN-004 which assumes a constant spectral resolution of R = 1700. With the final wavelength calibration the exact spectral resolution of each pixel can be determined and the flux be re-scaled.
- For each temperature setting plot the responsivity with bias voltage (overplot per module). For the blue detector plot in addition the responsivity with temperature for each bias setting.
- Determine the standard deviation of the differential signal within the stable part of the measurement. Determine the NEP according to the prescription in req. 1.2.10. For the incoming differential flux see above.
- For each temperature setting plot the NEP with bias voltage (overplot per module). Determine the minima. Determine for which setting the majority of minima occurs. Check that for these settings there are no spiking pixels. If yes, determine from which voltage they start to be spiky. Intercompare minima for the various temperature settings and where the absolute NEP minimum occurs. Decide on the best bias, and, for the blue detector, best temperature configuration.
- Compare with module level results.

Output, products

Optimum bias settings for low stressed and high stressed photoconductor arrays without any ionising radiation environment. These will be tabulated in a CalU file.

Status/version

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$Revision: 1.6 $
$Date: 2006/06/30 16:33:27 $
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Req. 1.2.2 Optimum detector temperature settings

Objectives

The low-stressed and high-stressed Ge:Ga arrays have different operational temperatures. While the high-stressed array of the red channel is coupled directly to the Helium bath of the Herschel cryostat via cooling straps adjusting the temperature to 1.6 . . . 1.7 K, the low-stressed array of the blue channel needs a higher temperature >2 K. This is achieved by active heating of the array. The detector temperature shall be tuned such that the NEP shows a minimum and the dark current is below the specified level. This optimum temperature setting shall be determined for the photon level under operational conditions for spectroscopy.

Fulfilling or fulfilled by

Tests are combined with those for req. 1.2.1 "optimum detector bias settings" in the case of the blue detector.
Tests are combined with those for req. 1.2.6 "detector dark current" in the case of the blue detector. The dark current level depends on the temperature.

Priority

A

When performed / frequency

- [1] As part of the ground module characterization.
- [2] During ILT tests.
- [3] In-flight during Commissioning Phase and Performance Verification Phase. Fine-tuning of the detector temperature when operating the detectors under reduced bias voltage may further improve the detector performance.

Required accuracy

The temperature setting yielding an absolute NEP minimum in the minimum NEP vs. temperature diagram and not leading to excess dark current for the majority of pixels should be selected. The NEP should be comparable with the expected $\mathrm{NEP_{BLIP}}$ from the PACS Instrument Model and Performance Prediction (3 - 4 $\times$ $10^{-17}\,\mathrm{W\,Hz^{-\frac{1}{2}}}$ for the blue channel). Determining the optimum detector temperature with an accuracy of ± 0.1 K is sufficient.

Inputs, prerequisites

1 Initial ranges for detector temperature variation are provided by the module level tests.

2 For the determination of the NEP the flux on a pixel in the spectral band must be known.

3 It should be verified that the detector read noise $\mathrm{NEP_{RO}}$ is as specified (cf. req. 1.2.10).

Sources

1 Module level tests: laboratory BBs internal (cold) or external (hot) to cryostat.

2 ILT and IMT/IST tests: internal calibration sources (IMT/IST) and OGSE BBs (ILT).

3 In-flight: celestial standards.

Calibration Implementation Procedure (CIP)

For ILT:

- See CIP for finding the optimum bias setting (req. 1.2.1). The bias scan to determine the minimum NEP is repeated for each temperature setting.
- See CIP for dark current determination (req. 1.2.6) to keep it within the specification.
- The temperature variation for the blue (low-stressed) array is between 2.1 K and 2.9 K in steps of 0.2 K, the optimum detector temperature at module level is 2.5 K.

Estimated time needed

See time estimates for req. 1.2.1 and 1.2.6 CIPs.

Calibration Analysis Procedure (CAP)

- Detector temperature HK has to be monitored on-line
- Follow the analysis steps in the CAP of req. 1.2.1.
- For each pixel:
  Once the minimum NEP has been determined for the NEP vs. bias scan of each temperature setting, plot minimum NEP vs. temperature and determine the optimum temperature setting for the majority of pixels.
- Cross-check that the dark current for this temperature is within the specified range. If that should not be the case, a lower temperature setting has to be selected.

Output, products

Optimum operational temperature setting for low-stressed photoconductor array. This will be tabulated in a CalU file. The feature of temperature setting for the blue detector array could not be tested during CQM-ILT.

Status/version

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$Revision: 1.7 $
$Date: 2006/07/03 12:51:19 $
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Req. 1.2.3 Dynamic range per selected integration capacitor

Objectives

The CRE is equipped with different integration capacitors in order to be able to cover a wide range in flux levels. It is expected that for most astrophysical sources the input flux will be dominated by the telescope background, so that the largest fraction of observations will be performed with the same capacitance (likely the smallest one) and even the same reset interval setting. The purpose of this requirement is to explore over which range of input currents, or equivalently input fluxes, a particular capacitor/reset interval configuration works with good dynamic range. The dynamic range per integration capacitor is defined by determining the minimum and maximum current for which a reliable signal can be determined. The lower end of the range is determined by possible non-linearities of the CRE and digitization noise, the upper end of the range is determined by loosing not too many data by saturation of the CRE output voltage stage (ADC).

Fulfilling or fulfilled by

Fulfilling req. 1.2.11 “Linearity of CRE read-out” for measurement configurations yielding full dynamic range for a selected reset interval/capacitance configuration (in particular for transmitted raw ramps).
Using different reset intervals for the same illumination level checks for any signal dependence on reset interval.
Using a wide range of known fluxes checks for the linearity of the detector-CRE system.
Fulfilling req. 1.2.10 “Noise Equivalent Power” for determinination of $\mathrm{NEP_{BLIP}}$ for various photon fluxes Φ_B and disentangling the range where $\mathrm{NEP_{RO}}$ dominates.
Consequently also fulfills req. 1.2.9 “Detective Quantum Efficiency” which needs $\mathrm{NEP_{BLIP}}$ and correponding Φ_B as input.

Priority

A, needed for AOT logic

When performed / frequency

- [1] As part of the ground module characterization.
- [2] During ILT tests.

Required accuracy

The dynamic range of the output voltage for a certain integration capacitor/reset interval combination due to a specified input flux from the sky plus the telescope background flux should be known with an accuracy of ±20%.

According to the “Requirements for the PACS-CRE” (PACS-ME-RS-002) the dynamic range of the output signal should be more than 2.0 V (goal). The actual range implemented in the DECMEC detector read-out is 6.11 V

Inputs, prerequisites

Flux predictions for OGSE BB settings. The current reference is “Flux estimates in-orbit and for OGSE” (PICC-KL-TN-004)

Sources

1 Module level tests: See setup as described in the documents “Test Procedure / Test Report, Functional Tests of PACS QM-FEEs” (PACS-MA-TR-004c) and “PACS Test Report, Results of Tests on QM FEE A02-038-15, Run 10/2001” (PACS-MA-TR-005).

2 ILT tests: OGSE BBs.

Calibration Implementation Procedure (CIP)

For ILT:

- Perform differential measurements for a wide range of fluxes which are around the typical spectroscopic observing conditions (i.e. $\Phi_\mathrm{B} \approx 2 \times 10^{-14}$ W for blue array and $\Phi_\mathrm{B} \approx 9 \times 10^{-15}$ W for red array and for the wavelength ranges specified below; PACS Instrument Model and Performance Prediction) with different reset interval lenths and for all 4 integration capacitors. This provides a matrix of measurements with ramps of different dynamic range.

- The illumination levels and the differential source signal are provided by the OGSE BBs 1 and 2. The minimum OGSE BB temperatures are determined by the requirement that the $\mathrm{NEP_{BLIP}}$ of the corresponding flux should be $< 5 \times 10^{-18}\,\mathrm{W\,Hz^{-\frac{1}{2}}}$ which is the goal $\mathrm{NEP_{RO}}$, so that the measurement is in the $\mathrm{NEP_{RO}}$ dominated range. This corresponds to fluxes of 4×10^{-16} W for the blue array or $0.02 \times \Phi_\mathrm{B}^{telB}$ and 1×10^{-15} W for the red array or $0.11 \times \Phi_\mathrm{B}^{telB}$. This yields lowest BB temperatures of 18.5 K for the blue array and 16 K for the red array. The highest fluxes are given by the upper OGSE BB temperature range which is <80 K. For $\mathrm{T_{BB}}$ = 75 K, $\Phi_\mathrm{B} \approx 22 \times \Phi_\mathrm{B}^{telB}$ for both the blue and the red array.
  Foreseen OGSE BB settings:

T_{BB1}	T_{BB2}	mean fraction of Φ_B^{telB}		diff. flux fraction of mean flux	
(K)	(K)	blue array	red array	blue array	red array
16.3	15.7	0.005	0.09	0.487	0.284
18.8	18.2	0.02	0.22	0.346	0.206
25.4	24.6	0.23	1.0	0.242	0.148
32.5	31.5	1.0	2.6	0.181	0.114
40.7	39.3	2.9	5.2	0.162	0.105
48.0	46.0	5.5	8.0	0.171	0.114
61.4	58.6	12.5	14.3	0.115	0.105
77.0	73.0	23	22	0.144	0.105

- The OGSE BB1 and BB2 settings are such that the differential flux is in the order of 10 – 20% of the mean flux, except for the lowest temperature settings which have a higher relative differential flux due to the already low absolute flux level.

- The grating should be configured close to maxima and flat parts of the RSRF and operated in fixed position. From CQM calibration this is 130 – 140 μm for the first order (red array) and 80 – 90 μm for the second order (blue array). From CQM calibration this corresponds to grating positions 794 300 . . . 724 660, i.e. 760 000 for the red array, and 575 115 . . . 409 210, i.e. 490 000 for the blue array. Hence, for each OGSE BB1/BB2 setting the grating has to be moved between the two positions requiring $\leq$15 s per angular movement.

- The bias voltage of the detectors is set to the optimum voltages found from the preceding tests related to req. 1.2.1. From module level tests these values are 200 mV for the blue array and 70 mV for the red array.

- The detector temperature of the blue array is set to the optimum value found from the preceding tests related to req. 1.2.2. From module level tests this temperature is 2.5 K.

- The check-out voltage for the CRE resistor channels should be set to the values found from the preceding tests related to req. 1.2.4. This has to be adjusted for each reset interval/ capacitance configuration.

- For each OGSE BB setting, covered read-out parameters are:

	C_{int}:	0.1	0.3	1.0	3.0
RI					
1/16		×	×	×	×
1/4		×	×	×	×
1/2		×	×	×	×
2		×	×	×	×

4 s reset intervals require an exotic SPU mode. 1/32 s reset intervals do not allow for 16 samples sub-slope fitting. 1/4 s and 1/2 s reset intervals are the basic settings for AOTs.

- The 16 sample sub-slope fitting SPU mode is selected in order to allow comparison with short reset intervals. This means 1, 4, 8 and 32 sub-slope signals for the 1/16, 1/4, 1/2 and 2 s reset interval, respectively.
- There should be 8 ramps per chopper plateau for the longest reset interval setting of 2 s. This means 32, 64 and 256 ramps for the shorter reset intervals. The OGSE chopper frequency has therefore to be 1/(4 $\times$ 16 s) = 0.01563 Hz. The FPU chopper remains at its zero position.
- There should be 4 chopper cycles giving 128 s measurement time for each configuration.

Estimated time needed

OGSE BB stabilisation = 8 $\times$0.3 h = 2.4 h
4 RI settings $\times$ 4 capacitance settings $\times$ 8 OGSE temperature settings $\times$ 2 grating positions $\times$ (128 s mt) +
8 OGSE temperature settings $\times$ 2 grating positions $\times$ (15 s gmt) = 33008 s = 9.2 h
(mt = measurement time; gmt = grating move time)
$\rightarrow$ total time $\sim$11.6 h

Calibration Analysis Procedure (CAP)

- For all pixels the sub-slope signal mode has been selected delivering 1, 4, 8, and 32 signals per 1/16, 1/4, 1/2 and 2 s reset interval.
- For some selected pixels raw ramps are transmitted; the pattern over the array is commutative with time.
- Evaluate raw ramps, determine reset level and signal by straight line fit after elimination of saturated read-outs. Check with corresponding signals from sub-slope fitting. Differential signals are not needed for this type of evaluation.
- For the subslope signals determine which ones are affected by saturation and discard them from further processing.
- Distinguish between signals on OGSE BB1 and BB2 which are for different fluxes. Get the synchronisation with the OGSE chopper wheel from the time stamps of its position read-outs. Signals which are affected by a chopper wheel transition are discarded from further analysis. Differential signals are needed for this type of evaluation, only absloute ones. Average all signals of clean OGSE BB1 and BB2 plateaux.
- The dynamic range is in voltage. The nominal voltage range $\Delta\, U_{\rm nom}$ is 6.11 V (TBC for FM). The effective voltage range $\Delta\, U_{\rm eff} = \Delta\, U_{\rm nom} - U^{\rm reset}$. The reset voltage level $U^{\rm reset}$ can be most accurately derived from the raw ramps.
- From the absolute average signals $s_{\rm i}$ the maximum voltage $\mid\, U_{\rm i}^{\rm max}\,\mid$ for the respective reset interval / integration capacity ($t_{\rm RI}$, $\mathrm{C_{int}}$) is derived as

$$\mid\, U_{\rm i}^{\rm max}\,\mid = s_{\rm i} \times t_{\rm RI} + \mid\, U_{\rm i}^{\rm reset}\,\mid$$

- The dynamic range is calculated as

$$\mid\, U_{\rm i}^{\rm max}\,\mid < \Delta\, U_{\rm eff} \quad \Rightarrow \quad R_{\rm i}^{\rm dyn}(RI, C_{\rm int}) = \frac{\mid\, U_{\rm i}^{\rm max}\,\mid}{\Delta\, U_{\rm eff}} \times 100 \;\; (\%)$$
$$\mid\, U_{\rm i}^{\rm max}\,\mid > \Delta\, U_{\rm eff} \quad \Rightarrow \quad R_{\rm i}^{\rm sat}(RI, C_{\rm int}) = \frac{\mid\, U_{\rm i}^{\rm max}\,\mid - \Delta\, U_{\rm eff}}{\mid\, U_{\rm i}^{\rm max}\,\mid} \times 100 \;\; (\%)$$

- If $R_{\rm i}^{\rm dyn}(RI, C_{\rm int}) < 5\%$, check with $R_{\rm i}^{\rm dyn}$ from shorter reset interval or smaller integration capacity whether non-linearities or digitization noise play a role. This is already an aspect of CRE linearity which will be addressed in more detail in the CAP of req. 1.2.11.

- Construct a table which gives for each total flux level the dynamic range or degree of saturation of the absolute signal for the respective reset interval / integration capacity configuration.
- Analysis details of the CRE linearity are described in more detail in the CAP of req. 1.2.11.
- Analysis aspects of $\mathrm{NEP}_{\mathrm{BLIP}}$ determination from the differential signals are described in more detail in the CAP of req. 1.2.10.
- The determination of the detector quantum efficiency from $\mathrm{NEP}_{\mathrm{BLIP}}$ limited measurements is described in more detail in the CAP of req. 1.2.9.

Output, products

The dynamic range per integration capacitor and selected reset interval vs. input flux in form of a table.

Status/version

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$Revision: 1.5 $
$Date: 2006/07/24 13:35:40 $
```

Req. 1.2.4 CRE check-out voltage

Objectives

The objective of this calibration requirement is the determination of the behaviour of the integration process of the CRE only, decoupled from any detector effect. To be able to do so, each CRE has two channels which are not connected to any detector pixel: The open channel and the dummy or resistor channel. The resistor channel is connected to an ohmic resistor ($R_{res} = 2\times10^9\ \Omega$ at room temperature, $R_{res} = 5\times10^9\ \Omega$ at LHe temperature). Instead of the bias voltage driving a photo current due to electrical carriers generated by the infalling IR flux, a *check-out voltage* U_{co} is applied which results in a current I_{co} which is integrated on the integration capacitor, too. This allows to monitor the CRE integration without any impact by the detector (like de-biasing). In case of non-linearities, effects by the detector and the CRE alone can be disentangled more easily. For each selected reset interval and integration capacitor combination an optimal check-out voltage should be found, for which the check of the linearity over the full dynamic range and non-saturation of the integration ramps is guaranteed.

Note: This measurement can also be done in the warm (some adjustment of the voltage due to the 2.5 times lower resistance may be necessary)! In the warm the bias voltages applied to the detector pixels have to be set to quite low values (a few mV).

Fulfilling or fulfilled by

Priority

B

When performed / frequency

1) During module level tests to see the CRE integration behaviour;

2) During ILT tests in order to find the settings for all subsequent tests using the CREs and as input for the AOT logic.

Required accuracy

The basic equations associated with the check-out voltage are shown in the following:

$$
\begin{aligned}
I_{\rm co} &= \frac{U_{\rm co}}{R_{\rm res}} \\
I_{\rm co} &= \frac{dU}{dt} \cdot C_{\rm int} \\
U_{\rm co} &= R_{\rm res} \cdot C_{\rm int} \cdot \frac{dU}{dt}
\end{aligned}
$$

The accuracy is driven by the requirement to properly measure the linearity of the integration ramps for the different reset intervals and integration capacitors settings. In the following table we compile the expected check-out voltages for several reset intervals in combination with the four integration capacities. We assume $R_{res} = 5\times10^9\ \Omega$ and a dynamic range of $\approx$6 V:

C_{int}	U_{co} (mV) for RI		
(pF)	$\frac{1}{32}$ s	$\frac{1}{4}$ s	2 s
0.1	96	12	1.5
0.3	288	36	4.5
1.0	960	120	15
3.0	2880	360	45

Inputs, prerequisites

In the detector lab check-out voltages of 30 and 60 mV voltages have been applied. This is just in the middle range of required check-out voltages and allows to perform a direct comparison of the dynamic range without adjusting the check-out voltage each time.

Sources

No source needs to be switched on, no external beam is needed. All OGSE stimulators and internal calibrators can be switched off. The OGSE M3 (mirror 3) can be put to 'dark' position.

Calibration Implementation Procedure (CIP)

Two different check-out voltages, different by a factor of two, are applied to the CRE resistor channel. This will allow to assess the linearity of the check-out voltage. We adopt the values of 30 to 60 mV used in the detector lab which were found to have a similar ratio to the largest required values as inversely to the smallest required values. Both check-out voltages are applied to different combinations of reset intervals and integration capacities, say minimum (1/32 s), medium (1/4 s; basic RI for spectroscopic AOT mode) and maximum (2 s, NB: a 4 s reset interval measurement can currently not be handled properly by the SPU) reset interval length for all 4 capacities. An integration time of 32 s should be sufficient.

Schemetically, the CIP has the following steps:

- Switch to spectrometer mode.
- The grating can remain in its current position.
- The focal plane chopper (FPC) can be directed to zero position.
- Since the resistor is mounted on the FEE with T=4.2K, the temperature control for the blue detector needs not to be switched on.
- The detector bias voltage is set to a very low voltage ($\leq$ 2 mV), especially, if this test is done in the warm!
- Select appropriate detector selection tables to have raw data mode for the resistor pixels of all CREs. (With the complete detector modules of the FM model the procedure may be split into blue and red detector module branch).
- Apply CRE check-out voltage of 30 mV to resistor pixels:
  Loop over all integration capacities and over selected reset intervals of 1/32 s, 1/4 s and 2 s.
  For each capacities and integration setting make a 32 s measurement of the resistor pixel ramp.
  (For some reset interval/capacitor configurations the ramps run into saturation, for others only a fraction of the full dynamic range is used).
- Repeat this procedure for the CRE check-out voltage of 60 mV.

Estimated time needed

Two CRE check-out voltages settings are applied, each with four integration capacitor settings in combination with three reset intervals. This gives a total of 24 settings. Each setting will have an integration time of 32 s. This comes down to an total time of 24×32 s = 768 s = 12.8 m = 0.22 h. Depending on the number of raw data pixels which can be transmitted per setting, the procedure may have to be repeated to cover all resistor pixels (e.g. this time is doubled, if blue and red channel are read-out separately). The total time should not exceed 0.5 h.

Calibration Analysis Procedure (CAP)

The following steps in the CAP have to be taken:

- First, the constancy of the applied CRE check-out voltages has to be monitored on-line, in addition to the CRE supply voltages.

- Second, the build-up of integration ramps of the resistor pixels should be monitored on-line by QLA to decide on a possible re-adjustment of the check-out voltage - however partial saturation of the ramps should be no problem.
- For the final signal analysis to be performed in IA the following steps are required:
  - For each resistor pixel the signal and dynamic range/saturation level has to be determined as a function of the integration capacity, reset interval and check-out voltage settings, from the recorded raw integration ramps.
  - Check the linearity of the signals for each CRE set-up and aplied check-out voltage:
    1) between integration capacitors for the same reset interval and check-out voltage setting (linearity of integration capacitance, effective capacitances have to be applied instead of nominal ones);
    2) between reset intervals for the same integration capacitor and check-out voltage setting (reset interval time linearity);
  - Check the linearity of the signals between the two check-out voltages for the same capacitor/reset interval setting (linearity of check-out voltage).
  - From this information compute an optimal check-out voltage setting (reaching e.g. about 80% of the dynamic range) for each selectable reset interval between 1/32 s and 2 s for the 4 integration capacitors. Possible limitations in check-out voltage ranges should be taken into account.

Output, products

Establish a table which lists this optimal check-out voltage for all possible reset interval and integration capacity combinations. This table may be converted or integrated into a calibration uplink file to be accessed by the AOT logic for properly setting the CRE check-out voltage in the AOT context.

The analysis of the CQM test data has been described in the report “Req. 1.2.4 CRE Check-out Voltage” as part of the PACS Test Analysis CQM-ILT part II (PICC-KL-TR-001, part 2).

Currently there is no data analysis recipe making use of the resistor channel ramps for linearising the detector integration ramps.

Status/version

Complete revision in preparation of FM ILT.

`$Revision: 1.2 $`
`$Date: 2006/06/12 18:19:24 $`

Req. 1.2.5 Signal-to-noise dependence on number of non-destructive read-outs per ramp

Objectives

Determine the variation of the SN ratio as a function of the number of NDR per ramp. The number of readouts is set by the reset interval as the readout rate is fixed at $\frac{1}{256}$ s. Effects of linearity of the ramps and the on-board processing (and compression of data) influence the optimal reset interval time.

Fulfilling or fulfilled by

Priority

When performed / frequency

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

Draft version

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$Revision: 1.2 $
$Date: 2002/09/20 08:59:29 $
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Req. 1.2.6 Detector dark current

Objectives

Measure the detector-CRE chain dark signal for each pixel. For the blue array this should be done for various possible detector temperatures in order to constrain the selection of the operating temperature with regard to the maximum acceptable dark signal. In principle the dark signal cancels out by differential measurements. The aim is to determine which fraction of the light current the dark current makes up and to optimize it for the blue array. The measurement also serves as reference for straylight assessment, if the FPU is mounted in different environments (PACS test cryostat, Herschel cryostat for various IMT and IST tests).

Above a blue detector temperature of T ∼2.9 K the dark current is thermally excited and its intensity is proportional to the Boltzmann factor $e^{-\frac{\Delta E_{\rm bgap}}{k\,T}}$ allowing a determination of the band gap energy when measuring in the temperature range ∼2.9 – ∼3.5 K.

Fulfilling or fulfilled by

Related to 1.2.2 for blue array detector temperature.

Priority

B

When performed / frequency

- [1] During module level tests
- [2] During ILT tests
- [3] During IMT and IST tests
- [4] During PV phase

Required accuracy

The specification for the dark signal is that the number of dark electrons per second, $N(e^-)_{\rm dark}$, should be $\leq 5 \times 10^4$ e^- s^{-1}, for both arrays. The dark current is

$$I_{\rm dark}[A] = s_{\rm dark}\ [V/s] \cdot C_{\rm int}\ [As/V]\ ,$$

$s_{\rm dark}$ being the measured dark signal and $C_{\rm int}$ the selected integration capcity of the CRE.
The dark signal can be expressed as dark electrons

$$N(e^-)_{\rm dark}\ [s^{-1}] = \frac{I_{\rm dark}}{Q_{\rm e^-}} \qquad Q_{\rm e^-} = 1.602 \cdot 10^{-19}\ [As]$$

The band gap energy can be determined with

$$I(T_{\rm i}) \propto e^{-\frac{\Delta E_{\rm bgap}}{k\,T}} \qquad k = 1.38 \cdot 10^{-23}\ [WsK^{-1}]$$

and for two temperature measurements at T_1 and T_2 in the thermal excitation range:

$$\frac{I(T_2\ >\ T_1)}{I(T_1\ >\ 2.9\,K)} = \frac{e^{-\frac{\Delta E_{\rm bgap}}{k\,T_2}}}{e^{-\frac{\Delta E_{\rm bgap}}{k\,T_1}}} = e^{-\Delta E_{\rm bgap}\,(\frac{1}{k\,T_2} - \frac{1}{k\,T_1})}$$

$$\Delta E_{\rm bgap}[meV] = 10^3 \cdot \frac{k}{Q_{\rm e^-}} \cdot T_1 \cdot T_2 \cdot \frac{ln\,I(T_2) - ln\,I(T_1)}{T_2 - T_1}$$

Inputs, prerequisites

All internal and external stimuli should be switched off to avoid straylight. This means that the measurement has to take place at the beginning of a test block before stimuli are powered up. When the spectrometer is switched on it should be avoided to heat up the internal sources immediately.
The conversion between heater current and resulting detector temperature must be known.

Sources

For ILTs the OGSE is set up to dark position and all stimuli are off. The PACS internal calibrators are off, too. In addition the dark current level will be determined by looking onto one of the cold PACS internal calibrators.

In-flight the telescope should be pointed to a 'blank' region of the sky.

Calibration Implementation Procedure (CIP)

- ILTs:
  - The OGSE Black Bodies should be off. The OGSE mirror M3 is put into dark position. If possible, the entrance to the OGSE cryostat should be closed.
- IMTs and ISTs:
  - All stimulators external to the PACS FPU inside the Herschel cryostat should be off.
- In-flight
  - The telescope should be pointed to a low surface brightness blank sky position.
- All:
  - The PACS internal calibrators should be off, and, if applicable, should be let to cool down sufficiently long.
  - The measurement is performed in staring mode. The chopper mirror is deflected to a position to view one of the cold internal calibration sources.
  - The CRE read-out should be adjusted to a low signal level (e.g. reset time of 2s in combination with smallest integration capacity for both blue and red array). For the blue array dark signal measurements at 3.2 K use a reset interval of 1 s and at 3.5 K use a reset interval of $\frac{1}{4}$ s.
  - The bias voltage of the detectors is set to the optimal one. Since this type of test may be performed before bias optimisation tests, for ILT test set-up the optimum bias voltages found during module level tests should be used.
  - During ground tests the telemetry mode is set to buffer transmission mode in order to acquire raw ramps. Two cycles, i.e. 10 s integration or 5 ramps and 3 min data transfer per cycle, should be sufficient, which gives 7 min per dark exposure.
  - The grating can remain at its default position.
- ILTs:
  - In order to check for wavelength independence of the dark signal (verification of straylight contribution) the measurement is repeated both in 2*nd* and 3*rd* order, selected for the blue array by rotating the order sorting filter.
  - For temperature setting optimization of the blue array a temperature loop (addressing aspects of req. 1.2.2) is included varying the blue array temperature between 2.1 and 2.9 K in steps of 0.4 K (twice the step size used in the bias scan) and for band gap assessment from 2.9 to 3.5 K in steps of 0.3 K. When changing the detector heating temperature allow for 60 s stabilisation time. In the second filter position the temperature steps are in reverse order.

Estimated time needed

Considering 5 temperature settings for the blue array (the red array is measured in parallel) and with the repetition for the 2*nd* and 3*rd* order:

$10 \times (60\,\mathrm{s}$ stabilization time $+\ 420\,\mathrm{s}$ measurement time$) = 4800\,\mathrm{s} \approx 1.4\,\mathrm{h}$

Calibration Analysis Procedure (CAP)

- The temperature HK has to be monitored on-line.
- The build-up of integration ramps of selected pixels has to be monitored on-line to decide on the selection of the best adapted reset interval.
- The final signal analysis is performed in IA. For each pixel the dark signal is determined by fitting the ramp slopes and averaging the signals of all ramps or signals may be determined from pair-wise read-outs.
- For the blue array this is done in dependence on the detector temperature and wavelength order.
  - Determine the relative increase of dark signal with temperature.
  - Check for consistency of the two temperature scans in the two different grating orders.
  - Check for reproducibility of the measurements with the red array.
  - Check whether there is some systematic behaviour of the dark signal of the red array with the temperature increase/decrease at the blue array.
  - Plot $\ln(\mathrm{I_{dark}})$ vs. $\frac{1}{T}$ to visualise the thermal exciation part by its linear behaviour. Determine band gap energy from data points on this linear part.
- The dark signals are converted into dark electrons per second and for temperatures $\mathrm{T} < 2.9\,\mathrm{K}$ the compliance with the specification is checked.
- The dark signals of all pixels shall be displayed in 2D colour plots to identify any gradient (possibly due to stray-light) or the location of peculiar pixels.
- The band gap energy of all pixels shall be displayed in 2D colour plots to compare with the pre-integration values from module level testing.

Output, products

The dark signals of all pixels will be provided in a dark signal matrix to be subtracted from the raw signals in staring mode measurements.

The analysis of CQM-ILT test data has been described in the Report “Req. 1.2.6 Performance test of dark current” as part of the PACS Test Analysis Report CQM-ILT part II (PICC-KL-TR-001, part 2).

The analysis of EQM-IMT test data has been described in the Report “Detector Dark Current Test on Internal Calibration Sources during Cold EQM-IMT” (PICC-MA-TR-003).

Status/version

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$Revision: 1.6 $
$Date: 2006/09/07 08:08:46 $
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Req. 1.2.7 Nominal Responsivity

Objectives

The responsivity is the essential absolute photometric calibration factor between the measured output voltage of the CRE (equivalent to the photo current onto the integration capacitor) and the incident illumination power onto the photoconductive detector. The absolute value of the responsivity depends on the detector settings, in particular the bias voltage. Here, mainly the assessment of the nominal responsivity under stable laboratory conditions is addressed.

The absolute value of the responsivity can vary with time, in particular under ionising radiation, but also due to variations of environmental temperatures. It is therefore important to monitor it in an appropriate way. This is done by repeated measurements on the PACS internal calibration sources which provide a stable and reproducible illumination. The absolute flux of the internal calibration sources is determined with regard to reference laboratory BBs or celestial standards which provide of course also a direct measurement of the responsivity. It is sufficient to measure the responsivity or band within the detector spectral response range, since it can be assumed that the relative system response remains constant. The latter calibration is covered in the case of a spectrometer by the Relative Spectral Response Function (RSRF, c.f. req. 4.3.8).

The absolute responsivity value refers to the wavelength of the peak of the relative spectral detector responsivity. If measured at another wavelength, this can be accounted for in the flux predictions by applying this relative spectral detector responsivity. If this is not the case, resulting responsivities must be scaled to the peak via the relative spectral responsivity ratio.

Fulfilling or fulfilled by

Fulfilled by all measurements which have an accurate flux estimate or calibration. Responsivites can therefore be derived from measurements related to req. 1.2.1 (optimum detector bias) and req. 1.2.3 (dynamic range of selected integration capacitor).
The impact of ionising radiation on the responsivity and its variations are addressed by req. 1.2.13.

Priority

A

When performed / frequency

- [1] During module level tests
- [2] During ILT tests

Required accuracy

$< 10\,\%$
The basic equation associated with the responsivity is:
per pixel i:
$R_i = \frac{S_i \times C_{int}}{\Delta\,\Phi_B}$ [A/W]
S_i = amplitude of the modulated signal ([V/s])
C_{int} = selected integration capacity ([F] = [A s/V])
$\Delta\,\Phi_B$ = difference power of modulated illumination ([W])

Inputs, prerequisites

Relative spectral responsivity to scale appropriately between measurement wavelength and wavelength of spectral responsivity peak.
Flux predictions for OGSE BB settings. The current reference is "Flux estimates in-orbit and for OGSE" (PICC-KL-TN-004).

Sources

1) Module level tests: laboratory BBs internal (cold) or external (hot) to cryostat.
2) ILT tests: OGSE BBs.

Calibration Implementation Procedure (CIP)

- Perform differential measurement on source(s) / background with predicted / known flux level.

Estimated time needed

See time estimates for CIP 1.2.1 and CIP 1.2.3

Calibration Analysis Procedure (CAP)

- Determine differential signals from measurement sequences related to reqs. 1.2.1 and 1.2.3, in particular for the optimum and nominal bias values.
- Calculate R accoring to the formula above, taking into account the selected integration capacity.
- The measurements of CIP 1.2.1 and 1.2.3 are not done for the peak of the relative detector responsivities, hence re-scale by dividing by $r_{\rm det}(\lambda)$:
  $\lambda_{\rm blue} \approx 85\,\mu$m; $\lambda_{\rm blue}^{\rm peak} \approx 120\,\mu$m; $r_{\rm det}(85\,\mu{\rm m}) \approx 0.65$.
  $\lambda_{\rm red} \approx 135\,\mu$m; $\lambda_{\rm red}^{\rm peak} \approx 180\,\mu$m; $r_{\rm det}(135\,\mu{\rm m}) \approx 0.7$.

Output, products

Nominal responsivity per detector pixel, hence also flat-field, as reference for in-flight performance under ionising radiation.

Status/version

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$Revision: 1.4 $
$Date: 2006/07/18 18:03:05 $
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Req. 1.2.8 Signal dependence on chopper frequency

Objectives

Given the relatively high telescope background in the PACS wavelength regime, differential measurements are a prerequisite for sensitive source detection. Furthermore, the hits by ionising particles lead to responsivity variations which can again be best coped with by chopping. The important issue are the time scales of these variations in order to provide a reliable reference measurement on the background within a stable period of time. While variations of the telescope background are expected to be slow, on hours scale, responsivity jumps may be on the seconds scale, requiring relatively fast chopping.

On the other hand it is known that photconductor detectors show signal transients after a flux change, accomodating after an initial signal jump to the final signal level with a certain time constant. The height of the signal jump and the transient time constant depend on the detector material, the flux jump and the total brightness on the detector. In order to have a consistent observing strategy and not introduce systematic photometric offsets, in particular if a range of chopping/modulation frequencies is used, it is important to assess these time constants and their relation to the chopper plateau length. Under unfavorable conditions significant signal losses may be encountered.

The purpose of this requirement is to explore in a systematic way the absolute signal levels and differential signals for different chopping frequencies and for different illumination levels and to characterise the effects of signal transients. Together with the operational conditions to cope with the background and radiation variations, this should contribute to the decision on an optimum chopper frequency.

Fulfilling or fulfilled by

Fulfilling req. 1.2.18 “Time constant flux changes” with regard to flux modulation by chopping.

Priority

A

When performed / frequency

- [1] As part of the ground module characterisation.
- [2] During ILT tests.
  The measurement sequence can be combined with the tests related to req. 1.2.3 which makes use of the same OGSE BB settings, thus reducing wait times for BB stabilisation. The req. 1.2.3 test for the same OGSE BB setting should precede in order to find the optimum integration capacitor setting.

Required accuracy

It shall be assessed whether there are signal time constants on a second-to-minute scale.
The percentage of the initial signal jump shall be assessed.
The dependence on the flux jump shall be characterised.

Inputs, prerequisites

Tests determining the optimum detector settings (reqs. 1.2.1, 1.2.2, & 1.2.6) should have been performed.
Flux predictions for OGSE BB settings. The current reference is “Flux estimates in-orbit and for OGSE” (PICC-KL-TN-004).

Sources

1) Module level tests: laboratory BBs internal (cold) and external (hot) to cryostat in combination with chopper wheels.

2) ILT-tests: 1 OGSE BB in combination with both internal calibration sources.

Calibration Implementation Procedure (CIP)

- The signal dependence of the PACS Ge:Ga detector / CRE chain is best characterised with the instrument internal modulation element, the PACS chopper. In order to have colours of the illuminating source during this test as close as possible to those expected for the science targets, the OGSE stimulators have to be used. They are also the only sources which can provide a sufficient range of contrast, hence flux jumps, by varying their temperature. Since 1 OGSE BB fills the complete sky FOV chopping with the internal chopper has to be done against the internal CS FOV as reference background. In order to have a symmetric chop the chop pattern is
  OGSE BB1 – CS1 – OGSE BB1 – CS2 – OGSE BB1 – CS1 . . . (on - off)
  The brightness of CS1 and CS2 will be kept constant at the default level.
  (In coordination with the measurements of req. 1.2.3, OGSE BB2 will be set to the requested temperature settings of req. 1.2.3, but the OGSE chopper mirror will be held in a fixed position on OGSE BB1 for req. 1.2.8).

- In order to determine the signal dependence on the chopper frequency, the same flux contrast shall be measured with different chopper frequencies in the range from ≈0.03 Hz to ≈1 Hz. Within one sequence over the range of chopper frequencies, the reset interval length shall be kept the same in order not to introduce additional systematic effects due to the switch of read-out timing. There must be at least two ramps per chopper plateau, which limits the maximum possible chopper frequency. Selection of very short reset intervals may not offer an optimum dynamic range.
  A reset interval of 1/4 s is selected which is foreseen to be used in spectrometer AOTs and which is the shortest one allowing to use 16 sample sub-mean averaging.
  The time per measurement is 128 s. For the smallest chopper frequency this gives 2 complete cycles.
  Start with the low chopper frequency and increase to the highest one.

commanded # of RI per plateau	plateau time (s)	ν_{chop} per half cycle (Hz)	# of chops BB1-CS1/BB1-CS2
1 + 1 = 2	0.5	1	64 + 64
3 + 1 = 4	1.0	0.5	32 + 32
7 + 1 = 8	2.0	0.25	16 + 16
15 + 1 = 16	4.0	0.125	8 + 8
31 + 1 = 32	8.0	0.0625	4 + 4
63 + 1 = 64	16.0	0.03125	2 + 2

  (For most of the OBCPs 1 ramp is added for synchronisation, the commanded number of ramps is final number - 1.)

- The integration capacity has to be adjusted to the flux level. This can be done monitoring on-line the dynamic range of the preceding req. 1.2.3 sequence for the same OGSE BB setting and adjusting the capacity value to the best matching one.

- The 16 sample sub-mean averaging SPU mode is selected providing 4 sub-mean voltages per ramp.

- The bias voltage of the detectors is set to the optimum voltages found from the preceding tests related to req. 1.2.1. From module level tests these values are 200 mV for the blue array and 70 mV for the red array.

- The detector temperature of the blue array is set to the optimum value found from the preceding tests related to req. 1.2.2. From module level tests this temperature is 2.5 K.

- The check-out voltage for the CRE resistor channels should be set to the values found from the preceding tests related to req. 1.2.4. This has to be adjusted for each selected capacitance.

- The measurements will be performed for the blue array in both the second and third order in order to check for any dependence on the wavelength and providing more flux ratios. Therefore the whole frequency sequence is repeated a second time after rotation of the order sorting filter. The second order is always observed before the third order. This means duplication of the measurement time and cycles for the red array.
  The grating will be fixed during this measurement to an angle of ≈49.5 deg, selecting the wavelengths of ≈60 μm and ≈90 μm for the blue array and ≈180 μm for the red array. Applying the CQM calibration this corresponds to a grating position of 425250.

- The internal calibration sources will be set to their default values which slightly differ from each other providing the background level of the chopper sequence. These values will be defined at the beginning of the test campaign. For CQM-ILT the default values were 70.5 K (800000) for CS1 and 76.0 K (920000) for CS2.

- The flux contrast is achieved by increasing the OGSE BB1 temperature from about telescope background level, 20 K for the red channel and 30 K for the blue channel, to a considerable multiple of the background flux (77.0 K, i.e. ≈ 25 – 30 times the telescope background).
  The OGSE BB1 settings in use are 18.8, 25.4, 32.5, 40.7, 48.0, 61.4 and 77.0 K.
  The expected flux ratios BB1/CS1 and BB1/CS2 are the following, assuming an emissivity of 0.04 for CS1 and CS2. Application of the smallest OGSE BB1 temperature depends on the final CS1, CS2 set-up.

$T_{\mathrm{OGSE\,BB}}$	T_{CS1}=70K wavelength			T_{CS2}=76K wavelength		
(K)	60 μm	90 μm	180 μm	60 μm	90 μm	180 μm
18.8	0.002	0.045	0.77	0.002	0.037	0.67
25.4	0.06	0.41	2.40	0.044	0.33	2.10
32.5	0.47	1.62	4.98	0.35	1.32	4.35
40.7	2.06	4.43	8.70	1.56	3.61	7.60
48.0	5.07	7.92	12.44	3.83	6.68	10.86
61.4	15.28	17.61	19.92	11.54	14.38	17.40
77.0	34.56	31.59	29.23	26.09	25.79	25.53

Estimated time needed

OGSE BB stabilisation = 7 × 0.3 h = 2.1 h
(If in combination with req. 1.2.3 measurement no additional stabilisation time overhead)
6 chopper frequencies × 7 OGSE temperature settings × 2 grating orders in blue × 128 s mt +
7 OGSE temperature settings × 2 grating orders in blue × 15 s fmt = 10962 s = 3.1 h
(mt = measurement time; fmt = filter wheel movement time)
⇒ total time ∼5.2 h, 3.1 h in combination with req. 1.2.3 measurements.

Calibration Analysis Procedure (CAP)

- Check on-line with QLA during the preceding measurement related to req. 1.2.3 (dynamic range of selected integration capacitor) which capacitor setting is best matched in dynamic range to each of the selected OGSE BB settings.

- The SPU set-up delivers 4 averaged voltages per ramp. Fit these points and derive signal per ramp.

- For each OGSE BB1 setting:
  Plot the signal time series of the 6 measurements with different chopper frequencies and visually inspect for any systematic changes.

- Derive average signal per chopper plateau and differential signal for BB1-CS1 and BB1-CS2 chops. Average signals per chopper plateau and differential signals belonging to the same chopper phase for all chopper cycles. Calculate ratios with regard to the signals of the measurement with the lowest frequency (considered as quasi-staring) and derive possible signal losses depending on the chopper frequency.

- Repeat steps of preceding block but only using the first signal per chopper plateau (no averaging over all plateau signals) to get the “initial” signal jump. Check whether this is different from the average signal per chopper plateau.
- Inspect signals along the chopper plateaux for any systematic trend (again calculating ratios).
- Also check for any longer term trends with systematic signal differences inbetween subsequent chopper plateaux for the same chopper phase.
- Derive percentage of initial signal jumps with regard to the “final” signal for the lowest chopper frequency measurement depending on the flux jump.
- Establish time constants of any transients observed. Check whether time constants are unique or depend on the flux jump.
- Depending on the outcome further transient assessment measurements may have to be designed.

Output, products

Characterisation of initial signal jump for fast chopping.
Time constants of transients on the second-to-minute scale depending on flux jump.
Empirical signal correction factors for some range of chopper frequency.
Recommendation for optimal chopper frequency.

Status/version

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$Revision: 1.3 $
$Date: 2006/07/21 12:40:28 $
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Req. 1.2.9 Detective Quantum Efficiency

Objectives

Measure the detector quantum efficiency for nominal detector bias (and temperature settings). For this measurement the noise of the detector must be dominated by photon noise, i.e. the BLIP = Background Limited Infrared Photoconductor case must prevail. The quantum efficiency is derived from measurements of the NEP_{BLIP} and is reversely needed to calculate NEP_{BLIP} in simulator and time estimator applications.

Fulfilling or fulfilled by

Req. 1.2.3 addresses the flux dependence of NEP_{BLIP} and the disentanglement of NEP_{RO} (c.f. req. 1.2.10) which allows to identify NEP_{BLIP} dominated measurements.

Priority

B

When performed / frequency

1) During module level tests.
2) During ILT tests.

Required accuracy

The basic equations associated with the QE are shown in the following:
$\eta(\lambda_{\mathrm{c}}) = 4\,\frac{h\cdot c}{\lambda_{\mathrm{c}}}\cdot\frac{\Phi_{\mathrm{B}}}{NEP^2_{\mathrm{BLIP}}}\cdot B^2$

η = QE
h = Planck constant
c = speed of light
λ_{c} = central wavelength of band
Φ_{B} = illumination power
$\mathrm{NEP_{BLIP}}$ = NEP as determined in CAP 1.2.10 for background limited case.
B = Bose factor = $\sqrt{1 + \frac{1}{e^{\frac{h\,c}{\lambda_{\mathrm{c}}\,k\,T_{\mathrm{BB}}}}-1}}$
$\mathrm{T_{BB}}$ = blackbody temperature
k = Boltzmann constant

Note that the quantum efficiency can also be derived from the detector responsivity R. This requires, however, knowledge of the photoconductive gain G:

$\eta\cdot G = \frac{h\cdot c}{\lambda_{\mathrm{peak}}}\,\frac{R}{e}$

e = electron charge

This second approach can be used to cross-check the photoconductive gain.

Inputs, prerequisites

In order to determine the peak QE, η_{peak}, the relative spectral responsivity $r_{\mathrm{det}}(\lambda)$ of the detectors must be known for scaling $\eta(\lambda_{\mathrm{c}})$ to η_{peak}:
$\eta_{\mathrm{peak}} = \frac{\eta(\lambda_{\mathrm{c}})}{r_{\mathrm{det}}(\lambda_{\mathrm{c}})}\quad,\ r_{\mathrm{det}}(\lambda_{\mathrm{peak}}) = 1$
Flux predictions for the OGSE BB settings. The current reference is “Flux estimates in-orbit and for OGSE” (PICC-KL-TN-004).

Input fluxes must be bright enough in order to provide the photon noise dominated range.

Sources

1) Module level tests: laboratory BBs internal (cold) or external (hot) to cryostat.
2) ILT tests: OGSE BBs, homogeneously illuminating the arrays.

Calibration Implementation Procedure (CIP)

- Perform differential measurements covering a range of fluxes which extends significantly below and above the telescope background, see CIP 1.2.3 for the selected levels. At the higher end the measurement is dominated by photon noise which can be identified, when $NEP_{\rm tot}$ starts to follow the $\Phi_{\rm B}^{1/2}$ relation. NEPs and $\Phi_{\rm B}$ from this range can be used to determine $\eta(\lambda_{\rm c})$.

Estimated time needed

See time estimate for CIP 1.2.3.

Calibration Analysis Procedure (CAP)

- Identify the range where NEP follows the $\Phi_{\rm B}^{1/2}$ relation, c.f. details of the CAP 1.2.10 description. Any pair of measured NEP / predicted $\Phi_{\rm B}$ from this range can be used for this calculation – use all available ones.
- The Bose factor is determined using the OGSE BB temperature.
- $\eta(\lambda)$ is calculated according to the formula above.
- The measurements of CIP 1.2.3 are not done for the peak of the relative detector responsivities:
  $\lambda_{\rm blue} \approx 85\,\mu$m; $\lambda_{\rm blue}^{\rm peak} \approx 120\,\mu$m; $r_{\rm det}(85\,\mu{\rm m}) \approx 0.65$.
  $\lambda_{\rm red} \approx 135\,\mu$m; $\lambda_{\rm red}^{\rm peak} \approx 180\,\mu$m; $r_{\rm det}(135\,\mu{\rm m}) \approx 0.7$.
- For the cross-check calculating $\eta \cdot G$, quoted responsivities (c.f. req. 1.2.7) are peak responsivities at $\lambda_{\rm peak}$.

Output, products

Quantum efficiency per detector pixel as input for PACS Instrument Model and Performance Prediction.
This kind of measurement can serve as a cross-check of the efficiency of the fore optics and detector cavities with regard to measurements of reference detector pixels in other configurations.

Status/version

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$Revision: 1.3 $
$Date: 2006/07/17 17:28:48 $
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Req. 1.2.10 Noise Equivalent Power

Objectives

The noise equivalent power (NEP) corresponds to that amount of illumination power that is needed to generate a signal-to-noise ratio S/N = 1 after 1/2 s of integration time in a chopped measurement (definition of 1 Hz bandwidth commonly used in astronomy, therefore the unit is W / $\sqrt{Hz}$). The noise signal has different sources, one is the photon noise, another one the read-out noise of the detector-CRE chain. The performance of PACS shall be limited by the photon noise of the telescope background represented by the NEP$_{\mathrm{BLIP}}$. The read-out noise of the detector system NEP$_{\mathrm{RO}}$ shall be below that, so that it never limits the PACS performance.

Fulfilling or fulfilled by

Reqs. 1.2.1 and 1.2.2 address the bias and temperature (for the blue detector array) dependence of the NEP. A minimum NEP in these sequences is the essential criterium for the selection of the optimum detector bias and temperature.
Reqs. 1.2.3 and 1.2.11 address the flux dependence of the NEP_{BLIP} and allow to disentangle the ranges where NEP_{RO} and NEP_{BLIP} dominate, respectively.
The value of the NEP may be severely altered under the presence of ionising radiation. This is addressed by req. 1.2.14.

Priority

A

When performed / frequency

1) During module level tests
2) During ILT tests

Required accuracy

The basic equations associated with the NEP are shown in the following:

$$NEP_{\mathrm{BLIP}} = 2\,B \cdot \sqrt{\frac{h \cdot c}{\lambda_{\mathrm{c}} \cdot \eta} \cdot \Phi_{\mathrm{B}}}$$

For an explanation of the symbols, see req. 1.2.9.

$$NEP_{\mathrm{RO}} \leq 8 \times 10^{-18} W\,Hz^{-1/2}$$

$$NEP_{\mathrm{tot}} = \sqrt{NEP_{\mathrm{BLIP}}^2 + NEP_{\mathrm{RO}}^2}$$

Inputs, prerequisites

Flux predictions for OGSE BB settings. The current reference is "Flux estimates in-orbit and for OGSE" (PICC-KL-TN-004).

Sources

1) Module level tests: laboratory BBs internal (cold) or external (hot) to cryostat.
2) ILT tests: OGSE BBs.

Calibration Implementation Procedure (CIP)

- For bias and temperature dependence, see detailed description of CIP 1.2.1.
- For determination of $NEP_{\rm RO}$ and $NEP_{\rm BLIP}$ perform differential measurements covering a range of fluxes which extends significantly below and above the telescope background, see CIP 1.2.3 for the selected levels. At the lower end the measurement noise should be dominated by read-out noise, at the high end by photon noise of the background flux level. $\mathrm{NEP}_{\rm BLIP}$ is proportional to $\Phi_{\rm B}^{1/2}$, $\mathrm{NEP}_{\rm RO}$ is constant with flux. Reducing $\Phi_{\rm B}$ from the highest value, $NEP_{\rm tot}$ should follow the $\Phi_{\rm B}^{1/2}$ relation until a transition range is reached when $NEP_{\rm tot}$ turns to the constant value of $NEP_{\rm RO}$.

Estimated time needed

See time estimates for CIP 1.2.1 and CIP 1.2.3.

Calibration Analysis Procedure (CAP)

- Basic definitions for the calculation of the NEP from CRE signals:

$$NEP_{\rm i} = \frac{S_{\rm noise,i} \cdot (2\,\Delta\,t)^{1/2} \cdot C_{\rm int}}{R_{\rm i}}$$

With the definition of $\mathrm{R_i}$ in req. 1.2.7:

$$NEP_{\rm i} = \frac{S_{\rm noise,i} \cdot (2\,\Delta\,t)^{1/2} \cdot C_{\rm int}}{\bar{S}_{\rm i} \cdot C_{\rm int}} \cdot \Delta\Phi_{\rm B} = \frac{S_{\rm noise,i} \cdot (2\,\Delta\,t)^{1/2}}{\bar{S}_{\rm i}} \cdot \Delta\Phi_{\rm B}$$

with
$\mathrm{S_{noise,i}}$ = $\sigma(\bar{S}_{\rm i})$ standard deviation of the mean differential signal determined from a chopper cycle ([V/s])
$\bar{S}_{\rm i}$ = mean differential signal determined from a chopper cycle ([V/s])
Δt = typical integration time = reset interval ([s] = $[\mathrm{Hz}]^{-1}$, see note below)
$\Delta\,\Phi_{\rm B}$ = difference power of modulated illumination ([W])
$\mathrm{C_{int}}$ = selected integration capacity ([F] = [A s/V])
$\mathrm{R_i}$ = responsivity per pixel ([A/W])

- Discussion of noise terms and typical integration time:
The NEP should be independent of the total measurement time. A small flux can be measured with a certain S/N ratio within a certain measurement time T:

$$\Delta\,\Phi = \frac{S/N \cdot NEP}{\sqrt{2\,T}}$$

Independence of the NEP of the measurement time and considering the integrating behaviour of the CRE can be achieved when using:
mean signal from n ramps with reset time $\mathrm{t_{ri}}$:

$$\bar{S} = \frac{1}{n}\sum_{i=1}^{n} S_{\rm i}$$

standard deviation of measurement with n ramps:

$$sdv = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(S_{\rm i} - \bar{S})^2}$$

standard deviation of mean:

$$\sigma(\bar{S}) = \frac{1}{\sqrt{n}}\,sdv$$

total measurement time: $T = n \cdot t_{\mathrm{ri}}$

$$NEP = \frac{\sigma(\bar{S}) \cdot \sqrt{2T}}{\bar{S}} \cdot \Delta\Phi = \frac{\frac{1}{\sqrt{n}} \cdot sdv \cdot \sqrt{n} \cdot \sqrt{2\,t_{\mathrm{ri}}}}{\bar{S}} \cdot \Delta\Phi$$

$\Rightarrow$ Either use standard deviation of mean signal $\sigma(\bar{S})$ in combination with total measurement time T or standard deviation sdv in combination with basic integration time = reset interval time t_{ri} (ideally set to 1 s).

- For bias and temperature dependent NEP_{tot} determination, see detailed description of CAP 1.2.1.
- For disentangling NEP_{BLIP} and NEP_{RO} dependent on the flux use the differential measurements of CIP 1.2.3. From the differential signals and their uncertainties between OGSE BB1 and BB2 determine the NEP_{tot} following the NEP definition above.
  Plot NEP_{tot} versus total flux $\Phi_{\mathrm{B}} = \mathrm{f} \cdot \Phi_{\mathrm{B}}^{\mathrm{telB}}$ in logarithmic units. For high Φ_{B}, $NEP_{\mathrm{tot}} \approx NEP_{\mathrm{BLIP}} \propto \Phi_{\mathrm{B}}^{1/2}$, i.e. $log(NEP_{\mathrm{tot}}) \propto \frac{1}{2} \cdot log(\Phi_{\mathrm{B}})$.
  This relation can be extrapolated towards smaller Φ_{B} giving the relative contribution of NEP_{BLIP} over the full flux range. For small Φ_{B}, $NEP_{\mathrm{tot}} \approx const = NEP_{\mathrm{RO}}$, by design of the measurement. The measurement points should turn onto a horizontal line.

Output, products

Verification of NEP_{RO} and $NEP_{\mathrm{BLIP}}(\Phi_{\mathrm{B}})$ as input for PACS Instrument Model and Performance Prediction.

Status/version

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$Revision: 1.6 $
$Date: 2006/07/17 13:48:10 $
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Req. 1.2.11 Linearity of CRE readout

Objectives

The issue of linearity has several aspects:

1 The linearity of the slope of the CRE output voltage ramps shall be checked over the full dynamic range. This shall be done for all integration capacitors. The results can have an impact on the selected method of on-board processing.

2 Related to this is the investigation whether the derived signal depends on the selected reset interval length. Beside non-linearities there may be an impact on the signal by the timing of the reset pulses.

3 The scaling of the detector–CRE output signal with flux.

Fulfilling or fulfilled by

Fulfilled by req. 1.2.3 (dynamic range per selected integration capacitor)

Priority

A

When performed / frequency

1) As part of the module characterization on ground.
2) During ILT tests.

Required accuracy

In order to measure small differential signals on top of the telescope background signal, the local peak deviation of the output voltage from a straight line fit to the ramp (e.g. measured by a 2^{nd} order fit) should be less than 3% (“Requirements for the PACS-CRE”, PACS-ME-RS-002).

Inputs, prerequisites

Flux predictions for OGSE BB settings. The current reference is “Flux estimates in-orbit and for OGSE” (PICC-KL-TN-004).

Sources

1 See setup as described in the documents “Test Procedure / Test Report, Functional Tests of PACS QM-FEEs” (PACS-MA-TR-004c) and “PACS Test Report, Results of Tests on QM FEE A02-038-15, Run 10/2001” (PACS-MA-TR-005).

2 OGSE BBs

Calibration Implementation Procedure (CIP)

See detailed CIP description of req. 1.2.3. For the investigation of the linearity of the ramps over the entire output voltage range, read-out combinations with long reset intervals yielding full dynamic range are of particular interest.

Estimated time needed

See time estimate for CIP 1.2.3

Calibration Analysis Procedure (CAP)

- For the analysis of ramp linearity select those measurements where the analysis of CAP 1.2.3 indicates $\mathrm{R}^{\mathrm{dyn}} >$ 80% or even saturation.
- For the transmitted raw ramps average the corresponding read-outs of all available ramps for the selected CRE configuration, perform line fits using a chi-square method, plot read-outs and line fits and visually inspect them for any systematic deviations. Alternatively use pair-wise read-outs for signal determination and plot those signals versus the mean absolute voltage of each read-out pair. Superimpose all available read-out pairs to improve the statistics by assessing the reproducibility. Any absolute voltage range with peculiar slope behaviour should show up in this way.
- For the absolute sub-slope signals s_{j} of 1/4, 1/2 and 2 s reset intervals calculate the signal ratios with regard to the first sub-slope signal, $\frac{s_{\mathrm{j}}}{s_1}$ for those sub-slope signals which are not saturated (differential signals are not needed for this type of evaluation).
  Calculate the approximate average absolute voltage for each sub-slope signal U_{j} as
  $$U_1 = U^{reset} + \frac{1}{2}\, s_1 \times \frac{1}{16} \quad \text{for j} = 1$$
  $$U_{\mathrm{j}} = U^{reset} + \sum_{k=1}^{j-1} s_{\mathrm{k}} \times \frac{1}{16} + \frac{1}{2}\, s_{\mathrm{j}} \times \frac{1}{16} \quad \text{for j} > 1$$
  U^{reset} from CAP 1.2.3.
  Plot the signal ratios $\frac{s_{\mathrm{j}}}{s_1}$ versus those absolute voltages and check for ratios systematically sticking out or for systematic trends. Check, whether ratios common to the 1/4, 1/2, and 2 reset intervals show reproducible behaviour.
- For pixels with raw ramp information derive sub-slope signals as robust means from read-out pair signals and plot such derived sub-slope signals versus the average absolute voltages which can be directly taken from the raw ramps. Compare both results for consistency.
- In case ramp non-linearities are found compare with the linearity of the resistor channels whether they show a similar behaviour. Also check with the ramp shape of the open channels whether some non-linearity can be explained by correlated cross-talk.
- For the analysis of signal dependence on reset interval length intercompare all 4 measurements taken with the same integration capacity and OGSE BB setting. Average non-saturated sub-slope signals and plot them versus the reset interval. Do this for all integration capacities and all OGSE BB settings, i.e. for
  4 (integration capacities) $\times$ 8 (OGSE BB settings) $\times$ 2 (BB1 $+$ BB2 plateaux) = 64 sets
  If any deviations in signals above the signal uncertainty occur, check whether this is systematic for certain reset intervals or whether it depends on the dynamic range of the respective measurement.
- For the analysis of signal linearity with flux select the signals of measurements with identical reset interval / integration capacity configuration, but different OGSE BB illumination. Distinguishing the slightly different illumination levels of BB1 and BB2 these are 16 different fluxes for 16 sets of reset interval / integration capacity configuration. Plot the signal versus predicted fluxes and check the linearity of the relations.

Output, products

1) In case ramp non-linearities are found, this may result in discarding signals for the part of the voltage range where the non-linearity occurs or in applying correction factors to linearise this part of the ramp or adjust the sub-slope signal respectively. A special application is the subtraction of the corresponding open channel signal to reduce the correlated cross-talk. From the raw ramp analysis implications for the on-board sub-ramp processing may result, e.g. discarding always the destructive read-out.
2) In case signals vary systematically with reset interval or integration capacity establish relations in order to scale the signals with regard to a reference reset interval / integration capacity configuration.

3) In case signals do not scale linearly with flux establish calibration relations which have to be connected with the RSRF calibration.

Status/version

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$Revision: 1.4 $
$Date: 2006/07/17 10:00:00 $
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Req. 1.2.12 Ionizing radiation: Reset time, spectrometer

Objectives

Investigate the influence of ionizing radiation on the usable reset time interval.

Two aspects have to be investigated. One, the number of read-outs required to obtain an accurate slope determination (which will depend on the input flux), the glitch rate, and the OBSW processing in terms of deglitching and ramp fitting. Two, the possible change in the slope after the impact by a glitch (see also req. 1.2.19), and, related, if (part of the) data taken after a glitch can be used in the analysis.

Fulfilling or fulfilled by

Related to 1.2.19.

Priority

A

When performed / frequency

- Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV

Required accuracy

not applicable

Inputs, prerequisites

Glitch rate predictions for the Herschel orbit. Full modelling of the energy spectrum of particles reaching the detector (protons, secondary particles, electrons and delta-rays), and their deposited energy.

Range of allowable values for the DR and NDR frequency.

Sources

On ground: a source of radiation and a source that provides an input flux comparable to the telescope background.

In PV observations of sources of different flux levels.

Calibration Implementation Procedure (CIP)

Module level test: Measure output signal as a function of time under various conditions of ionizing radiation (type of particle; energy; rate) and different detector settings. To be considered are the bias voltage, detector temperature, capacitance, low/high-stress module, reset time interval.

PV: on sources of different fluxes, obtain observations using different reset times (likely only for nominal detector settings).

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

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$Revision: 1.9 $
$Date: 2003/09/26 15:51:23 $
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Req. 1.2.13 Ionising radiation: Responsivity, spectrometer

Objectives

Investigate the influence of ionizing radiation on the responsivity of the spectrometer, also as function of time.

Fulfilling or fulfilled by

self-standing, related to 1.2.14 (Ionising radiation: Noise, spectrometer)

Priority

A

When performed / frequency

- Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV

Required accuracy

Inputs, prerequisites

Glitch rate predictions for the Herschel orbit. Full modelling of the energy spectrum of particles reaching the detector (protons, secondary particles, electrons and delta-rays), and their deposited energy.

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

QM Module level test: measure the responsivity of the stressed and unstressed detectors for various bias levels and input powers [similar to the test described in PACS-ME-TR-001 'PACS TIA Tests on Detector Module 6' and PACS-ME-TR-003 'PACS TIA Tests on Detector Module 6-Part 2'], under different levels of particle impacts (in terms of particle type, energy, hit rate) as a function of time. One measurement without particle irradiation for each detector setting should also be performed. These measurements need to take a sufficiently long period of time (preferably upto 1-day if needed) to detect measurable changes in the responsivity in order to derive characteristic time scales for responsivity changes.

In-orbit: derive the responsivity using observations of celestial standards during an operational day.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

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$Revision: 1.9 $
$Date: 2003/09/26 15:51:23 $
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Req. 1.2.14 Ionising radiation: Noise, spectrometer

Objectives

Investigate the influence of ionizing radiation on the noise voltage of the spectrometer detectors (as function of time, TBC).

Fulfilling or fulfilled by

self-standing, related to 1.2.13 (Ionising radiation: Responsivity, spectrometer)

Priority

A

When performed / frequency

- Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV

Required accuracy

Inputs, prerequisites

Glitch rate predictions for the Herschel orbit. Full modelling of the energy spectrum of particles reaching the detector (protons, secondary particles, electrons and delta-rays), and their deposited energy.

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

Module level test: measure the noise voltage of the stressed and unstressed detectors for various bias levels and input powers [similar to the test described in PACS-ME-TR-001 'PACS TIA Tests on Detector Module 6' and PACS-ME-TR-003 'PACS TIA Tests on Detector Module 6-Part 2'], under different levels of particle impacts (in terms of type of particle, energy, hit rate) as a function of time. One measurement without particle irradiation for each detector setting should also be performed.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.10 $
$Date: 2003/09/26 15:51:23 $
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Req. 1.2.15 Ionising radiation: Dark current, spectrometer

Objectives

Investigate the influence of ionizing radiation on the dark current (noise) of the photoconductors. The two instruments onboard ISO with Ge:Ga detectors come to different conclusions concerning the effect of glitches on the dark current. For ISOPHT the dark signal increased because of low energy glitches (ISO/FIRST Glitches Working Group Final report). LWS found no change in the dark current level from mid- to end of a revolution (Swinyard etal 2000, Explanatory Astronomy, 10, 157), which led to the conclusion that the glitches had no effect on the dark current. This was contrary to the expectation on basis of their ground calibration measurements.

Fulfilling or fulfilled by

related to 1.2.6.

Priority

C. This depends on the outcome of req. 1.2.6. If the contribution of the dark current is important than we need to know whether the ionising radiation has an impact.

When performed / frequency

- Module level tests on high-stressed QM#3 at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.
- FM tests at the Paul Scherrer Institute (TBC).
- PV. Possible occasional measurement in routine phase.

Required accuracy

Inputs, prerequisites

Glitch rate predictions for the Herschel orbit. Full modelling of the energy spectrum of particles reaching the detector (protons, secondary particles, electrons and delta-rays), and their deposited energy.

Sources

On ground: a source of radiation

Calibration Implementation Procedure (CIP)

On ground: Determine dark current level with the OGSE closed. The dark current should be measured several times over a timespan of a PACS operational day.

In orbit: Determine dark current level by looking at the cold internal calibrators. The dark current should be measured several times over a timespan of a PACS operational day.

Straylight may be a concern to determine the “true” dark current. For the blue detector it may be possible to move the filterwheel in a blocked filter position.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

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$Revision: 1.9 $
$Date: 2003/09/26 15:51:23 $
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Req. 1.2.16 Time constant: switch-on spectrometer

Objectives

It is essential to assess the various stabilisation times of the spectrometer subinstrument after switch-on in order to establish operational constraints which will have to be taken into account for mission planning and/or AOT design.

There are several longer term (> several seconds) time constants of elements of the spectrometer operation. These are:

1) stabilisation times of the CREs after switch-on;
2) stabilisation times of the internal calibrators after switch-on;
3) stabilsation times of the detector signals after bias voltage change.

The last two aspects are covered by other requirements:
item 2) ⇒ req. 2.5.3 (Time constants: heat-up and cool down times of PACS calibration sources);
item 3) ⇒ req. 1.2.17 (Time constant: Bias change spectrometer).
Therefore, the only remaining aspect to be considered here is item 1, the stabilisation times of the CREs after switch-on. Document PACS-IM-PS-001 "Performance specifications for the PACS-CRE" states under item 27, Switch-on behaviour (off to on): "Stable operation within the requirements of stability of output signal and reproducibility after 30 minutes". This time constant will be verified.

Fulfilling or fulfilled by

req. 2.5.3 stabilisation times of the internal calibrators after switch-on;
req. 1.2.17 stabilsation times of the detector signals after bias switch-on.

Priority

B

When performed / frequency

- [1] During module level tests
- [2] During ILT tests

Required accuracy

Stable operation within the requirements of stability of output signal and reproducibility should be achieved after 30 minutes.

Inputs, prerequisites

Sources

simple version: no stimulators needed
more comprehensive version: internal calibration sources or OGSE BB(s)

Calibration Implementation Procedure (CIP)

The test can be done on two different levels:

1) As simple test using only the open and resistor pixel outputs (warm and cold)
2) As a more comprehensive cold test using all detector pixel outputs and with

a) either a constant internal calibration source (CS) or OGSE BB illumination;

b) a differential illumination chopping between CS1 and CS2 or chopping between OGSE BB1 and BB2.

The type of test depends on the availability of stimulators and the test context. If the test is performed early in the block of spectrometer camera performance tests together with CRE check-out and dark signals tests, type 1 has to be applied. Type 2 should be applied for verification after the detector bias optimisation.

Simple test form:

- There is no special requirement on the OGSE set-up. No source needs to be switched on, no external beam is needed:
  all OGSE stimulators can be switched off;
  internal calibration sources (CS) can be switched off;
  OGSE M3 (mirror 3): mirror drive to position: dark;
  focal plane chopper (FPC) directed to zero position.
- Switch-on spectrometer, but leave CRE in off-mode.
- The grating can remain in its current position.
- Since the resistor is mounted on the FEE with T = 4.2 K, the temperature control for the blue detector needs not to be switched on.
- The detector bias voltage is set to a very low voltage ($\leq$2 mV), especially, if this test is done in the warm!
- Select intgration capacity of 0.3 pF and reset interval of 1/4 s.
- Apply CRE check-out voltage of 20 mV to resistor pixels.
- Select buffer transmission mode to get the full time resolution for the shape of integrations of open and resistor channel.
- Switch CRE on (the exact position of this step in the sequence has to be checked with the CRE switch-on procedure by the manufacturer! Its position in this description wants to point out that the CRE should be switched on as late as possible in order to monitor the stabilisation).
- Start a 1 h measurement reading out open and resistor pixels in raw data mode (this accepts incompleteness in time coverage). Simultaneously start to record and monitor CRE supply voltages/currents.

Comprehensive test form:

- If internal CS mode, switch on CS1 and CS2 to nominal levels (70 $\pm\delta T$ K) and wait for stabilization time.
  OGSE M3 (mirror 3): mirror drive to position: internal path.
  If OGSE BB mode, wait for stabilsation of OGSE BB temperatures, which should be 30 $\pm\delta T$ K.
  OGSE M5 (mirror 5): mirror drive to position: OGSE BBs
- Switch-on spectrometer, but leave CRE in off-mode.
- The grating should be moved to a default position (key wavelength), select 2nd order for the blue array.
- Internal CS mode: staring on CS1 or differential mesurement mode with focal plane chopper frequency = 1 Hz, chopping between CSs.
- OGSE BB mode: staring on OGSE BB1 or differential measurement mode with OGSE chopper M8 (mirror 8) frequency = 0.5–1 Hz.

- Switch bias voltage of red array to optimal value (cf. req. 1.2.1).
  Switch bias voltage of blue array to optimal value (cf. req. 1.2.1).
  . Switch temperature control of blue array on to optimal temperature (cf. req. 1.2.2).
- Select intgration capacity of 0.3 pF and reset interval of 1/4 s.
  Apply CRE check-out voltage of 20 mV to resistor pixels.
- Select buffer transmission mode to get the full time resolution for the shape of integrations of open, resistor and detector channels.
- Switch CRE on (the exact position of this step in the sequence has to be checked with the CRE switch-on procedure by the manufacturer! Its position in this description wants to point out that the CRE should be switched on as late as possible in order to monitor the stabilisation).
- Start a 1 h measurement reading out all CRE channels in raw data mode (this accepts incompleteness in time coverage). Simultaneously start to record and monitor CRE supply voltages/currents.

Estimated time needed

The proper measurement time is 1 h, including set-ups $\approx$1.2 h (not including stabilisation times for calibration sources).

Calibration Analysis Procedure (CAP)

- Monitor the CRE supply voltages/currents on line.
- Offline:
  - CRE supply voltages/currents:
    Plot the voltages/currents with time and check for any trends,
    alternatively,
    Plot ratio of voltages/currents to average voltages/currents of last 5 minutes with time and check for any trends.
  - CRE open channel output:
    Plot signal sequences per reset interval with time and check for any change in features like hooks, kinks, etc.,
    alternatively,
    produce “average ramp” for signal sequences of last 7 minutes (2 raw data dumps).
    Compare for selected times open channel output with this average ramp.
  - CRE resistor channel output:
    Plot ramps with time and check for any change in shape,
    alternatively,
    produce average ramp and standard deviation for output ramps of last 7 minutes (2 raw data dumps). Compare for selected times output ramps with this average ramp.
    Derive signals from raw output ramps, plot with time and check for any systematic trend,
    alternatively,
    plot ratio of signals to average signal of last 7 minutes and check for any trends.
    Derive noise of signals, plot it with time and check for any systematic trend,
    alternatively,
    plot ratio of noise to average noise of last 7 minutes and check for any trends.
  - CRE detector channel output:
    As for resistor channel output for either staring mode or differential mode signals.
  - If trends are found, clarify that there is stabilisation within the measurement time (otherwise test may have to be repeated with longer measurement time).
  - Determine from repeated tests that the stabilsation time is reproducible.

Output, products

The derived CRE stabilisation time should be used in the operational switch-on procedure of the spectrometer mode (SPEC_orbit_prologue), to be maintained in a CalU Table.

Status/version

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$Revision: 1.7 $
$Date: 2006/06/16 11:59:06 $
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Req. 1.2.17 Time constant: Bias change, spectrometer

Objectives

Determine the time constants for stable detector operation after changing the bias voltage. Currently, there are no operational needs and concepts of a frequent switch in bias voltage, once the optimum bias voltages have been found. Bias changes occur when the spectrometer is switched on and the bias voltages are applied to the detector pixels. These stabilisation times have to be covered by the spectrometer switch-on procedure. Another reason for changing the bias voltage could be curing by a bias boost, but this has turned out to be not an efficient method, so that it will not be applied.

Fulfilling or fulfilled by

Fulfilled by 1.2.1, when switching through discrete bias voltages.

Priority

C

When performed / frequency

- [1] During module level tests
- [2] During ILT tests

Required accuracy

The stabilisation time to a new bias voltage setting are expected to be in the order of 30 s. The time to stabilize the bias voltage to the new value should be known with an accuracy of 1 s. In parallel the impact of bias changes on the detector output signals should be monitored and signals should become stable within a few percent.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

The investigations are done as part of the bias optimization tests. Bias changes

	20 mV	→	30 mV	(+50%)		80 mV	→	110 mV	(+37.5%)
	30 mV	→	40 mV	(+33%)		110 mV	→	140 mV	(+27%)
	40 mV	→	50 mV	(+25%)		140 mV	→	170 mV	(+21%)
for the red detector are	50 mV	→	60 mV	(+20%)	and for the blue detector	170 mV	→	200 mV	(+18%)
	60 mV	→	70 mV	(+17%)		200 mV	→	230 mV	(+15%)
	70 mV	→	80 mV	(+14%)		230 mV	→	260 mV	(+13%)
	80 mV	→	90 mV	(+12.5%)		260 mV	→	290 mV	(+11.5%)

The measurement times of the procedure of req. 1.2.1 amount to 180 s so that the expected time constants can be recognized in the signal time series..

Estimated time needed

No extra time on top of bias scans (see 1.2.1).

Calibration Analysis Procedure (CAP)

- The house-keeping data of the bias voltage are monitored on-line.
- The off-line analysis determines how fast the voltage settles to the new value.

- The detector output signals are checked for any drift which may be introduced by switching the bias voltage.

Output, products

If time constants are longer than 30 s, then these have to be taken into account for the operational procedure to switch bias voltages, should this become necessary in flight.

Status/version

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$Revision: 1.9 $
$Date: 2006/06/30 17:04:05 $
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Req. 1.2.18 Time constant: flux changes, spectrometer

Objectives

Photoconductor detectors show the behaviour that after a flux change the output signal is not instantenously adjusted to the new flux level, but an initial signal jump to a certain percentage of the final signal is followed by a signal transient with a certain time constant. The height of the initial signal jump and the transient time constant depend on the detector material, the flux jump and the total brightness on the detector.

Flux jumps for the detectors can be introduced in the following ways:

1) by chopping between on-source and off-source position with different brightness levels.
2) by switching the grating between an on-line and off-line position (technique of wavelength switching).
3) by switching between the 2nd and 3rd order for line scan measurements in both wavelength regions of the blue array.

Item 1 is addressed by investigating the signal dependence, both for absolute and differential signals, on the chopper frequency (req. 1.2.8) which allows to establish time constants related to the chopped flux modulation.
Item 2 is a basic AOT design issue and will be addressed in this context.
Here, item 3 is addressed in more detail. This mode of flux change can mean significant flux jumps due to the source spectrum and the shape of the relative spectral response function, when switching at a certain grating position instantenously over several tens of micron by rotating the order sorting filter for the blue detector channel.

Fulfilling or fulfilled by

Measurements related to req. 1.2.8 fulfill the aspect of investigating time constants due to flux modulation with the chopper.

Priority

B

When performed / frequency

- [1] During ILT-tests.
  The test can be combined with the tests related to req. 1.2.3 and req. 1.2.8 making use of the same OGSE BB setting, thus reducing wait times for BB stabilisation.
  for a certain OGSE BB setting the sequence is:
  - req. 1.2.3 block

  - grating movement to 425500
  - req. 1.2.8 block 2nd order

  - chopper to CFOV
  - req 1.2.18 block 2nd ⇒ 3rd order

  - req. 1.2.8 block 3rd order

  - chopper to CFOV
  - req. 1.2.18 block 3rd ⇒ 2nd order

  - grating movement to 760000 (1st order req. 1.2.3 block for next OGSE setting)

Required accuracy

The amplitude of the signal transient due to order sorting filter rotation and the signal stabilisation time shall be determined.

Inputs, prerequisites

Sources

1) ILT-tests: OGSE BB

Calibration Implementation Procedure (CIP)

- The time constants of signal adjustment when rotating the order sorting filter wheel for the blue detector channel are determined from staring measurements on various OGSE BB levels. Staring mode is selected in order not to induce other time constants by e.g. chopping. For one OGSE BB setting a forward and backward rotation of the filter wheel is performed. The length of each staring measurement is 240 s (4 min).
- The CRE configuration is the same as for the req. 1.2.8 measurements, i.e. RI = 1/4 s and the integration capacity adjusted to the flux level as determined from the preceding req. 1.2.3 measurement.
- The 16 sample sub-mean averaging SPU mode is selected providing 4 sub-mean voltages per ramp.
- The bias voltage of the detectors is set to the optimum voltages found from the preceding tests related to req. 1.2.1. From module level tests these values are 200 mV for the blue array and 70 mV for the red array.
- The detector temperature of the blue array is set to the optimum value found from the preceding tests related to req. 1.2.2. From module level tests this temperature is 2.5 K.
- The check-out voltage for the CRE resistor channels should be set to the values found from the preceding tests related to req. 1.2.4. This has to be adjusted for each selected capacitance.
- The grating will be fixed during this measurement to an angle of ≈49.5 deg, selecting the wavelengths of ≈60 μm in 3rd order and ≈90 μm in 2nd order for the blue channel. Applying the CQM calibration this corresponds to a grating position of 425250.
- Before the measurements and the filter wheel movement the chopper has to be moved to its zero position and it remains there for the whole time of this measurement.
- The flux contrast is achieved both by the SED shape of the illuminating source and the ratios of the RSRF for the two wavelengths. The RSRF ratio, $\frac{RSRF_{90}}{RSRF_{60}}$ is moderate, ≈1.2. Strong contrasts are introduced by cold sources, for which 60 μm is on the Wien branch.
  The OGSE BB1 settings in use are 18.8, 25.4, 32.5, 40.7, 48.0, 61.4 and 77.0 K.
  The expected flux ratios between 90 μm and 60 μm are:

$T_{\mathrm{OGSE\,BB}}$ (K)	$\frac{f_{90}}{f_{60}}$
18.8	20.8
25.4	6.9
32.5	3.5
40.7	2.1
48.0	1.6
61.4	1.2
77.0	0.9

- This measurement is intimately linked with the measurement of req. 1.2.8 which is again coordinated with req. 1.2.3 measurements. The coordination of blocks of all three measurements is described under "When performed" above.

Estimated time needed

OGSE BB stabilisation = 7 $\times$ 0.3 h = 2.1 h
(If in combination with req. 1.2.8 measurement no additional stabilisation time overhead)
7 OGSE temperature settings $\times$ 2 filter wheel changes (2nd $\Rightarrow$ 3rd order and reverse) $\times$ 2 staring measurements before and after wheel rotation $\times$ 240 s mt +
7 OGSE temperature settings $\times$ 2 filter wheel changes $\times$ 15 s fmt = 6930 s = 1.95 h
(mt = measurement time; fmt = filter wheel movement time)
$\Rightarrow$ total time $\sim$4.1 h, 1.95 h in combination with req. 1.2.8 measurements.

Calibration Analysis Procedure (CAP)

- Check on-line with QLA during the preceding measurement related to req. 1.2.3 (dynamic range of selected integration capacitor) which capacitor setting is best matched in dynamic range to each of the selected OGSE BB settings.
- The SPU set-up delivers 4 averaged voltages per ramp. Fit these points and derive signal per ramp.
- For each OGSE BB1 setting:
  Plot the signal time series of the 4 measurements 2nd $\Rightarrow$ 3rd . . . 3rd $\Rightarrow$ 2nd order and visually inspect for transients and reproducibility of final signals.
- Determine the variation of the signal along the measurement time and establish initial signal jump and final signal levels.
- Derive time constants for possible transients and check whether they depend on the height of the flux jump and / or absolute flux level.
- Determine conservative signal stabilisation time of signal after filter wheel movement.

Output, products

Signal stabilisation time after filter wheel rotation.

Status/version

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$Revision: 1.10 $
$Date: 2006/07/21 18:40:56 $
```

Req. 1.2.19 Time constant: cosmic ray hits, spectrometer

Objectives

Investigate the behaviour of the detector after a glitch. Just like with flux steps, it can take a certain time before a pixel relaxes to its nominal state. Here we want to investigate the duration of such an event and how the pixel stabilises after a glitch.

Fulfilling or fulfilled by

Priority

B

When performed / frequency

-QM Module level tests on low- and high-stressed modules at the Centre de Recherches du Cyclotron (CRC) at the Université catholique de Louvain-la-Neuve.

-PV

Required accuracy

10-20%.

Inputs, prerequisites

None

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

On ground: nominal data from CRC-UCL are sufficient. Investigate the time behaviour of slope versus time after a glitch.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Examples of the transient effect after a glitch are illustrated in Figure 13 of PICC-Kl-TN-022 (FM proton irradiation tests high & low stress modules I: Glitch effects and curing, by P. Royer).

Al though no formal fitting has been attempted, a fit of the form $\exp(-t/t_0)$ would lead to a value of order $t_0 \sim 0.75s$, for the High Stress modules, and a smaller value for the Low Stress module.

This time constant, corresponding to several ramps, implies that it will **NOT** be possible to correct for this effect on a single glitch basis, as a chopper plateau will consist of 1-2 ramps only according tot the current AOT design. This implies there is no baseline to fit a model to the signal versus time. At best one may hope to construct "templates" of how the transient effect after a glitch behaves as a function of time, glitch strength, signal.

If desired, such a database needs to be build during PV using the radiation environment in space.

Status/version

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$Revision: 1.9 $
$Date: 2006/05/12 16:07:04 $
```

Req. 1.2.20 Time variation responsivity spectrometer

Objectives

Investigate the time variation of the responsivity of the spectrometer, on time scales ranging from that of a single ramp (below 1 sec) to that of an operational day (hours), as well as long term variations (months).

Fulfilling or fulfilled by

Priority

A

When performed / frequency

QM, PV and routine phase

Required accuracy

Not applicable

Inputs, prerequisites

Time series of responsivity measurements.

Sources

Cyclotron during QM-level tests

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Trend analysis of a time series of responsivity measurements.

Output, products

The results of the QM-level tests in the Cyclotron in Louvain-la-Neuve regarding responsivity drifts and jumps are described and summarised in:

-PACS-ME-TP-009 "Test Plan and procedure for investigation of glitch event rate and collected charge variation in the Ge-Ga detectors during proton irradiation at UCL-CRC", by Katterloher et al. (Issues 1, 2 and 3 for the 3 test campaigns)

-PICC-Kl-TN-023 "FM proton irradiation tests high & low stress modules II: Noise evolution, Curing frequency, Detector settings", by P. Royer

-PICC-Kl-TN-022 "FM proton irradiation tests high & low stress modules I: Glitch effects and curing", by P. Royer

Briefly, these tests allowed to verify the behaviour of the responsivity on a time scale of seconds to a few hours. Different effects can be noted: (1) events dubbed "responsivity jumps", i.e. a sudden change in the slope, often but not in all cases related to a visible glitch in that ramp; (2) a long term increase in responsivity due to the prolonged irradiation. On a time scale of hours a plateau in responsivity is reached; (3) the effects of self-curing after strong glitches.

Implications for calibration are difficult to draw because the radiation environment in space are different than during the tests. The time constant to reach a plateau of hours makes it difficult to decide if one would cure, and hence need to calibrate the change in responsivity quite accurately over an operational day, or if one does not cure, and hence allow oneself to be in a condition with higher noise but a more stable responsivity.

Status/version

$Revision: 1.10 $
$Date: 2006/05/12 13:14:38 $

Req. 1.2.21 On-board software processing, spectrometer

Objectives

This requirement has become obsolete.

Previously, it was considered possible for the on-board software (OBSW) to have uploadable calibration files for the different processing steps under consideration, e.g. linearisation, ramp fitting, glitch detection, ramp rejection.

It is now known that the only processing on-board will be either slopefitting, or averaging over n non-destructive readouts, next to data compression. The value of n will be driven by CPU considerations only.

Fulfilling or fulfilled by

Priority

When performed / frequency

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.9 $
$Date: 2006/06/09 13:49:16 $
```

Req. 1.2.22 Cross-talk, electrical, spectrometer

Objectives

Determine the electrical cross-talk between detector pixels of the spectrometer.

Fulfilling or fulfilled by

Priority

B

When performed / frequency

-QM Module level tests at the CRC-UCL (only a linear array will be available).

-In-orbit.

Required accuracy

Inputs, prerequisites

Sources

On ground: a source of radiation and a source that provides a relevant background level.

Calibration Implementation Procedure (CIP)

Analyse cosmic ray hits where only ONE pixel is hit. Check for the response of neighbouring pixels.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

In PICC-KL-TN-011 (Draft 2) PR describes the investigation of cross talk in the March 2004 data set taken at CRC-UCL. Among neigbouring detectors he finds that about 2.2% of events are simultaneous.

Theoretical work by Christian Bongardo using the GEANT4 toolbox described in PICC-TS-SIM-006 indicates that for protons and alfa-particles about 4-5% of events should lead to 2 pixels being affected. This number is in reasonable agreement with what is found observationally, considering that not both events need to be detected by the glitch detections algorithm

Status/version

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$Revision: 1.10 $
$Date: 2006/06/08 15:49:49 $
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Req. 1.2.23 Curing, spectrometer

Objectives

A) Verify the effectiveness of possible different curing procedures.

B) Investigate the necessary frequency of curing.

C) Determine the time constants involved after curing.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

A) On Ground: After the first radiation test in March 2004 at CRC-UCL it became clear that strong responsivity changes could be observed, both on timescale of hours, as well as in the form of "responsivity jumps" (RJ). These RJ were not always related to a visible glitch in the ramp.

One of the major changes in the test set-up for the subsequent tests in April 2005 and October 2005 was the inclusion of a "flasher" (a cryogenic BB source). Good results are obtained using a current of 4mA for a duration of 30s (sometimes 3 x 30s with 30s gaps).

In addition "bias boost" (to 2.5 V) and "detector heating" (upto 5-6 K) have been tried as curing method. Analysis of the results (PICC-KL-TN-022, Royer) indicate that the use of the flasher is the recommended curing method. The detector heating provides equal good curing but it takes around 2 minutes for the detectors to cool down to 1.9K again.

B) On Ground: The test at CRC-UCL have provided first insights into the responsivity changes. To reach a responsivity plateau takes several hours under the irradiation conditions during the tests. On the other hand the radiation conditions in L2 are different and to determine the timescale of responsivity change will require extensive testing during PV.

Note that this is coupled to the detector setting. Both tests at MPE and pre-beam data in the cyclotron have shown that the best S/N is achieved for A) a certain bias value, B) for the smallest capacitance and C) the longest ramps.

The analysis of the radiation data suggest other wise. The typically high bias values suggested as optimum from data without irradiation let the detectors spike. In the case of the low-stress module a bias value of say 120 mV or lower is suggested rather than 200-210 mV. In addition the best S/N is in most cases achieved for ramps of 1/4s.

The best compromise between curing (leading to a continuous change of responsivity, but at detector settings that lead to the best S/N in the absence of irradiation) and no curing (small or no longterm change in responsivity, but at detector settings that lead to sub-optimum S/N in the absence of irradiation) needs to be found during PV.

What needs to be in place and tested during FM-ILT are the baseline procedures. Calling these procedures and the frequency thereof are then a matter of AOT finalisation.

C) During FM-ILT no source of irradiation will be present, and the main aim of these tests will be to test the procedure for

- curing by flashing, and
- curing by detector heating.

and determine time scales for the "system" to reach pre-curing status.

Required accuracy

Timescales to within 10%.

Inputs, prerequisites

Sources

On ground: Cyclotron at UCL-CRC.

FM-ILT: none

Calibration Implementation Procedure (CIP)

<u>Curing by Flashing</u>

parameters: n= number of flasher events, t1= duration of flasher event, t2= time between 2 flasher events, I= current used.

Proposed are:

- 3 * (20 + 30) sec at I= 3,4,5 mA

- 1 * 30 sec at 4 mA

- 1 * 60 sec at 3 mA

- 3 * (60 + 30) sec at 4 mA

with a wait time of 30 min (this can possibly be reduced based on the outcome of the performance tests)

detector settings: nominal bias and smallest capacitance.

<u>Curing by Detector Heating</u>

parameters: H= Heater value, t1= duration of heating event.

Default values will be determined from performance tests, but the heating will typically take a few minutes with a wait time of 50 minutes to monitor the heat dissipation.

detector settings: nominal bias and smallest capacitance.

Estimated time needed

The tests described above would take 3.5h for the flasher sequence and 1h for the heater test. The 3.5h could be reduced if the performance tests indicates that the wait time of 30 minutes can be reduced.

Note that the performance tests are *not* described here and are estimated to take 9 hours !

Calibration Analysis Procedure (CAP)

During FM-ILT no change in the detector signal is expected. The analysis consists of monitoring the time behaviour of house-keeping data.

Output, products

Status/version

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$Revision: 1.10 $
$Date: 2006/05/05 11:27:21 $
```

Req. 1.2.24 Spectral Responsivity

Objectives

The aim is to characterise the relative spectral response of the low- and high-stressed Ge:Ga detectors. Of particular importance is the determination of the cut-off wavelength (i.e. the point where 50% of the maximum responsivity is reached), and to determine the unformity in responsivity over one detector module (see PACS-NT-DS-004 "Detector arrays: Design and Performance Specification").

Fulfilling or fulfilled by

Priority

A

When performed / frequency

During module level tests

Required accuracy

10 % (goal) in the relative measurement of a single detector. Uniformity of 15 % (goal) in the peak relative responsivity over 16 detectors.

Inputs, prerequisites

Sources

Described in PACS-NT-PL-002 "Relative Spectral Responsivity Measurement Configuration".

Calibration Implementation Procedure (CIP)

Described in PACS-NT-PL-002 "Relative Spectral Responsivity Measurement Configuration".

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

For every pixel : the relative spectral response tabulated: (e.g. response : signal/flux density [(microvolts/sec)/(W/cm^2/Hz)] versus Wavelength [micrometer])

Status/version

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$Revision: 1.7 $
$Date: 2003/09/22 15:32:39 $
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Chapter 2

Optical Components

2.1 Filters

Req. 2.1.1. Filter transmission nominal

Objectives

The knowledge of the wavelength dependent absolute filter transmission is an essential part in the determination of the relative system response of the photometer. The relative system response is needed for sensitivity calculations with the time estimator and hence linked to the AOT logic as well as for the deduction of color correction factors. The absolute transmission of the photometric filters shall be measured.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

As part of the ground module characterization. Filter transmission curves will be provided by the manufacturer, but also be measured independently.

Required accuracy

5% in peak (TBC) and with a resolution of 0.2 μm (TBC).

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Measure the transmission curve with a Fourier Transform Spectrometer (TBC).

Estimated time needed

Calibration Analysis Procedure (CAP)

Results are an outcome of the FTS measurements. A threshold above which the transmission values are meaningful shall be specified.

Output, products

Table: filter transmission versus wavelength, threshold of meaningful transmission values

Status/version

Second draft version, 14-02-02

Req. 2.1.2. Filter leaks

Objectives

Depending on the spectral energy distribution of celestial sources out-of-band filter leaks can lead to wrong photometric fluxes. The delivered filters should be checked for possible leakage inside the sensitive wavelength range of the detector systems. In-flight measurements on celestial standard sources with blue and red SEDs should confirm either no leakage or the amount of contamination by filter leaks.

Fulfilling or fulfilled by

In-flight fulfilled by 3.2.2 (Full System Calibration Photometer: relative system response and color corrections)

Priority

A

When performed / frequency

- [1] As part of the ground module characterization
- [2] During PV Phase as part of the full system calibration of the photometer

Required accuracy

Verify that the out-of-band suppression is as good as TBD. Probe that in steps of 10 μm (the bolometers are sensitive out to at least 400 μm).

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Measure the transmission curve with a Fourier Transform Spectrometer (TBC).

Estimated time needed

Calibration Analysis Procedure (CAP)

Results are an outcome of the FTS measurements. A threshold above which the transmission values are meaningful shall be provided.

Output, products

Table: filter transmission versus wavelength (extended range), threshold of meaningful transmission values.

Status/version

Second draft version, 14-02-02

Req. 2.1.3. Transmission of order sorting filters

Objectives

The Littrow-mounted grating is operated in 1st, 2nd or 3rd order, respectively to cover the full spectrometer wavelength range. Corresponding wavelength bands are 105–210 μm, 72–105 μm and 57–72 μm. Suppression of out-of-band contributions due to other grating orders is achieved by a dichroic beam splitter and order sorting filters. The transmission properties of the spectrometer order sorting elements shall be determined to verify that the transmission is nominal inside the specified wavelength range and sufficient suppression is achieved outside this wavelength range. Any shift of the order sorting filter wavelength range w.r.t. the specified band can lead to features in the instrumental response function. Insufficient higher order suppression will lead to wrong flux calibration, depending on the source SED.

Fulfilling or fulfilled by

In-flight fulfilled by 4.3.8 (Relative spectral response function, spectrometer)

Priority

B

When performed / frequency

- [1] As part of the ground module characterization. Filter transmission curves will be provided by manufacturer (TBC), but also be measured independently (TBC).
- [2] During PV Phase as part of the full system calibration of the spectrometer

Required accuracy

Verify that the transmission range is matched to the specified grating wavelength range within 1 μm (TBC). Verify that the out-of-band suppression is as good as TBD over the sensitive wavelength range of the photoconductor cameras.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Measure the transmission curve with a Fourier Transform Spectrometer (TBC).

Estimated time needed

Calibration Analysis Procedure (CAP)

Results are an outcome of the FTS measurements. A threshold above which the transmission values are meaningful shall be provided.

Output, products

Table: filter/dichroic transmission versus wavelength (extended range), threshold of meaningful transmission values.

Status/version

First draft version, 14-02-02

2.2 Grating

Req. 2.2.1 Grating efficiency spectrometer

Objectives

The spectrometer uses a reflective diffraction grating in Littrow mount. The grating is a diamond ruled aluminium grating. Knowledge of the grating efficiency of the spectrometer (as function of wavelength) is important in view of the investigation of the overall sensitivity of the spectrometer. The grating efficiency, in combination with the responsivity of the detector and transmission of the filter determines the full system RSRF.

Fulfilling or fulfilled by

Ground-test. It is planned to perform an interferometric test (at CSL?) to measure the actual surface accuracy of the grooves.

It is not intended to measure the grating efficiency independently. What can be used is the theoretical grating efficiency. This has been calculated using the PCGRATE EM code. According to Norbert Geis, this calculation is assumed to be accurate up to 5% (not taking into account the manufacturing tolerances). However, assuming that everything is within the tolerances specified in the grating requirements doc, there should be no systematic errors more than 1%

It is foreseen to measure the FIR grating sample (10 cm size) performance with the FTS spectrometer at MPE. This measurement is expected to be deliver, at best, 10% accuracy in intensity, allowing large dicrepancies to be detected.

Priority

A

When performed / frequency

No implication for Commissioning or PV.

Required accuracy

The calculation of the efficiency is assumed to provide 5% accuracy.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

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$Revision: 1.6 $
$Date: 2007/10/26 13:18:11 $
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2.3 Chopper

The focal plane chopper is a central optical element of the PACS instrument, both for the photometer and spectrometer section. It serves as a

1) beam modulator allowing to perform differential measurements and step scans within the sky field-of-view;

2) feeding-in mirror for the internal calibration sources to monitor the stability of the detectors.

An overview of its basic principle is given in "A Cold Focal Plane Chopper for the PACS Instrument of the FIRST (now: Herschel) Satellite – Tests of an Advanced Prototype" (PACS-MA-TR-001). Detailed specifications of the chopper performance are outlined in the document "Chopper Specification" (PACS-ME-RS-001) and its design description is given in the document PACS-MA-TN-405. An overview of the module level tests is provided in the document "Verification and Test Plan for the PACS Chopper" (PACS-MA-PL-409). A 4 K life time test verified that the chopper mechanics allows ≈ 570 million cycles in observation mode (on sky) and ≈ 63 million cycles in calibration mode (on internal calibrators), see document PACS-MA-TP-422. Various chopper models have undergone a number of cool-down and heat-up cycles without showing any malfunctions. The specifications of the flight model FM1 are summarised and outlined in the "Electrical Interface Control Document" (PACS-MA-TR-678) and the "User Manual and Handling Procedure" document (PACS-MA-HM-655). Similar documents for the flight spare model FS2 (formerly QM) are PACS-MA-TN-464 and PACS-MA-DP-445.

Req. 2.3.1. Angular Calibration of the Focal Plane Chopper

Objectives

This requirement deals with the establishment of the focal plane chopper (FPC) angular calibration, i. e. chopper deflection angle vs. read-out of the field-plates, the chopper position sensors. This calibration is mainly done on module level by the manufacturer. However two aspects affect the chopper integrated in the FPU and operated by the DECMEC:

1) the determination of the mechanical zero point with no drive current and the corresponding offset correction of the DECMEC read-out;
2) the precise amplification factors (specification of 2 decimal places) of the field-plate output voltage which are different for the Zeiss EGSE (measurements by manufacturer) and the DECMEC. They are needed for a proper scaling of the DECMEC read-outs.

The verification of this calibration measurement with ground calibration devices and celestial astrometric standards is dealt with in the related Req. 3.1.2. Since the chopper angular calibration curve is non-linear and asymmetric in its positive and negative branch, scanning features in the focal plane (like e.g. the edges at the boundary of the calibration sources field-of-view) with the bolometer matrices can be used to verify the absolute chopper deflection, since for regular differential chopper rotations the chopper read-out steps change with deflection.

For redundancy the chopper has two field plates, each of which an angular calibration relation has to be established for.

The offset of the mechanical zero point (no drive current) from the optical zero point (normal to the interface plate surface, determining the mounting orientation of the chopper in the FPU) is measured by Zeiss with an alignment telescope with regard to a reflecting "mirror" on the interface plate as the normal reference. Special shims are then produced to trim the offset to better than $1'$. This measurement is done with the optical chopper axis mounted in vertical position in the test cryostat at Zeiss. It should be noted that, after mounting the chopper device in the FPU and due to different orientations of the axis during ILT, IMT, etc. tests, some variation in the flex pivots torque in combination with gravitational forces (during ground tests) may cause slightly different mechanical zero positions. Therefore, for each ground test and also finally in orbit, one of the first actions with regard to the chopper operation should be to determine the offset position on the angular calibration curve. Once this is done, the DECMEC read-out is corrected for this offset, so that the mechanical zero position should be defined by a zero read-back of the position sensor for this specific test configuration. Then the mechanical zero position is also the electrical zero position. The reproducibility should be checked from time to time.

The amplification factors were established both by Zeiss and CSL with sensitive calibration devices and different methods. Only for the EQM DECMEC used during CQM-ILT the accuracy of the amplification factor was too rough.

A repetition of the static chopper deflection under open loop conditions, i.e. directly commanding the drive current with the control loops disabled for a range of currents and angles, can be used to get a more precise value of the specific torque $S = c \cdot \frac{\Phi(ROU)}{I_{\mathrm{drive}}}$, with c being the spring rate of the blades of the flex pivots determined during module level tests. The specific torque is the most essential characteristics of the chopper motor and is needed for the control loop simulations and adjustments of some control loop parameters.

Fulfilling or fulfilled by

Complementary to req. 3.1.2 "Relation between Chopper Position and Angular Displacement on Sky" which verifies the angular calibration of the chopper converted to the scale on the sky.

Priority

A

When performed / frequency

- [1] Establishment of the angle versus (amplified) field-plate output voltages during component-level chopper verification by manufacturer for each chopper model (QM, FM, FS). Calibration curves with Zeiss amplification factors are part of the EIDPs.

- [2] During component-level accurate measurements of the field-plate amplification factors for both Zeiss EGSE and DECMEC (mind operational temperature of DECMEC in orbit!).
- [3] During ILT and IMT tests: Measure DECMEC read-out with drive current and control electronics disabled to determine mechanical zero point for the specific test configuration (mounting and orientation).
- [4] During ILT tests: Measure angular deflections under open loop configuration (control electronics disabled) for different currents covering the angular range. This measurement is used to determine the specific torque.
- [5] During Performance Verification: Repeat test items [3] and [4] in orbit.
- [6] During Routine Phase: Repeat in longer intervals (1 year) items [3] and [4] to check that there is no fatigue of mechanical elements or change in the magnetisation of the permanent magnets of the chopper motor.

Required accuracy

- [1] The required accuracy in the sky window ($-4.1^\circ < \Phi < +4.1^\circ$) for the chopper deflection is $\pm 1'$ translating to $0.75''$ on the sky or ≈ 0.2 of a blue photometer pixel with the conversion factor $1:80.69$ from the Zemax data base ($80.69'$ rotation of the chopper mirror corresponds to $1'$ move on sky). The required positional accuracy in the calibration windows ($\approx \pm 8^\circ$) for the chopper deflection is $\pm 2'$.
  The following factors contribute to the final measurement accuracy of the angular deflection during ground tests:
  - resolution of the CCD camera (method A, see below): $< 0.5'$;
  - measurement of distances on projection screen (method B): $< 0.8'$;
  - measurement of distances to projection screen (methods A&B): $< 0.7'$
    (depends on chopper throw)
  - uncertainties of refraction indices (cryostat window, methods A&B): $< 0.5'$.

  The absolute angular accuracy of determining the mechanical zero point is $< 0.5'$.
- [2] The average sensitivity SFP of the field plates is ≈ 1 V / rad. The amplified output voltage is $U_{\text{out}} = SFP \cdot a \cdot \Phi$. The output voltage accuracy is influenced by the rotation accuracy $\Delta\Phi$ and the accuracy of the voltage amplification factor Δa. According to Gaussian error propagation, the total uncertainty of the amplification factor a can be written as:
$$\Delta a = \sqrt{\left(\frac{\partial a}{\partial U_{\text{out}}}\,\Delta U_{\text{out}}\right)^2 + \left(\frac{\partial a}{\partial \Phi}\,\Delta\Phi\right)^2} \Leftrightarrow \frac{\Delta a}{a} = \sqrt{\left(\frac{\Delta U_{\text{out}}}{U_{\text{out}}}\right)^2 + \left(\frac{\Delta\Phi}{\Phi}\right)^2}$$
  The achievable accuracy for measuring the field-plate output voltage is $< 0.1\%$. For $\Delta\Phi = 1'$ and the maximum angle $\Phi = 8^\circ$ this gives $\frac{\Delta a}{a} \approx 0.23\%$. In case of $a = 50$, $\Delta a < 0.12$, in case of $a = 34$, $\Delta a < 0.08$, i. e. two decimal places must be specified for the amplification factors.

Inputs, prerequisites

The offsets of the two field-plates are different, switching to the redundant one needs a new offset calibration. The offset measurement must be done with no drive current and control disabled. Open loop measurements stabilise only with the damping time constant of the electromechanic system. The chopper angular calibration which is established at ≈ 7 K in the Zeiss test cryostat is also applicable to lower temperatures.

Sources

- [1] The angular calibration on module level is established in a two-fold way (schematic views of the test set-up are shown in PACS-MA-TN-410 “Position Measuring Device Description for the PACS Chopper”):

method A: An optical laser beam is reflected by the chopper mirror and its elongation with regard to the zero position is projected on a defusing screen which is imaged onto a CCD camera.
method B: An optical laser beam is reflected by the chopper mirror and its elongation with regard to the zero position is projected on a screen on the wall.
The determination of the mechanical versus optical zero point position is done with an alignment telescope.

Calibration Implementation Procedure (CIP)

- [1] Part of the module level characterisation by the manufacturer, see PACS-MA-PL-409, "Verification and Test Plan for PACS Chopper". The chopper mirror is rotated in steps of typically $0.3°$ and the deflection of a laser beam is measured with methods A and B:
  method A: optical laser – chopper mirror – defusing screen – CCD camera
  The centre of the laser light spot is measured on the CCD image. The full deflection angle range (deflection angle = 2 · rotation angle) of $36°$ is covered on a 4096 pixel array with the above resolution.
  method B: optical laser – chopper mirror – projection screen on wall
  Sufficient distance of more than 2000 mm enables precise visual reading.
  Small refractive effects at the cryostat window are taken into account in the analysis.
  The alignment of the chopper with the optical axis within ± 1 is achieved with shims.
- [2] Amplification factors are determined by measuring precisely the field-plate output voltage and the amplified voltages with calibrated multimeters. Larger angles implying larger absolute voltages and voltage differences over larger ranges give higher accuracies for these factors.
- [3] Determination of DECMEC read-out offset for mechanical zero point
  1) Switch field-plates on (should be on when DECMEC is on).
  2) Set chopper read-out offset = 0.
  3) Disable chopper control.
  4) Switch off drive current.
  5) Measure chopper read-out value.
  6) Set chopper read-out offset = $-1\cdot$ measured read-out.
  7) Convert read-out offset value to offset voltage on Zeiss calibration curve to make this point the new origin of the calibration curve.
- [4] Open loop tests of chopper in nominal and redundant DECMEC set-up for determination of specific torque after offset correction:
  1) Switch field-plates on (should be on when DECMEC is on).
  2) Disable chopper controller.
  3) Switch to open-loop and select coil configuration
     (nominal mode: 3 coils, degraded mode: coils 1+2, 2, 2+3).
  4) Enable chopper controller.
  5) Command chopper in open loop mode, i. e. by direct commanding of the drive current.
  6) Cover a reasonable range of the permitted angle range. For maximum currents of different coil configurations check available Electrical Interface Control Documents (EICDs).
  7) When changing the drive current the chopper mirror shows a damped oscillation around the final plateau position. Measure longer than this swinging-in period (determined by the damping constant) to get a proper angle measurement.
  8) Note that the specific torque changes for different coil configurations, i.e. for degraded modes with coils 1+2, 2 only and 2+3 this measurement must be repeated. Then also higher maximum currents are needed. In this case, the output limit must be adjusted accordingly to prevent unpredictable chopper movements.

Estimated time needed

- [3] a few minutes
- [4] $\frac{1}{2}$ h per coil configuration

Calibration Analysis Procedure (CAP)

- [1] See document PACS-MA-PL-409, PACS-MA-TN-410, curves are in PACS-MA-TN-464 (FS2, former QM) and PACS-MA-TN-678 (FM1).
  Following the determination of the mechanical zero point for the respective test conditions (mounting and orientation of FPU, in particular for ground tests) and the nulling of the offset in the DECMEC read-out, the corresponding point on the Zeiss curve (obtained by $\frac{ROU_{\mathrm{offset}}}{32767} \cdot 10\,\mathrm{V} \cdot \frac{a_{\mathrm{ZEISS}}}{a_{\mathrm{DECMEC}}} = U^{\mathrm{ZEISS}}_{\mathrm{offset}}$) must be shifted. Zeiss voltages are then converted into DECMEC read-out units via $ROU = \frac{32767}{10\,\mathrm{V}} \cdot \frac{a_{\mathrm{DECMEC}}}{a_{\mathrm{ZEISS}}} \cdot U^{\mathrm{ZEISS}}_{\mathrm{corr}}$. The resulting curve can be fitted by polynomials to provide a smooth representation of the calibration curve for any angle/ROU. Differences of the tabulated values with the values provided by the fit should be minimised. Possibly three ranges for polynomial fits may be defined, see "Angular Calibration and Zero Point Offset Determination of PACS FM1 Chopper for cold He II ($T = 4.2\,\mathrm{K}$) conditions", PICC-MA-TR-021 for details.
- [2] See Chopper and Control Parameters Electrical Interface Control Documents (EICDS), PACS-MA-TN-464 (FS2, former QM) and PACS-MA-TN-678 (FM1) for Zeiss amplification factor (34.35).
  See DECMEC User Manual PACS-CL-SR-002 for DECMEC amplification factor (QM: 50.243, FM nominal: 50.091, FM redundant: 50.607).
- [3] The negative value of the DECMEC read-out DMC_CHOP_CUR_POS under no drive conditions is used as the offset value.
- [4] Plot Φ(DMC_CHOP_CUR_POS) versus commanded drive current I (DMC_CHOP_OUTPUT). Check for linear parts of the curve.
  Specific torque: $S = c \cdot \frac{\Phi(ROU)}{I_{\mathrm{drive}}}$
  The spring constant c is documented in the EICD of the relevant model: PACS-MA-TN-464 (FS2, former QM), PACS-MA-TN-678 (FM1).

Output, products

- [1] Table with position sensor (field plate) voltage/read-out versus chopper angular deflection, see "Angular Calibration and Zero Point Offset Determination of PACS FM1 Chopper for cold He II ($T = 4.2\,\mathrm{K}$) conditions", PICC-MA-TR-021. The relation can be fitted by polynomials. Because the accuracy requirement is different for "sky range" and the two "calibration source ranges" and slopes are changing between the two, it is recommended to do polynomial fits to the ranges $-10.5^\circ < \Phi_{\mathrm{negCS}} < -4.1^\circ$, $-4.1^\circ < \Phi_{\mathrm{sky}} < +4.1^\circ$, $+4.1^\circ < \Phi_{\mathrm{posCS}} < +10.5^\circ$ separately, see PICC-MA-TR-021 for the analysis.
  The calibration product is either
  a) the original Zeiss table which needs to be zero point offset corrected, rescaled with the amplification factor ratio and converted to read-out units (10 V = 32767 ROUs) – this is the current implementation in IA Cal Files PacsCal_ChopperAngle_FM_2_0.fits and PacsCal_ChopperAngleRedundant_FM_2_0fits.
  b) coefficients of the polynomials which give a smooth representation of the calibration curve already converted to DECMEC read-out units. The derivatives of these polynomials give the necessary step size for an angular rotation depending on the absolute deflection, see PICC-MA-TR-021 for details.
- [2] The two amplification factors whose ratio is used to rescale the original Zeiss calibration curve to the DECMEC read-out units. For solution [1b] the ratio is included in the determination of the polynomial coefficients.

- [3] The offset value is written with DMC_WRT_CHOP_CONF_PAR to word 9 (“PosOffset”).
- [4] Average value or table of specific torque dependent on angle for each coil configuration.
- [5] Minimum value or table of rotational eigenfrequencies dependent on angle.
- [5] Average value or table of oscillation damping time constants dependent on angle.

Status/version

Complete revision in preparation of FM ILT to manifest essential steps on module level and in preparation of verification measurements covered by req. 3.1.2.

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$Revision: 1.8 $
$Date: 2008/08/07 17:55:53 $
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Req. 2.3.2. Duty cycle of waveforms

Objectives

The chopper mirror should spend a high percentage of a chopper cycle and with high accuracy in a defined plateau position allowing measurements, transition times should be minimal. For on-sky measurements a duty cycle of 80% in square wave mode with maximum peak-to-peak throw (±3') and with a chopping frequency of 10 Hz is required, i.e. a plateau time of 40 ms and a transition time of 10 ms. For measurements on the internal calibration sources with more than the double elongation angle a duty cycle of 70% in square wave mode and with a frequency of 5 Hz is required, i.e. a plateau time of 70 ms and a transition time of 30 ms. Since transition time and plateau time can be individually commanded and the former one can be kept constant while extending the plateau time, for lower chopping frequencies the duty cycle will be better than the specifications above.

For more complex on-sky modulation functions like staircases in triangular or sawtooth mode the duty cycle value should hold: transition times shorter than 10 ms should be achievable with the same slope as for the maximum peak-to-peak transition in square wave mode due to the smaller delta throw. However, for a large number of plateaus in one cycle there may be a larger transition overhead and this has to be verified by tests. The manufacturer of the chopper demonstrates the achievement of the duty cycle for the square wave mode according to the chopper specification.

In order to achieve fast transition times and high plateau position accuracy with small overshoots an active control of the drive is needed. The implementation comprises a PID loop, a velocity loop, a current feedback loop and an electronic filter for suppression of axial resonances. The parameters of these loops must be tuned for an optimal performance of the chopper. Detailed descriptions of the control loop design and simulations are in the Chopper Electrical Interface Control Documents (EICDs) PACS-MA-TN-464 (FS2, former QM) and PACS-MA-TN-678 (FM1) for the Zeiss breadboard electronic (hereafter EGSE), and PACS-CL-TN-036 (Chopper Control Description) and PACS-CL-SR-002 (DEC/MEC User Manual) for the DECMEC electronic, respectively. There are some differences in the design of both electronics, so that care must be taken to translate the Zeiss EGSE control parameter set into the DECMEC control parameter set (see below under item input).

For each chopper model (FM1, FS2), Zeiss has established two parameter sets, one each for the on-sky elongation regime and for the calibration source regime, respectively, which is due to non-linearities of the chopper drive properties. After an upgrade of the FM DECMEC software by implementing the non-linear chopper field-plate calibration curve, the position sensor read-out could be linearised. As a result, only one set of controller parameters is needed for the entire angular range. Only a minor adjustment of the parameters is needed for redundant chopper operations.

In case of degraded mode operations with a reduced number of drive coils (1 or 2 instead of 3 nominal ones) some control parameters must be adjusted.

Fulfilling or fulfilled by

Priority

B

When performed / frequency

- [1] During module level tests by manufacturer: For each chopper model (FM, FS) the parameter sets for square wave modulation with 10 Hz and 5 Hz, respectively, are established for cryo-operation Lifetime tests have demonstrated that the chopper design allows execution of 570 million cycles in on-sky mode (90% of operation time) and 63 million cycles in calibration mode (10% of operation time).

- [2] During ILT ground tests: The corresponding chopper model is tested for the first time controlled by the DECMEC electronics. Parameter sets established with the Zeiss EGSE must be translated to the DECMEC system, serving as a reasonable starting point for the optimisation procedure. However, considerable changes of several parameters should be expected.

- [3] During Performance Verification: The optimum parameter set found on ground will be verified. Fine-tuning may be necessary due to slight alterations caused by the launch and non-gravity conditions.
- [4] During Routine Phase: Should quality control of data processing discover degradations, which may be caused by fatigue of mechanical elements or change in the magnetisation of the permanent magnets of the chopper motor, adjustment of the control parameters becomes necessary.

Required accuracy

The required duty cycle is 80% for maximum sky chop of $\pm 4.1°$ (±3' projected on the sky) for 10 Hz square wave chopping, i. e. 40 ms plateau time and 10 ms transition time, with a plateau accuracy of $\pm 1'$ ($\pm 0.75''$ projected on the sky or 0.23 of a blue photometer pixel). Duty cycles and plateau accuracies of other waveforms should behave accordingly.

The required duty cycle is 70% for a chop between the two calibration sources with an elongation angle of $\pm 8°$ for 5 Hz square wave chopping, i.e. 70 ms plateau time and 30 ms transition time, with a plateau accuracy of $\pm 2'$ ($\pm 1.5''$ projected on the sky or ≈0.5 of a blue photometer pixel).

Note that the angular step size, and hence also the plateau accuracy threshold, in DECMEC readout units varies with angular elongation, see e. g. "Angular Calibration and Zero Point Offset Determination of PACS FM1 Chopper for cold He II ($T = 4.2$ K) conditions" (PICC-MA-TR-021).

Inputs, prerequisites

- [1] The angular calibration of the chopper position sensor as described under req. 2.3.1.
- [2] The sets of chopper control parameters established with the Zeiss EGSE at cryo temperatures and as described in the corresponding EICD of the chopper model.
- [3] A proper transfer from Zeiss EGSE to DECMEC parameters, see translation table below.
- [4] Characteristic parameters of the chopper model, like specific torque, rotational eigenfrequency, damping constant, spring rate, momentum of inertia, coil resistance and coil inductance, either coming from specific module level or ILT measurements, as input for chopper control loop simulations in MATLAB.

Sources

No source is needed for this type of measurement. The chopper drive electronics will be commanded to the required modulation function and the chopper throw will be defined by setpoints derived from the angular calibration req. 2.3.1. The chopper position sensor (field plate) read-out is contained in the instrument housekeeping telemetry (HK TM).

Calibration Implementation Procedure (CIP)

- [Step 1:] Verification of Zeiss EGSE parameter settings:
  a) Transfer Zeiss EGSE parameters into DECMEC parameters according to translation in DECMEC User Manual (PACS-CL-SR-002) and Table 2.1.
  b) Verify the stability of the chopper for the current controller parameter set. This can be done by enabling the chopper controller for a series of increasing time intervals from 1 second up to 5 minutes. Repeat this test for different chopper angles.
  c) Verify parameter set for $\pm 4.1°$, 10 Hz square wave modulation with 10 ms transition time and 40 ms plateau time according to the chopper specification.
     - start with a smaller throw of $\pm 1°$ and increase in steps of $1°$.
     - start with softer transition slope, i.e. longer transition time, say 20 ms, and decrease in steps of 5 ms.

Table 2.1: Transfer of ZEISS Control Loop Parameters (see EICD PACS-MA-TN-678) into DECMEC Control Loop Parameters (see DECMEC User Manual PACS-CL-SR-002, V4.3).

	ZEISS EGSE	**DECMEC**
stimulus transition shape transition time dwell time reference throw	 sinoid time time $V_{\mathrm{deg}}\cdot$ CTRLMult · FPMPS / FPMNS (V_{deg}: e.g. 4.1 deg ⇒ 4.1 V) CTRLMult: non-linearity of deflection FPMPS, FPMNS: asymmetry of deflection	 sinoid $\frac{\text{setpoint+} - \text{setpoint}-}{\text{rate}\cdot\text{samplefrequency}}$ bolometer: time spectrometer: # of ramps per plateau with reset interval RI setpoint+ setpoint− from chopper angular calibration curve setpoint = $\frac{a_{\mathrm{CSL}}}{a_{\mathrm{ZEISS}}} \cdot V_{\mathrm{ZEISS}}^{\mathrm{ZPcorr}}(\Phi) \cdot \frac{32767}{10\,V}$
position readout field plate feedback offset correction	 $V_{\mathrm{FP}} \cdot a_{\mathrm{ZEISS}}\cdot$ FPMult · FPMPS / FPMNS FPMult: field plate adaptation VZO	 $V_{\mathrm{FP}} \cdot a_{\mathrm{CSL}} \cdot \frac{32767}{10\,V}$ -ROU (no drive, no control)
PID control stimulus - field plate feedback	 KP KI KD	 Kp = KP · 75180 · FPMult · $\frac{\mathrm{FPMPS+FPMNS}}{2} \cdot \frac{a_{\mathrm{ZEISS}}}{a_{\mathrm{CSL}}}$ Ki = KI · 75180 · FPMult · $\frac{\mathrm{FPMPS+FPMNS}}{2} \cdot \frac{a_{\mathrm{ZEISS}}}{a_{\mathrm{CSL}}}$ Kd = KD · 75180 · FPMult · $\frac{\mathrm{FPMPS+FPMNS}}{2} \cdot \frac{a_{\mathrm{ZEISS}}}{a_{\mathrm{CSL}}}$ 75180 = $\frac{10\,V}{133\,mA} \cdot 1000$
velocity control field plate feedback	 KDT (damping) FDT (cut-off frequency)	 Kf = KDT · 75180 · FPMult · $\frac{\mathrm{FPMPS+FPMNS}}{2} \cdot \frac{a_{\mathrm{ZEISS}}}{a_{\mathrm{CSL}}}$ discrete elliptical filter
current control	 KICUR (negative current feedback)	 KiCurr = KICUR · 100000
notch filter suppression of axial resonances	 F1 (central frequency) DA (bandwidth)	 implementation of an elliptical filter covering the ZEISS notch frequency with sampling frequency 8192 Hz
control loop type **control loop gain** **voltage-to-current conversion**	 voltage control CLG —	 current control independence of harness resistance ControlLoopGain = CLG · 1000 knowledge of coil resistance coil inductance

Table 2.1: continued.

	ZEISS EGSE	**DECMEC**
degraded modes	parameter sets for 1, 2, 3 (nominal) coils operation (FS) 4.1 & 9 deg	$\mathrm{CLG}_{\mathrm{degr}} = \mathrm{CLG}_{\mathrm{nom}} \cdot \frac{S_{\mathrm{nom}}}{S_{\mathrm{degr}}}$ $\mathrm{KiCurr}_{\mathrm{degr}} = \mathrm{KiCurr}_{\mathrm{nom}} \cdot \frac{S_{\mathrm{degr}}}{S_{\mathrm{nom}}}$ S = specific torque from open loop measurements
limits	output limits for controller & field plates —	output limit (current) $\mathrm{I}_{\mathrm{max}}$ = 133 mA sufficient for 1 coil operation position limit field-plates: $\pm$25 000 ($\sim 9.5^\circ$)

- for safety reasons, during the first trials the maximum current and chopper angle can be limited via the parameters "OutputLimit" and "PositionLimit",respectively, that have to be set according to the static measurements (cf. req. 2.3.1) plus margin.

In this way, one can verify how the chopper modulation functions as documented in the EICD are reproduced and when possible deviations start to occur. Each measurement should comprise at least 10 chopper cycles to verify the reproducibility. The modulation function with the required frequency of 10 Hz may be accomplished by a sequence of DMC_MOVE_CHOP_ABS commands, to execute the transition, and wait statements, to command the plateau dwell time (no synchronisation with detector read-outs is needed).

c) Verify applicability of parameter set for $\pm 8^\circ$, 5 Hz square wave modulation with 30 ms transition time and 70 ms plateau time according to the chopper specification. Each measurement should comprise at least 10 chopper cycles to verify the reproducibility.

- [Step 2:] Optimisation of the original Zeiss EGSE parameter settings:

a) If the chopper performance after step 1 is perfect, then this step can be omitted.

b) If the chopper performance achieved with the Zeiss EGSE is not reproduced, an optimisation process must be started. The gradual approach of step 1 should tell which transition time / throw to start the optimisation with (start with the first one where the performance is not sufficient any more). There is no unique and straight forward procedure which parameter needs optimisation depending on the resulting plateau shape (over/undershoots, gradients, oscillations), as can be seen from the simulation examples in PACS-MA-TN-678. However, the plateau shape gives hints in which direction special parameters may have to be tuned. The optimisation process also depends on practical experience so that participation of control electronic specialists from Zeiss and CSL during the ground tests is appreciated. Simulation tools can provide feedback which parameters may be the most important ones in the tuning process and whether to increase or decrease certain parameters, as demonstrated in PACS-MA-TN-678. With these tools it can also be checked what the impact of updated drive characteristics, like specific torque and damping constant, with regard to the original characterisation at Zeiss is.

c) The optimisation process performs a sequential variation of individual parameters from the best Zeiss EGSE values. Therefore, the basic step of the procedure consists of uploading an updated set of parameters with the command DMC_WRT_CHOP_CONF_PAR and to execute at least 10 chopper cycles to verify the reproducibility. One has to be aware that tuning one parameter may require (partial) compensation by tuning a related parameter. By comparing the waveform for the new setting with the previous one with regard to plateau accuracy and relative duration of transition and plateau, the decision must be taken whether the latest step in the optimisation gave an improvement or not. Depending on the resulting waveform and with the help of the above mentioned auxiliary tools it must be derived which parameter to change next and to which delta.

- [Step 3:] Finding parameter settings for degraded modes:

  Degraded mode means operating the chopper with a reduced number of drive coils. This may be due to a contingency but also be simulated deliberately by setting switches thus bypassing one or even two coils. For static as well as dynamic angular elongation this means that a higher drive current is needed due to the reduced coil resistance and inductance. Simulations of the current control type loop indicate that mainly the control loop gain and the current control parameter have to be adjusted according to the ratios of the specific torque as indicated in the table under item 'input'.

- [Step 4:] Verification of parameter settings for other than square wave modulation functions:

  a) Repeat step 1b for three plateaus ($-4.1°$, $0°$, $+4.1°$) triangular chopping (pattern: -1, 0, +1, 0, -1, 0,...) with equal transitions and optionally for three plateau sawtooth chopping (pattern: -1, 0, +1, -1, 0, +1,...) with unequal transitions. Apply as final "rate" parameter the slope for $\pm 4.1°$ square wave chopping.
  b) Perform staircase sawtooth chopping with 64 plateaus and constant step sizes of 4.3' (3.2" on sky, note that the step size between the commanded set points will not be constant due to the non-linearity of the chopper angular calibration) around the zero point (simulation of a freeze frame chopped pattern) with a plateau time of (400 ms $-$ transition time), assuming a telescope move of 8" / s. Apply different transition times from 10 ms down to 1 ms (or shorter depending on the performance). Also check the "rate" parameter setting corresponding to the slope for $\pm 4.1°$ square wave chopping.

Estimated time needed

The whole procedure is highly interactive, since each commanding block needs interactive inspection and a decision process how to proceed. For the interactive inspection, the TM must be available in the data base and the CAP must provide quantitative assessment for the decision process. All this means time overheads so that a basic block in the optimisation loop may need 10 – 20 min. Depending on the degree of necessary optimisation and the volume of trials to find a unique parameter set, this may span a time range from a few hours to a few days.

Calibration Analysis Procedure (CAP)

The core of the analysis is to provide a fast and quantitative feedback on the quality of the chopper waveform with regard to:

a) duty cycle, i. e. sufficiently fast transition time

b) plateau accuracy within the specified limits

c) reproducibility

Since for each trial several chopper plateaus are recorded, the reproducibility issue can be addressed by averaging positive and negative chopper plateaus, respectively (for more complex modulation functions the plateaus of the corresponding phase must be averaged). The transition through the electrical zero position can be used for synchronisation. The standard deviation is determined for time bins of the size of the chopper read-out sampling. In the ideal case, mainly digitisation noise will be observed.

The formal duty cycle determination should be done by analysing this averaged chopper cycle and determining the fraction of time the chopper spends within the position range defined by the setpoints $\pm$ the plateau accuracy limits with regard to the total chopper cycle time. Ideally the chopper plateau time should be contiguous, but occasional overswings may still be acceptable. An example for the FM1 chopper performance evaluation is given in PICC-MA-TR-031 (IMT 504 Chopper Performance Test during cold FM ILT/IST).

For the control parameter optimisation process either the superposition for the averaged chopper cycle or for simplicity the selection of a specific chopper cycle (e.g. the 3rd out of 10) should be offered. The following features will aid the analysis:

- plot of the measured cycle from DMC_CHOP_CUR_POS;
- zoomed views of either the positive or the negative plateau with selectable angular range;
- overplot, in a different colour, of the plateau setpoint and the transition sinoid, i.e. the stimulus as the ideal modulation function, synchronised to the zero transition of the real chopper read-out;
- horizontal lines indicating the accuracy threshold of the plateau - Note that these depend on the absolute read-out value;
- vertical lines indicating the length of the nominal plateau (with regard to the ideal modulation function);
- allow overplot, in a different colour, of the corresponding plateau of the previous measurement;
- (optional:) indicate achieved plateau percentage by a two digit number in the plot window;
- provide in a separate plot, spanning the same time frame, the shape of the drive current as contained in DMC_CHOP_OUTPUT. In particular the shape of the peaks during the transition may give feedback on parameter tuning.

  Another aspect of the analysis procedure for the optimisation process is the simulation of the chopper model and the drive and control electronics, e. g. in MATLAB, for getting clues which parameters to trim into which direction.

Output, products

The set(s) of control parameters for optimum performance of the chopper should be stored in a CalU table for the chopper configuration.

The DECMEC holds a default parameter set. It is TBD whether an optimised parameter set can be permanently uploaded into this default table or whether it has always to be written via DMC_WRT_CHOP_CONF_PAR before the chopper controller is switched on and enabled.

The final chopper performance, in particular also the synchronisation with an impact on detector read-outs may have an impact on the design of the analysis software.

Status/version

Revision in preparation of PV. Full inclusion of chopper control optimisation.

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$Revision: 1.4 $
$Date: 2007/10/24 10:23:39 $
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Req. 2.3.3. Optimal Positioning of Chopper on Internal Reference Sources

Objectives

The focal plane chopper mirror is used to image the internal reference/calibration sources (CS) onto the detector arrays by deflecting it outside the sky field-of-view. Since the internal source measurements are used for responsivity assessment and flat-fielding, the illumination of the detector arrays by both sources should be as homogeneous as possible. There are sharp intensity drop-down edges at the borders of the calibration source FOV which should be avoided to be imaged onto the photometer array. On the other hand the calibration source FOV is slightly larger than the long axes of the photometer arrays, so that the detector FOV can be moved around via the chopper mirror to find the most homogeneous illumination. This has to be adjusted for each calibration source individually. Since photometer and spectrometer FOV are offset with regard to each other and the spectrometer FOV is considerably smaller, there may be two independent optimum positions on each calibration source. There may be also the issue of spectral homogeneity of the calibration sources for both the photometer and the spectrometer.

Fulfilling or fulfilled by

This requirement is covered by req. 2.5.2 “Spatial stability (isotropy and homogeneity) of PACS calibration sources” which should demonstrate either the flatness of the sources over the nominal filed of view or give feedback on flat parts or parts with intensity gradients. The spectral homogeneity aspect can be addressed by

a) verifying the optimum position at several wavelengths, e.g. in a blue or red filter of the photometer;

b) by req. 2.5.4 “Emissivity of PACS calibration sources”, if performed on at least 3 positions of the CS FOV (two extreme ones and centre) with the spectrometer.

Priority

A

When performed / frequency

- [1] During ILT tests, when a combined operation of the chopper, the internal reference sources and the detector arrays in the completely mounted FPU is possible.
- [2] During satellite commissioning (no view outside the instrument is necessary), if loss of alignment due to the launch load should be a concern, i.e. verification of the positions selected after the ground tests.
- [3] During routine phase, if checks of the chopper performance should reveal a fatigue of mechanical elements, a change in the magnetisation of the permanent magnets of the chopper motor or a change in the sensitivity of the field plates.

Required accuracy

The illumination by the internal sources should be as flat as possible yielding (differential) detector signals in the range of the flat-field. For reproducibility the selected positions should be acquired with the accuracy as specified under req. 2.3.1 for the calibration source range.

Inputs, prerequisites

The chopper must have fine stepping capabilities in the deflection range on the internal sources to probe their flatness structure with a range of pixels. The absolute chopper positions and the step sizes are given by the chopper angular calibration, as established by req. 2.3.1. The chopper should not be deflected beyond $\approx\ \pm 9.5^o$ in order to avoid mechanical damage. The nominal centre of the calibration sources is expected to be around $\pm 8^o$ chopper deflection.

Sources

The measurement is purely on the internal reference sources. In order to verify that there is no impact by possible straylight due to external sources in the sky FOV, in particular during ILT tests external stimulators (OGSE BBs, hot plate, external BB) should be off and the OGSE mirror 3 drive in dark position. Full field-of-view scans with switched-on OGSE BBs will serve as references.

Calibration Implementation Procedure (CIP)

For FM:
A more detailed description is covered by the corresponding items under reqs. 2.5.2 and 2.5.4. The following presents an outline of steps which are considered as necessary in finding the optimum chopper positions on the CSs:

- [1] Power the calibration sources to the to be expected temperatures used for operation. Wait for their stabilisation (req. 2.5.3: "Time constants: heat-up and cool-down times of PACS calibration sources"). All OGSE stimulators are off and the "sky FOV" should be as dark as possible.
- [2] Verify the spatial homogeneity of the reference sources. Perform a scan with the chopper on both calibration sources from chopper angle $+5^o$ to $+9.5^o$ and -5^o to -9.5^o, respectively (the nominal inner edge of the reference sources is at $\pm 5.27^o$, the $\pm 9.5^o$ are the upper safe chopper deflection limits).
  The scan step size should be an integer multiple of the detector pixels, corresponding to 3.2" on the sky for the blue bolometer array, 6.4" for the red bolometer array and 9.4" for the spectrometer. Spectrometer measurements can be done at fixed (default) grating positions. The scan may be part of a full field-of-view scan with "dark sky" conditions.
  The observations are done in a staircase modulated sequence staring for a few seconds on each chopper position and performing up- and down-scans for reproducibility verification and improvement of sensitivity.
- [3] Verify the spectral homogeneity of the calibration sources. As a first step, this will be addressed by measuring with the blue and red arrays of each subinstrument simultaneously. With the spectrometer a full SED scan over all three spectral orders for three chopper positions inside the calibration source FOV at $\pm 6^o$, $\pm 8^o$ and $\pm 9.5^o$ should be performed to have the verification for all wavelengths on a coarse spatial grid.
- [4] Compare with full field-of-view scans with the OGSE BBs illuminating the sky window. Such scans better reveal the structure of the relative sharp edges of the CS FOV and provide information on excessive straylight depending on the chopper position. Full SED measurements of the OGSE BBs are needed for reference in determining the emissivity of the calibration sources.

Estimated time needed

cf. estimates for reqs. 2.5.2 and 2.5.4.

Calibration Analysis Procedure (CAP)

For FM:
Responsivity drifts are considered as negligible for ground measurements in the absence of ionising radiation hits. The analysis can be done on signal level, since only ratios along the chopper scan are of importance. For the bolometer, a flat-field correction may be of advantage, since individual pixels will not scan the full extent of the calibration source.
The signal ratios along the chopper staircase scan and backwards will tell the flatness of the source or the presence of any gradients, structures or vignetting effects at the corners of the array. These may depend on wavelength. All these effects will have to be weighted for the final decision on the best chopper position on each of the two calibration sources, for photometer and spectrometer, respectively.

Output, products

A Table (CalU) with the chopper position sensor read-outs for both calibration sources in photometric and spectroscopic mode.

Status/version

Revision in preparation of PV.

```
$Revision: 1.6 $
$Date: 2007/10/24 10:23:39 $
```

2.4 Imaging Optics

This section collects a number of requirements mostly corresponding to modelling of optical components, in order to later optimally execute and interpret the instrument and system level spatial, spectral, and photometric calibrations.

Req. 2.4.1 Spatial Distortion: Photometer

Objectives

Model the spatial distortions induced by PACS, as input and interpretation aid for the photometer spatial calibrations described in Sect. 3.1

The fast Herschel mirror system induces a curved and distorted “focal bowl” in which PACS is located off center. PACS is designed for that situation, and to partly compensate for the distortion induced by the Herschel telescope. This makes the telescope focal plane an ill-suited location for many modelling and measurement tasks. The approach taken below is to provide optical modelling of (a) the combination Herschel and PACS and (b) the combination test optics and PACS which both can be confronted with actual measurements (Sect. 3.1.3). If ILT measurements on the combination test optics and PACS deviate significantly from the appropriate model, model predictions for Herschel and PACS can be corrected equivalently, provided the test optics is well understood. `do we need special tests on test optics alone to be sure?`

Modelling already done by N.Geis indicates distortions of up to 2/3 of a blue channel pixel if the chopper centers the FOV on the optical axis. Distortions will be larger when chopping with a significant offset.

Fulfilling or fulfilled by

Self-Standing

Priority

A

When performed / frequency

Before/during ILT

Required accuracy

Models must describe the relation between telescope and array coordinates to a small fraction of a blue pixel (1/10 TBC). This requires sufficient sampling of spot diagrams to obtain reliable centers of gravity.

Inputs, prerequisites

PACS, Herschel, and test optics optical model in Zemax

Sources

none

Calibration Implementation Procedure (CIP)

none

Estimated time needed

No observing time but computation intensive.

Calibration Analysis Procedure (CAP)

Use Zemax to compute spot diagrams for a large number of input positions on sky, and for several chopper positions. If possible make use of symmetries to reduce number of points (this may not be the case). Compute centers of gravity for spot diagrams. Derive transformations from array to telescope coordinates and vice versa (both are additionaly a function of chopper position), and fit suitable parametrizations.

Do this both for the ILT (test optics and PACS) and in-orbit (Herschel and PACS) situation.

Computation requirements: Needs a three dimensional grid (two spatial positions and chopper throw). Computations fast but setup time of software significant. Number of grid points to achieve desired accuracy and number of spots in spot diagram TBD.

Output, products

Parametrized transformations between array and telescope coordinates, for both ILT and in-orbit situations.

Status/version

Has to be converted into a workplan for modelling

```
$Revision: 1.2 $
$Date: 2002/12/11 15:08:33 $
```

Req. 2.4.2 Spatial Distortion: Spectrometer

Objectives

Model the spatial distortions induced by PACS, as input and interpretation aid for the spectrometer spatial calibrations described in sect. 4.1

The same general considerations as for the photometer section apply. The requirements are relaxed in some sense because of a smaller array and larger pixels, but diffraction in the slicer induces additional complications: Spatial distortion is in addition a function of wavelength, and the relation between array and telescope coordinates is for one dimension not a simple trend but somewhat modulated with position inside a pixel.

Fulfilling or fulfilled by

Self-Standing

Priority

B

When performed / frequency

Before/during ILT

Required accuracy

Models must describe the relation between telescope and array coordinates to a small fraction of a spectrometer pixel (1/10 TBC).

Inputs, prerequisites

PACS, Herschel, and test optics optical model in Zemax.

Sources

none

Calibration Implementation Procedure (CIP)

none

Estimated time needed

No observing time but computation intensive.

Calibration Analysis Procedure (CAP)

Use Zemax and Glad to compute centroids for a large number of input positions on sky, for several chopper positions and several wavelengths. Make use of symmetries to reduce number of points, if this is possible. Compute centroids. Derive transformations from array to telescope coordinates and vice versa (both are additionally a function of wavelength and chopper position), and fit suitable parametrizations.

Do this both for the ILT (test optics and PACS) and in-orbit (Herschel and PACS) situation.

Computation requirements: Needs a four dimensional grid (two spatial dimensions, wavelength, chopper throw), Computing effort TBD (Zemax calculations with Glad ”corrections”?). Number of grid points to achieve desired accuracy TBD.

Output, products

Parametrized transformations between array and telescope coordinates, for both ILT and in-orbit situations.

Status/version

Needs to be converted into a modelling workplan

```
$Revision: 1.2 $
$Date: 2002/12/11 15:16:35 $
```

Req. 2.4.3 Spectral Distortion

Objectives

Model spectral distortion induced by PACS (i.e. deviations of the surfaces of constant wavelength from a plane in the datacube), as input and interpretation aid for the photometer spectral calibrations described in sect. 4.2. Modelling already done by N. Geis indicates 'smile-shaped' shifts of the order 1 spectral pixel, depending on grating angle and pixel. The shift varies along the spectral dimension of the array, i.e. there is local nonlinearity.

Fulfilling or fulfilled by

Self-Standing

Priority

B

When performed / frequency

Before/during ILT

Required accuracy

1/5 of a spectral pixel (TBD)

Inputs, prerequisites

PACS, Herschel, and test optics optical model.

Sources

none

Calibration Implementation Procedure (CIP)

none

Estimated time needed

No observing time but computation intensive.

Calibration Analysis Procedure (CAP)

Use Zemax to compute spot diagrams for a number of wavelengths.

Output, products

Examples of spectral distortion for a number of wavelengths.

Status/version

Needs to be converted into a modelling workplan

```
$Revision: 1.2 $
$Date: 2002/12/11 15:25:00 $
```

Req. 2.4.4 Straylight Suppression in Optics

Objectives

Characterize straylight inside PACS. The instrument is designed to minimize straylight (baffles, black paint etc.) but verification is highly desirable. Both a full end-to-end PACS straylight model and tests using directed far-infrared radiation appear impracticable. The approach taken is to use simple qualitative tests with optical laser light during assembly of the instrument. Related topics at system level are addressed in requirements 3.1.6, 4.1.5, and 7.3.

Fulfilling or fulfilled by

Self-standing

Priority

B

When performed / frequency

During assembly of instrument, taking into account insertion of optically intransparent filters

Required accuracy

Qualitative tests

Inputs, prerequisites

Sources

Optical laser

Calibration Implementation Procedure (CIP)

Send laser light into instrument at various angles

Estimated time needed

Calibration Analysis Procedure (CAP)

Check whether light shows up at undesired locations.

Output, products

Status/version

Draft

```
$Revision: 1.3 $
$Date: 2002/12/18 10:23:01 $
```

Req. 2.4.5 Optical Throughput

Objectives

Quantify effects relevant for the throughput/transmission of the instrument that are not covered by other requirements. Such information is needed to properly interpret the system level (photometric) response. Explicitly covered by other requirements but related are: Filter transmissions (2.1), Grating efficiency (2.2.1), Detector responses (1.1.2, 1.2.7.) Detector spectral responses (1.1.22, 1.2.23) Two factors remain to be quantified:

- Mirror reflectivities. The large number of reflections in the folded light path induces an overall noticeable effect despite high individual reflectivities.
- Diffraction losses in the spectrometer. Mirrors and grating are somewhat oversized but induce losses in particular at long wavelengths.

Fulfilling or fulfilled by

Self-standing

Priority

B

When performed / frequency

Before/during Instrument Level Tests

Required accuracy

10% each for total mirror reflectivity losses and diffraction losses. These numbers do not enter the final photometric calibration accuracy, but rather are needed to find out whether the measured absolute response is in line with expectations for the PACS design.

Inputs, prerequisites

Sources

none

Calibration Implementation Procedure (CIP)

Estimated time needed

No observing time in ILT or orbit.

Calibration Analysis Procedure (CAP)

Mirror reflectivities: Estimate total loss on the basis of the number of reflections for a particular light path, and assuming wavelength-independent 99±0.5% reflectivity (TBC) for each reflection (This reflectivity is notoriously ill-known and difficult to measure). Example: For 13 reflections in one of the bolometer paths the total loss is 12% (6 to 18%).

Spectrometer diffraction losses: TBD Modelling or estimates, sampling wavelength dependency at a few points.

Output, products

Status/version

Early incomplete draft

$Revision: 1.2 $

$Date: 2002/12/11 16:03:28 $

2.5 Internal Reference Sources

The internal reference sources are used to monitor the performance of the detector arrays. They serve as transfer calibrators for regular but less often performed flux calibrations on celestial standards. They shall provide a uniform illumination of all pixels in all detector arrays. Their fluxes shall be comparable to that from the telescope to avoid changes in the IR-radiation load. An overview of their basic principle and performance requirements is given in the document “Calibration Source Performance Requirements” (PACS-ME-RS-010). Basic measurement schemes on module level are outlined in this document as well. A more detailed design of the calibration sources is provided in the document “FPFPU Calibration Source Interface Control Document” (PACS-KT-ID-007). More detailed aspects on the Calibration sources can be found in “FPFPU Calibration Source Interface Control Document”, PACS-KT-ID-007. Results from the first sub-unit level test can be found in “Emissivity of PACS Calibration Source Baseline Model”, PACS-ME-TR-010 and “Calibration Source Thermal Characteristics: Test Results and Analysis for the Baseline Model”, PACS-ME-TR-011.

Req. 2.5.1. Temporal stability of PACS calibration sources

Objectives

Both PACS detector types, bolometers and photoconductors, show drifts in their responsivity induced by ionizing radiation hits. For accurate absolute photometry these drifts have to be monitored by frequent transfer measurements against a stable reference source which itself is absolutely calibrated against a laboratory blackbody or celestial standards. Such a source must be highly stable over a time period covered by a celestial calibration and reproducible in illumination in order to be not the limiting factor in the final photometric accuracy. Its long term stability must be monitored against celestial standards.

Fulfilling or fulfilled by

During FM-ILT fulfilled by 0.7.11/12.

In-flight fulfilled by 3.2.2 (monitor nominal responsivity variations of photometer with time) and 4.3.2 (flux reproducibility internal sources, spectrometer).

Priority

A

When performed / frequency

- [1] As part of the on-ground module characterization
- [2] During ILT tests
- [3] In-flight monitoring program

Required accuracy

The steady state stability (achieved ~ 45 min after switch-on of the sources) should be as good as 0.05 % peak-to-peak over all time periods between 0.1 s and 1 week. This means a relative temperature stability of 10^{-4} for the heater (cf. document "Calibration Source Performance Requirements" (PACS-ME-RS-010)). Technically the temperature is determined via a resistance measurement of the heating element and controlling this resistance value.

Inputs, prerequisites

Sources

BB reference sources for ground tests, non-variable celestial standards in-flight.

Calibration Implementation Procedure (CIP)

- [1] The thermal characterization of the first calibration source gave a reproducible resistance-temperature relationship for the PT500. Ballistic heating and cool-down characteristics were recorded in the full required temperature range. Steady state values were obtained over several hours.
- [2] ILT tests: repeated long lasting exposures (test 0.7.11/12) for checking the temporal stability of the internal PACS CSs resistor values.
- [3] In-flight: repeated checks against the same non-variable celestial standard. The measurement of the standard should be performed in raster mode to illuminate as many pixels as possible in order to show the stability of the homogeneity, too.

Estimated time needed

Calibration Analysis Procedure (CAP)

Aanalyze calibration source resistor values on absolute level before and after long exposures (0.7.11/12), see also CQM Calibration Report “Functional Test of PACS Calibration Sources AVM/CQM ILT, Calibration Analysis Report, PTD 0.7.11 and PTD 0.7.12, Version 2” and FM Calibration Report “Functional and Performance Test of PACS Internal Calibration Sources during cold FM ILT, PTD 0.7.11, PTD 0.7.12, PTD 2.5.1”.

Output, products

possible refinement of I control parameter, if variation amplitudes exceed requirement.

Status/version

Second draft version, minor upgrade,

```
$Revision: 1.6 $
$Date: 2007/10/30 16:24:59 $
```

Req. 2.5.2. Spatial stability (isotropy and homogeneity) of PACS calibration sources

Objectives

The calibration sources shall uniformly illuminate all pixels of the photometric cameras in order to monitor their flat-field behaviour. For the spectrometer a uniform illumination of the grating is important for the assessment of the spectral flat-field.

Fulfilling or fulfilled by

Related to 3.2.8 (Measure the photometer full system flat-field) and 4.3.9 (Flat-field spectrometer internal sources). Related to 2.3.3 (Optimal Positioning of Chopper on Internal Reference Source).

Priority

A

When performed / frequency

- [1] As part of the on-ground module characterization and modelling of the calibration source behaviour
- [2] During ILT tests
- [3] In-flight

Required accuracy

The isotropy of the sources in surface brightness averaged over the exit aperture is required to be better than 0.05% for all angles of exitance within ± 11.5 deg from the source axis (definition of illuminated field of view). The homogeneity shall be better than $\pm$ 5% (cf. document "Calibration Source Performance Requirements" (PACS-ME-RS-010)).

Inputs, prerequisites

Sources

BB reference sources for ground tests, celestial sources in-flight.

Calibration Implementation Procedure (CIP)

The isotropy of the PACS calibration sources can be tested in the following way:
a) in chopper direction by scanning the calibration sources (different chopper amplitudes) against an OGSE black body (see req. 2.3.3). b) perpendicular to the chopper direction via an externally flat-fielded detector array (isotropy in spacecraft z-direction over the size of the detector array).

- [1] On-ground module characterization: see document PACS-ME-RS-010.
- [2] ILT tests:
  - a) Comparison of signal pattern of arrays from illumination with internal calibration source with that of scan with point-like BB source (only for illuminated pixels) (flat enough external illumination unlikely?).
  - b) Scan of internal calibration sources with chopper (cf. req. 2.3.3).
- [3] In-flight: Comparison of signal pattern of arrays from illumination with internal calibration source with that of scan with point-like celestial source (only for illuminated pixels) (inhomogeneity of telescope background?)

Estimated time needed

Calibration Analysis Procedure (CAP)

see req. 2.3.3. for the analysis of chopper scan sequences, req. 4.3.10. for the analysis of flat-field spectrometer external sources and req. 3.2.8 for the photometer full system flat-field.

Output, products

Status/version

Second draft version, minor upgrade

```
$Revision: 1.3 $
$Date: 2003/09/26 15:23:11 $
```

Req. 2.5.3. Time constants: heat-up and cool down times of PACS calibration sources

Objectives

The heater sources of the internal calibrators need to be heated up and to stabilize before they remain in a more or less steady state during the PACS operational period. For any upward adjustment a temperature control circuit applies a ballistic heating pulse followed by a stabilization period. Since there is no active cooling, the thermal time constant of the heater source, determined by the heat capacity of the heater and its coupling to the FPU thermal bath, determines the cool-down time. These time constants should be known for operational procedures and mission planning constraints. If necessary, modification of the PI parameters has to be done and the test procedure will be carried out again.

Fulfilling or fulfilled by

fulfilled by 0.7.11/12 (functional and performance test of CSs, nominal and redundant)

Priority

A

When performed / frequency

- [1] As part of the component tests during on-ground module characterization.
- [2] During ILT tests (nominal switch on and off procedures).
- [3] In-flight during commissioning (no view outside the instrument necessary).

Required accuracy

Switch-on time $\sim$ 30-35 minutes according to PACS-ME-RS-010 2.draft. The temperature read-out of the control circuit needs to be as accurate as 10^{-4} of the heater temperature to verify the required stability of the source (see req. 2.5.1).

Inputs, prerequisites

Calibration of the temperature sensor.

Sources

Calibration Implementation Procedure (CIP)

The read-out of the temperature sensor is monitored for heating pulses of certain temperatures including stabilization times and cool-down times. See DEC/MEC User manual for a detailed description of the temperature/resistance read-out and the control loop.

Estimated time needed

Calibration Analysis Procedure (CAP)

The read-outs of the temperature sensor of the heating loop are plotted with time.

1 The switch-on time constant is determined for a temperature reaching 5% of the final temperature.

2 The stabilization time constant is determined for a temperature stability being within $\pm 10^{-4}$ of the steady state temperature.

3 The cool-down time constant is determined for a temperature reaching a stable value close to bath temperature; cool-down for up to 2 hours should be sufficient for determining the cool-down time assuming an exponential decay, see also CQM Calibration Report "Functional Test of PACS Calibration Sources AVM/CQM ILT, Calibration Analysis Report, PTD 0.7.11 and PTD 0.7.12, Version 2".

Output, products

Heat-up and stabilization times for cal-U tables; cool-down times for operational constraints.

Status/version

```
$Revision: 1.4 $
$Date: 2007/10/30 16:24:44 $
```

Req. 2.5.4. Emissivity of PACS calibration sources

Objectives

The calibration sources shall simulate the thermal background emission from the Herschel telescope. The emission spectrum of the telescope is assumed to behave like a gray-body. Because of the wide wavelength range of 2 octaves and the simultaneous use of short and long wavelength arrays, the calibration sources must mimic the colour and temperature of the telescope, i.e. they should be gray, too. Due to the uncertainty of the final telescope emissivity during the development phase, which may be a factor of 2, the effective emissivity of the sources must be configurable in order to be adjusted during AIV activities, once the telescope emissivity will be better known.

Fulfilling or fulfilled by

Fulfilling reqs. 2.5.2/2.3.3 with regard to the aspect of spectral homogeneity.

Priority

A

When performed / frequency

- [1] As part of the on-ground module characterization (configuration of final emissivity)
- [2] During ILT tests (verification of final emissivity)
- [3] During IMT, IST tests and in commissioning phase, to investigate possible straylight impact on the signals and to verify the post launch performance.

Required accuracy

The emissivity of the sources has to compensate a different optical path. The range of anticipated telescope emissivity is $\varepsilon_{\rm tel} \sim 0.3\,\%...3\,\%$ (revised, previous values ranged between $\sim 2\,\%...8\,\%$). By design, the effective emissivity of the sources was made configurable between $0.02 < \varepsilon < 0.16$. For the QM CSs emissivities between 4 and 10 % were measured. With regard to the CQM results the FM sources have been configured to produce $\sim 50\,\%$ less output flux, by blackening parts of the internal surface foreseen for this adjustment. For the FM CSs emissivities between 5 and 7 % were measured, the emissivity depending on the wavelength.

Inputs, prerequisites

Heating current vs. temperature relation of the emitter.
Emissivity and temperature of the Herschel telescope.

Sources

Calibrated BB (inside cryostat) with temperatures typical for the passively cooled telescope (50...100 K) coupled into the sky beam.

Calibration Implementation Procedure (CIP)

The emissivity of a radiator of temperature T is defined as the ratio of the radiance of this radiator to the radiance of a BB source of the same temperature.

During ILT:

- [1] Measure the emission of the calibration sources at several temperatures. The expected telescope temperature can currently only be characterised to lie within the temperature range 60 – 100 K with a best estimate of 85 K. Also the effective telescope emissivity cannot be specified accurately and may finally be in the range 0.3 – few %.

Assuming an average CS emissivity of 4%, the corresponding CS temperatures must be in the range 36 – 100 K to adjust the CS emission to the telecope background level. For an average parameter combination of ε = 0.01 and T = 85 K the corresponding T_{CS} = 59.8 K. 5 different temperature settings for both CSs should be selected to test the reproducibility of the CS emissivity. These are 36 K, 48 K, the default value of ≈60 K (check for the finally selected default set-up of CS1 and CS2), 80 K and 100 K.

The table gives more details of the telescope and CS emission comparison.

Table 2.2: Matching of telescope and and CS emission for the wavelength range 50 to 210 μm assuming an average $\varepsilon_{\rm CS}$ = 0.03 and different combinations of telescope temperatures and emissivities. $\Delta_{\rm peak}$ gives the maximum deviation from unity, Δ_{aver} the average one for the wavelength range. In case of not matching emissivities and temperatures, selecting a lower temperature leads to an asymmetric peak deviation but a slightler lower average deviation.

$T_{\rm tel}$ (K)	$\varepsilon_{\rm tel}$	$T_{\rm CS}$ (K)	$\Delta_{\rm peak}$ (%)	Δ_{aver} (%)
100	0.03	100	0	0
85	0.01	59.8	±42	±31.8
		57.6	+71 −39	±30.6
60	0.003	37.6	±75	±61.5
		36.7	+126 −74	±60.7

Adopting an average CS temperature of 59.8 K to match the average telescope characteristics would lead to the following proposal for CS1 and CS2 default set-ups assuming a certain percentage of higher and lower flux around this average value:

Table 2.3: CS1 and CS2 default settings for the 59.8 K average flux level matching best the emission of a 85 K warm telescope with emissivity of 0.01. ΔF gives the average percentage above and below the flux level of the 59.8 K warm source (in parantheses peak values).

ΔF (%)	$T_{\rm CS1}$ (K)	$T_{\rm CS2}$ (K)
±5 (±3–9)	60.9	58.7
±10 (±6–19)	62.0	57.5

Note that for adjusting the lower CS temperatures starting from the default level a sufficiently long cool-down time must be admitted (cf. outcome of req. 2.5.3). Heating up takes stabilisation times in the order of ∼45 min for the selected temperature step sizes.

- [2] The observations are done in staring mode with the chopper positioned on each of the CSs. For the 5 different temperatures this is done for the nominal optimum position ($\sim \pm 8^{\rm o}$, cf. outcome of req. 2.3.3, full FOV scans). For the default temperature setting this is repeated for a position at chopper deflection $\sim \pm 6.5^{\rm o}$ and $\sim \pm 9.5^{\rm o}$.

- [3] The SED mode set-up is selected for the measurement: RI = $\frac{1}{8}$ s with SPU mode 32 samples slope fitting and 8 ramps per grating position (no chopping).

- [4] The SED mode grating sampling (step size = 2500, 2400 in 3rd order), yielding 570 grating steps is selected.

- [5] For each blue order an up- and down-scan is performed, the red channel is measured in parallel for the corresponding wavelength ranges.

- [6] Measure the signal of OGSE BB1 for at least two different temperatures (30 and 40 K) as ε=1 reference by executing the same kind of grating scans. The PACS chopper is commanded to the zero position, the OGSE chopper is positioned on OGSE BB1.

Estimated time needed

Each SED-mode staring up- and down-scan takes 1140 s plus overheads (1300 s).
2 calibration sources $\times$ 5 temperature settings $\times$ 2 blue orders $\times$ 1300 s = 7.2 h
2 calibration sources $\times$ 2 extra chopper positions $\times$ 1 temperature setting $\times$ 2 blue orders $\times$ 1300 s = 2.9 h
2 OGSE BB1 settings $\times$ 2 blue orders $\times$ 1300 s = 1.5 h
temperature stabilisation times: 0.5 h each for OGSE BB1 and CS temperature stabilisation (assuming proper cool-down to adjust the lowest required temperatures by controlled heat-up)
2 OGSE BB1 settings $\times$ 0.5 h = 1 h
5 CS1/2 temperature settings $\times$ 0.5 h = 2.5 h (consider parallel heat-up of CSs to required temperatures)
total time: 15.1 h.

Calibration Analysis Procedure (CAP)

- [1] Evaluate the signals of the grating scans on the CSs and the OGSE BB:
  $S_{\mathrm{CS}}(\lambda) \propto \varepsilon_{\mathrm{CS}}(\lambda) \cdot BB(\lambda, T_{\mathrm{CS}}) \cdot RSRF(\lambda)$
  $S_{\mathrm{OGSE\,BB}}(\lambda) \propto BB(\lambda, T_{\mathrm{OGSE\,BB}}) \cdot RSRF(\lambda)$
- [2] Calculate reference ratios between ideal BBs at the calibration source temperatures and ideal BBs at the used OGSE BB temperatures:
  $\frac{BB(\lambda,T_{\mathrm{CS}})}{BB(\lambda,T_{\mathrm{OGSE\,BB}})}$
- [3] Division of the signal ratios of the scans on the internal sources to the scans on the OGSE BB by these respective reference ratios finally provides the source emissivities as a function of wavelength:
  $\varepsilon_{\mathrm{CS}}(\lambda) = \frac{\frac{S_{\mathrm{CS}}(\lambda)}{S_{\mathrm{OGSE\,BB}}(\lambda)}}{\frac{BB(\lambda,T_{\mathrm{CS}})}{BB(\lambda,T_{\mathrm{OGSE\,BB}})}}$
- [4] Check for the consistency of the emissivities depending on the CS temperature.
- [5] Check for the consistency of the emissivities depending on the chopper position for the default CS temperature (spectral homogeneity of the CSs).

  FM ILT analysis can be found in test report “Emissivity of PACS calibration source, FM data, PICC-NGSC-TR-003”.

Output, products

A number of source emissivities vs. wavelengths as input to the adjustment of the sources to the effective in-orbit telescope emissivity considering already the possible range of temperature adjustment. Emissivity measurements of the first PACS calibration sources have been performed resulting in an emissivity value of 19±4 % (specification between 4 and 16 %!). For the CQM model sources emissivities in the range 4 . . . 10 % have been found as described in the Report “Emissivity of the PACS Calibration Sources, AVM/CQM ILT - Calibration Analysis, PTD 2.5.4”. Adjustments with respect to the emissivity have been made (by Kayser Threde) for the FM sources and model predictions give now an emissivity value of about 2-4 %. However, during FM ILT we measured emissivities between 5 and 7 %. The combination of source emissivity and temperature determines the final reference level to mimic the telecope background by the CSs.

Status/version

```
$Revision: 1.5 $
$Date: 2007/10/30 16:25:15 $
```

2.6 Telescope Pointing Quality

Req. 2.6.1 Absolute Pointing Error

Objectives

Herschel pointing requirements as specified in section 5.12.2 of the IID-A are crucial for success of PACS observations, and PACS as the highest spatial resolution instrument is key for testing whether they are met. IID-A section 5.12 also gives the definitions of APE, PDE, RPE, AME.

The purpose of this requirement is to verify that the separation between (instantaneous) actual direction and commanded direction for pointed observations is within the IID-A requirements/goals. The same measurements will verify the a posteriori AME for pointed observations. This specification covers 'fine pointing' (cf. First Scientific Pointing Modes Document). 'Raster pointing' which is a sequence of fine pointings, as well as 'position switching' and 'nodding' (also sequences of fine pointings) are implicitly covered by the same observations.

This verification should also be done for SSOs.

Fulfilling or fulfilled by

Most of the analysis can be done one the basis of other data, taken e.g. for photometric calibration, and on the basis of science observations. Any observation of a bright (point) source with position known to subarcsecond accuracy is suited. Dedicated observations are likely needed very early as part of commissioning, related to establishing the central pointing position (see PCD Section 3.1.1). Loosely speaking, 3.1.1 uses many observations to derive the mean position while 2.6.1 analyses the scatter.

Priority

A — Needed for reliable identification of objects. Note also that observations with HIFI are impossible without good pointing.

When performed / frequency

Dedicated observations in commissioning or early PV, also used for 3.1.1. Data analysis of other observations all over the mission. Some dedicated SSO observation (see also relation to AOT verification)

Required accuracy

The satellite 1σ AME goal is <=1.2". Using the blue bolometer channel, a random error of $\sim$0.3" of an individual measurement corresponds to $\sim$beam/20 or pixel/10 which should be realistically achievable despite systematic effects. Assuming positions can be derived to $FWHM/(2 \times S/N)$, measurements need a S/N well above 10 to be of use. In the following we require S/N>20. Adding in quadrature 0.3" measurement error and 0.3" error of the catalogue source position gives $\sim$0.5" accuracy of an individual measurment which would constrain the goal APE at the $> 2\sigma$ level and the required APE (3.1") at higher significance. Brighter sources are obviously better.

Inputs, prerequisites

Assumes the central pointing position has been established i.e. a pointing sends on average the source "to the center of the array" for a standard chop. Note close relation to section 3.1. If data are taken in others than the "standard chop", FOV distortions etc. have to be known.

Sources

Bright point sources with position known to better than 0.3". Faint haloes don't matter. As outlined in 3.1.1, a flux above 150mJy in the blue band is suggested for the shortest versino of the dithered point source AOR.

This assumes that systematic effects like flatfield are already under control and sensitivity is nominal. For the very first measurements, yet brighter objects should be chosen.

Source list as for 3.1.1, plus archival data.

In addition, point source AOR observation of ~10 SSOs, selected as e.g. 8 asteroids and 2 planetary satellites, all with accurate orbits. Since the star tracker looks 180deg away from the target there should be no difference due to (non)presence of a bright nearby planet between the two classes, but just to be sure...

Calibration Implementation Procedure (CIP)

Standard chopped/nodded photometric AOT. Using the dither option will help to reduce residual flatfielding issues.

Estimated time needed

Overhead and slew dominated, at least several minutes per source.

Calibration Analysis Procedure (CAP)

Measure centroids on chop/nod subtracted and flatfielded images for all three dithers and derive difference from the nominal position. Procedure very similar to 3.1.1. Apply correction if a 'good' source was observed with commanded position close to but other than the best available one (e.g. in a sloppy GT/OT program which used a poor input position). Build up a large database of offsets, derive statistics, look for systematics e.g. with solar aspect angle.

Output, products

Status/version

Draft, reviewed post FM-ILT

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$Revision: 1.4 $
$Date: 2008/01/29 11:11:38 $
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Req. 2.6.2 Relative Pointing Error

Objectives

Verify that the the telescope RPE is indeed as low as specified. The IID-A specifies for pointed mode a 1min RPE of <=0.3", i.e. within a minute the actual pointing will scatter by this amount (1σ) around its average direction. This is acceptable for all PACS observations. This specification covers 'fine pointing' (cf. First Scientific Pointing Modes Document). 'Raster pointing' which is a sequence of fine pointings, as well as 'position switching' and 'nodding' (also sequences of fine pointings) are implicitly covered by the same observations.

This verification should also be done for SSOs.

Fulfilling or fulfilled by

Self-Standing

Priority

A - This priority refers to verifying that the RPE is not in fact much larger than specified. Accurately measuring the RPE at the specified level is neither simple nor very important.

When performed / frequency

Early in PV or commissioning, repeated later if reasons for change

Required accuracy

Verifying a 0.3" scatter implies measuring source positions to below 1/10 of a blue pixel. Systematic effects (e.g. uniformity of pixels, req. 1.1.3) may become important. Note however that the <1/10 pixel position accuracy is needed here only to detect small relative shifts, not in an absolute sense, which makes it more realistic to achieve. High S/N in short integrations is needed.

Inputs, prerequisites

Sources

Observe a very bright point source. If we want S/N>100 in a 1s chopper plateau, we need about 6Jy or more. A faint halo does not matter.

Suitable sources include the sources that can also be used for bolometer PSF determination (3.1.4). In addition, bright late type stars with some level of faint dust shells are acceptable, since the goal is a centroid for the bright star rather than characterisation of the wings.

The procedure should also be run on SSOs (asteroids), preferentially ones that are moving significantly during the observation.

Calibration Implementation Procedure (CIP)

Do a chopped/nodded observation. Because any telescope movement (nod!) will spoil the time series due to its associated positioning error, the standard point source AOR is not optimal. The suggested procedure uses chop and nod throw as in the point source AOR, no dither, and an ABBA nod pattern with 4×5 minutes, thus providing in its middle a 10min stretch where the telescope stares and PACS simply chops. Times could be adjusted if found necessary, within limitations set by background and detector stability for the nod subtraction.

Science observations will typically not stare long enough at a very bright source and may use dither which complicates the analysis, but some observations probing for faint shells near very bright stars may be long enough to be analysed under the limitations of the shorter nod periods.

Estimated time needed

20 minutes on source. Suggested to be run on a small number of different sources, e.g. 3 stellar sources and 3 SSOs (moving bright asteroids)

Calibration Analysis Procedure (CAP)

Derive chop/nod subtracted images for each chopper plateau. Derive source centroids for each chopper plateau and look at scatter and drifts.

Output, products

Limit or measurement for noise and drift over 10 minutes.

Status/version

Draft, reviewed post FM-ILT

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$Revision: 1.5 $
$Date: 2008/01/29 11:11:44 $
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Req. 2.6.3 Absolute Pointing Error - Scan mode

Objectives

PACS is using scan mapping as its main mapping mode. The basic pointing mode differs from ‘fine pointing’, as do the IID-A pointing requirements. The goal for the a posteriori AME is 1.2”+0.02*w with w the scanspeed in arcsecond/second. In order to not put the modulation frequency of point sources below the bolometer frequency cutoff, the scanspeed can be at most of the order 10-60 arcsec/sec. We assume in the following that we have to verify an accuracy of the order 1.2” to 2.4”.

Fulfilling or fulfilled by

Self-Standing Observation. Perhaps later supplemented by analysis of galactic surveys.

Priority

A – Identification of objects from maps, as well as proper coaddition of repeated maps for deep surveys, needs good pointing.

When performed / frequency

Performance Verification

Required accuracy

We require a source to be detected at S/N>20 after a single pass over the array which will last of the order 5-30 seconds.

Inputs, prerequisites

Distortions have to be characterized ‘first’. In fact this is partly a parallel process of interpreting given scan map data.

Sources

Ideally, a field of TBD size (e.g. 30’ long but relatively narrow) is needed which has a significant number of bright sources with accurate position. Given the accuracy request, these have to be above ≈400mJy in the blue channel. A technical note PACS-ME-TN-035 (D.Lutz, B.Ali) describes attempts to identify such fields. There were no reliable ‘far-infrared astrometric clusters’ identified, only some sets of binary sources

We will have to combine very simple checks crossing a single bright point source with a more crude scheme that tests reproducibility rather than absolute error: a field (star forming region) with heavy and bright (but a priori unknown) structure is repeatedly scanned with different parameters, and results compared.

The identification of such ‘structured but non-astrometric fields’ for PACS is TBD.

Calibration Implementation Procedure (CIP)

Do a line scanning map with standard AOT. Initially slow speed to mimimize detector related beam shift/smearing and assign any offsets found to the telescope or the analysis software. Later also needed for the higher speeds.

Some such observations scanning across very bright point sources are already planned for FOV distortion, ghost searches etc. (PCD 3.1)

Estimated time needed

TBD, will be significant

Calibration Analysis Procedure (CAP)

Measure positions from reduced map and compare to known intrinsic positions. N.B.: This is a pipeline/IA software test as well!

Output, products

Status/version

Draft. Reviewed post FM-ILT

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$Revision: 1.5 $
$Date: 2008/01/29 11:11:52 $
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Req. 2.6.4 Relative Pointing Error - Scan mode

Objectives

The IID-A goal for the RPE in scanning mode is 0.8”. This jitter is difficult to verify since it is superposed on the smooth scan motion, and mixed with effects of field of view distortion. Possibly, the cross-scan jitter is better to constrain than the in-scan jitter.

Fulfilling or fulfilled by

Data analysis only, of scanning observations taken to map field of view distortion (3.1.3), and other scanning observations crossing very bright sources.

Priority

B

When performed / frequency

Performance Verification and later.

Required accuracy

Inputs, prerequisites

Reconstructed pointing history of satellite during the scan, at appropriate time resolution. We should make sure to be in a constant speed regime, so that deviations from a smooth motion in the PACS data must be due to jitter or PACS optical distortion, not due to speed variations of the Satellite...

Sources

Very bright point source. As for 3.1.4, we require S/N>100 in 1sec, i.e. flux of at least 20Jy.

Calibration Implementation Procedure (CIP)

Scan map crossing a bright point source. The scan length should be long enough to have the satellite already in the constant speed regime when the source crosses the FOV.

Estimated time needed

Calibration Analysis Procedure (CAP)

Measure position of source on array (first in subarray coordinates, then transformed to array coordinates) as a function of reconstructed satellite pointing position while array is crossed by a bright point source, and determine deviations of the measured positions from a simple trend corresponding to the satellite pointing. These are due to field of view distortions and pointing jitter. Use physical knowledge of the instrument (sect. 2.4) to identify components of this deviation that are likely optical distortions (e.g. a quadratic(?) trend all over the array), and use what ever remains to put limits on, or measure the, pointing jitter RPE.

Output, products

Status/version

Draft. Reviewed post FM-ILT.

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$Revision: 1.4 $
$Date: 2008/01/29 11:11:49 $
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Chapter 3

Full System Calibration Photometer

3.1 Spatial Calibration

The requirements described below address the spatial calibration of the photometer section of PACS under the following assumptions and definitions:

Coordinate systems used are

- Subarray coordinates p,q: A coordinate system trivially assigning the center of each pixel with a ”clean” coordinate like p,q=(4,5), starting at (0,0). This is the system in which we will actually measure source centroids. For simplicity and consistency with IA frames, the count includes all subarrays. Physical inter-subarray gaps exist e.g. between 15 and 16 which have to be considered when interpreting these coordinates.
- Array coordinates u,v: A coordinate system in the focal plane (offsets in mm) in which the centers/corners of all pixels of all subarrays are known. The long ’v’ axis is parallel to the chop direction.
- Instrument coordinates y,z: This is an ”on the sky” coordinate system centered on the optical axis of the PACS bolometer (the single central ’virtual aperture’ for the photometer). Its coordinate axes are aligned with the spacecraft y and z axis, coordinates are in arcseconds.
- Sky coordinates RA,DEC. Note that RA, DEC of the commanded position of the Herschel spacecraft will not automatically be identical to the source coordinates, because of chopping/nodding or scanning.

Coordinate conversions between these various systems include the following elements:

- Subarray — Array: Considers gaps between subarray matrices and possible misalignments of the array assembly. Related calibrations are addressed in requirements 1.1.15 and 3.1.3.
- Array — Instrument: It would be desirable (and easier to calibrate) to decompose this into a simple angular shift due to chopping and an optical distortion. According to optical modelling (Norbah el Quais and Muhammar al Poglitsch, priv. comm.) this is not possible for PACS/Herschel: Distortion is a clear function of chopper position. The transformation from array coordinates to instrument coordinates is a complicated function f(u,v,chopperposition). This includes the plate scale and rotation of the arrays wrt the spacecraft y,z axes, but also all the optical distortions introduced by PACS. This transformation is addressed in Requirement 3.1.3. Nevertheless, a less extensive 0th order characterization of the chopper effects, establishing a chop direction wrt the spacecraft yz coordinates, and an angle vs. encoder readout characteristic curve is foreseen in 3.1.2.

- Instrument — Sky: This includes the normal trigonometrical conversions due to position on sky and telescope roll angle, but also the offset between commanded and actual pointing (sect. 2.6). For an individual measurement, this implies an uncertainty of the order of the APE or AME in this conversion step. Needs for calibration initiated by this step are: Definition of the PACS photometer optical axis/central pointing position (3.1.1) and characterisation of APE/AME (sect. 2.6).

These transformations are written here in the sequence from detector to sky corresponding to the calibrations that will be applied to science data. Inverse transformations will be needed for other purposes. See also PICC-ME-TN-019 which gives more detail on these steps and the spatial calibration files involved.

A detailed astrometric error budget remains to be done. In the following, we assume that for a high S/N source errors other than the pointing accuracy shall be minimized in order to not dominate over the pointing AME (goal 1.2”). Assuming we have a chain of factors influencing the total error, this is taken care of below in a preliminary way by assuming 0”.5 for one step. This may turn out to be overambitious for certain steps, but the preferred approach is to selectively relax individual requirements if detailed analysis shows this to be necessary, rather than starting with an overall generous budget.

Req. 3.1.1 Photometer Central Pointing Position

Objectives

Establish the relation between a defined spot on the bolometer arrays, for a defined chopper position, and the satellite pointing, so that commanding the satellite to the position of an object sends that object on that spot on the array if the chopper is in the specified position. (Sometimes also called 'focal plane mapping')

At first, there are conflicting needs on where to put this spot. From a scan mapping point of view, one would place this at the center of symmetry of the PACS arrays which is a gap between matrices, however. From the point of view of point source photometric obervations and to make it actually calibratable, one will choose a point giving simultaneously good data for both blue and red channel. Given the current design of the photometer AOT, these two views can be reconciled because of the symmetry of the chop/nod scheme for point source photometry.

In the following, we make use of the concept of the Point Source Photometry AOT, which is (see SAp-PACS-MS-0186-03 version 2.1) a moderate throw chopped observation symmetric around the defined 'optical zero' (PCD 2.3.1) chopper position, chosen to put an object alternatingly on two positions on two of the inner blue matrices, symmetric to the minor axis of symmetry of the detector assembly. The offset from the major axis of symmetry of the detector assembly is chosen such that positive/negative beam are near the centers of these inner blue subarrays. An additional nod is done orthogonal to the major axis of symmetry to put the chopped images near the centers of the other two inner blue matrices. According to D. Cesarsky (pr. comm. 2006/06/29, differing from SAp-PACS-MS-0186-03 version 2.1) the plan is to use a single virtual aperture for the photometer which is at the center of symmetry of the array, and to implement the point source photometry AOT by using this virtual aperture and a CUS 'offset' of exactly half the nod throw along the z direction = array minor axis of symmetry. From this position, the nod would then be done using the composite nodding mode and the full nod throw.

We then define the central pointing position (photometer virtual aperture) as the position where, for the chopper set to the 'optical zero' defined in 2.3.1, a source is placed at the center of symmetry of the blue array i.e. the zero point of the 'array' coordinate system. Since this is poorly measurable in a direct way, it is implemented by the following measurement procedure:

- Perform a point source photometry observation as described above, for the nominal symmetric chop and the nominal nod throw. Use the (chopper) dithering option of the AOR to improve robustness to flatfielding/bad pixels
- For each dither, measure the pixel coordinates p_i, q_i of the four beams in a double-differential reduction. Note that pixel coordinates on both sides of the inner 'blue' gaps are p=15;16 and q=31;32 in a scheme counting from 0.
- Convert the 3×4 measured positions to the array coordinate system. Note that the conversion from subarray to array coordinates, i.e. the relative alignment of the matrices in the cold focal plane, should be the same in orbit as in ILT – the pre-launch calfile is ok.
- Take the mean of all 4×3 u,v positions which should be close to zero. Note the systematic shift of the chop dithers, which will cancel if all measurements can be used, if not corrections based on the ILT spatial calibration can be applied explicitly.
- Convert the u,v array coordinate offset to a y,z instrument coordinate one. This will be initially based on a preliminary ILT-based PhotArrayInstrument calfile, but small scale and orientation errors are uncritical since the goal is to zero a small offset around the zero point.
- If not yet centered to half a blue pixel, compute shift needed to make these offsets zero and change satellite pointing parameters. Repeat to verify.

Note that this procedure involves a spacecraft nod. The resulting offset effectively is a mean offset for the two nod positions.

Fulfilling or fulfilled by

Self-Standing

Priority

A — You can't observe without it. ILT version is in principle C but in practice mandatory to some level for efficient execution of other tests.

When performed / frequency

ILT pre-exercise version. Result is sensitive to relative movements between test cryostat cold part and warm setup on the outside of the cryostat, and to accuracy of XY stage/mask/hole mounting.

In orbit very early in commissioning. Later, this is regularly verified by APE checks, which would show systematic drifts if the central position changes.

Required accuracy

There are two different accuracies involved: a) Accuracy with which the central point matches the desired one. This is probably not very critical, perhaps half a blue pixel or so. b) Accuracy to which this position is known. This is central to any further astrometry and needs to be very accurate, 0.5" TBC, in order to makes its contribution to the position error of an individual science observation negligible.

Inputs, prerequisites

Early in commissioning/PV, the telescope focus is expected to still change with main mirror cooldown by 1mm/20K. This corresponds (for f=28500mm and d=3280mm) to an additional 'beam smearing disk' of diameter 0.8arcsec/20K. This very rapidly reaches an acceptable regime since initial mirror cooldown after the end of heating is fast. No lateral focus displacement due to differential cooldown of the secondary supports is expected (email GRP Jan 28, 2008). Increased telescope background will however directly affect the detector noise and the necessary bias tunings.

Bolometer operational settings have to be defined. These may be preliminary ones during telescope cooldown, as long as the sensitivity loss is small enough for reaching a sufficient number of targets.

The 'defined chopper position' has to be known first. This should be close to the PACS instrument optical axis and should be established in a separate requirement, e.g. looking for the center of symmetry between the two internal calibration sources. See requirement 2.3.1. In FMILT 2 and 3, we used the 'optical zero' at CPR 664, chopper angle 0.2158 degree.

Sources

ILT: Single hole of $\sim$5arcsec diameter in front of external hot blackbody. Smaller hole would be in principle desirable but is not recommened for the limited contrast achieved with the realistic OGSE setup

In orbit: Bright point sources with very accurate positions ($<<$1arcsec). Sources should be bright enough so that the random position error of an individual AOR should be well below the AME goal. The HSPOT 3.2 point source 1 sigma for the shortest point source AOR is 3-5mJy depending on band. Sources should have at least 150mJy in the blue band to also have some reserve for initial reduction problems. At that flux level and 5mJy RMS, the S/N of one of the 4×3 peaks measured is $150/5/\sqrt{12} = 8.6$. Using the canonical estimate for the position error $FWHM/(2 \times S/N)$, the error is < 0.4" already for a single one of the 12 peaks. The sources need not be absolute flux calibrators als long as the flux is known to be bright enough. Some faint fuzz is acceptable as long as the point source strongly dominates and has an accurate position.

Such observations are planned for spacecraft commissioning, likely already quite early during cooldown of telescope. This may imply increased telescope background and different bolometer settings, and thus sensitivity reduced by a TBD factor that may be above simple photon noise reasoning. In that case, the flux limit above may be too optimistic and much brighter sources needed during that phase.

Possible candidates:
- Late type stars

• AGN dominated by nonthermal emission (Blazars)
• A very carefully selected subset of infrared galaxies
In this category, we need many targets, so that at each moment of the mission one can be reached without excessive (>60deg) slew. In addition, during comissioning, instantaneous visibility of a significant number (∼10-20) of sources is highly desirable, in order to verify pointing on different targets/regions/orientations and quickly obtain meaningful averages that are not just repetition of the exact same observation on the same target. This likely means at least several dozen targets are needed, better more. See PICC-MA-TN003 (Overview), PICC-ME-TN-024, PICC-MA-TN-004 for source lists.

In orbit for possible first wide angle search:
• Very bright reasonably compact IRAS 60/100μm source with position known to the few arcsec level, that clearly stands out of its ∼1 degree scale neighbourhood. No misidentification should be possible if source is on map (e.g. very bright IRAS galaxies like Arp220, N253 nucleus, N4945 nucleus, late type stars.). See PICC-ME-TN-023 for a list.

Calibration Implementation Procedure (CIP)

ILT: Set up OGSE with single hole and blackbody on xy stage. Be sure to select the appropriate attenuation filter for the bolometer channel used and the appropriate bolometer settings. After switching on everything, locating the source and (if necessary) focussing the xy stage, do something similar to the point source photometry AOT by (a) doing a chopped observation with throw ∼54 arcsec (projected on sky), then nodding the xy stage by the same amount in cross-chop direction and chopping again. Iterate measuring beam centroids and offsetting xy stage until positive and negative beams are on the desired spot, i.e. the above sums are 0. Such procedures were used in FMILT for the focus sequence (PHOT_Central_Point_3_1_1_OBS) but not to actually finetune the central pointing. The central pointing position itself had been quickly identified before under QLA control (letting the source fall into the central gap) and was later measured accurately from the ILT3 FOV distortion rasters.

In orbit: Do a point source photometry (chopped/nodded) observation with default chop and nod throw. It is advised to use the 'chopper-dithered' version to be able to improve on flatflielding and bad pixel effects. Duration 5.5 minutes including 3min overhead. A related observation which could also be called AOT verification: if the central pointing for the point source AOR has been obtained, re-observe the same target with a short small extended source AOR and a small scan map, to verify proper handling of offsets/chop/nod.

The misalignment after launch between instrument line of sight and star tracker is expected to be less than 1 arcmin (Herschel Star Tracker Support Assembly performance analysis report H-R-RP-AI-0104 and email Marc Oort to Bruno Altieri 9.6.2008). The notion that it could be as large as 0.3 degree (System Design Report H-P-1-ASPI-RP-0312 Issue 1, 6.5.3.4.3) is superseded by this information. The needs for a very first wide angle search observation, as a sufficently large scan map or raster or repetition of pointed observations, are thus reduced to a smaller area.

An overall flow could be:
• Wide angle search
• Derive quick correction (near-real time?)
• Second wide angle search
• Derive correction
• Standard procedure on 20 targets
• Derive average correction
• Standard procedure on 20 targets
• Derive average correction
• Verification using standard procedure on 20 targets
• Test run of one small extended source AOT and one small scan map
Where 'derive correction' implies obtaining data, reducing, deriving correction and feeding back correction to ESA and into pointing system. This implies significant interleaving with other tasks and/or 'speculative execution' of subsequent steps.

Note this flow assumes possibility of AOT observations already early in commissioning.

Estimated time needed

In orbit: Individual measurements are overhead dominated and will take just 5.5 minutes (HSPOT 3.2 including 3min observatory overhead). Note, however, that at least $(APE/0.5")^2$ measurements are finally needed. Time can be saved by sharing with e.g. photometric calibrations.

For wide angle search, detailed numbers depending on TBD implementation decision. Since 1 by 1 degree maps are no longer needed with the improved knowledge of misalignment after launch , total need should be below an hour.

The 'overall' flow above would correspond to about 10 hours of integration time, but spent over a longer period, and with a need for contingency!

Calibration Analysis Procedure (CAP)

ILT: Measure centroids of all four beams. If they are not centered on the desired position, offset xy-stage accordingly and repeat. Note final setting of xy stage for later use.

In orbit: Measure centroids of all 3×4 beams and average/convert as described above. Note that a flatfield and bad pixel mask should be applied to the data before fitting. If they are far off the desired position, trigger change of satellite attitude control parameters or (TBC) change an equivalent global CUS parameter. If it is near (less than 0.5 pixel) to the desired position, save results for later averaging/trend analysis to improve the a posteriori knowledge, but stop updating pointing parameters

In orbit wide angle search: Use a simple background subtraction and mapping as appropriate for the respective mode (e.g. 'naive' mapping and projection) to produce a map on which source can be located. Determine measured peak and compare to expectation. Note this assumes availability of pointing information or at least clear ID of raster position/scan leg.

Output, products

Updates to satellite attitude control parameters or CUS, accurate knowledge of reference position on array.

Status/version

added new info on after launch knowledge

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$Revision: 1.10 $
$Date: 2008/06/10 08:44:41 $
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Req. 3.1.2 Relation between Chopper Position and Angular Displacement on Sky

Objectives

To establish a relation between commanded chopper position (in chopper readback units) and the displacement of the FOV on sky, in direction and amplitude.

Optical distortions make this relation strictly valid only for a given point on the arrays.

Fulfilling or fulfilled by

Self-Standing, but data also useful for 3.1.3. ILT pre-tests may be very closely related to 3.1.3.

Priority

A

When performed / frequency

PV, pre-tests in ILT

Required accuracy

Amplitude: $1''$ on sky for a standard chop, extrapolation to other situations by 3.1.3

Direction: to $<$1 degree, as determined by errors of the four centroid measurements ($\sim$0.5" each) and chop throw (1-2'). This is well above the uncertainty of the satellite roll angle (3', IID-A sect. 5.12, this is the quantity called "around line of sight")

Inputs, prerequisites

Relation between chopper readback and chopper tilt (Zeiss lab measurement, see also req. 2.3.1) and PACS optical model for nominal transfer into displacement on sky.

Definition of the chopping zero point (with respect to the internal blackbodies) is done in requirement 2.3.1.

Sources

- [1] ILT: Punched hole masks outside test optics and hot plate, combined with modelling of test optics. Alternatively single hole combined with movement of XY stage. Hole sizes approx 5 arcsec or more because of limited OGSE contrast. Relative positions of hole centers known to 0.2 arcsec (36μm) or better.
- [2] In Orbit: Double point sources (some faint halo does not matter), with $>$160mJy each in the blue (70μm) channel, separations up to 3.5 arcmin, and position angle close to the chopping direction at the time of the observation. Chop direction is parallel to the spacecraft Y-direction. Both separation and position angle have to be accurately known at the time of the observation. See PACS-ME-TN-035 for attempts to identify such sources, more are needed.

Calibration Implementation Procedure (CIP)

- [1] If contrast with background and flatfielding is good enough to measure good positions without background subtraction: Use a mask with many holes in a $\sim$20arcsec spaced grid. Step chopper from one end of its range to the other (partly) using smallest possible chopper increment. Dwell a few seconds per step. This is the same observation as used in such a favourable case for 3.1.3. If contrast and flatfield quality is not good enough, use single hole mask, chopping, put the positive beam near the center of one of the blue subarrays, and then apply a translation of the OGSE xy stage that moves the negative beam to the previous location of the positive beam. If necessary to improve background subtraction, do at each of the two positions an additional orthogonal nod of the xy stage. One could also use a double-hole procedure similar to the one in orbit, but the single hole one does not need a new mask to be manufatured for each chopper throw.

- [2] Two possible similar methods, both making sense only if position angle of double star is *at the time of the observation* close to the chop direction: (a) Do a normal chopped observation, placing the negative beam of star 1 close to (but not exactly on) the positive beam of star 2. Repeat for different stars / chop throws. If possible don't nod or nod orthogonal to chop direction, to avoid effects of pointing inaccuracies on the centroids measured. (b) Do a symmetric triple chop which has, for the chopper in center position, the middle between the double source placed in the center of a blue subarray. Then alternatingly 'triple-chop' the two sources to this center by moving 1/2 of the double star distance in either direction.

  Both (a) and (b) imply chopped/nodded observation with chop/nod that may be different from the standard point source or small extended source AOT - standard AOT will be fine only in few lucky cases.

Standard data compression

Estimated time needed

For the multi-hole mask version of [1] a few minutes to an hour depending on sampling density. Single-hole version of [1] about 15 minutes but longer if also serving FOV distortion analysis. [2] acquisition overhead dominated, a few minutes per source.

Calibration Analysis Procedure (CAP)

- [1] Note that ILT measurements can only give a consistency check for the PACS optical model since their scale is based on the test optics model for the transformation of hole spacings or xy translations into 'angles on the sky'. Also, relative orientations may be slightly different because of the involvement of the test optics.

  Multi-hole mask version: Compare the difference of the positions measured for the images of a single hole at different chopper positions with the scale that is projected onto the array by the mask grid at a single chopper position, by the combination of mask metrology and test optics model. Use situations where chop 'throw' and grid spacing are nearly commensurate.

  Single hole mask version: Measure the small offset between the positive and negative beam obtained in the two steps of the procedure and convert to an angle on the sky using approximate PACS plate scale. Convert the xy stage offset into an angle using test optics plate scale and add the two. Compare to result expected on the basis of 2.3.1. In practice, the related section of the FMILT test report used a global fit to a set of seven large xy rasters at different chopper positions to derive the PhotArrayInstrument calfile. The aproximating scales and misalignment discussed here were derived from this fit.

- [2] (a) Subtract on and off and apply flatfield. Measure offset between star 1 positive and star 2 negative beam and use approximate PACS plate scale to convert the difference in pixel to an angle on sky to be added to the double source separation. An approximate plate scale/orientation is fine for this as long as offset is small. Note that this interacts with FOV distortions if the offset is too large. (b) Subtract central 'off' chop position from the two different 'on' ones and apply flatfield. Measure centroids of the two sources. If identical, then the chop throw betwen the two ends of the triangular chop corresponds exactly to the separation. If slighlty different (e.g. due to not perfect position angle match to chop direction), apply correction based on this offset and an approximate plate scale/orientation. (a) and (b): Compare to results expected on the basis of 2.3.1.

A version corresponding to the ILT single hole mask version has been defined for CQMILT with initially only the spectrometer operating. For simplicity, the CIP was kept under this requirement despite referring to the spectrometer!

Output, products

Chop direction, chop throw for chopping between two chopper readouts.

Status/version

Post FMILT review.

```
$Revision: 1.9 $
$Date: 2007/10/29 15:33:12 $
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Req. 3.1.3 Photometer Field of View Distortion

Objectives

Determine the optical distortions introduced by the PACS instrument optics and the telescope optics. The optical distortions depend on position on the array as well as chopper position, i.e. the chopper introduces more than a trivial translation.

ILT measures the distortion from XY stage to the PACS detector plane (i.e. OGSE and PACS) while in-orbits measures distortions from sky to the PACS detector plane (i.e. Herschel telescope and PACS). An additional modelling step is needed to transfer ILT results into in-orbit expectations.

FMILT3 was able to provide good results for the relation XY-stage to detector plane for both blue and red channel. This relaxes a little the needs for the in-orbit situation: If distortions sky to detector plane can be confirmed/measured for the blue channel with its smaller beams in orbit, the ILT results are available to transfer to the red channel.

See also PICC-ME-TN-019 for the related calfile concept.

Fulfilling or fulfilled by

Self-standing. Some relation to 3.1.2

Priority

A – if completely uncorrected the distortions will dislocate sources and smear them in averaged maps.

When performed / frequency

ILT

PV

Required accuracy

Directly affects astrometry. 0.5 arcsec (TBC). ILT3 solution in blue was good to about 0.2 arcsec.

Inputs, prerequisites

Zemacs optical modelling giving an indication of magnitude and shape of effects. For the bolometer, the distortions are suggested to be a smooth function of source and chopper position.

Misalignments between the individual detector matrices were measured at room temperature as described in requirement 1.1.15 (K.Okumura priv. comm.), and from the FMILT3 rasters (see FMILT test report). The transformation from coordinates measured in 'subarray' pixel coordinates on one of the matrices to 'array' coordinates for the focal plane of the respective camera is thus possible using the SubarrayArray calfile, which is based on FMILT3 and thus measurements at cryogenic operating temperature that implicitly consider any possible differential contractions. These are prerequisite to the derivation of the 'PhotArrayInstrument' distortion calfile described here.

Further optical modelling (in preparation by N. Geis) is needed to determine the transformation from XY stage coordinates to the sky and thus convert ILT results to expected in-orbit calibration.

Sources

ILT: Because of the limiting constrast achievable with the actual OGSE, two versions were prepared:

(1) Use single hole in front of OGSE external blackbody. For several (stationary) chopper positions, raster the hole over the full FOV of the array. This version is known to be feasible based on CQM experience. Possible choice would be 5 chopper positions spread over the full range for which the bolo FOV is fully open, from the position where all of the array just stays off one internal calibration source, to the one where its just stays off the other calibration source. Hole sizes roughly 5-10 arcsec, depending on contrast and whether both blue and red are to be done simultaneously. Because

of time pressure, FMILT(3) only executed this version, with 31*61 rasters at 7 different chopper positions and a 1.5mm (8.3arcsec) aperture serving both red and blue.

(2) Use a punched hole mask with many accurately known hole positions back-illuminated by hot plate in front of test optics. With the current OGSE, use of the densest masks and unchopped observations is not realistic. Choose hole pattern for good coverage of the FOV but avoiding confusion. Of the masks specified in PACS-ME-DS-003, the ‘RP’ and perhaps with good contrast and luck ‘BP’ might be just feasible. For a range of chopper positions covering the FOV between and slightly on to the calibrators, chop by a throw corresponding to half of the y direction hole spacing of the mask. Repeat this loop after moving the mask on the X-Y stage to a few different raster positions to further improve the sampling and provide information to check the relative geometry of the subarrays. This version has not been tried in FMILT.

In-Orbit: The simple equivalent of the ILT procedure would be large rasters over a bright point source, for different chopper positions. These rasters would require a very accurate Herschel pointing with accuracy a small fraction of the beam in the blue channel. This is not ensured with nominal Herschel pointing performance. The APE would enter every individual measurement, rather than cancelling out as for measuring offsets between sources of a cluster.

Other options include:

(i) Observing clusters of FIR point sources (>160mJy) spread over a few arcmin, with accurate positions known. PACS-ME-TN-035 discusses unsuccessful attempts to identify such far-infrared clusters.
(ii) Observing heavily structured regions/clusters (but with unknown accurate absolute positions) at different poitings and chop elongations, to probe for differential distortion. No systematic search for such (star forming?) regions has been made, also constraints on the approach to background subtraction in data reduction have not been discussed.
(iii) Line scanning very bright point sources across the array. While success is not guaranteed, such observations should be made. Ways to improve the pointing reconstruction by Gyro propagation need to be investigated. ‘Very bright’ here means S/N>100 in 1sec (i.e. still good S/N in 10Hz samples), or a source flux of at least 20Jy

Calibration Implementation Procedure (CIP)

Blue channel: Mostly use 70μm filter for best spatial resolution and then do a quick verification for other filter.

ILT: The back-illuminated holes of the current OGSE have contrast of just a few percent superposed on a modulated background caused by the cryostat window, making staring observations with densely punched masks difficult. For version (1) rasters with 2 second dwell time per position were successfully used after addressing some synchronisation issues. Version (2) was never tried. Because of the low contrast it would have to use a less busy mask and a TBD combo of chopping and nodding to subtract the background. The chopper would be also used to sample not only the central part of the FOV but also the edges used for large chop throws. The mask would have to be moved further with x-y stage to improve sampling, and to provide information to recheck relative alignment of subarrays (1.1.15).

In orbit: A number of chopped(?) observations of complex regions or clusters could be defined once such have been identified, variously offset and with varying chopper throw.

In orbit: Do linear scans of a very bright (>20Jy) point source parallel to array major and minor axis, at several offsets and for several chopper positions/throws. The absolute positions measured will be uncertain by the AME and hence of limited use, but the curvature of the track measured for a linear scan may constrain the optical distortions.

In orbit: To compare different methods, do also an ILT-like 31*61 staring raster, only for chopper at optical zero.

Standard data compression

Estimated time needed

ILT: In ILT3 we needed 7*1.5 hours for one run of version 1. Several hours would be needed for one run of version 2. Both might be repeated for different holes/masks.

Possibly very long duration in orbit. As an example, a scan map with 10arcmin long legs (to be able to ignore the region immediate after turnaround in which scan speed still stabilizies), 10arcsec/sec scan speed, and 60 scan legs spaced by 4arcsec cross-scan step (to finely cover the full array) needs about 1.5 hours. Two scan directions and 7 chopper positions would imply 21 hours total.

A 31*61 in-orbit staring raster would take at least 31*61*10sec = 5.3h, assuming 8sec slew plus 2sec dwell per point. Detailed value to be checked.

Calibration Analysis Procedure (CAP)

The reduction of the ILT3 distortion rasters is described in the related section 3.1.3 of the FMILT test report. Signals were background subtracted, averaged for each raster position and compiled into a 4D array for each pixel (2D) and raster step (2D). To be more robust against flatfielding and bad pixel effects, peaks were then fitted in the 'raster plane' of these arrays for each pixel separately. The resulting large dataset was used to solve first for the misalignments of the matrices (SubarrayArray), and then for a global distortion (PhotArrayInstrument) given by a polynomial model.

In-Orbit: No dedicated attempt is foreseen to recheck the matrix alignment (SubarrayArray).

For cluster/complex region observations: Measure centroids of structures in subarray coordinates and transform to array coordinate system. Compare results to the ones expected for a single invariable structure observed at different offsets/chopper angles and the ILT-based distortions, and try to derive correction to those from the residues This comparison will likely be a pretty complex system of equations including also the unknown pointing offsets of the individual observations. Subtle background subtraction/reduction issues could be important.

For line scans measure tilt and cross-scan deformation of track and compare to ground test results and model. Beware of possible effects of spacecraft jitter (Req. 2.6.4).

Output, products

Calibration file between array coordinates, chopper angle, and instrument coordinates (PhotArrayInstument).

Verification or update of calibration file between subarray and array coordinates (SubarrayArray).

Status/version

In-orbit raster as additional element

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$Revision: 1.6 $
$Date: 2007/11/15 15:03:21 $
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Req. 3.1.4 Photometer Point Spread Function

Objectives

Determine the Point Spread Function of the Photometer for the three filters. Do this possibly for both 'hot' and 'cold' sources, to account for color terms in the fairly broad photometric bands which can cause PSF width differences up to 10% between different spectral slopes. Do this for several positions in the Bolometer FOV (at least the centers of the 8 blue matrices) to test for possible variations. At least near center of FOV, also exercise small sub-pixel offsets.

Preliminary tests can be done during ILT, but the difference between telescope and test optics and the complexity of the test optics setup (background structure, reflections in filters or dewar window?) preclude a direct transfer of results. In particular, the Herschel telescope is not required to be diffraction limited for the PACS blue channel, although the goal is to be close to diffraction limited. This uncertain situation will not be adequately reproduced in ILT. The quality of the ILT results for PSF is limited by the low few percent contrast achievable in the current OGSE setup, and the sensitivity to spatial structure in the background. No reliable statements on faint wings of the PSF are expected from ILT.

In the original bolometer double-differential readout scheme, there was a possibility that the bolometer "blind pixels" used to compensate drifts see some light from a very bright point source near to the appropriate edge of the subarray. This would offset signals for part of the detectors in the respective subarray (Req. 1.1.17). Since this readout mode has been abandoned, there is no more need to include tests for this effect into observations to determine PSF and Ghosts.

Fulfilling or fulfilled by

Self-Standing, but partly benefitting from analysis of photometric calibrations etc. Observations will partly fulfill 3.1.5. Some observations can be shared with AOT verification for parallel mode.

Some photometer obervations to check spectrometer PSF calibrators (4.1.3) are booked here.

Priority

A

When performed / frequency

PV and later. Pre-tests in ILT

Required accuracy

In orbit: S/N $>$ 300 in the peak in order to have decent S/N down to faint wings at the few percent level. ILT: limited by systematics to FWHM measurements and statements about structure at the level of 10% of the peak or more.

Inputs, prerequisites

Library of model PSFs at least for central part of FOV and for various sub-pixel positions. Model PSFs have been computed for the ILT situation (OGSE without central obscuration), see FMILT test report. Computation for the in-orbit situation is ongoing. Req. 7.x?

Sources

Bright point sources without far-infrared halo or nearby structure. One also has to take care to not integrate into the structure of the background, long integrations don't make sense. At 160μm, e.g., we expect one extragalactic background source of $\sim$30mJy in a 2 by 2 arcmin region. We hence have to go to very bright sources to get the dynamic range and still be confident that some maximum is a PSF structure and not an interloper source. 10Jy should give a dynamic range of 300 with respect to the mentioned chance background source. The effect of cirrus structure on measuring faint wings on the arcmin scale is estimated in PICC-KL-TN-028. Suitable sources might be asteroids moving through clean fields, or stars selected to most likely not have dust shells. Options for cold point sources include: (1) Distant infrared galaxies (lensed as long as not too widely separated?), but these will often give only low S/N and little dynamic range wrt background, hence good for a FWHM at best. (2) Nonthermal emission from Blazars (rising to the red, though not very steeply) and/or (3) distant solar system objects like KBOs. All these will be fainter than desired. See PICC-KL-TN-028 for an assessment of stellar PSF sources, and PICC-ME-TN-024 for an assessment of blazars.

Based on these source list documents, it is proposed to use three types of PSF sources for the bolometer:

- A bright stellar source (hot for PACS) from table 2 in PICC-KL-TN-028, excluding the ones with remarks about shells and non-stellar FIR flux ratios. In particular, the brightest of the flux calibrators on that list, like α Boo, α Tau, β Peg, are interesting and provide additional use for fluxcal or flatfielding. The red channel may provide lower S/N than desired.
- A bright $>>$10Jy asteroid (hot for PACS) in a low background region and moving as slow as possible to minimize possible effects of SSO tracking on the PSF. If it is stationary (moving by $<<$ RPE over the observation), a normal non-SSO AOR could be used to be sure.
- A Blazar (cold for PACS) of the ones flagged suitable for PSF in PICC-ME-TN-024. S/N will be insufficient for measuring faint wings.

ILT: Single hole in front of external blackbody, mounted on xy stage. The hole size is a tradeoff between PSF smearing and contrast. A useful start may be $\sim$ 5 arcsec for the blue channel, 10 arcsec for red channel. Use of smaller apertures of 2 arcsec or less is in principle highly desirable but limited by lower contrast.

Calibration Implementation Procedure (CIP)

ILT: Set up OGSE with single hole on XY stage with blackbody behind. Be sure to select the appropriate attenuation filter for the bolometer channel used. Setup bolometer for OGSE external window observations. The total procedure has several steps some of which may be skipped depending on what was done before:

- Switch on PACS and OGSE, wait for stabilization of internal calibrators etc.
- If not yet done in this ILT phase, locate the source on the PACS array under QLA control and center it properly.
- If not yet done in this ILT phase, do a focus sequence for the z coordinate of the XY stage.
- Measure PSFs for a number of locations of the source. Because of the peculiar background behaviour of the OGSE external window, the basic procedure does not use a simple chopped measurement, but in addition to chopping needs a nod orthogonal to the chop direction. Added observations of the internal calibrators are desirable to allow a posteriori improvements of flatfielding.

Many variations of the basic procedure are conceivable to test for PSF variations with large scale or sub-pixel position changes, chop throw, hole size, and to test for focus differences blue vs. red array or with position of the XY stage. Staring rasters with the hole source similar to the ones done for 3.1.3 have also proven to be useful to probe for PSF variations.

For the FMILT several chopped tests were done with the PSF at the center of each blue matrix (by using a large chopper throw in addition to the normal one) and for a fine raster moving the chopped PSF procedure in additional loops over the size of a pixel. In addition, finely sampled staring XY stage rasters for the three filters were done covering the size of one matrix. Some AOT-like tests with scanning XY stage are useful for characterizing PSF smearing (Note that compared to nominal bolometer setting, low gain setting used with the OGSE external window should not harm, but different Vh-Vl biases, when used, affect the time constant).

In orbit: Chopped observations and small maps.

Use various positions of the source on the array and chop throws to sample the PSF over the entire FOV. Typically, use a large chop throw and nod to outside FOV to minimize disturbances by negative beam. This suggests a chopped/nodded procedure similar to the normal point source / small extended source AORs, with flexibility on where to place the positive beam on the array, the chop throw, and the nod throw and direction

From repeated but slightly offset observations, a sub-pixel raster or using proper motion of asteroids ensure that PSFs are obtained for various positions of the peak within a pixel.

The finely sampled 'staring' rasters successfully used with the stable XY setup in ILT appear less promising here because of pointing stability issues. Also the minimum raster step of 2 arcsec is a constraint.

There is a clear need to characterize the PSF smearing for line scan AOTs, in particular at the fast speeds. Maps across a bright PSF source at all three scan speeds and for all filters are needed. These could take very different scope from a single pass across a source to characterize basic smearing properties to maps that sample well a very large PSF by a single pixel only and include orthogonal scanning. The current plan is for modest maps with 3arcsec cross-scan separations and 15 legs of sufficient length.

The SPIRE/PACS parallel mode uses the same scan speeds 20 and 60 arcsec/sec as the faster PACS scan maps, but according to current planning averages the blue channel by a factor 2 to 5Hz sampling rather than 10Hz, in order to save datarate. Under the *assumption* that, as currently planned, this is a true averaging rather than dropping part of the samples, and that the bolometer will use the same settings/biases in parallel mode and in PACS prime, the additonal calibration effort can be kept small. One parallel mode scan map for each scan speed and each filter should be done on a PSF calibrator (as also planned for AOT verification purposes, 5.1.5). PSFs with more detail could be extrated from the PACS prime scanmap data taken on PSF calibrator for the same scan speed, by a posteriori averaging of samples.

Standard data compression, note the differences prime/parallel and remark on using prime data for parallel mode PSF.

For the spectrometer, there is a difficulty to find very bright but truly pointlike PSF calibrators. Bright sources with potentially non-ideal spatial structure have to be used. In this situation, the source chosen should also be covered with a fast small extended source photometer AOR. While these observations relate to PCD 4.1.2 they are executed here.

Estimated time needed

ILT: individual measurement are short, of the order 1 minute. Significant setup overheads or large rasters can easily produce overall times of a few hours, though.

In orbit: Short, overhead driven integration times. One should stay on source for a few min to also include smearing by pointing jitter. Doing this for 3 filters * 3 source types * n positions in FOV and doing some sub-pixel stepping for part of the positions may give considerable overall times, though.

A first quick draft assuming 5 minutes for each run of the quick chopped/nodded procedure, and 15 min for a scan map with several narrowly cross-scan spaced passings of the source is:

- Special chopped/nodded procedure for source at the centers of all 8 blue matrices, blue and green filter, and 2 hot (star and asteroid) and 1 cold (blazar) celestial source: About 4 hours (8*2*3*5min).
- Normal point source AOR (with dither) for blue and green filter and 2*hot and 1*cold source: 2*3*5 min (may be shared with other e.g. pointing related tasks).
- Chopped/nodded procedure with additional sampling of sub-pixel steps, for source at the centers of one of the blue matrices, blue and green and red filter (different steps here for red!), hot and cold source: 1*3*2*5min*16 (for a 4*4 sampling of a pixel): 8h, should be possible to cut the time by reducing the time at each position here. Since the smallest raster step is 2 arcsec and we are reaching the limit of the pointing, this may need special implementation as well as analysis. Wait for in-orbit experience with stars or asteroids before deciding what to use as hot source.
- Default AOT scan maps for blue and green, low, medium, and high scan speed, hot and cold PSF source: 2*3*2*20min (4h).
- Parallel mode scans on a PSF/flux calibrator for both scan speeds and filters as described in 5.1.5: 3.6h.

Calibration Analysis Procedure (CAP)

Subtract background, apply flatfield, interpolate over bad pixels/array gaps, and derive a library of normalized PSFs for various locations in FOV, compare to model expectations.

Characterize the PSF smearing and shift as a function of line scan speed and of direct/parallel mode averaging schemes.

In ILT, additional steps of QLA monitoring for locating the source, and IA to evaluate the focus sequence, and estimate systematic problems in background.

Output, products

PSF library and associated products like FWHM tables and pixel efficiency factors

Status/version

More detail on parallel mode

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$Revision: 1.8 $
$Date: 2008/06/27 15:45:52 $
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Req. 3.1.5 Photometer Ghosts

Objectives

Test for presence of ghosts in photometer images (=compact false sources or structures in the bolometer data, due to Herschel or PACS internal reflections caused by the signal of a strong real source at a different position).

Ghosts were seen in the FMILT at a level relevant for science observations, in some cases clearly originating inside PACS (thus expected also in orbit), in other cases ambiguous and perhaps related to the OGSE setup. In-orbit measurements are needed.

Fulfilling or fulfilled by

Partly by analysis of data taken for PSF determination (Req. 3.1.4), FOV distortion (Req. 3.1.3) and science data.

The additional specific observations described here are also of interest for 3.1.6

Priority

A

When performed / frequency

PV and later, pre-tests in ILT

Required accuracy

Ghosts should be measured or limits placed to a peak level well below a % of a bright point source, for sources within 10 arcmin from the center of the bolometer FOV.

For the FMILT setup, the low point source contrast of the current OGSE+hole setup limits in practice the ability to spot faint ghosts to the few % level.

Inputs, prerequisites

Sources

ILT: XY stage setup with hole and hot external BB. For good contrast, hole size may be chosen similar to or slightly above PSF width, a little larger than for PSF measurements.

In orbit: Very bright (almost) point sources, as isolated as possible. Moving solar system objects give additional options to discriminate Ghosts or PSF structures from background objects. For a dynamical range of 10^3 compared to background objects, around 100Jy should be chosen.

Calibration Implementation Procedure (CIP)

Discrimination of ghosts from real structures on the sky or OGSE setup, and from the PSF is by scanning or rastering. Real structures stay constant for all observations of a point on the sky by different pixels, while ghosts will only be seen towards a direction by some pixels but not others.

ILT: Do XY rasters or scans for all filters covering as large as possible a part of the XY stage range with a bright hole source. Step width not above PSF width convolved with hole size, in order to not miss compact ghosts.

In orbit: Observe a point source with different positions on and off array, and perhaps different chop positions. If source is a moving SSO target, re-observing the same spot after it has left may give additional information on possibly detected structures.

Specifically, the following observations are proposed:
(1) Quantification of the ‘blue streak’ ghost seen on ground: Do four medium scan speed, 5 arcmin leg length, 4 arcsec cross scan step, 76 leg scan AOTs centered on the very bright source for (a) blue filter, chopper at optical zero, (b,c) blue

filter and chopper at the two extreme positions in the free FOV and (d) green filter, chopper at optical zero.
(2) Exploratory search over a wider region: For blue filter, chopper at optical zero, do one high scan speed, 20 arcmin leg length, 6 arcsec cross scan step, 201 leg scan AOT centered on the very bright source.

Other scanned/rastered PV tests and science data may be inspected as well.

Estimated time needed

In orbit:
(1) a-d needs 4*1h
(2) needs 4h

Calibration Analysis Procedure (CAP)

Look for signals that neither always stay at the same astrometric position (as real background sources would do) nor always move with the point source (as PSF structures do). The discrimination between PSF features and ghosts is somewhat fuzzy...

OGSE test optics (ILT) differs from in-orbit setup, ghosts seen there may not necessary be the same as in orbit.

Output, products

Maps showing location and strength of ghost compared to the point source causing it, for later consideration in data processing.

Status/version

Post-FMILT review

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$Revision: 1.6 $
$Date: 2007/10/30 15:56:46 $
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Req. 3.1.6 Photometer Straylight

Objectives

Determine or put limits on signals detected by the PACS photometer that are due to bright sources of radiation outside the field of view. Note that such radiation of significant strength may remain undetected in chopped observations if it is only weakly dependent on chop position, and that the bolometers give relative fluxes subject to drifts rather than absolute fluxes. Sources of straylight to be considered include

- Very bright compact sources (late type stars, Planets) within a few arcmin of the bolometer FOV. Note also the possibility of compact reflections - see also 3.1.5
- Very bright sources at large angles from the FOV, with reflections off the secondary mirror support (see e.g. the various scenarios in the Herschel Telescope Straylight Analysis HER.NT.0017.T.ASTR Issue 3.0). The assumption previously made was that these are non-specular reflections and spread over a large area, thus being more of an addition to the background rather than an image with structure on the scale of the FOV or less. This may not be true given the as-built Herschel telescope where the secondary supports are covered with a fairly specular and flat foil. The issue was discussed in the Sciops WG in spring 2008 but is on hold until better predictions allow to guide the positions for possible searches. No specific measurements to trace this effect are described below for the time being, this may need to be revisited if improved input on expected straylight becomes available.

A signal that could be called 'straylight' is caused by chopping in the presence of telescope temperature gradients, and is being fought by nodding or position switching. Trend analysis of this signal is covered in requirement 3.2.x????

There is a certain semantic ambiguity between what is called 'straylight' here and the 'ghosts' as discussed in 3.1.5., for the moment we consider 'straylight' an additional illumination that is more diffuse over the FOV compared to a more compact ghost.

Fulfilling or fulfilled by

Specific observations discussed in 3.1.5 are relevant here as well. Also inspection of science data.

Priority

B

When performed / frequency

PV and later, pre-tests in ILT.

Required accuracy

Inputs, prerequisites

Modelling of Herschel straylight properties to guide search.

Sources

Very bright >100Jy sources: Mars, Jupiter, late type stars...

ILT: External blackbody and single hole on xy stage. Because of the limited contrast and background structures, only very strong straylight of the type considered here would be detectable with the real OGSE setup.

In orbit: An exploratory 2deg×2deg fast scan AOR around a bright isolated source should be done. If a bright planet is available in PV and in a low background region, use this one and revisit the region later after planet has moved, to better discriminate straylight from real structure. If no planet is available in PV, use a bright isolated source from PICC-ME-TN-023 in PV and do the planet exercise later.

If better predictions for the straylight reflected off secondary supports or baffles become available, the basic scheme would be: (1) Do a fast scan map or cross of elongated scan maps over the spot where the straylight from a very bright SSO source (e.g. moon) is expected at a specific time. (2) Redo the observation days or weeks later at the same sky position but with the straylight moved away together with its cause.

Calibration Implementation Procedure (CIP)

There are two basic possibilities to probe for straylight:
(a) chopped observations at various positions relative to the bright source. Probably suggested for a range of positions where radiation is still near the PACS aperture.
(b) unchopped fast line scan or raster passing over or near the bright source, aiming to detect a temporary signal excess at a level that can be discriminated from background/sensitivity drifts and from real structure of the sky.

ILT: The external blackbody and single hole on XY stage was used to try out possibility b). The only clear detection was the compact 'blue streak' ghost, see also 3.1.5. Note that the OGSE test optics setup is complex and different from telescope.

In orbit: Fast scan, optimal coverage scan maps at an angle filling the matrix gaps should be a good approach.

Estimated time needed

In orbit: A 2deg$\times$2deg fast scanmap, optimum coverage, map orientation angle 20deg in array coordinates takes 1.9h. One or two such maps in PV, zero to two later according to the plan outlined above.

Calibration Analysis Procedure (CAP)

In the specific observations described in 3.1.5 or archival calibration and science data, search for excess signals that are not plausibly due to structures in the real sky.

In orbit: Reduce map in the standard way and look for conspicuous signals that are not associated with known sources. For the planet, subtract the two maps with planet on and off to improve discrimination.

Output, products

Limits on straylight or quantification under which conditions it occurs.

Status/version

More detail on possible large angle reflections

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$Revision: 1.7 $
$Date: 2008/07/07 15:12:54 $
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Req. 3.1.7 Background Structure in the Photometer Field-of-View over the Full Chopper Angle Range

Objectives

Assess the background homogeneity and structures over the full field-of-view accessible to the photometer by moving the chopper within its maximum angle range. This comprises the FOVs of the two calibration source and the sky sections as well as the two boundaries inbetween. It verifies the dynamic range for typical observing conditions for the given bias settings for low and high gain. It is an efficient way to check for saturation (for both gain settings, both filters, and in bright sky regions). It is an important addition to flat-field determination and also serves for straylight assessment induced from one section onto the other, i.e. additive emission by the sky to the internal calibration source emission and straylight of the internal calibration sources into the sky-field-of-view. Furthermore it is a good data source for cross-talk investigations.

Fulfilling or fulfilled by

Related to req. 3.2.8 Measure the photometer full system flat-field,
req. 3.2.9 Telescope background and its stability,
(req. 3.2.10 (TBW) Straylight onto the internal calibation sources),
req. 1.1.17 Measure the level of optical cross-talk in the detector and
req. 1.1.18 Measure the level of electrical cross-talk

Priority

A

When performed / frequency

- [1] During ILT tests
- [2] During IST tests
- [3] In-flight during Performance Verification

Required accuracy

Localize features and emission gradients down to 1% level of the actual sky and CS background (may vary with CSs on/off and cooling-down telescope in PV Phase)

Inputs, prerequisites

1 Optimum detector biases (Reqs. 1.1.1 and 1.1.1bis)

2 Chopper angular calibration (Req. 2.3.1)

Sources

1 ILT and IMT/IST tests: internal calibration sources (IMT/IST) and OGSE BBs (ILT).

2 In-flight:

- dark sky field to have maximum contribution by the telescope background and internal calibration sources on various temperature levels.
- very bright sky field in galactic plane for additional straylight checks

Calibration Implementation Procedure (CIP)

For ILT/IST:

- Perform chopper multi-step scan with fine step sizes in the order of the pixel scale between maximum allowed negative and positive chopper deflections.
- Consider all possible sky field backgrounds when looking from the instrument along the various OGSE paths to the different stimulators.
- Consider detector operation in direct and DDCS mode.
- Consider ow and high gain detector operation
- Consider internal calibration sources on various temperature levels.

The following illumination combinations have been probed during FM-ILT, for both blue filters

- detector DDCS mode
  - cold CS1 (<8 K), cold FOV, cold CS2 (<8 K)
  - warm CS1 (71 K), cold FOV, warm CS2 (76 K)
  - warm CS1 (71 K), BB1 at 22 K, warm CS2 (76 K)
  - warm CS1 (71 K), window 1, warm CS2 (76 K)
  - warm CS1 (71 K), window 2, warm CS2 (76 K)
  - warm CS1 (55 K), BB1 at 17.89 K, warm CS2 (60 K)
  - warm CS1 (55 K), cold BB1, warm CS2 (60 K)
  - warm CS1 (55 K), warming up BB1, warm CS2 (60 K)
  - warm CS2 (60K) restricted to +13000 . . . +23000 chopper deflection (sharp feature investigation)
- detector DDCS mode
  - warm CS1 (55 K), cold integrating sphere + laser line at 70.5 μm, warm CS2 (60 K)
  - warm CS1 (55 K), cold IS + laser line at 170 μm, warm CS2 (60 K)
  - cold CS1 (<8 K), BB1 at 40 K, cold CS2 (<8 K)
  - cold CS1 (<8 K), cold FOV (BB1 at 6 K), cold CS2 (<8 K)
  - FM-IST reference scan
  - warm CS1 (55 K), BB1 at 10.0 K, warm CS2 (60 K)
  - warm CS1 (55 K), BB2 at 15.0 K, warm CS2 (60 K)
  - warm CS1 (55 K), BB1 at 20.0 K, warm CS2 (60 K)
  - warm CS1 (55 K), BB2 at 22.5 K, warm CS2 (60 K)
  - warm CS1 (55 K), BB1 at 25.0 K, warm CS2 (60 K)
  - warm CS1 (55 K), BB2 at 30.0 K, warm CS2 (60 K)
  - warm CS1 (55 K), BB1 at 35.0 K, warm CS2 (60 K)
  - warm CS1 (55 K), BB2 at 40.0 K, warm CS2 (60 K)
  - warm CS1 (40 K), BB1 at 21.815 K, warm CS2 (50 K)
  - warm CS1 (40 K), BB2 at 23.496 K, warm CS2 (50 K)
  - warm CS1 (45 K), BB2 at 23.496 K, warm CS2 (65 K)

- warm CS1 (45 K), BB1 at 21.815 K, warm CS2 (65 K)

For additional information, cf. PICC-ME-TR-005, OGSE characterization during CQM/FM-ILT.

For PV:

- Perform chopper multi-step scan with fine step sizes in the order of the pixel scale between maximum allowed negative and positive chopper deflections.
  225 steps up and down between chopper positions ± 23000;
  both blue filters (wavelength dependence of straylight)
  80 read-outs per chopper position.
- Consider low gain (foreseen in Commissioning Phase) and high gain detector settings.
- Consider the cool-down of the telescope which provides different absolute illumination levels of the sky section allowing to scale the relative contribution to the neighboring sections.
  Mid and end of PV.
- Consider internal calibration sources on various temperature levels.
  CS1/CS2 off, CS1/CS2 at nominal temperatures, CS1/CS2 at higher than nominal temperatures.

Estimated time needed

For ILT: About 25 FOV scans, 0.5 h each during the 3 FM-ILT campaigns.
For PV: 0.5 h per chopper up- and down scan in two blue filters for each illumination combination
$\Rightarrow$ 3 (CS illumination levels) $\times$ 2 (telescope background levels) $\times$ 0.5 h = 3 h + 2 $\times$ 0.3 h (CS stabilization to higher T) = 3.6 h
0.4 h for 2 low gain FOV scans during Commissioning Phase.

Calibration Analysis Procedure (CAP)

- Use data reduction techniques as e.g. outlined in PICC-NHSC-TR-002, Bolometer FOV chopper scans
- Construct flat-fields for different illumination conditions and detector settings
- Quantitatively characterize level and gradient of sky/telescope straylight into the CS sections as e.g. outlined in SAp-PACS-KO-0675-08, Straylight on the internal calibration sources
- Quantitatively characterize level and gradient of CS straylight into the sky section
- Identify cross-talk features and the originating area as e.g. outlined in SAp-PACS-KO-0676-08, transient electrical cross-talk

Output, products

1) FOV maps of the bolometer for the various illumination combinations
   for FM-ILT, cf. PICC-NHSC-TR-002, PICC-NHSC-TR-010
2) Scalable straylight maps for CS and sky sections; for FM-ILT, cf. SAp-PACS-KO-0675-08
3) Saturation limits for the PACS photometer;
   for FM-ILT, cf. SAp-PACS-MS-0680-08
4) Description of cross-talk phenomena;
   for FM-ILT, cf. SAp-PACS-KO-0676-08

5) Chopper and bolometer pixel angular scale verification for FM-ILT, cf. PICC-MA-TR-009

Status/version

```
$Revision: 1.1 $
$Date: 2008/08/07 18:16:15 $
```

3.2 Photometric calibration

Req. 3.2.1 Derive photometer nominal responsivity

Objectives

To obtain, for the complete instrument, the relation between a voltage output readout and the absolute sky brightness. This is one of the most important calibration item of the whole system.

Fulfilling or fulfilled by

This is completely covered by requirement 1.1.1bis when the measurement is made with an integrated instrument. In fact the chain of requirements 1.1.0 to 1.1.1bis set at detector level applies for the full system as well.

Priority

A.

When performed / frequency

ILT and later phases.

Required accuracy

The photometric accuracy: 5% (TBC)

Inputs, prerequisites

The nominal detector responsivity as we have to understand how the detector's responsivity relates to the full system one.

Sources

Internal calibrations sources, well controlled black-bodies (for the ground tests) as well as celestial standards.

Calibration Implementation Procedure (CIP)

See requirements 1.1.0 to 1.1.1bis

Estimated time needed

See requirements 1.1.0 to 1.1.1bis

Calibration Analysis Procedure (CAP)

See requirements 1.1.0 to 1.1.1bis

Output, products

A table of conversion factors from readout units to sky brightness.

Status/version

Revised for PV phase version of the PCD.

Req. 3.2.2 Monitor nominal responsivity variations with time

Objectives

Previous bolometer-based detectors have exhibited responsivity variations for a number of reasons, some or all of which can be expected to affect the PACS bolometers. Proper monitoring of variations in the PACS bolometer response requires that we first identify the relevant causes of these variations and the pertinent time-scales on which these variations manifest themself. Since response variations directly impact photometric calibration, these variations must be suitably characterized and corrected to reach photometric accuracy goals.

For ground-based bolometer instruments (*e.g.* SCUBA) the variations in background sky dominate responsivity variations. For Herschel, thermal emission from the telescope's primary mirror is the dominant "sky". The absolute level of telescope emission is expected to remain constant to less than one percent (TBC) and is, therefore, not a significant source of variation for bolometer responsivity. Variations in the level of astrophysical background sources, for example, zodiacal light intensity as a function of time, are also insignificant compared to telescope background level.

However, sky variations that are potentially significant causes of responsivity changes can originate either as variations in the amount of stray light (change of emission from inside the cryostat), and spatially, rather than temporally, as non-uniformity of coating on the primary mirror surface. Stray light variations may come from Herschel's position angle and, possibly, as time since last cooling cycle. While the bolometer thermal bath is expected to reach thermal equilibrium quickly, other surfaces within the cryostat may reach this equilibrium at different time-scales, hence, leading to possible variations in the stray-light level. Non-uniform coating on primary mirror leads to non-uniform emissivity. However, this particular requirement is not concerned with spatially induced response variations. Instead, see requirement XXX.

The variations in the bath temperature of the bolometer are potentially another significant contributor to responsivity variations. One source of this type of variation is variation in the efficiency of the coolant pumping leading to variations in system temperature. [*Note from author: We need an estimate of the max fluctuations from the cryo-folks as well as time scale of these fluctuations*].

Variations in responsivity may also originate from the bolometer electronic components: (i) Systematic or random variation in the bias voltage supply, (ii) variations in the thermal conductance, (iii) gain drifts and (iv) random events such as impact by charged particles and/or solar storms.

Given the above mentioned possible causes, the time-scales of interest are:

- At switch-on of the instrument.
- Time since cooler recycling.
- Orbital position of the telescope.
- Life-time of the instrument.
- After a charged particle impact.

Unfortunately, not all of the time-scales can be predicted for these causes ahead of time.

It is important to distinguish this requirement from Requirement number 3.2.1 – measuring the full system responsivity. Requirement 3.2.1 is concerned with bolometer responsivity over the full rdynamical range of fluxes, and uses a more sohpisticated (and time consuming) CIP that is not needed to monitor responsivity changes with time. Instead time variations of responsivity will be measured at a "nominal" (see CIP below) flux level by assuming that any responsivity changes above and below the nominal flux are also determined by changes in the nominal level.

Fulfilling or fulfilled by

This is the full system version of req. 1.1.4 "Monitor nominal responsivity variations with time". At ILT and subsequent phases, the two requirements are not distinguishable and in fact, req. 3.2.2 fulfills req. 1.1.4.

Priority

B.

When performed / frequency

An accounting of previous bolometer instruments yields the following time-scales for responsivity monitoring:

- SCUBA – Every minute (goal). Sky variations dominate response variations.
- SHARC – Hourly. Sky variations dominate response variations. They have noted evidence for a second factor, but have not identified what it is.
- Boomerang – Every 18 minutes.
- PLANCK – At multiple times during each scan. However, they are aided by the presence of the cosmic microwave background in the low-frequency instrument and by FIRAS data in the high frequency band.
- CSO – Every minute using an independent sky monitoring set-up.

The above discussion has attempted to provide an estimate of what time-scales are relevant (give the set of probably causes) and what other similar instruments have used (though their causes may be different from PACS). In some cases, particular those that originate in the electronic, the time-scales can not be determined accurately without actual measurements. Hence, the author recommends the following basic philosophy: "monitor as often as practical, characterize any observed response variations, and either ease-up or speed-up as dictated by the data."

The following time-table is thus recommended for in-flight monitoring:

1. Measure at every switch-on.
2. Measure before every switch-off.
3. Measure after a (TBD) selected glitch events.
4. Measure every (TBD) minutes for the first hour (TBC).
5. Measure hourly between switch-on and switch-off.

Note that during ILT a number of ground based artifacts may lead to responsivity variations that will not be present in the complete instrument and thus may require more frequent monitoring.

Required accuracy

$< 5\%$ (goal). This accuracy is driven by the final photometric accuracy we are aiming at.

Inputs, prerequisites

The nominal value of the full system responsivity. The range of variations observed at the detector level to be able to design sensible calibration measurements.

Sources

- in-flight: celestial sources and internal calibrators.
- ground & flight: EGSE blackbodies and the internal calibrators.

Calibration Implementation Procedure (CIP)

The telescope background dominates the total flux seen by the detector and is present in all PACS's images. It is therefore, a natural "nominal" value at which responsivity variations will be measured. There are two methods available for repeatedly measuring the PACS's bolometer responsivity:

1. By using the internal calibrators.
2. By using Astrophysical sources (in-flight) or EGSE blackbodies (during ILT).

It is not clear at this point that both methods are feasible or even necessary. However, as mentioned above, we intend to monitor the responsivity "as often as practical" until more accurate variability time-scales have been established.

1. By using the internal calibrators. In this case, the internal calibrators are set to produce approximately the same number of photons as are being produced by the telescope background. The required photometery accuracy is less than 5%. Therefore the total signal (over the integration period) must have signal-to-noise ratio of 20 or higher. The measurement is repeated with the time-resolution identified above. Once the calibrators stabilize at the nominal flux level, the procedure is to chop between the two internal calibrators for a (TBD) amount of time such that the final signal-to-noise ratio is higher than 20.

2. By using the OGGE blackbodies or astrophysical sources. During ILT, two additional calibrators are available. No specific setting is required for the OGSE calibrators as long as the "nominal" level is one of the settings used during measurements. This will allow this CIP to be harmoneously integrated with other similar CIPs. As for the method above, signal-to-noise ratio of 20 or higher are required to meet the photometry accuracy goals. The time-resolution is identified above. An advantage of using both the OGSE and internal blackbodies will be to isolate any responsivity variations as either "inside" or "outside" the cryostat. The procedure is to chop between the two EGSE calibrators for a (TBD) amount of time such that the final signal-to-noise ratio is higher than 20.

The additional calibrators are replaced by astrophysical sources during flight. However, inflight measurements levy additional overheads in the form of telescope slew and settle times. Therefore, it may not be possible to use this method as frequently.

Estimated time needed

The time needed to achieve signal-to-noise ratio of at least 20.

Calibration Analysis Procedure (CAP)

Since we have defined the nominal flux level (see above), the process of isolating responsivity variations is tremendously simplified. By definition, the responsivity is a product of detector efficiency and the input flux divided by the bolometer readout voltage. The detector efficiency is constant, and by keeping the input flux level constant as well, one only needs to monitor the variations in the readout voltage. This is simply the median value of the frame.

The responsivity measurements at each time-step are plotted versus time to identify and characterise any observed variations with time.

Output, products

Responsivity correction factors as a function of elapsed time since determined events.

Status/version

Revised for the PV phase preparation version of the PCD.

Req. 3.2.3 Calibrate the photometer's non-linearity

Objectives

For large flux dynamics, the bolometer arrays are highly non-linear (the higher the flux level, the smaller the measured signal for a given input). We need to make sure this non-linearity is well calibrated although we will try to operate in regions of flux where a linear approximation is correct. This non-linearity calibration will have to be used when observing very bright sources (possibly planets) and even some of primary calibrators (Uranus inputs as much power on the array as the background).

Fulfilling or fulfilled by

This is the full system version of req. 1.1.13 "Calibrate the detector non-linearity". At ILT and subsequent phases the two requirements are not distinguishable from each other and in fact req. 3.2.3 fulfills req. 1.1.13 and vice-versa. Note that req. 1.1.1 and 1.1.1bis, when fulfilled for the full system already provide rather detailed information on the non-linearity of the photometer.

As much more can be done on the ground than in space, we separate the two versions of the requirement when needed.

- **On the ground:** The proposed CIP also fulfills
  req. 3.2.1 "Derive photometer nominal responsivity",
  req. 3.2.4 "Establish the linearity of the full system",
  and is also used in
  req. 3.2.8 "Measure the photometer full system flat-field"
  although for this last requirement it needs to be expanded.

- **in Orbit:** The CIP is restricted to fulfilling this requirement only (it could be expanded to fulfill req.3.2.4, but this would increase the complexity).

Priority

A. We need to establish the non-linear behavior of the photometer before we determine the operating flux dynamics. Note however that this is not expected to change abruptly and thus, when in space, we will have an already precise idea of the dynamical range.

When performed / frequency

At ILT and subsequent phases, for all instrument models that have detectors. This needs to be done again in space, possibly more than once as a health monitoring activity.

Required accuracy

Driven by the global photometric accuracy we wish to achieve.

Inputs, prerequisites

The detector non-linearity curve as established at the module level tests, for information, as it is not really required to design the test.

Sources

- **On the ground:** A set of external source settings so as to produce a series of fluxes covering a representative dynamical range (generally small), as well as a series of background levels covering a very wide dynamical range.

- **In Orbit:** Here we only have access to a single value of the background per filter, i.e. that give by the telescope. We then need a series of celestial calibrators with fluxes extending well into the known non-linear regime of the bolometers.

The following sources spanning a grid of fluxes from 2 Jy to 1000 Jy are proposed:

flux (Jy)	blue band	green band	red band
2	HD 89758, γ Eri	ε Car	31 Euphrosyne
10	7 Iris, 94 Aurora	88 Thisbe	Mrk 231
50	511 Davida, AFGL 811	4 Vesta, HD 161796	2 Pallas, V1300 Aql
200	2 Pallas, V1300 Aql	NGC 7027, α Ori	AFGL 618
500	AFGL 2343	Neptune	Neptune
1000	Uranus	Uranus	Uranus

Calibration Implementation Procedure (CIP)

if the “direct” and “DDCS” mode are still competing for the position of “official” readout mode, the measurement needs to be repeated in both modes.

- On the ground: The power sources are the external black-bodies (i.e. not those inside the instrument), and we assume that there is a way to make a number (> 5) of small ($dP/P < $ TBD) power steps around a nominal power.

Elemental procedure (this is the core of the test).

procedure `make_small_power_steps`

- select mean level of input power (P_b, such as in background) and set the power source accordingly.
- set the blind pixels heater so that it cancels this input power (i.e. readout voltage is 0).
- for a series of small (TBD) power increments $j.dP$, obtain a series of readouts on the detector (j is an integer varying betwen $-N$ and $+N$, including 0 to obtain a readout corresponding to the optimal setting of the blind pixels). We call the measured voltage $V(P_b, j.dP)$.
- **optional step**: for a series of large (TBD) increments $k.\Delta P$, obtain a series of readouts on the detector (k is again an integer varying between $-M$ and $+M$, and we have $DP >> dP$ and $N >> M$). We call the measured voltage $V(P_b, k.\Delta P)$.

end of procedure `make_small_power_steps`

For non-linearity, linearity and responsivity calibrations, the principle is to repeat `make_small_power_steps` while using different the values of the background power around the nominal background power. The idea of the optional step is to make sure that the linearization curve is unique and does not depend on the actual value of the background. This optional step does not need to be performed when only the linearity or responsivity calibrations are to be derived.

- In Orbit: For each filter (red-band measurements are done simultaneously with either the blue or green band), we will perform point-source AORs on each celestial calibrators in the list. The advantage of using the point-source AOR is that it includes a calibration block that can be used to monitor intrinsic gain drifts that could mask the trend we are looking for.

It is more than likely that to fit both the sky background and the sources on the dynamical range of BOLC, we will have to make the measurement in low gain.

Estimated time needed

0.1 h per measurement, i.e. 1.7 h in total.

Calibration Analysis Procedure (CAP)

- On the ground: For each measurement $V(P_b, j.dP)$ or $V(P_b, k.\Delta P)$, we use the average readout over a predefined region of the array (the same as is used to normalize the Flat-Field).

With the $V(P_b, j.dP)$ readouts, we can compute a responsivity R in two ways: either as $R = V(P_b, j.dP)/j.dP$ which assumes that indeed the readout when $j = 0$ is 0, or as: $R = [V(P_b, j.dP) - V(P_b, 0)]/j.dP$ where we use the actual measurement obtained when the input power is the reference power. This may be better if there is a large scatter in the offset measured on the seeing pixels (there is a ratio of 8 seeing pixels to 1 blind pixel, so the offset compensation offered by the blind pixel may not be perfect). Thus, we fulfill the requirement to measure the responsivity.

By identifying on which part of the interval explored by j we obtain the same value of R (within the measurement uncertainties) we establish the intervals around the different values of P_b where the linear approximation is valid.

For each of these intervals we thus have a responsivity R, per values of P_b.

By plotting the different values of R as a function of P_b, we calibrate the non-linearity of the system. We can then use the $V(P_b, k.\Delta P)$ measurements to check that the responsivity values we obtain for incident powers far from the background power are indeed compatible with the curve $R = f(P_b)$ we have just obtained.

-In Orbit: This is rather straightforward, and can in fact be done by the pipeline. For each observation, we perform photometry of the calibrator keeping raw units (using a consistent method for all sources) as well as derive the possible variation of the gain from the calibration block.

The point source measurements, corrected by the trend observed on the internal calibration source if present, provide us with a (flux, responsivity) curve on which we can quantify the non linearity.

Output, products

For each pixel (in the ground-based case), or for each array (in space) a relative linearisation curve. These curves are normalized to give 1 for the range of fluxes we will have selected as the operating range.

Status/version

```
$Revision: 1.8 $
$Date: 2008/08/07 17:58:27 $
```

Req. 3.2.4 Establish the linearity of the full system

Objectives

Although the detector is globally non-linear, for small flux changes around a mean value, it can be considered as linear. In principle we will work under this linearity assumption. We will therefore verify that for the expected range of observed fluxes, the detector indeed behaves linearily.

Fulfilling or fulfilled by

This is the full system version of
req. 1.1.14 “Establish the detector linearity”.
At ILT and subsequent phases, the two requirements are not distinguishable from each other. In fact, req. 3.2.4 fulfills req. 1.1.14 and vice-versa.

On the ground, this requirement can be fulfilled by the CIP and CAP of req. 3.2.3 “Calibrate the photometer’s non-linearity”. In Orbit this could also be the case although it is more simple (schedule-wise) to keep it separate. The rest of the description in this requirement refers to the in-orbit version.

Priority

A. Basic element in the definition of operating modes

When performed / frequency

ILT and subsequent phases.

Required accuracy

Driven by the required photometric accuracy, so typically better than 5%.

Inputs, prerequisites

- Definition of the operating background level.
- Results from the detector non-linearity measurements so as to define more precisely the list of sources we need to sample here.

Sources

Celestial calibration sources with fluxes sampling the interval defined as the operational one, over a background corresponding to the operational one.

The following sources spanning a grid of fluxes from 20 mJy to 200 Jy are proposed:

flux (Jy)	blue band	green band	red band
0.02	HD 15008	HD 159330	HD 138265
0.1	HD 138265	β Hyi	α Per
0.5	α Per	HD 32887	β UMi
2	HD 89758, γ Eri	ε Car	31 Euphrosyne
10	7 Iris, 94 Aurora	88 Thisbe	Mrk 231
50	511 Davida, AFGL 811	4 Vesta, HD 161796	2 Pallas, V1300 Aql
200	2 Pallas, V1300 Aql	NGC 7027, α Ori	AFGL 618

Calibration Implementation Procedure (CIP)

Perform a series of point-source AORs on each source in the list, for each filter (the red-band measurements are done simultaneously). The advantage of the point source AOR is that it contains a calibration block (using the internal calibration sources) from which we can extract the intrinsic gain drifts if there are any.

To avoid adding uncertainties to the measurement, all the sources should be measured within the same cooler cycle and preferably one after the other.

Estimated time needed

5.7 h. For the lowest fluxes the integration times are determined such that a S/N = 30 is achieved as a minimum. For the higher fluxes S/N $>$ 30 is obtained for measurement times of $\approx$0.1 h.

Calibration Analysis Procedure (CAP)

Extract possible gain drifts from the calibration block measurement. The perform point source photometry on all sources (there is no need to convert the signal from V to Jy). The plot of V (measured) versus Jy (predicted flux) should be well fitted by a straight line whose slope is the responsivity.

Output, products

Certification that the detector is linear within the operating range.

Status/version

```
$Revision: 1.4 $
$Date: 2008/08/07 18:00:54 $
```

Req. 3.2.5 Relative system response and colour corrections

Objectives

The relative system response is essential to correctly tie our calibration sources to the flux of the observation target which will generally have a very different spectral shape. Unfortunately the relative system response is difficult to measure so this will mostly consist of checking on sources with well-known SED that the relative system response we build from the module level test is correct.

Note that during ground-based test, a low resolution full system relative response measurement will be possible.

Fulfilling or fulfilled by

Self-standing

Priority

B. To a first approximation we can assume that the relative system response can be build correctly from its individually measured components, and check that at low resolution during the ground-based tests.

When performed / frequency

ILT and subsequent phases.

Required accuracy

Driven by the requested photometric accuracy.

Inputs, prerequisites

Individual relative responses from all sub-components (filters, bolometers, etc).

Sources

Sources with well-known spectral energy distributions.

Calibration Implementation Procedure (CIP)

We will use the tuneable laser facility (TUFIR, not available for the CQM tests). In the OGSE set-up, when we want to have all pixels illuminated by the laser, we have to go through an integrating sphere. Accounting for radiation coming from the entrance window, as well as from the room background, computation show that the laser flux to background radiation is probably much smaller than 1. Furthermore the background is not calibrated and its spectral shape is unknown. We thus need to make measurements by pairs: one with the laser on and one with the laser of. We will set the laser to its maximum power to get the highest contrast.

From the description of TUFIR (found in **PACS Cryo Test Equipment and OGSE specification - PACS-ME-DS-002**) we find that there is a calibrated reference detector to which the laser beam can be sent. We will use this detector to measure the laser power at each step.

For each band of the PACS photometer

For a set of wavelength adequately covering the band

set the tuneable laser wavelength to this wavelength
set the laser power to its maximum value
measure the laser power with the reference detector
observe this source through the integrating sphere till we have a signal-to-noise ratio of 10.
switch the laser off or turn it away from the entrance window without closing the window (so that we have the same background level

observe this background for the same amount of time

end of loop on wavelength

end of loop on photometer bands

Estimated time needed

Calibration Analysis Procedure (CAP)

The response function is automatically created by the ratio of the measured flux to the incoming flux. By comparing with the detector relative response function we will evidence the modification brought by the optical chain. Color-correction terms can then be computed on demand according to the input spectrum.

Output, products

Tables with the relative full system response for all bands.

Status/version

Draft version. CIP and CAP filled for version 6 of the PCD.

Req. 3.2.6 Noise and minimum detectable flux

Objectives

Derive the Noise Equivalent Power for the full system photometer. Compare with the bolometer detector NEP and understands the difference. One may wish to use alternate readout mode for the detector to avoid differentiating on board as in some cases this may help disentangling different sources of noise.

In order to derive the minimum detectable flux, noise measurement will probably have to be performed using all the available observing strategies available to PACS.

Please also see the discussion on NEP in chapters 1.1.12 and 4.3.6.

Fulfilling or fulfilled by

This is the full system version of requirement 1.1.12 “Measure the bolometers NEP”. At ILT and subsequent phases, the two requirements can no longer be distinguished from one another and in fact req. 3.2.6 fulfills req. 1.1.12.

Furthermore, as requirement 1.1.12 has been absorbed in requirements 1.1.0 to 1.1.1bis, this requirement is fulfilled once this suit of requirements is fulfilled at full system level.

Priority

A. Defines what is achievable with PACS and how to reach a given flux limit.

When performed / frequency

ILT and subsequent phases.

Required accuracy

Driven by the global photometric accuracy we are aiming at.

Inputs, prerequisites

The bolometer NEP to be able to notice any strong departure from it.

Sources

A constant illumination source to minimize all possible sources of variation. The internal sources should be adequate given their very strong temperature stability specifications.

Calibration Implementation Procedure (CIP)

There is a high probability that the minimum detectable flux depends highly on the observing strategy so one will have to repeat the noise measurement using all strategies available to PACS. Given that the observing strategies are still being designed, no further update is available on the minimum detectable flux.

The NEP, on the other hand, can be derived from simple chopped measurements. Chapters 1.1.12 and 4.3.6 discuss how one determine the NEP. The reader is referred to those sections for more details. In summary, a chopped signal where the chopped amplitude is also known in power (Watts) is all that is needed to estimate the NEP.

Estimated time needed

see 1.1.12

Calibration Analysis Procedure (CAP)

see Chapter 1.1.12 and also Chapter 4.3.6 for general discussion on how to analyze chopped results for NEP estimates.

The results from CQM test data analysis are summarized by K. Okumura in ”Draft CQM ILT report for the bolometer” (available from PACS central file). Following CQM data analysis no critical changes are needed in the currently devised scheme for measuring the full system NEP.

Output, products

NEP and minimum detectable flux as a function of the observing strategy.

Status/version

Revised for the PV phase preparation version of the PCD.

Req. 3.2.7 Pseudo-noise, photometer

Objectives

To determine and characterize the pseudo-noise, due for instance to timing jitter of the readout process, timing jitter between the chopper motion and the readout, settling time for the chopper at each of its positions, digitization noise, the effect of data compression.

Fulfilling or fulfilled by

Self-standing mostly although some pseudo-noise sources can be investigated using other calibration measurements (for instance the undifferentiated, uncompressed data stream that we extract to investigate offset drifts can be used to study the effect of data compression).

Priority

B. Expected to be small contribution due to the very small time constants of the bolometer.

When performed / frequency

ILT and subsequent phases.

Required accuracy

The pseudo-noise is required to be at a level of less than 20% of the system noise.

Inputs, prerequisites

None.

Sources

A well calibrated constant source so as to minimize all possible sources of signal variation and noise.

Calibration Implementation Procedure (CIP)

TBD.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Level of the pseudo-noise contribution as a function of the observing strategy. Possibly limitations on the use of some observing modes.

Status/version

Draft version, added after the December 01 meeting.

Req. 3.2.8 Measure the photometer full system flat-field

Objectives

Note: The flat-field measurement now has a dedicated thread in the PACS calibration and pipeline working group. This supersedes the present requirement which is kept there for consistency reasons.

Each pixel will have different gain from its neighbor (detector flat-field), and transmission of the system may not be spatially homogenous (optical flat-field). This needs to be calibrated to obtain accurate photometry. Distinguishing between the detector and optical component is generally impossible, unless the detector component has been measured before independantly, and is relatively constant. Note that the detector comes with a gain specification of an 8% *rms* fluctuation over a whole 16×16 matrix.

One will also need to monitor changes in the flat-field, as we cannot exclude that it changes with time.

There are two ways of deriving the flat field which have different sources of error. The confrontation of the both results is usefull.

- Assuming that the small power change induces an increase or decrease by a constant ratio of the illumination on all the array, the flat field is proportional to the difference of 2 images $V(P_b, j\ \mathrm{d}P)$ and $V(P_b, j'\ \mathrm{d}P)$ (see req. 3.2.3). All independent pairs of measurement can provide a flat field image. After normalization by the central area of the detector, they are averaged together to form the flat field correction. A pair of images should be taken within a same calibration source of different temperature to avoid the possible difference of the illumination pattern between two calibraion souces. Nevertheless, this method is sensitive to the possible difference of the illumination pattern between 2 different temperatures of a same calibration source.
- Compute the responsivity for each pixels without averaging over the central area used for the flat field normalization. This provides a responsivity map. Then the normalized map gives a flat field and the normalization factor represents the responsivity. This method is sesnsitive to the error on the input flux estimate.

Fulfilling or fulfilled by

This is fullfilled by the photometric calibration on internal sources in req. 3.2.1, req. 3.2.3 and req. 3.2.4.

Priority

A. Essential for map reconstruction.

When performed / frequency

ILT and subsequent phases.

Required accuracy

Better than a few percent. Impacts on the achieved photometric accuracy.

Inputs, prerequisites

An a priory knowledge of the flat-field may be helpful depending on the adopted measurement strategy.

Sources

Depends on the adopted measurement strategy, but most likely the internal calibration sources.

Calibration Implementation Procedure (CIP)

A first method was to observe one of the internal reference sources and change its flux level. This will not work as we will not want to change the temperature of the internal source. A second method is to find a reasonably flat region of sky but at the PACS wavelengths, this is unlikely to happen. A third solution is to measure the flat-field in highly redundant observations. For this method a first guess of the flat-field is usefull. A fourth method exists: if we know the illumination pattern of the internal source with sufficient precision, then we can use the flux calibration to also measure the flat-field. Finally, we can use a variable temperature black-body at ILT to calibrate the illumination pattern of the internal sources and then use that to flat-field the detector. Note that distortion may have to be taken into accound in that case.

The flat field is a by-product of the responsivity measurements described in req. 3.2.3 which uses a set of sub-procedure defined by **make_small_power_steps**. The optional steps are not used for the derivation of the flat field. If the OGSE allows it, a slight scan of PACS chopper may also be used to correct for the possible irregularity of the OGSE black body sources.

Estimated time needed

Calibration Analysis Procedure (CAP)

The data are reduced in the standard way. First method:

- Compute the difference D for every pairs of different temperatures of the same calibration source $D(j, j') = V(P_b, j\ \mathrm{d}P) - V(P_b, j'\ \mathrm{d}P)$.
- Normalize these differences $F(j, j') = D(j, j')/M(D(j, j'))$, where $M(D(j, j'))$ is the median value of the central part of the detector array.
- Compute an avearged flat field $F = (\sum F(j, j'))/N$, where N is the number of pairs
- Do the same for the other calibration source
- Check the consistency and if positive, make the average of these 2 results to improve

Second method:

- Derive the responsivity map following the CAP of req. 3.2.3, but without averaging over the central area of the detector
- Compute the normalization factor as the median value of the central area of the detector. This gives a set of responsivity values.
- Normalize the responsivity map which provide a flat field

Output, products

Images of the flat-field.

Status/version

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$Revision: 1.4 $
$Date: 2008/02/05 14:36:35 $
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Req. 3.2.9 Telescope background and its stability

Objectives

The emission from the telescope will be the major flux source in all PACS observation, driving quite a number of choices in the instrumental set-up or observing strategy. As far as possible we need to characterize the amplitude of temperature gradients and structures that can be seen in the PACS field of view as well as the temporal stability of these patterns. The result of these investigation may lead to simplification of observing modes.

There could be some problem distinguishing telescope signal from stray-light so this is why the CIP is quite complex.

Fulfilling or fulfilled by

Self-standing

Priority

A. Needed to validate/modify our observing strategies.

When performed / frequency

In-flight as only there will we have a reasonable “model” of the telescope.

Required accuracy

Driven by the required photometric accuracy.

Inputs, prerequisites

None.

Sources

The telescope.

Calibration Implementation Procedure (CIP)

There can be many different ways to perform this, here we list two possibilities:

chopped measurements: Explore a not too complex region of the sky with all possible chopping throws. Repeat that observation with a slightly offset pointing. Features that move on the resulting maps should be in the sky while residual gradients and structures that appear identical on all maps are in the telescope background.

To distinguish between telescope background and stray-light, one may want to repeat the measurement with a bright source in the field.

Repeat regularly if the telescope temperature is changing (telescope temperature is provided in the housekeeping data).

Field-of-view scans: This is a well-know measurement where the chopper is used to scan the complete field of view from one internal calibration source to the next. By performing two such scans with a slight pointing offset between the two we can separate the sky structures from the telescope structures.

By performing it at different solar aspect angles, we can also check for variations of the contamination by stray-light.

It is also possible to change the settings of the internal calibration sources to investigate whether, and how, they spill on the open field of view.

Estimated time needed

Calibration Analysis Procedure (CAP)

These are rather simple observations to process. There are however two points that will require some attention. (1) We need a flat-field image, or a way to correct for the flat-field effect. Otherwise our ability to separate sky structure from telescope structure will be affected. (2) The impact that instrument drifts can have on the implementation strategy remains to be investigated.

Output, products

Prescription on the best observing strategy.

Status/version

```
Draft version, revised after the December 01 meeting.
Revised for PV preparation - 05/02/08
```

3.3 Mutual influence

Req. 3.3.1 Investigate the influence of SPIRE in the partner mode

Objectives

Though it is not decided whether there will or will not be a partner mode where both PACS and SPIRE and on, we have to prepare for this and study the possible influence of SPIRE on the PACS photometer.

Fulfilling or fulfilled by

Self-standing

Priority

C. Partner mode is not decided yet.

When performed / frequency

In flight or possibly when all three instruments are integrated on the spacecraft.

Required accuracy

Driven by the required photometric accuracy aimed at for the partner mode (probably relaxed from that aimed at for the prime mode).

Inputs, prerequisites

None

Sources

Standards (could be the internal sources)

Calibration Implementation Procedure (CIP)

Perform a typical noise measurement to check that we measure the same noise level as in prime mode.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Validation of the Partner mode.

Status/version

Draft version, added after the December 01 meeting.

Chapter 4

Full System Calibration Spectrometer

This Chapter describes the calibration requirements on the spectrometer from the point of view of a “full system” rather than the more “modular” point of view in Chapter 1.

The requirements cover tests to be done both during ILT and in-orbit.

The main topics addressed in the following sections are the spatial, spectral and photometric calibration of the spectrometer.

4.1 Spatial Calibration

The basic calibration strategy is similar to the one for the photometer. Larger and fewer pixels relax some of the constraints and accuracy requirements, but slicer diffraction effects, grating alignment, and wavelength dependence induce additional complexity. The 5*5 spatial pixels of the spectroscopic arrays may look simple but are arranged in the complex chain of slicer, spectrometer, and detector assembly. Using the naming conventions of 3.1, the 'array' coordinates are in principle defined by the slicer. The real detector arrays have to be aligned with respect to the slicer/spectrometer output, misalignments cause effects more complex than a simple rotation/shift. Measurements of central pointing position (4.1.1), FOV distortions (4.1.2) and PSF/ghosts (4.1.3/4.1.4) are sensitive to such misalignments in that chain as well as to the more global effects referred to in their names.

On-array chopping is currently not an offered spectrometer AOT option, because only 5×5 pixels are available. It is, however, considered as an AOT validation test in non-standard mode (cf. Section 5.2) and is considered also as an optional alternative measurement mode of the central pointing position assessment (cf. req. 4.1.1). On-array chopping would be performed with the source being located in "pixels" #2 and 4, hence with a chopper throw of 19". All spatial calibration aspects of on-array chopping are considered as being fulfilled by the lay-out of the calibration implementation procedures of reqs. 4.1.2 and 4.1.3.

Req. 4.1.1 Spectrometer Central Pointing Position and Grating Alignment

Objectives

Establish the relation between the spectrometer central module position and the satellite pointing for a defined chopper angle. When commanding the satellite to the position of a celestial target, the object shall be placed on the central module if the chopper is deflected to this specified angle.

In that process, also verify the relative alignment of blue and red spectrometer arrays, the grating alignment, and some aspects of internal alignment of the spectrometer arrays.

Establish the boresight between photometer and spectrometer section of PACS.

Fulfilling or fulfilled by

Self-Standing. See also 7.4.1

Priority

A

When performed / frequency

- [1] Related procedure in ILT, to verify alignment.
- [2] Early in commissioning or PV to first establish pointing for the PACS spectrometer
- [3] Regular monitoring during mission from repeat of dedicated measurements and/or analysis of normal science AORs on suitable bright sources with accurate positions.

Required accuracy

One fifth of a spectrometer pixel, i.e. 9.4”/5 = 1.9”. Unlike for the photometer, the requirement is *not* split into a more sloppy requirement on the placement of the nominal position, and a strict requirement on the accuracy of knowledge of this position. For the few and somewhat undersampling spectrometer pixels it shall be possible to put sources into a single pixel as good as possible to optimize the S/N.

Inputs, prerequisites

- The ‘defined chopper angle’ has to be known first (req. 2.3.1).
- It is assumed that in orbit the photometer central pointing position (req. 3.1.1) is established first, providing a good first estimate for the offset of the smaller spectrometer FOV, with the relative offset established during the ILT measurements as a starting point for the central position iteration.

Sources

- [1] ILT:
  Single punched hole, size ∼8 arcsec to get reasonable contrast with current OGSE setup. First source searching may use even bigger aperture if needed.
- [2] In-orbit:
  Based on ILT experience: Bright (100 Jy) (almost) point sources, very faint haloes do not matter, also a slight arcsec extent is ok, as long as it is symmetric. Taking into account that the 16 spectral pixels can be averaged, the requirement on the source brightness could be relaxed by a factor of 4.

  For the two observing strategies outlined below, and requiring S/N>20 per resolution element the following minimum requirements are derived:

- (1) 9×9 raster, chopping 12 s on each raster position ⇒ at least ∼40 Jy in the blue and 20 Jy in the red.
- (2) On-array chopping/nodding with 1 min each for each nodding position ⇒ at least ∼100 Jy in the blue.

These numbers already assume some averaging over the spectral pixels of a resolution element.

The PACS pointing calibration targets document PICC-MA-TN-003 lists 59 targets brighter than 10 Jy at 70 μm. 4 are brighter than 100 Jy, 3 are brighter than 50 Jy, 4 are brighter than 40 Jy, 3 are brighter than 30 Jy, 14 are brighter than 20 Jy and 34 are brighter than 10 Jy. For initial search also the sources from the bright isolated FIR sources (not necessarily point-like) can be used.

Calibration Implementation Procedure (CIP)

- [1] ILT:
  The low contrast for the xy-stage blackbody plus hole setup and its background properties suggest a non-chopped strategy with nodding/offseting that uses the xy-stage rather than the chopper.

  Locating the source: Set the chopper fixed to the 'optical zero' defined in req. 2.3.1. Use hot blackbody and single hole on xy-stage. For a nominal wavelength that gives signal in both blue and red, first take an observation at some off position of the xy-stage to be used as background in QLA. Then, under QLA supervision, manoeuver xy stage to bring source to central pixel.

  Various different combinations of rasters/scans with offset positions for background could then be used for refinement. In practice, the FMILT observations most relevant for this and other purposes were a small series of finely sampled (1/4 spectral pixel) staring 27×27 and 9×9 xy-stage rasters, also including different fixed chopper and grating positions.

  A similar series of small staring 5×5 rasters (1/3 pixel step) with off-position, obtained at different z positions of the xy-stage, was used as a focus sequence. Because of the large pixels and limited focus adjustment range, this does not provide a clear minimum and only serves as a consistency check with photometer results.

  Observations at/in different wavelengths/filters check the grating alignment.

  The photometer central pointing position should be obtained during the same cryocycle to minimize the effect of differential contractions of the test cryostat, and, if possible, 'in one go' to minimize misalignments of the xy-stage.

  CQM-ILT: with only part of the detector modules available, only limited staring observations with offset position were obtained.

- [2] In-orbit:
  - (1) Chopped raster: For chopper at central position, nominal source position on central module. Chop with a throw larger than the FOV in one direction, e.g. to the +medium throw (1.5') used in the AOR. Perform a 9×9 raster with 0.2 spatial pixel step, i.e. 2" around this position.
  - (2) On-array chopping: Do chopped observations symmetric to the center of FOV. Place the source nominally in the central pixel of row 2. Use a chopper throw of 2 pixels, i.e. 18.8" thus chopping between column 2 and column 4. This ensures both beams being inside the array and well separated. Integrate for 1 min, nod orthogonally to row 4 and integrate again for 1 min.
    This method has the advantage that it only minimally relies on the S/C relative pointing accuracy along a raster (for the nod). Due to the limited FOV it can only be applied, once the S/C pointing is close to the final pointing accuracy (<10").

  For both types of measurements grating remains in a fixed position for 77 μm in the blue channel and 154 μm in the red channel.

  For both types, combine with observations of the internal calibrators that can be linked to flatfield, and with a photometer point source AOR on the same source to constrain phot/spec boresight rather directly.

  Both types of procedure have pros and cons and should be prepared and tried early during the mission.

  For a few sources, several grating/filter positions should be done to verify the grating alignment.

Estimated time needed

- [1] ILT:
  The full sequence of source searching, focus sequence, and measurement is estimated to take something between 3 hours and a day.
- [2] In orbit:
  A major difference to ILT is the presence of ionizing radiation and associated glitch tails and sensitivity drifts, suggesting the use of chopping in the procedures. A fine raster plus chopping by more than a FOV would be the natural extrapolation of the ILT experience. This is meaningful, although not ideal comparing pointing errors to the spectrometer pixel size, but quite time consuming and perhaps sensitive to responsivity drifts. For this and other reasons we suggest two procedures:
  - One 'elementary' observation of type (1) with 12 s integration per raster point and 10 s slew to the next raster points lasts for:

    $(9{\times}9 \times 10\,\mathrm{s})_{slew}$+$(9{\times}9 \times 12\,\mathrm{s} \times 2)_{chop}$ = 46 min
  - One elementary observation of type (2) will need about 5 min.

  Procedure (1) should be applied on 5 different targets with different solar aspect angles: 4 h.

  If the derived average position shows a significant offset from the central module, correct satellite/instrument pointing parameters (SIAM) and repeat.

  Once the offset has been trimmed to the nominal value, the 5 measurements should be repeated and 15 measurements of procedure (2) on 5 pointings sources with 3 different grating positions should be added: 4 h $+$ 15 $\times$ 5 min = 5.3 h.

  It may be of advantage to run the req. 3.1.1 bolometer procedure on the same target in immediate succession to help separating the photometer/spectrometer offset from other effects.

Calibration Analysis Procedure (CAP)

- [1] ILT:
  After manoeuvering (with QLA help) the hole to being properly centered at the nominal wavelength (77/154 μm), measure and compare peaks/centroids of the maps for the 16 spectral pixels, for other spectrometer channel and for a set of wavelengths to verify alignment.

  Determine boresight wrt. photometer channel by comparison to results of req. 3.1.1, obtained during the same cryocycle and, if possible, xy-stage mounting period.
- [2] In orbit:
  - (1) Subtract chopped data, average spectrally if needed for achievement of S/N. For each module individually derive a 9×9 map and determine in which module the maximum is located: If source is already reasonably well centered on central source , derive the small correction based on the map for this pixel. If not, identify the pixel that is best peaked and derive the larger correction w.r.t. the central module.
  - (2) Subtract double differential chopped/position switched data and measure centroid of positive and negative beam (note undersampling, this might mean fitting a simple model!). For the two nod positions, derive a centre of symmetry that is consistent with all data at this wavelength.

  At the nominal wavelength where most measurements are done: If after repeated measurements on different sources the average position differs from the central module, update satellite/instrument attitude control parameters (SIAM) so that future observation will be properly centered.

  Compare centroids for red vs. blue array and for various grating settings to quantify possible grating etc. misalignments.

  Check for trends within the 16 spectral pixels that might indicate misalignment of the spectrometer array.

Output, products

- Spectrometer pointing offset relative to telescope boresight.
- Information or limits on misalignment.

Status/version

PV preparation

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$Revision: 1.10 $
$Date: 2008/06/20 19:15:32 $
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Req. 4.1.2 Spectrometer Field of View Distortion

Objectives

Determine the optical distortions introduced by the spectrometer slicer, PACS instrument optics and the telescope optics. The optical distortions depend on position on the array as well as chopper position, i.e. the chopper introduces more than a trivial translation.

It is expected that diffraction inside the slicer modulates the relation between input position and measured centroid on a pixel scale, and creates a wavelength dependent astigmatism, both at measurable levels.

The transformation from array to telescope coordinates is hence a function of two spatial dimensions, chopper position, and possibly wavelength.

Fulfilling or fulfilled by

Complementary to req. 4.1.3, spectrometer PSF

Priority

A

When performed / frequency

- [1] During ILT. CQM ILT had only partial spectrometer arrays, thus limiting the range of meaningful settings. More extensive measurements were done during FM ILT.
- [2] At a late stage of PV or later. One should not do this too early since satellite a posteriori pointing information is used.

Required accuracy

1/4 of a spectrometer pixel. With a pixel size of 9.4", i.e. steps as fine as 2.5" are required.

Inputs, prerequisites

Optical modelling giving an indication of magnitude and shape of effects. Preliminary modelling suggests that diffraction effects in the slicer induce both a wavelength dependence of distortion and (in one spatial direction) a modulation of the relation between input position and measured centroid. (N.B.: This effect has not yet been found in the FM-ILT data).

Sources

- [1] ILT:
  Single punched hole in front of blackbody on xy-stage. Diffraction effects in slicer should not be smeared out by a too large source. Try hole sizes as in PSF measurement (req. 4.1.3). Small aperture like 2 arcsec would be desirable in order to be close to a true point source, but the limited OGSE contrast suggests large apertures of at least 5 – 8 arcsec.
- [2] In orbit:
  Very bright point source, $\sim$1000 Jy for instantaneous good S/N at the peak in each pixel (including the spectral pixels). Choosing an as bright as possible point source will save time by serving FOV distortion and PSF characterization at once. In FM-ILT the desired goals were reached by means of a 27×27 raster at fixed grating position, 0.25 spatial pixel step ($\approx$ 2.5"), 12 seconds of dwell time per raster position, with a source flux estimated to be 100 Jy at 77 and 42 Jy at 154 μm, respectively. Under these conditions a S/N equal to 100 and 12 per resolution element at the peak in the blue and red, respectively, was achieved which was sufficient to determine FOV distortion and PSF characteristics for every spectral pixel.

Taking into account that in orbit one has to chop, in order to achieve the same results as in FM-ILT3 in a reasonable amount of time, a source brighter than what was used in FMILT has to be selected.

The prime targets which are practically point-like and have fluxes of several hundred Jy, are Neptune (2.0 –2.2 arcsec size) and Uranus (3.1 – 3.7 arcsec size).

As backup targets, also in case of visibility restrictions, not strictly point-like but very bright (several hundred Jy) IR sources can be selected for FOV distortion measurements. These are:
CRL 2688 (24 μm MIPS point source), IRAS 21078+5211, IRAS 22134+5834, IRAS 09452+1330 (IRC+10 216, IRAC point source) and NML Cyg (ISO-SWS calibrator). For application of these targets as PACS spectrometer calibrators it is highly desirable to obtain images of the most suitable candidates w.r.t. visibility and compactness with the PACS photometer camera before.

With a source of several hundred Jy brightness a chopped raster with 4 s on-source dwell time at each raster position will provide sufficient S/N.

An equally good S/N can be achieved with a slow speed (3”/s) scan map. In case of chopping, this means 9.4/3 = $\sim$1.5 s on-source integration time per pixel. With 4 scan repetitions, hence a total of 6 s on-source integration time is achieved.

Calibration Implementation Procedure (CIP)

- [1] ILT:
  Given the background properties of the OGSE, the most successful tests for this and other purposes used non-chopped xy-stage rasters large enough so that the source/PSF was seen and covered by each spatial pixel, with a step size of about 1/4 pixel (0.425 mm, corresponding to 0.425/1.7 $\times$ 9.4” = 2.35”). In FM-ILT, such 27$\times$27 rasters were done for three different chopper positions: Optical zero and the two extreme values for ‘large’ chop throw. Off positions were included for background subtraction but they turned out to be not usable for this purpose due to strong signal drifts in such long measurements. Analogous big rasters covering more chopper positions and wavelengths could not be executed in the available time. Smaller rasters centered on module 12 were executed at different wavelengths distributed over all bands with the chopper at optical zero position. From these measurements it was verified that there is no significant dependence of the distortion on wavelengths.

- [2] In Orbit:
  One fundamental difference from FMILT is that, given the presence of ionizing radiation associated glitch tails and sensitivity drifts, the use of chopping appears to be mandatory.

  The strategies outlined below, have chopper and grating positions as parameters:
  They should be repeated for at least 5 of the scientific chopper positions (optimum is all 7): -2.5’, -1.5’, -0.5’, 0, 0.5’, 1.5’, 2.5’ ($\pm$2.5’ instead of $\pm$3’ is selected, becuase a chopper throw of -1.5’ would lead to vignetting in case of the -3’ deflection.
  A wavelength in filter B which is on a sensitive part of the RSRF should be selected. 77 μm (order 2) were chosen in FM-ILT meaning 154 μm in order 1. The dependence of the distortion on wavelength is expected to be negligible according to the FM-ILT results. Therefore, it can be probed by smaller rasters with the source placed in the central module. Pointing and/or PSF measurements therefore verify this dependence.

  – (1) Chopped raster:
    Chop with such a throw to avoid subtracting the wings of the PSF. At 80 μm (diffraction limited), the 3^{rd} Airy ring diameter is equal to 36 arcsec. Therefore, a medium chopper throw of 1.5 arcmin is selected which is a throw used for science operation. Chopping shall be performed perpendicular to the raster leg. The raster step size should be equal to 2.5” with the source centered on the raster for the positive beam. An on-source dwell time of $\sim$4 s should be sufficient, for the assumed brightness of the calibrators. The total raster should be 27$\times$27 yielding a total size of 64 arcsec^2.
  – (2) Chopped scan map:
    This mode is somewhat more time efficient (spectroscopic scan maps are not yet implemented as scientific observation templates). Chop with frequency of 1 Hz and a medium throw of 1.5’, i.e. larger than the spectrometer FOV (0.78’). Chop perpendicular to the scan direction. The total area covered by this scan map

should be a bit larger than for the 27×27 chopped/raster map above, because of lower S/N at the edges of the final maps. Use a slow scan speed of 3"/sec so that the smearing within a single chopper on-off cycle is negligible. Repeat scan maps 4 times for the achievement of a sufficient S/N. 2 maps should have an orthogonal orientation. Before and after the scan map, point to a clean off-position while chopping. A leg length equal to 1.5 arcmin, and 31 legs spaced by 3 arcsec, centering the source in the positive beam, would give a final map of 1.5×1.5 arcsec^2.
Considering normal detector settings (64 readouts per ramps, i.e. a reset interval length of 0.25 s, there will be 2 on-source and 2 off-source ramps during 1 chopper cycle. There will be 1.5 chopper cycles per pixel transition time with the scan speed of 3"/s.
An observation with this second method also serves as a reference for the larger scan maps proposed under reqs. 4.1.4 (Spectrometer Ghosts) and 4.1.5 (Spectrometer Straylight).

Estimated time needed

- [1] FM-ILT:
  The 27×27 rasters were done with 12 s dwell time per raster point, providing satisfactory contrast for a 1.5mm hole. The total time per such raster is about 3 hours. Shorter 'cross scan' versions are conceivable but will provide much less complete information and difficult analysis, also considering the complex slicer misalignments.
- [2] In orbit:

  - Required time for the 27×27 raster on a ∼1000 Jy source:
    $(27\times27\times2\times4\,\mathrm{s})_{chop} + (27\times27\times10\,\mathrm{s})_{slew}$ = 13 122 s = 3.7 h
    For all 7 specified chopper deflections and 1 grating position, this gives a total time of 25.9 h.
  - Required time for a scan map on a ∼1000 Jy source:
    1.5×1.5 arcmin^2, i.e. 90 arcsec leg length, with 3 arcsec distance among the legs, i.e. 31 legs and 3 arcsec/s scan speed:
    $(90/3\,\mathrm{s} \times 31)_{chop} + (31 \times 20\,\mathrm{s})_{slew}$ = 1550 s = 0.43 h
    This time has to be multiplied by 4 scan repetitions in order to achieve the required S/N, yielding a total duration of 1.72 h.
    For the 5 mandatory chopper deflections required here and 1 grating position, this gives a total time of 8.6 h.

The mapped area with such depth can already provide feedback on the nature of the ghosts detected in FM-ILT data in the BLUE at a 1% level as further followed up under req. 4.1.4, if the source is close to point-like.

Calibration Analysis Procedure (CAP)

- [1] In FMILT:
  The aim of this data reduction is to produce a PSF-map for each pixel. Data have to be first averaged for each xy-stage position. Then the background is determined for each pixel by fitting a polynomial to the signal history of the pixel excluding the range of time where the pixel sees the source. Then a 27×27 raster is built for each spatial and spectral pixel. Gauss2D fitting is performed on these rasters to get the xy-stage position of the PSF peaks. This produces xy-stage coordinates of each Ge:Ga pixel at each chopper position. The following 2 calibration files are derived:

  1) For a chopper deflection equal to the optical zero, the coordinates of each module w.r.t. module 12 in xy-stage positions and /or in arcsec (in the 5×5 representation).
  2) Polynomial fits in both XY stage coordinates for all chopper deflections. The outcome of these fits, i.e. the order of the polynomial in x and y and the coefficients, allows to derive the xy-stage (or sky) positions for any module and for any chopper deflection.

- [2] In Orbit:

1) Raster/chopped maps
   The data reduction will be very similar to what was done in FM-ILT, since the data acquisition is very similar. The best way to make use of the modulated signal to correct for glitches should be found.
2) Scan map
   Exact data reduction strategy still TBD. There are some FM-ILT data taken with the xy-stage to test first steps.

Output, products

- Calibration file between array and telescope coordinates for spectrometer.
- Alignment check
- Information on sub-pixel modulation.

Status/version

PV preparation

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$Revision: 1.8 $
$Date: 2008/06/09 16:16:14 $
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Req. 4.1.3 Spectrometer Point Spread Function

Objectives

Determine the Point Spread Function of the Spectrometer for several wavelengths spread over the PACS wavelength range. Do this for a small sub-pixel raster near the center of the FOV and for a default chop throw. Do spot checks in other parts of the FOV and for other chop throws.

Check for non-nominal PSF components that might indicate shifts or optical crosstalk suggesting misalignment of the spectrometer arrays, or electrical crosstalk.

Fulfilling or fulfilled by

Self-Standing, but in orbit partly benefiting from analysis of photometric calibrations. Part of observations are shared with 4.1.2.

Priority

B

When performed / frequency

- [1] Pre-tests in ILT. CQM-ILT has only partial spectrometer arrays, thus limiting the range of meaningful settings.
- [2] Relatively late in PV (need confidence in pointing, and a very bright point source is necessary) and /or later.

Required accuracy

S/N$>$ 100 in the peak.

Inputs, prerequisites

- Req. 4.1.1 has to be done first.
- PSF Models are needed for comparison. Models for the ILT situation are available. Full modelling for in-orbit is required.

Sources

- [1] ILT:
  External blackbody behind single hole on xy-stage. Useful hole size may be 5 – 8 arcsec given the low contrast of the current OGSE setup. Smaller aperture desirable if feasible in terms of contrast.
- [2] In orbit:
  Bright point sources without far-infrared halo. Sources have to have $\sim$1000 Jy, see source characterisation under req. 4.1.2.

  The prime targets, which are practically point-like and have fluxes of several hundred Jy, are Neptune (2.0 – 2.2 arcsec size) and Uranus (3.1 – 3.7 arcsec size). Contributions by the rings are negligible for both planets (cf. R. Moreno's calculations, total flux $<5 \times 10^{-4}$ of total planet flux)

Calibration Implementation Procedure (CIP)

- [1] ILT:
  Based on CQM-ILT experience, the low contrast for holes and the OGSE background properties suggest a non-chopped strategy with nodding to an off-position that uses the xy-stage. Hole diameter 5 – 8 arcsec or less, limited by contrast.

Procedure (1): Set chopper to 'optical zero' of req. 2.3.1. Set grating and order sorter such that both red and blue are served, and wavelengths on the high response part of the RSRF are selected. First dwell at an off-position of the xy-stage. Then do a 2-D raster covering most of the spectrometer FOV at pixel or better sampling. Revisit off-position at end. This was done in FM-ILT3 in the form of three 27×27 rasters at 1/4 pixel (0.425 mm corresponding to 2.35") sampling.

Procedure (2): Similar, but choosing a smaller area raster covering the full central pixel or a little more in smaller steps. Repeat procedure 2 for several grating/order sorter combinations, overall covering the full PACS wavelength range. Several 9×9 rasters were done in FM-ILT.

- [2] In orbit:
  - (1) Chopped 27×27 raster, 8 s dwell time per raster position, i.e. 4 s on-source. 2.5" raster step size in S/C x and y-direction with source centered on the raster for the positive beam. Chop throw 1.5 arcmin, chop perpendicular to raster leg.
    For 7 chopper deflections at 0, ±0.5', ±1.5', and ±2.5'.
    Fixed grating position at 77 / 154 μm.
    Already covered under req. 4.1.2.
  - (2) Chopped 9×9 raster, 8 s dwell time per raster position, i.e. 4 s on-source. 2.5" raster step size in S/C x and y-direction with source centered on the raster for the positive beam. Chop throw 1.5 arcmin, chop perpendicular to raster leg. Clean off-positions before and after the raster. (Mapped area equal to 22× 22 arcsec^2, essentially covering the central pixel and should be sufficient to get at least the first Airy ring in the diffraction limited case.)
    For 5 chopper deflections at 0, ±0.5', ±1.5'.
    Fixed grating positions at 55 / 110 μm and 90 / 180 μm.

For the central pixel this complements the distortion assessment with regard to wavelength (negligible according to FM-ILT results).
Off-positions are needed, because fitting a polynomial to the history of the pixels to evaluate the background and then subtract it, as done for the large 27×27 rasters, is not a successful strategy here.

Estimated time needed

- [1] ILT:
  The 27×27 raster with 12 s dwell took about 3 hours. Shorter rasters at several grating positions of order 20 minutes.
- [2] In orbit:
  - (1) Chopped 27×27 raster as calculated under req. 4.1.2: 3.7 h per chopper deflection and grating position.
  - (2) Chopped 9×9 raster:
    $(9\times9\times2\times4\,\mathrm{s})_{chop} + (9\times9\times10\,\mathrm{s})_{slew} = 1\,458\,\mathrm{s} = 0.41\,\mathrm{h}$
    For 5 chopper deflections and 2 grating position this gives a total time of 4.1 h.

Calibration Analysis Procedure (CAP)

- [1] Large raster in ILT:
  Subtract background and derive 'PRF' maps per pixel.
- [2] Rasters in orbit:
  - Subtract chopper on-off.

- Subtract (interpolated?) off positions.
- Derive 'PRF' maps per pixel.
- Extract information on PSF profiles and FHWMs as function of wavelength.
- Study effects of sub-pixel shifts on the poorly sampled PSF.
- Compare PSF parameters with theoretical ones.
- Check for weird behavior (e.g. PSF shift or PSF deformation between the 16 spectral planes) that might indicate misalignment of the spectrometer array.
- Try to get faint wings of PSF.

In addition analyse normal AORs on bright point sources.

Note that Herschel pointing accuracy may lead to considerable PSF distortions depending on how (in)dependent pointing errors for different positions are.

Output, products

PSF library and associated products (FWHM etc.)

Status/version

PV preparation

```
$Revision: 1.8 $
$Date: 2008/06/09 16:18:32 $
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Req. 4.1.4 Spectrometer Ghosts

Objectives

Test for presence of spatial ghosts (i.e. false sources or structures due to internal reflections) in spectrometer data.

A faint ghost (1%) of unclear origin was seen in spectrometer FM-ILT3 data. This should be either confirmed or rejected by in-orbit measurements.

Fulfilling or fulfilled by

Partly covered by analysis of data taken for FOV distortion (req. 4.1.2) and PSF determination (req. 4.1.3), and science data.

Priority

B

When performed / frequency

PV and later, pre-tests in ILT

Required accuracy

Detection of Ghosts at the level of 1% of the source peak. Careful reduction of ILT data detected such a ghost at the sensitivity limit of the blue data set (S/N for red channel was insufficient).

Inputs, prerequisites

Sources

- [1] ILT:
  External blackbody behind single hole on xy-stage. Useful hole size may be 5 – 8 arcsec given the low contrast of the current OGSE setup. Smaller aperture desirable if feasible in terms of contrast.
- [2] In orbit:
  Very bright point sources, as isolated as possible and with clean background. Sources have to have $\sim$1000 Jy.

  The prime targets, which are practically point-like and have fluxes of several hundred Jy, are Neptune (2.0 – 2.2 arcsec size) and Uranus (3.1 – 3.7 arcsec size). Check for their actual background environment!

Calibration Implementation Procedure (CIP)

- [1] In orbit:
  Partly (inner part around the PSF) covered by the rasters and scan maps as described under reqs. 4.1.2 (FOV distortion) and 4.1.3 (PSF). It is helpful to supplement these observations by larger areas covered by a coarser sampling scan map that reaches well beyond the FOV:
  Chopped scan map:
  Chop with frequency of 1 Hz and a large throw of 3', i.e. larger than the map FOV. Positive chopper beam on 0. Chop perpendicular to the scan direction. Use a slow scan speed of 3"/s so that the smearing within a single chopper on-off cycle is negligible. Repeat scans 4 times for achievement of a sufficient S/N. 2 maps should have an orthogonal orientation. Before and after the scan map, point to a clean off-position while chopping. A leg length equal to 3 arcmin, and 45 legs spaced by 4 arcsec, centering the source in the positive beam, would give a final map of 3×3 arcsec^2.
  The scan map should be repeated 8 times (see CIP in-orbit item 2 of req. 4.1.2 on S/N considerations for the targets considered also here).
  Fixed grating position at 77 μm (order 2) and 154 μm (order 1).

Further combinations of chopper deflections and wavelengths will be only implemented, if analysis of the available data sets suggests any dependence on chopper position or wavelength.

Estimated time needed

In orbit:

- Required time for a scan map on a ∼1000 Jy source:
  3×3 arcmin^2, i.e. 180 arcsec leg length, with 4 arcsec distance among the legs, i.e. 45 legs and 3 arcsec/s scan speed:
  $(180/3\,\mathrm{s} \times 45)_{chop} + (45 \times 20\,\mathrm{s})_{slew} = 3600\,\mathrm{s} = 1.0\,\mathrm{h}$
  This time has to be multiplied by 8 scan repetitions in order to achieve the required S/N, yielding a total duration of 8.0 h.

Calibration Analysis Procedure (CAP)

- Search for intensity features that neither stay at the same astrometric position (as real background sources would do) nor move with the point source (as PSF structures do). (The discrimination between PSF features and ghosts is somewhat fuzzy...).
- Use FM-ILT findings as guidelines; confirm or reject these findings.

Test optics (ILT) differs from in-orbit set-up. Because of the limited contrast achieved with the real OGSE hole setup, only strong ghosts are detectable.

Output, products

Limits on ghosts, or quantification under which conditions they occur.

Status/version

PV Preparation

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$Revision: 1.5 $
$Date: 2008/06/09 16:21:23 $
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Req. 4.1.5 Spectrometer Straylight

Objectives

Determine signals measured by the PACS spectrometer that are due to bright sources of radiation outside the field of view. Note that such radiation of significant strength may remain undetected in chopped observations if it is only weakly dependent on chop position. Spectral structure in the source that causes straylight may help discriminating straylight from other backgrounds.

Sources to be considered include

- Very bright compact sources (late type stars, Planets) within a few arcmin of the FOV (possibility of compact reflections?)
- Very bright sources at large angles from the FOV, with reflections off the secondary mirror support. The assumption is that these are non-specular and diffused over a larger area.

A signal that could be called ‘straylight’ is caused by chopping in the presence of telescope temperature gradients, and is being fought by nodding or position switching. Trend analysis of this signal is covered in requirement 4.3.4 (TBC). See also req. 4.3.11 for the investigation of the telescope background structure.

Fulfilling or fulfilled by

Self-standing

Priority

B.
Pre-test in ILT: C

When performed / frequency

Pre-tests in ILT, PV and later

Required accuracy

Scattered light from outside the telescope FOV should be $<1\%$ of the background radiation level induced by the self-emission of the telescope.

Inputs, prerequisites

Modelling of Herschel straylight properties to guide search

Sources

Mars, Jupiter, very bright >500 Jy late type stars. Sources should be located in a clean region of the sky (Mars and Jupiter cross the galactic plane).

ILT: External blackbody and single hole on xy-stage. Because of the limited contrast, only very strong straylight of the type considered here is detectable with the real OGSE setup.

Calibration Implementation Procedure (CIP)

- [1] ILT:
  Note that the test optics set-up is complex and different from the telescope, results have to be interpreted with caution.
  Using a staring observation and a large (at least 5 – 10 arcsec) hole in front of the external blackbody, do a finely sampled cross scan over the full x- and the full y-range, centered on the FOV, and a more coarse raster over the full

range of the xy-stage. Choose a wavelength giving simultaneous data in both channels. Because of the limitations of the OGSE set-up (low source contrast, background structures), such a measurement is considered low priority. ⇒ Such a measurement was not done in FM-ILT due to lack of time.

- [2] In orbit:
  Chopped scan maps around extremely bright source. Source should not be in the map FOV, but boarder of maps should stay away by about 1 arcmin. Chop with frequency of 1 Hz and chopper throw of 1.5 arcmin in scan direction. 15 arcmin leg, 31 legs, 30” separation. Use a slow scan speed of 3”/sec so that the smearing within a single chopper on-off cycle is negligible. Repeat maps twice to disentangle glitch effects and increase S/N (second map in orthogonal orientation). Before and after the scan map, point to a clean off-position while chopping. Do 4 maps on each side of the source.
  If e.g.. Jupiter is selected fix grating at prominent line so that instantaneous spectrum of any intensity feature could support origin by Jupiter. Since Jupiter moves with about 3’ per day the maps with suspicious “straylight” features could be repeated when Jupiter is off the area further constraining the nature of the feature.

Estimated time needed

- [1] ILT:
  About one hour
- [2] In orbit:
  - Required time for 1 scan map:
    $15{\times}15$ arcmin^2, i.e. 900 arcsec leg length, with 30 arcsec distance among the legs, i.e. 31 legs and 3 arcsec/s scan speed:
    $(900/3\,\mathrm{s} \times 31)_{chop} + (31 \times 20\,\mathrm{s})_{slew} = 9920\,\mathrm{s} = 2.8\,\mathrm{h}$
    This time has to be multiplied by 2 scan repetitions and 4 maps on each side of the source, yielding a total duration of 22.4 h.
    If the whole map comprising all 4 parts is repeated a second time with the source off this adds another 22.4 h.

Calibration Analysis Procedure (CAP)

- [1] ILT:
  - Subtract running median background for each pixel
  - Apply flatfield
  - Look for unusual signals.
- [2] In orbit:
  - Subtract chopper on-off thus defining and subtracting running background.
  - Alternatively check background subtraction making use of the signals from the clean off-position.
  - Apply flatfield.
  - Average spectral pixels, produce a map and look for unusual features that do not correspond to faint real sources.
  - If those are present, make use of the spectral information at the location of the feature and check for spectral signatures of the central straylight source.
  - Compare maps with straylight source in and out.

Output, products

Limits for straylight, or quantification of its strength and the conditions under which it occurs.

Status/version

PV Preparation

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$Revision: 1.7 $
$Date: 2008/06/09 16:26:14 $
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4.2 Spectral Calibration

This section addresses the requirements related to the spectral calibration of the spectrometer.

The requirements cover the wavelength calibration, instrumental profile, spectral purity and spectral ghosts.

In all cases a full characterisation is essential during ILT tests, with only refinements and verification of the calibration forseen in the mission.

Req. 4.2.1 Grating Wavelength calibration

Objectives

Determine the relation between the grating angle and the central wavelength of the grating response. This has to be done for each different pixel as the central wavelength is shifted as function of pixel in a module and module specific second order distortions and residual misalignments. The amplitude of the shift is related to the grating angle.

Fulfilling or fulfilled by

Fulfilling 2.2.1 & 4.2.2

Priority

A, fundamental

When performed / frequency

a) ILT

b) PV Phase

c) Routine Phase to monitor possible shifts. For the monitoring only the central pixel has to be observed and only a few lines have to be measured.

Required accuracy

Peak position to within 10-20% of a spectral resolution element.

Inputs, prerequisites

For the water vapour cell wavelength calibration during ILTs a line list is needed with central wavelengths. The online HITRAN database (http://cfa-www.harvard.edu/HITRAN/) can be used to list molecular transitions (including the 4 most abundant water isotopes) and tools like WEBGEN can be used to simulate a certain vapour cell configuration filled with a gas mix. Lists of all other relevant molecular calibration lines are also contained in HITRAN. Relevant atomic fine structure line lists are available at www.mpe.mpg.de/ir/ISO/linelists/FSlines.html.

Sources

- During ILTs:
  The reference calibration source is a water vapour absorption cell in front of a hot plate. As an alternative medium CO gas can be used. The nominal working conditions and parameters of the water cell are specified in document PACS-ME-DS-002.
  Emission lines can be produced by the CO-pumped methanol laser for certain wavelengths.

- In orbit:
  Sources with well identified emission lines which are not blended. These are
  - PNe (see ISO-95-015, PNe to be used as ISO-SWS Astronomical Calibration Sources);
  - HII regions;
  - late type stars with water lines (see PICC-ME-TN-013 for late type stars).

  An extended source with strong, well-known emission lines would be useful to study efficiently (otherwise a compact source has to be rastered) the shift of the central wavelength as function of pixel.
  Sources with water emission lines and well known rich spectral structures are the four giant planets. The most favourable source for this calibration would be Jupiter, filling the entire spectrometer field-of-view at once. Although it will require non-standard CRE reset and capacitor settings this target has high priority, just because it would save a factor 25 in observing time, compared to point sources.

Calibration Implementation Procedure (CIP)

- During ILTs:
  Perform a full grating scan (CUS mode Wave_Cal) to measure the water vapour absorption cell absorption line spectrum (external calibration source aligned with the PACS cryostat). The wavelength calibration is based on the study of line center position as a function of grating angle. Line centers are identified on pixels of the detector frequency domain. The extended radiation of the absorption vapour cell is assumed to be homogeneous and isotropic at the exit pupil of the cell providing a homogeneous illumination of the detector pixels in the spatial domain. The most appropriate reference source setup (hot-plate temperature, pressure of vapour, absorption path length, stabilization times length, . . . etc.) is determined during the short spectral calibration done in FM ILT1.
  Concerning the detectors, the whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to an other capacitor has to be done. An optimization of reset interval and/or integration capacitor shall be considered when switching between grating orders.
  The measurement sequence is done in range spectroscopy mode (2 $\times$ 3 scans, change of diffraction order in between). A full wavelength range scan shall be performed where the typical grating step size may be of the order of $20''$ to obtain a sampling on each pixel of around 1/5 FWHM. Using the WEBGEN [1] water absorption spectrum simulator one can obtain that the typical FWHM for a strong isolated line is $\leq 0.05\,\mu$m. Assuming a resolving power of 2000 @ 100 μm, the whole profile is covering $\sim 1 - 8$ spectral pixels instantaneously. With sampling of 1/5 FWHM the line profile is represented by $\sim$ 5-30 data points (@ $3\,\sigma$ assuming a Gaussian profile, $\Gamma = 2.35\,\sigma$) when scanning the line over the detector pixel. This resolution provides a statistical uncertainty in the determination of the line center of 0.001 - 0.06 μm (from 60 to 200 μm). In order to discriminate between spectral features and characteristics of detectors, filters, windows and the vapour cell itself, two separate grating sequences are required: one with vapour and one without. The ratio of filled/empty cell measurements can provide a rough transmittance baseline.
  For a characterization of the instrumental profile both up and down grating sequences are required.
  The wavelength calibration is also checked for a dependence on the chopper throw.

  The methanol Laser can be used for checking and refining the wavelength calibration, if necessary. The following table summarizes the FIR methanol laser wavelengths available for PACS spectral testing. During the FM-ILT wavelength calibration all spectral lines presented in the table below will be used. Laser lines available off the nominal order cannot be considered for this measurement and are not indicated here.

Wavelength (μm)	Expected output power	Remarks
70.511638	mW	CH_3OH
77.405660	μW	CH_3OH
96.522408	μW	CH_3OH
110.43240	mW	$^{13}CH_3OH$
115.82324	mW	$^{13}CH_3OH$
118.834107	mW	CH_3OH
134.6±0.1	μW	$CH_3^{18}OH$
162.647	μW	$CH_3^{18}OH$
163.03352	mW	CH_3OH
170.576394	mW	CH_3OH
203.63577	mW	$^{13}CH_3OH$
219.801	mW	$CH_3^{18}OH$

  The measurement sequence is done in line spectroscopy mode at least with Nyquist sampling per resolution element. If the laser wavelength tuning takes longer time than the order-switching procedure of the PACS spectrometer, then measurements in a single grating order should be executed in a common block. The grating up and down scans

[1] http://nitrogen3.atmosp.physics.utoronto.ca/webgen_lab_in.html

have to be repeated to reach a signal-to-noise ratio of at least ∼10.
In order to assess the background noise rms, a series of background measurements must be performed at the beginning and at the end of the test sequence. During these background sequences the experimental set-up is the same, but the laser is switched off. In this configuration PACS can measure all components contributing to the background.
Other test conditions and set-up should be nominal. The laser radiation is expected to be point-like at the exit pupil of the half-transmitting laser mirror. During the test sequences the illuminating flux should be chosen as maximum as possible, but detector saturation should be avoided.
The whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to another capacitor has to be done. An optimization of the reset interval and/or integration capacitor set-up shall be considered when switching between grating orders.

- In orbit:
  In-flight the same CUS modules may be used as during FM ILT, however they need to be converted in order to contain a dedicated pointing request.
  Fainter sources will be measured in chopped/nodded mode while the very bright targets will be observed unchopped to avoid transient effects. Point-like sources will require multiple chopped/nodded observations positioned on the different spatial pixels.
  Initially the calibration obtained on ground will be checked with short observations in flight and after settling the observing strategy the long grating scans will be done on the targets from the wavelength calibration target list.
  The foreseen CUS observing modes are called PacsCal_WaveCalChop and PacsCal_WaveCalNoChop. They will be parameterized from within XHSPOT for each required observation separately. Nominal PACS AORs will not be suited for this kind of measurements, since the spectral sampling per pixel is not sufficient. AORs may however be used later in routine phase for regular weekly/monthly wavelength calibration checks.

Estimated time needed

$\geq$ 7200 sec

Calibration Analysis Procedure (CAP)

- During ILTs:
  The calibration analysis can be made offline. An input data set is required where each pixel signal is provided with grating position and time, also the grating scan direction must be indicated. The anlysis is based on the FITS files generated by the ExportPacketRecorderArchive2Fits tool of PCSS. Another input dataset is the model line list for the 4 most abundant isotopes of H_2O taken from the HITRAN database. Line by line optical depths need to be calculated taking into acccount each individual line strength, pressure broadening and pressure induced lineshifts for composing the respective Voigt profiles. The result can then be convolved by a gaussian instrumental profile of the predicted resolution of PACS for the respective wavelength range including an additional slit convolution for an extended source like the vapour cell. The resulting relative intensity spectra serve as input for a correlation analysis with the observed spectra.
  Note that due to the test set-up (warm cryostat window, etc.) there is a substantial undefined thermal foreground signal, which is not in the absorption path. Therefore, the reference spectra have been manually adapted (offset and scaled) to roughly fit to the measurements.
  In the case of the water absorption measurements the signal obtained during the water vapour measurement must be divided by the signal obtained during the respective vacuum measurement. In order to facilitate this division, the vapour spectrum has to be interpolated onto the same grating sampling as the vacuum measurement. Each up and down scan shall be scaled separately to the mean of all data of that pixel by a high order polynomial function derived from the data itself. After this kind of auto-flatfielding, the division of the gas spectrum by the vacuum spectum should be preformed. This result is stored and kept for all further steps. The grating positions in this data set are already transformed to wavelengths according to the input calibration.
  The spectral range to be calibrated has been divided into discrete intervals for each grating order (see Table 4.1.

  Starting from the initial wavelength calibration (FM-ILT 1) the wavelength scale of the measurements should be varied in a loop around this starting calibration, individual for each spectral interval, module and pixel. The stepsize

Table 4.1: Spectral Calibration Intervals

Grating order	Spectral Intervals used for correlation[μm]
1	**[102,112], [112,122.5], [121,131] [131,141], [141,157], [157,172], [172,190], [190,220]**
2	**[65.5,75.0], [74.5,81.0], [79.5,88.0], [87.0,94.0], [93.0,100.0], [99,105]**
3	**[54.0,57.5], [57.5,61.0], [61.0,64.5], [64.5,68.0], [68.0,73.0]**
2'	**[54.0,57.5], [57.5,61.0], [61.0,64.5], [64.5,68.0], [68.0,73.0]**

of this variation has to be chosen to be compliant with the specified calibration accuracy of 10 – 20% of a spectral resolution element. For each variation, the linear Pearson correlation coefficient can be computed and the maximum value of all variations shall be taken as optimum wavelength calibration for the particular grating range under investigation. This method has turned out to be more efficient and robust against outliers and noise than fitting individual peaks.
The correlation procedure results in a set of wavelength deviations per interval. These deviations are transformed into grating angles and then a third order polynomial fit is performed. This results in an improved calibration by adding new coefficients to the coefficients of the old one:

$\alpha_{new} = \alpha_{old}$ + polynominal coefficients (see below)

Due to the slight iterative nature of this approach, the entire procedure is executed at least twice.

The Littrow grating equation for PACS can be written as: $\lambda = \frac{g}{n}[sin(\alpha - \delta\alpha) + sin(\beta + \delta\beta + \delta pix \times (pix - 8))]$
with:
λ = wavelength,
g = grating constant,
n = grating order,
α = input angle onto the grating,
β = output angle from the grating,
$\delta\alpha$ and $\delta\beta$ = angular deviation from ideal Littrow case,
δpix = angular distance between pixels within a module,
pix = pixel number within a module (1-16), Pixel 8 is considered as the reference with the δpix multiplier becoming zero.

The grating constant has been measured by Zeiss for the CQM grating and has then be calculated (priv. comm. NG) for LHe temperatures, assuming that FM grating and CQM grating have the same grating constant :
g_{LHe}=117.175μm
In order to treat all higher order distortions to the Littrow equation it appeared adequate to fit all deviations by a third order polynomial separately for each pixel. Furthermore, the following relations have been used:
$\alpha = \alpha_0 + (p_1 - 1) \times (\frac{gratpos}{dgrat}) + p_2 \times (\frac{gratpos}{dgrat})^2 + p_3 \times (\frac{gratpos}{dgrat})^3$
and
$\alpha = \beta$
with:
α_0 = grating angle at grating position zero
$dgrat$ = 23301 grating steps per 1 degree grating angle (from DMC SUM)
The value of $dgrat$ has been left untouched, i.e. no optimization for this value.
$\delta\alpha$ = $\delta\beta$ = 0.6253 (priv. comm. NG, design value)
The δpix values for each grating order are kept constant as approximated mean values:
$\delta pix_{n=1}$ = 0.0372947; $\delta pix_{n=2}$ = 0.0364869; $\delta pix_{n=3}$ = 0373207;

The data reduction of laser monochromatic lines is very similar, although some consideration is required to produce the final wavelength calibration product (based on both water and laser lines). The laser lines are considerably narrower than water absorption lines, laser lines typically show the instrumental profile at a certain wavelength. As a

consequence, the wavelength calibration at the laser line wavelength is more accurate than a single line calibration derived from a water line. On the other hand, the small number of laser lines makes it difficult to get an accurate full PACS range wavelength calibration by an interpolation process.
Substantial laser power variations and a non-uniform illumination of the spectral field of view cause an additional complication for the use of laser lines in wavelength calibration. Instead, they are used for wavelength checking and instrumental profile determination rather than calibration.

- In orbit:
  In flight the same format of input data (FITS products from ExportPacketRecorderArchive2Fits) for wavelength calibration analysis is required. In order to perform a similar correlation analysis on planetary or water star spectra, good, high resolution models need to be available. For the observations of planetary nebulae, availability of accurate vacuum rest wavelengths will be sufficient. In both cases, for molecular spectra and atomic fine structure lines, the above described correlation analysis can be done, should any change in wavelength calibration be observed in flight. Short observations of selected lines early in PV phase will provide already an indication about such possible shifts. The principal method for the calibration is the same, starting from the calibration obtained during FM-ILT 3.

Output, products

Calibration file(s) containing the following information:
g$_{LHe}$=117.175μm
$dgrat$ = 23301
$\delta\alpha$ = $\delta\beta$ = 0.6253
$\delta pix_{n=1}$ = 0.0372947; $\delta pix_{n=2}$ = 0.0364869; $\delta pix_{n=3}$ = 0373207;
The polynomial coefficients α_0, p_1, p_2, p_3 for each pixel and grating order

Status/version

revised for flight

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$Revision: 1.8 $
$Date: 2008/03/13 18:17:04 $
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Req. 4.2.2 Grating Instrumental Profile

Objectives

The instrumental profile is defined as the instrument response when scanning over a line which is intrinsically much narrower, i.e. unresolved, than the profile itself. The characterisation will be done by determining the FWHM level and also the 5% level of the peak to assess the impact of the wings.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

a) ILT

b) PV Phase

c) Later refinements in the mission can be done on the analysis of a larger sample of observations, selected from scientific measurements (see ISOLWS analysis).

Required accuracy

The expected uncertainty of the IP's FWHM is 5%.

The achievable accuracy is very much dependent on the intrinsic line shapes of the calibrator lines. If a modeled profile only poorly represents the real intrinsic line shape, then the deconvolved IP will not show the real IP of the spectrometer. While the vapour cell reference emitter has relatively broad absorption lines, the laser source provides much narrower profiles - almost monochromatic lines - and therefore diminishes this bias. If only theoretical assumptions are available for the intrinsic profiles (the WEBGEN spectrum with freely chosen profile pattern), the IP is representative only in terms of its linewidth instead of the overall profile. Only if the spectrum of the vapour cell source were known with higher resolution than the PACS instrumental one, this would lead to a well determined line profile. Instrumental broadening and noise in this reference spectrum can be ignored when determining the IP of the PACS spectrometer with substantially lower resolution.

Emission lines have another advantage, if straylight has to be taken into account. Straylight may fill absorption features leading to unrealistic profiles close to the line center. To properly account for straylight, one needs to measure the IP over the entire wavelength interval of the system. Degradation of the spectrum might be caused also due to the presence of ghosts. Spectral ghosts (which are usually due to periodic ruling errors) scale in strength as the square of the grating order. Therefore ghosts can be produced not only in the vicinity but also far from the parent lines leading to uncertain spectral features and influencing the IP reconstruction accuracy in certain wavelength regimes.

From a computational point of view an uncertainty in the IP is introduced due to the approximation made in discretizing the convolution. This uncertainty in the derived IP scales as $1/\sqrt{N}$, where N is the number of spectral lines containing IP information.

When AOT type calibration measurements performed (FM and PV phase) the grating step size and scanning speed must be variable. Since the step sizes will be more around $\geq$20" it has an impact on the accuracy of the IP reconstruction procedure. Tcl scripts must have to allow the tuning of these parameters.

Inputs, prerequisites

Calibration measurements required to be completed before:

1) Req. 2.4.5, (In order to get as narrow a profile as possible a perfectly focused spectrometer needed)

2) Req. 2.4.4 & req. 4.1.5 (Straylight). Not available for CQM!

3) Req. 4.1.4 & req 4.2.4 (Spectral/spectrometer ghosts). Not available for CQM!

Sources

a) CQM-ILT: List of WEBGEN generated model spectrum lines of the water vapour applying nominal cell conditions ($p = 20$ mbar, $T_{\rm cell} = 298$ K, $l_{\rm absorption\ path} = 0.3$ m, $T_{\rm hot\ plate} = 450$ K, # of H_2O isotopes: 10, line shape: Voigt, line model: HITRAN '96). The number of scanned lines might be increased to establish better the wavelength - resolving power relation.

   1) 1st order (57-72 μm): 59.35, 65.16, 71.07 [μm]
   2) 2nd order (72-105 μm): 76.42, 92.81, 98.5 [μm]
   3) 3rd order (105-210 μm): 121.74, 160.51, 187.11 [μm]

b) FM-ILT: Methanol laser source is available (besides the water vapour cell). For possible transitions to be detected see below.

c) PV Phase: List of astronomical sources with isolated lines which are narrow in comparison to the profile from ILT measurements. PN and HII regions are expected to provide these. Also the water lines observed in objects W Hydra. CO lines.

Calibration Implementation Procedure (CIP)

Perform individual grating scans in line spectroscopy mode to measure the specified 9 absorption lines (see list under "Sources") in the water vapour spectrum. Both up and down grating sequences are required. The extended radiation of the absorption vapour cell is assumed to be homogeneous and isotropic [Requirements, specifications see PACS-ME-DS-009] at the exit pupil of the cell providing a homogeneous illumination of all 25 detector pixels in the spatial domain. The most appropriate reference source setup (hot-plate temperature, pressure of vapour, absorption path length, stabilization times length... etc: TBD) should be determined during the short spectral calibration (CQM-T03). Concerning the detectors, the whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to another capacitor has to be done. An optimization of the reset interval and/or integration capacitor set-up shall be considered when switching between grating orders. The lines are to be measured down to the smallest grating step of $10''$ with sufficient wavelength coverage to observe the wings at 5% of the peak level and determine the continuum. Using the WEBGEN [2] water absorption spectrum simulator, one obtains a typical FWHM for a strong isolated line of ≤ 0.05 μm. Assuming a resolving power of 2000 @ 100 μm the whole profile is covering $\sim 1 - 8$ spectral pixels instantanously. With the finest grating step of $10''$ a sampling of 1/10 FWHM is achieved. In this case the line profile is represented by $\sim 10 - 60$ data points (@ 3σ assuming a Gaussian profile, $\Gamma = 2.35\sigma$) when scanning the line over the detector pixels. In this calculation the instrumental broadening has not been taken into account, as a consequence, during measurements the number of data points over the line profile has to be higher. This spectral sampling enables the application of the goodness-of-fit parameter estimation technique described in the CAP. For the selected lines we assume a S/N < 1000. The integration time per line is about 10 minutes.

Additionally to the above scenario, during the FM-ILT the methanol laser can be used for IP characterisation. The almost monochromatic lines provide a much more robust way to measure the instrumental profile. The following table summarizes the initial FIR methanol laser wavelengths available for PACS spectral testing. Further lines are feasible after successful technical upgrade of the laser system. During the FM/ILT the IP measurements should be performed using both strong mW and weak μW spectral lines presented in the table. Laser lines available off the nominal order cannot be considered for this measurement and not indicated here.

The measurement sequence is done in line spectroscopy mode. The grating up- and down scans are performed in a similar way as for the absorption lines, a sampling of 1/10 FWHM has to be achieved. If the laser wavelength tuning takes longer time than the order-switching procedure of the PACS spectrometer, then measurements in a single grating order should

[2] http://nitrogen3.atmosp.physics.utoronto.ca/webgen_lab_in.html

Wavelength (microns)	Expected output power	Remarks
70.511638	mW	strong
96.522408	μW	weak
118.834107	mW	strong
133.119600	μW	weak
170.576394	mW	strong

be executed in a common block. In order to get the background noise rms a series of background measurements must be performed at the beginning and at the end of the test sequence. During these background sequences the experimental set-up is the same, but the laser is switched off. In this configuration PACS can measure all components contributing to the background. Other test conditions and setup should be nominal. The laser radiation is expected to be point like at the exit pupil of the half-transmitting laser mirror. During the test sequences the illuminating flux should be chosen as maximum as possible, but avoid detector saturation. The whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to another capacitor has to be done. An optimization of the reset interval and/or integration capacitor set-up shall be considered when switching between grating orders.

The laser beam is targeted on the central pixel of the 5×5 spectrometer FOV and measurements have to be repeated on the foure corners as well to characterize distortions in the IP if there is any.

Estimated time needed

$\geq$ 1000 sec

Calibration Analysis Procedure (CAP)

The recorded spectra $g(x)$ may be represented as

$$g(x) = \int_{-\infty}^{\infty} f(x')\phi(x - x')dx',$$

where the kernel $\phi(x - x')$ describes the unknown IP and $f(x)$ is the true underlying function of the intrinsic line profile (x represents the pixel position in the spectral domain). From the recorded spectrum $g(x)$, $\phi(x)$ has to be determined. One way is to invert the above equation by using discrete Fourier or wavelet functions. However, these deconvolution techniques are imperfect: lines in these representations are smoothed, leading to a broader IP. An alternative method is therefore proposed: an analytic form of the IP is selected and the high resolution line spectrum $f(x)$ is convolved with this kernel according to the discretized form of the expression above,

$$g_i = \sum_{j=i-p}^{i+p} f_j \phi_{i-j},$$

where i represents the pixel's mid-position, j is the oversampled position and p is the half-size of the kernel. Since the IP generally falls below 5% of its peak intensity a few pixels away from the line center, we may assume ϕ_{i-j} is zero when $|i - j| > p$. This synthetic spectrum is then rebinned to match the pixel locations in the observed spectrum and modified by a linear term to fit the baseline and the line peaks (valleys). By iteration of this procedure the IP parameters can be optimized using maximum-likelihood, χ^2 or other standard parameter estimation techniques. The derived parameters of $\phi(x)$ should be adopted at 95% confidence level. A fairly general $\phi(x)$ function (e.g. gaussian) should be used initially, when the basic form of the IP is unknown. If neither the laser nor high resolution measured water vapour spectra were available, then the WEBGEN generated profile should be applied to approximate $f(x)$ during the ILT phase. Profile asymmetries could be recognized, if the above fitting procedure were done separately for the blue and red wings relative to the line center. Profiles obtained in the 25 spatial channels must be compared. Wavelength/order dependence of the IP must be followed up. If absorption lines are not as deep as expected, then a straylight correction has to be applied (TBD). (Note: the SWS IPs have a Gaussian shape up to accuracies of a few percent. The only systematic differences from a Gaussian profile are a slight shoulder on the blue side of the base of the profile and a depression on the red side as compared to a purely Gaussian profile which varies with the position in the slit.)

Output, products

Calibration file containing the instrumental profiles (if needed for different wavelength regimes (TBD) or at least for the different orders). Wavelength dependent resolving power of the spectrometer (a convolution of the IP and pixel size).

Status/version

Draft version

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$Revision: 1.4 $
$Date: 2006/07/30 16:08:34 $
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Req. 4.2.3 Spectral Purity

Objectives

To measure any contamination of the spectrum by light from outside the nominal grating order. This will be done by measuring strong lines in the wavelength range covered by the detector response but outside the bandpass of the selected order sorting filter.

Fulfilling or fulfilled by

Self-standing

Priority

B

When performed / frequency

- ILT (No monochromatic line source was available for the CQM/ILT phase)
- PV Phase

Required accuracy

The accuracy of the impurity characterization procedure is noise limited, the noise rms should be derived during the test sequence.

Inputs, prerequisites

- PV phase: Sources with bright pronounced emission lines and a relatively low continuum level, ideally no line forest e.g. PNe lines (TBC).
- ILT: CAPs required to be completed before for req. 4.1.5 & req. 4.2.4

Sources

- ILT: Molecular FIR laser source
- PV phase: Bright line-sources (possibly one already well measured with LWS). If observability constrains allow use the same targets as proposed for req. 4.2.1 & req. 4.2.2.

Calibration Implementation Procedure (CIP)

The following table summarizes the initial FIR methanol laser wavelengths available for PACS spectral testing. Further lines are feasible after successful technical upgrade of the laser system.

During the FM/ILT the spectral impurity should be investigated using at list the three strong mW range spectral lines presented in the table. Low priority measurements should be repeated for the weak lines as well in case impurity occurs while illuminating the detectors with strong lines. Weak lines can be used too if the measured signal-to-noise is high enough (typically $>$100) to use them or imprity tracing.

Two configurations of spectral purity investigations can be considered using monochromatic spectral lines. The applicability of configuration (a) and/or (b) depends on the wavelength of the illuminating line.

(a) Checking the presence of any parasitic light in the parallel order for a given line. No grating repositioning is required for this measurement.

Wavelength (microns)	Expected output power	Remarks
70.511638	mW	strong
96.522408	μW	weak
118.834107	mW	strong
133.119600	μW	weak
170.576394	mW	strong
223.500	μW	weak (off the nominal order)
232.7	μW	weak (off the nominal order)
242.79	μW	weak (off the nominal order)
253.6	μW	weak (off the nominal order)

(b) Checking the occurence of a line in higher and/or lower grating order(s) with respect the nominal order where the line should appear in the PACS order selection scheme. The grating positions to search for parasitic lines in non-nominal orders are determined by the grating equation.

Configuration (a) provides the opportunity to characterize quantitatively the ratio of in-band light passed through the spectrometer to that light transmitted from outside the selected spectral band at a specific grating position. This type of impurity might occur due to straylight, imperfect ruling of the grating substrate or contamination by vignetted orders.

Configuration (b) is useful to characterize relative filter transmission ratios for neighbouring orders at a given wavelength. From operational point of view this configuration is less important since cutoff wavelengths are enforced by grating positions leaving no chioce for overlapping of neighbouring orders.

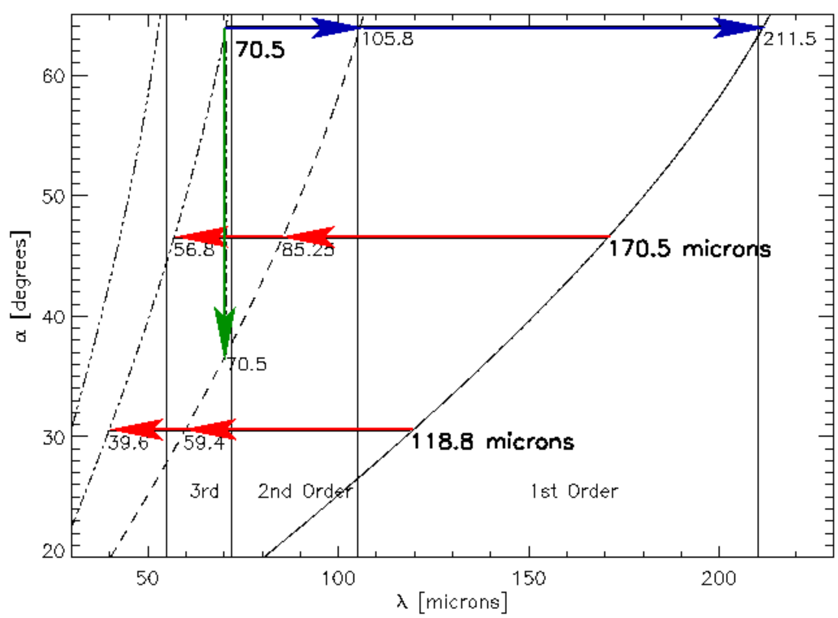

Figure 4.1: Spectral purity measurement scheme using three strong methanol laser lines (bold font). Red and blue vertical lines are referring to configuration (a), the green line represents the only choice to measure in configuration (b)

In these configurations the FIR laser has to produce lines outside the range of the selected grating order. In case of spectral impurity a laser line can contaminate the selected spectral order, the goal is to find wavelengths where the intensity of the unwanted line is above the 3σ noise level. The settings for the configurations in the table below are determined by the following factors: (i) operational regime of the PACS grating in terms of the angle of the incident light (which can be expressed by the grating throw, too), (ii) grating equation, (iii) nominal wavelength range of the order-sorting filters (iv) the sensitivity ranges of the PACS Ge:Ga arrays. The relative spectral response drops to zero at ~ 35 μm for both the stressed and low-stressed detectors defining a blue cutoff, while the long wavelength cutoff is assumed to be at ~ 160 μm for the blue detector and ~ 250 μm for the red one (the latter one is not relevant for the configuration design since lies outside the nominal grating angle range).

The grating equation is given by $m\lambda = d(\sin\alpha + \sin\beta)$, where m is the diffraction order, d is the grating constant, α is the grating angle of incidence and β is the diffraction angle with respect to the grating normal direction. In the Littrow condition which applies to the PACS design the incident and diffracted rays are (nearly) in auto-collimation (i.e. $\alpha \approx \beta \approx \omega$), ω is the groove angle on the incident facet. In this condition the grating equation is simplified to: $m\lambda/2d = sin\alpha$ (see e.g. Fig. 6.2-10 in PACS-ME-GR-002).

Applying the grating equation the respective wavelengths of the proposed strong lines for the two configurations are calculated and summarized in the following table.

Measurement Nr.	λ_{Laser} [μm]	Nominal order	Configuration a/b	$\lambda_{\mathrm{Impurity}}$ [μm]	Impurity expected in order	Remarks
1	70.511	3	(a)	105.767	1	
2	70.511	3	(a)	211.535	1	
3	70.511	3	(b)	70.511	2	
4	118.834	1	(a)	59.417	2	Line out of 2nd order
5	118.834	1	(a)	39.611	3	Line out of 3rd order
6	170.576	1	(a)	85.288	2	
7	170.576	1	(a)	56.859	3	

The measurement sequence starts with acquisition dark frames (laser switched off or the beam is blocked) and followed with direct detection of the laser lines in line spectroscopy mode. Configurations collected in the table above have to be measured afterwards. The laser beam should be targeted on the mid-pixel of the 5×5 spectrometer FOV.

If on-the-fly data reduction is available and in case of unwanted line detection three further steps are needed for a detailed impurity characterization: (i) a high density line scan in at least Nyquist sampling should be performed in addition. This procedure is completed when the impurity line intensity drops below the noise level. In step (ii) the unwanted impurity line intensity with regard to the laser line intensity ($I_{\mathrm{I}}/I_{\mathrm{Laser}}$) has to be characterized. The I_{Laser} can be obtained at the beginning of the measurement sequence.

In case of impurity identification the spatial dependence should be followed up: (iii) at least the four spatial corner pixels of the spectrometer FOV should be measured in addition. For these sequences, the laser beam displacement is supported by the test equipment.

Contamination by higher orders ($m > 4$) is assumed to be negligible due to the decreasing grating efficiency, while the zero order (direct reflection from the grating substrate) could be always present in the Littrow condition. If the laser wavelength tuning takes longer time than the order-switching procedure of the PACS spectrometer, then measurements of different configurations should be executed in a common block. In order to get the background noise rms a series of background measurements must be performed at the beginning and at the end of the test sequence. During these background sequences the experimental set-up is the same, but the laser is switched off. In this configuration PACS can measure all components contributing to the background. Other test conditions and setup should be nominal. The laser radiation is expected to be point like at the exit pupil of the half-transmitting laser mirror. During the test sequences the illuminating flux should be chosen as maximum as possible, but avoid detector saturation. The whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to another capacitor has to be done. An optimization of the reset interval and/or integration capacitor set-up shall be considered when switching between grating orders.

Estimated time needed

Calibration Analysis Procedure (CAP)

Spectral purity can be expressed quantitatively as the ratio of the in-band light passed through the spectrometer to that light transmitted from outside the selected spectral band. After the determination of the noise rms and removal of the background level obtained by the background sequences, peaks above the 3σ level should be searched for.

An impurity of the system might occur due to straylight, imperfect ruling of the grating substrate (when $m\lambda/d \neq \mathrm{const}$) and contamination by the vignetted orders. The last effect might be significant only if the transmission of the order sorting filter does not drop to zero at the nominal cut-off wavelengths. According to the filter performance requirements the out-of-band suppression of the filters multiplied by the detector suppression factor lies between $\sim 10^{-4}$ and $\sim 10^{-3}$. The grating efficiency for 2^{nd} order is 50-70% providing an additional attenuation. This leads to the assumption that in case of nominal conditions the contaminating out-of-band lines must be very strong (TBD) and the occuring impurity is substantially related to parasitic light passing through the dichroic and/or order-sorting filters.

Output, products

List of unexpected lines above the 3σ noise level in all identified configurations with the corresponding laser wavelength and their relative strength to the original lines.

Status/version

third draft

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$Revision: 1.7 $
$Date: 2007/10/31 19:13:50 $
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Req. 4.2.4 Spectral Ghosts

Objectives

To check to which extent ghosts are present at various distances to the principal maximum by making a very detailed scan of a source with bright lines or TUFIR lines during ILT.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- ILT
- PV Phase

Required accuracy

Ghosts should be detected down to the noise level, the noise rms should be derived during the test sequence.

Inputs, prerequisites

Identification of astronomical sources with well identified bright lines and the list of these lines.

Sources

- On ground during ILT tests grating scans on the methanol laser source will be performed. Check for inter-order lines with respect to the illuminating laser line wavelength.
- In orbit: Scan a source with a well known spectrum of lines. Look for lines not present in the true spectrum. Sources already well studied with LWS (so that the lines are identified) should be good targets.

Calibration Implementation Procedure (CIP)

Since the ghost separation from the parental line is not known at the time of the measurement (see CAP), a full grating scan in three orders with high resolution is required. The methanol laser will be tuned over all available transitions falling in the PACS range. The following table summarizes the initial FIR methanol laser wavelengths available for PACS spectral testing. Further lines are feasible after successful technical upgrade of the laser system. During the measurement both strong mW and weak μW range spectral lines can be considered to measure. Further laser lines falling off the nominal order cannot be used for this measurement and not indicated in the table.

Wavelength (microns)	Expected output power	Remarks
70.511638	mW	strong
96.522408	μW	weak
118.834107	mW	strong
133.119600	μW	weak
170.576394	mW	strong

For a given laser line wavelength a grating range scan must be performed over $\pm\Delta\lambda/5$, where $\Delta\lambda$ represents the nominal bandwidth for each order (leading to $\pm 21.0, 6.6$ and 3.4 microns in the $m = 1, 2, 3$ orders). The TUFIR laser beam should be targeted on the mid-pixel of the 5×5 spectrometer FOV. In case of ghost identification in the central pixel position and if on-the-fly data reduction is applicable then at least the four spatial corner pixels of the spectrometer FOV should be measured in addition. The laser beam displacement has to be supported by the test equipment. On-the-fly ghost identification is an indication to extend the observed spectral range too. For each laser line the full spectral order has to be scanned in which the laser line is measured. Focal plane chopper positions different from zero might also be used for a detailed ghost follow-up. Concerning the detectors, the whole Ge:Ga setup shall be nominal, the procedure should allow to set only the reset interval at run time. In case of saturation the switch to another capacitor has to be done. An optimization of the reset interval and/or integration capacitor shall be considered when switching between grating orders. The measurement sequence is done in range spectroscopy mode (2×3 scans with up- and down sequences, change of diffraction order in between) where the typical grating step size may be of the order of $20''$ to obtain a sampling on each pixel of around 1/5 FWHM of the TUFIR lines (TBC). The illuminating laser line flux should be chosen as the maximum one possible, just to avoid detector saturation. In order to get background noise rms a series of background measurements must be performed at the beginning and at the end of the test sequence. During these background sequences the experimental set-up is the same but TUFIR is switched off. In this configuration PACS can measure all components contributing to the background. Other test conditions and setup should be nominal.

Estimated time needed

Calibration Analysis Procedure (CAP)

Ruled gratings exhibit ghosts due to ruling errors on the grating substrate. This parasite light is focused in the dispersion plane, while stray light is almost randomly scattered and not focused. Generally, ghosts should follow the grating equation, but for spatial frequencies other than $1/d$ and m (the diffraction order) holds not to be integer. The analysis is straightforward: search for narrow (line-type) spectral features above the noise level. After the determination of the noise rms and removal of the background from the background sequences, peaks should be searched for above the 3σ (TBC) level. The goal is to find the ghost intensity relative to the parent line, record the displacement of the ghost intensity maximum from the parent line center and try to specify the type of the grating error. Rowland ghosts - due to longer-term periodicities (much larger than the groove spacing) - are located closely and symmetrically on both sides of the parent diffracted line. The separation of the Rowland ghosts from the parent line depends on the period of the ruling error, and they intensity depends on the amplitude of this error. The displacement from the parent line at λ shall be expressed by $\delta\lambda = \pm\lambda/d * D_p$, where d is the groove density and D_p represents the pitch of the ruling engine. Additional ghosts might be located at integer multiples of $\delta\lambda$. Applying this equation with the PACS grating constraints (TBC) we get $\delta\lambda = n*$ (TBD) as a prediction for the location of Rowland ghosts with respect to the parent line. The relative Rowland gost intensity in Littrow condition is approximated by $I_{RG}/I_P = d^2m^2e^2\pi^2$, where I_{RG} is the ghost intensity, I_P is the parent line intensity, d is the groove density, m is the order and e represents the error in the position of grooves. Adopting the PACS grating values according to the specifications $d = 8.5$ mm^{-1} and $e = 0.3$ μm, in $m = 2$ order one can get $I_{RG}/I_P \simeq 2.6 * 10^{-4}$. Note that ghost intensity in the order of 10^{-4} is typical for high quality gratings. The measured I_{RG}/I_P ratios should be checked by the above expression. When more periodic deviations are present in the groove spacing, interference of the ghost diffraction patterns can generate spurious lines far from the parent line - these are the so called Lyman ghosts. Lyman ghosts are usually caused by short-term periodicities (in the order of few times the groove spacing) and are located in fractional-order positions. These positions are determined by the number of grooves per period e.g. an error every five grooves corresponds to a fraction order of $1/5$. Random (rather than periodic) irregularities in groove placement leads to a faint background between orders, rather than sharp ghosts (grass effect) but this unwanted light feature is interpreted as a component of straylight and supposed to be traced in req. 4.1.5.

Output, products

List of parasitic peaks as a function of TUFIR wavelength and grating position.

Status/version

Second draft version, complete upgrade

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$Revision: 1.4 $
$Date: 2006/07/30 16:08:25 $
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Req. 4.2.5 Grating Wavelength calibration, dependence on source position in slit

Objectives

Determine the relation between the grating angle and the central wavelength of the grating response as a function of the position of a point source within the spectrometer slit. Due to similarity with other pixels, it is assumed that a detailed characterization on the central spatial pixel shall provide sufficient information for the entire spatial field of view.

Fulfilling or fulfilled by

linked to 4.2.1, the basic grating wavelength calibration

Priority

A

When performed / frequency

a) ILT

b) PV Phase

c) In routine phase only in case of observed calibration discrepancies.

Required accuracy

Peak position of line to within 10-20% of a spectral resolution element.

Inputs, prerequisites

This observation requires strong (100 Jy) narrow lines from point sources. Atomic fine structure lines in the PACS wavelength range will be suited for these measurements. Relevant atomic fine structure line vacuum rest wavelengths are available at www.mpe.mpg.de/ir/ISO/linelists/FSlines.html.

Sources

- [1] During ILTs:
  No point-like line emitters were available during ILT.
- [2] In orbit:
  Sources with well identified emission lines which are not blended. These are essentially PNs and HII regions. However the source extent should be at least below 3 arcsec.

Calibration Implementation Procedure (CIP)

- [1] During ILTs:
  Since no sources/setup will allow for suitable measurements, this is not applicable.
- [2] In orbit:
  For in-flight (PV phase) the CUS module WaveCalNodRaster may be used. This observing mode definition will allow for a flexible execution of a chopped and nodded raster around a suitable point source with line emission. The adjustable grating step size will facilitate both, measurements for line peak determinations on each spectral pixel of a module and sufficient sampling for studying possible effects on the instrumental line profiles. Since this observing mode definition also contains a call to the standard calibration block during the acquistion slew, further information on the line flux as a function of source position in the slit can be obtained as well. The CUS module will be available from within XHSPOT for parameterization. A raster step size of 5 arcsec may be used to place

the source position just at ± 2.5, ± 7.5 arcsec around the central spatial pixel. Execution of such a raster may be required several times (3-4) for different wavelengths.

Estimated time needed

$\geq$ 4 hours per selected wavelength

Calibration Analysis Procedure (CAP)

- [1] During ILTs:
  Not applicable, see above.
- [2] In orbit:
  The starting point for the offline analysis will be Level 0 products in FITS format. As a first approximation, gaussian fits to the spectra of each pixel of the central spatial module will provide possible systematic effects on the detected line centers in comparison to the expected vacuum wavelength of the transition under investigation. The second part of the analysis will then focus on the detailed profiles of the lines at the different raster positions in order to identify all deviations from profiles taken at center pointing positions.

Output, products

- Shift of fitted line peak positions for each spectral pixel of the central module.
- Tabulated widths of the profiles at different relative profile heights (e.g. 10, 30, 50, 70, 90 % of peak).

Status/version

PV Preparation

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$Revision: 1.1 $
$Date: 2008/06/09 16:34:36 $
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4.3 Photometric Calibration

This section addresses the requirements related to the photometric calibration of the spectrometer.

The Astronomical Observation Templates (AOTs) contain one or more reference measurements on the internal calibration sources. These are short spectral scans at one or a few so-called key wavelengths per spectral band. The main purpose of this section is to use the signals measured in these reference measurements to convert the signal at sky positions to an absolute flux density. This includes the following steps:

- For every detector, the relative response to the same input flux density at different wavelengths is characterised in the Relative Spectral Response Function (RSRF). This is determined on system level, and includes the filter transmissions and detector-specific wavelength dependend sensitivity. In the data processing, this correction is applied normalised to one key wavelength per spectral band, i.e. the signal at the key wavelengths is not altered.
- The absolute flux calibration uses observations of celestial calibration sources to determine the absolute flux density difference between the two internal calibration sources in the central spatial pixel at the key wavelengths. In the data processing, this is used to calculate a signal to flux density conversion factor based on the internal calibration source measurement in the AOT.
- Internal flatfield: from the internal calibration source scans at the key wavelengths we can derive a pixel-to-pixel variation in sensitivity at the key wavelengths. This includes the intrinsic detector sensitivity, the system transmission and differences in the integrating capacitances.
- The sky calibration sources are pointlike, and only illuminate one spatial pixel. The external flatfield translates the absolute flux calibration of the central spatial pixel to the other spatial pixels. This is stored as a ratio with respect to the internal flatfield.

A second objective of this section is to characterise the linearity with flux.

The third goal of the requirements in this section is to verify the reproducibility of the measurements involved in the absolute flux calibration. These encompass the reproducibility of the internal reference measurements, reproducibility of spectral scans on the sky, stability and homogeneity of the telescope background, and instrumental polarisation.

Req. 4.3.1 Absolute flux calibration internal sources, spectrometer

Objectives

The absolute flux calibration of the spectrometer is covered by requirement 4.3.3. In requirement 4.3.1 we want to establish the best way how the calibration block, where we measure the internal PACS sources, should be executed. It is planned to have a calibration block at the start of each AOR measurement. This will allow to correct for responsivity drifts of the detector.

Fulfilling or fulfilled by

Related to
Req. 4.3.3 Absolute flux calibration external sources, spectrometer;
Req. 4.3.8 Relative spectral response function, spectrometer;

Priority

A

When performed / frequency

ILT: calibrate the PACS calibration sources against the OGSE black bodies.
PV phase: early in PV phase, only on internal sources
Routine phase: monitoring. A calibration block, making a small scan on the internal sources at a key wavelength will be performed at the start of each AOT.

Required accuracy

To achieve a 20% (10% goal) [instrument requirements document] absolute flux calibration at any wavelength we need a better than 10% determination at the key wavelengths.

Inputs, prerequisites

Basic detector, filter, grating and chopper characterisation; Nominal PACS calibraton sources and OGSE black body performance; Nominal optical and grating alignment; No straylight influences; Nominal spatial and spectral calibration. Knowledge of the homogeneity of the PACS internal sources (req. 2.5.2 Spatial stability of PACS calibration sources) or at least a well established position should be determined which should then always be used when observing the calibration block.

Sources

In this requirement we will only use the internal PACS sources.

Calibration Implementation Procedure (CIP)

The responsivity drifts of the instrument will be monitored by measuring a calibration block at the start of each AOT ("AOT related aspects for the PACS Spectrometer" PICC-ME-SD-004; and "PACS Spectrometer Calibration Block: Implementation adn Evaluation" PICC-ME-GP-009). It is foreseen to be performed as a chopped up and down scan (16 steps, step-size $\approx$ 1 pixel) on the two CSs at one of the three key wavelengths. In this requirement we want to establish how we get the best measurement in terms of signal/noise. Different observing parameters will be tried out as indicated below.

- number of readouts per ramp: 64 32
- number of ramps per chopper plateau: 2 3 4
- number of cycles: 1 2 3 4
- number of grating steps: 1 4 8 16

- number of up/down scans: 1 2 3

To restrict the number of combinations we start with a default observing setting and only allow one parameter to vary, except for the ramp lengths. For all combinations we try 1/4 and 1/8 sec ramp length. The default setting is 2 ramps per chopper plateau, 1 cycle, 16 grating steps, 1 up and down scan. The grating step size is taken at 168.

We assume that the best capacitance value is determined in the tests on finding the best settings for the GeGa detectors.

Observations with different parameters need to be observed within the constraint of a total duration of the calibration measurement of about 2 minutes.

In total 22 different settings with different parameters are planned, each will be observed three times.

Estimated time needed

The average duration of the different calibration blocks costs about 2 minutes. Total time is about 2 hours.

Calibration Analysis Procedure (CAP)

Analyse the measurents in terms of S/N

Output, products

A relation between internal source signal levels and reference flux scale set by the OGSE cryo black bodies (during ILT) and the celestial standard sources (in-orbit) at grating/band key wavelengths and, together with the RSRF, at all wavelengths. Note: The OGSE cryo-BBs are extended sources, celestial standards are point-sources!

Status/version

Update after PV planning excercise (end July 2008)

```
$Revision: 1.9 $
$Date: 2008/07/31 15:37:18 $
```

Req. 4.3.2 Reproducibility internal sources, spectrometer

Objectives

Verify the reproducibility of the spectrometer signal using the internal calibrators. This should be performed on different timescales.

Fulfilling or fulfilled by

Related to 4.3.1, fulfilled by 4.3.4.

Priority

C

When performed / frequency

During ILT and PV. Monitoring during routine phase.

Required accuracy

5% (3% goal) [instrument requirements document]

Inputs, prerequisites

The calibration block, which will be observed (on key wavelengths) at the start of each AOT ("AOT related aspects for the PACS Spectrometer" PICC-ME-SD-004), needs to be well established.

Sources

Measurements on PACS internal sources are verified versus OGSE black-bodies during ILT and standard stars in orbit.

Calibration Implementation Procedure (CIP)

Repeat a series of measurements as described under 4.3.1 with identical setups. The implementation of the CIP is directly coupled to that of 4.3.4. as the measurements combines observing the input fluxes from the internal sources and of the OGSE during ILT or calibration stars in orbit. The measurement on the internal sources is done through the regular calibration blocks as it will be measured at the start of each AOT measurement.

Estimated time needed

see 4.3.4.

Calibration Analysis Procedure (CAP)

Analyse sequences of absolute flux calibration measurements (4.3.3).

Output, products

Status/version

Update for FM ILT campaign.

```
$Revision: 1.8 $
$Date: 2006/06/13 15:42:42 $
```

Req. 4.3.3 Absolute flux calibration external sources, spectrometer

Objectives

Determine the absolute flux calibration at the key wavelengths of the spectrometer using well known calibration sources.

Fulfilling or fulfilled by

Related to
Req. 4.3.1 Absolute flux calibration internal sources, spectrometer;
Req. 4.3.8 Relative spectral response function, spectrometer;

Priority

A

When performed / frequency

During ILT tests and during PV phase. Monitoring during routine phase.

Required accuracy

To achieve a 20% (10% goal) [instrument requirements document] absolute flux calibration at any wavelength we need a better than 10% determination at the key wavelengths.

Inputs, prerequisites

Needs basic detector settings, wavelength calibration, RSRF, straylight characterisation, PACS calibration source characterisation (spatial, spectral and time stability).

Sources

Celestial standards with absolute flux calibrated spectra of various flux-levels in PV and later phases. Spectral features of the celestial standards have to be well known. A mixture of different types of celestial standards will allow to identify unknown features in certain object classes.
A first test by modelling the spectrum of α Boo (primary calibrator) at the key wavelengths does not show strong features which may hamper the measurements.

A list of eight fiducial stars exists with 90 μm flux densities in the range of 100 - 10,000 mJy. For these sources it is demonstrated they do not show excess at mm wavelengths (see Eva Bauwens et al presentation at the Herschel Calibration Workshop II). At all times there are at least three of these calibrators observable, with γ Dra and β Umi in the constant viewing zone.

MARCS models up to 700 μm will be made available in the calibration sources database at a resolution of 4000. These SEDs are absolutely calibrated using Selby K-band photometry and will be checked against further goundbased photometry and spectroscopy. Four of the fiducial stars (α Boo, β And, γ Dra and β Peg) will also be observed for the SPIRE photometer flux calibration. The accuracy of the stellar models in the far infrared wavelengths is assumed to be 5%.

For planets also an absolute flux calibration accuracy is assumed of 5 %. In comparison we will have to take into account the linearity (see req. 4.3.5).

Calibration Implementation Procedure (CIP)

The absolute flux calibration should be performed on several short scans at the so-called key wavelengths of celestial standards with well estblished spectral energy distributions. The primary list to be used are the stars from the list of fiducial standards with flux densities of more than 100 mJy at 100 μm. The key wavelenths are taken at high responsivity parts of the RSRF but avoiding steep slopes or spectral features (see “AOT related aspects for the PACS spectrometer” PICC-ME-SD-004). It is also investigated through modelling that the celestial sources do not to contain uncertain spectral features at the key wavelengths (like molecular bands in the case of stars). The absolute calibration of the full wavelength range will be established together with the RSRF (Req. 4.3.8). Absolute flux calibration requires celestial sources which cover a wide range in flux densities at the given wavelengths of the short scans. This is strongly connected to req. 4.3.5 Linearity with flux. Regular flux reproducibility checks on celestial standards are part of req. 4.3.4.

ILT CIP:

1. Switch-on/Setup spectrometer, select grating position corresponding to one of the primary key wavelengths.
2. OGSE black body at temperature required for a good S/N measurement at the selected key wavelength
3. Short chopped grating scans on PACS internal sources, the so-called calibration block: up and down scan chopped measurement on both CSs.
4. Same grating scan chopping between PACS CS1 and OGSE BB. Repeat as if it were the second nod position.
5. Repeat the calibration block measurement.
6. Continue this observation until all 3 primary key wavelengths have been measured.

Note: During ILT, the internal reference sources are only calibrated against extended cryo black bodies, no point-source absolute calibration will be done on ground.

Update for PV:
Small range scan measurements are performed on fiducial standard stars at the 3 key wavelengths. This is done at high sampling density, leading to a signal to noise better than 50.

Estimated time needed

With overheads about 15 minutes per key wavelength. Three different optimal temperatures for the OGSE are required. While measuring on 1 OGSE BB, the other BB can be stabilizing to another temperature. If time permitting additional measurements could be done on the secondary key wavelengths.
For PV: Three stars, each measurement costs a bit more than 1.5 hrs. Total about five hours.

Calibration Analysis Procedure (CAP)

The measured signals are products of the celestial or black body source spectrum, filter transmissions, grating efficiency, spill-over factors and detector efficiency. The input fluxes from the OGSE BBs have to be calculated for each temperature setting (see also PTD_4.3.1.) It should be checked if the signal measured in the other order at the secondary key wavelength is useful to include in the analysis. Perform wavelength calibration, including spectral distortion. Divide the resulting spectral scans by the RSRF to get the true shape of the observed spectrum. Divide the absolute flux calibrated spectrum of the celestial standard by this sprectrum to get the conversion from physical units to observed units.

Output, products

A relation between PACS calibration source signals and signals from the celestial standard at grating/band key wavelengths and, together with the RSRF, at all wavelengths. Note: The celestial standards are mainly point-sources, while during ILT only extended sources (cryo-BBs) are used.

Status/version

Update after PV planning excercise (end July 2008)

```
$Revision: 1.10 $
$Date: 2008/07/31 15:38:59 $
```

Req. 4.3.4 Flux reproducibility external sources, spectrometer

Objectives

Verify the continuum and line flux reproducibility of the spectrometer using external sources.

Fulfilling or fulfilled by

Fulfilling 4.3.2, related to 4.3.3

Priority

C

When performed / frequency

During ILT and PV. Monitoring during routine phase.

Required accuracy

5% (3% goal) [instrument requirements document]

Inputs, prerequisites

The grating needs to be wavelength calibrated (Req. 4.2.1). The basic detector settings (like bias, readout) should be established. Nominal PACS calibration sources performance.

Sources

OGSE black-bodies during ILT, celestial standard in orbit (PV and routine phase). A standard star from the list of fiducial stars would be prefered. γ Dra is in the constant viewing zone, but is still relatively faint ($F_{90} = 2$ and $F_{180} = 0.5$ Jy). For this reason a brighter secondary calibrator in the high visibilty zone is suggested: MWC 349. This is a Herbig Ae/Be star, also observed by other mm-regime observatories. To make sure that there are no small amplitude variations, unnoticed so far, we would propose to have this object also observed regularly by the photometer, where it should be combined with a measurement on γ Dra, which is known not to be variable. Having the source in the high visibility zone is important in case of problems with the instruments after which a test measurement on such a calibrator could be useful.

Calibration Implementation Procedure (CIP)

The reproducibility test in CQM is performed by scanning small wavelength ranges with both detectors. We select scans that overlap with the short scans observed for the absolute flux calibration (req. 4.3.1.). The measurements should be repeated 10 times. Most likely this could be combined with the test measurements of 4.3.1. The present description only concerns the reproducibility of measuring a continuum source and does not concern line fluxes.

Short chopped grating scans on OGSE BBs and PACS internal sources (1 scan per detector).

a) red array, 1st order
Temperatures of OGSE BBs to $T_{BB1} = (20 - x)K$ and $T_{BB2} = (20 + x)K$, with x chosen such that it produces a well-characterised signal, but avoid transients (x= 0.2 K will produce a 10% flux difference)
- grating scan (up and down) 150 to 153 micron, switching between both OGSE BBs (OGSE chopper), several read-outs per chopper plateau, several chopper cycles per grating position
- grating scan (up and down) 150 to 153 micron, switching between both PACS calibrators (PACS chopper), several read-outs per chopper plateau, several chopper cycles per grating position
Repeat the above sequence nine times.

b) blue array, 2nd order
Temperatures of BBs to $T_{BB1} = (32 - x)K$ and $T_{BB2} = (32 + x)K$ (x= 0.3 K will produce a 10% flux difference)
- repeat sequence with grating scan (up and down) 90 to 93 micron for a total of 10 measurements

Update for FM:
Although the initial test description for CQM was foreseen as a chopped measurement both for the PACS internal sources as for the OGSE black bodies, the measurements were finally performed as staring measurements (see “PACS Test Analysis Report CQM-ILT” -Part II). It is not possible to get chopped measurement on the OGSE black bodies in a way which would be representative for the chopped measurements in orbit by using the chopper wheel operating between the 2 blackbodies (PACS-ME-DS-002).

The measurement starts by performing a calibration block on the internal PACS sources (as is done at the start of each AOT, “AOT related aspects for the PACS Spectrometer” PICC-ME-SD-004; see also requirement 4.3.2.). This calibration block will be a reference measurement allowing to monitor sensitivity drifts and correct for them. It is foreseen to be performed as a chopped up and down scan (16 steps, step-size 1 pixel) on the two CSs. The exact way of executing this calibration block needs to be tested in the FM ILT test campaign and should be established before the start of this measurement.

To observe the OGSE black body in a chopped measurement, it is suggested to observe the OGSE BB in combination with the PACS internal source which would serve as “background”. In this measurement we repeat the the same up and down grating scan as was performed in the calibration block, but perform it twice as if it were a nodding measurement.

After this measurement, the calibration block should be repeated.

The whole measurement is done at least 10 times on 2 key wavelengths (one for the blue and 1 for the red detector). As it is a short measurement, it can be fitted in between other larger blocks.

In Orbit:
The nominal flux calibration measurement with short grating scans on the internal source and the calibrator as described in requirement 4.3.4 should be repeated on one selected calibration source.

Estimated time needed

ILT:
OGSE BB temperature settings → possibly .5 - 1h stabilization time (depends on starting temperature)
Each individual measurement will take approximately 15’. Ten measurements are proposed, but this measurement should be (partly) performed in combination with other measurements. In orbit:
Each individual measurement will take approximately 15’. About ten measurements should be done during PV.

Calibration Analysis Procedure (CAP)

The measured signals are products of black body emission, filter transmission, grating efficiency, spill-over factors and detector efficiency. The input flux from the OGSE BB has to be calculated for each temperature setting.

- Comparison and averaging of up- and down-scans per reference scan range (filter-order combination) for sequences on internal calibrators and sequences on cryo-black-bodies.
- Reproduceability has to be checked by comparing averaged up and down scans and comparing the up scans and the down scans seperately. This should be done for the ‘naked’ signals obtained from the internal PACS BBs and OGSE BBs and also for ‘calibrated’ signals for which the signal obtained by measuring the OGSE BBs is calibrated by using the measurement from the closest measurement in time on the PACS internal sources. Comparison is performed by determining the spread of signals per wavelength position (and visualised by plotting sigma as function of wavelength).

Output, products

The variation in measured signals on the internal and external sources.

Status/version

Update for PV.

```
$Revision: 1.11 $
$Date: 2008/03/20 13:53:28 $
```

Req. 4.3.5 Linearity with flux

Objectives

Determine the scaling relation for detector responsivity as function of incident flux (source + background).

Fulfilling or fulfilled by

Priority

A

When performed / frequency

ILT, in PV with some repetition (once in 3 months) during the further mission.

Required accuracy

Inputs, prerequisites

Outcome of requirements 1.2.3. (Dynamic range per selected capacitor) and 1.2.11. (linearity of CRE readout). Determination of the dark current (1.2.6).

Sources

OGSE Black bodies for the ILT.

In orbit; We need to measure astronomical sources with as wide or possibly even a wider range in flux densities than can be expected from the science measurements. For this we need to select from the list of stellar calibrators (primary but possibly also from the additional list of fainter ones), but also asteroids and planets as the stars will not be bright enough.

Calibration Implementation Procedure (CIP)

For ILT:
Measurement has to be done for the blue and red detectors. For each channel a key wavelength is selected and considered representative for the whole channel. At the key wavelengths the flux of the OGSE blackbodies will be measured at a range of temperatures. Most astronomical targets that will be measured have fluxes which are only a small fraction of the expected telescope background flux.

In principle linearity is measured by measuring the responsivity as function of input flux. A first test is to start from the background level and see how responsivity changes as function of increasing flux.

OGSE3: Two internal cryogenic blackbodies are available, which can be set at different temperatures between 20 and 100K ("PACS Cryo Test Equipment and OGSE Specification", PACS-ME-DS-002). We are still waiting for answers on the OGSE black bodies, but I assume that the accuracy of the temperature determination is 15mK.

As the emissivities of the OGSE black bodies cannot be adjusted we need to use a certain black body temperature to obtain an input power per pixel corresponding to that of the telescope background (emissivity=0.04, T=80 K assumed). Wait for sufficient stabilization of the BBs and the signal. Measure the BBs at different (increasing) temperatures (this should correspond to telescope + a source of 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000, 10,000 Jy).

This has to be done for the blue and red detector. Red: starting temperature of BB1 at 25K, select grating position corresponding to 130 μm. Blue: starting temperature of BB1 at 30K, select grating position corresponding to 100 μm.

Update for FM:
The measurement will be done in chopped way, as is the case for 4.3.4. The 2 key wavelengths on which we will measure are: B3: 58 μm and R1: 148 μm.

PV phase:
The nominal flux calibration measurements are to perform small grating scans, on astronomical standard. The scans are

performed around the Key Wavelengths. This measurements are performed with the Range Scan AOT (high density) and will start with a calibration block measurement on the PACS internal sources. The number of scans depends on the flux density of the calibration standard.

For this requirement we need to cover a flux range which corresponds to the flux range of science targets that we expect to observe. It will not be possible to do this with stars alone, so that we will need to include different types of calibrators like asteroids and planets.

Estimated time needed

For ILT:
This measurement is identical to 4.3.4., accept for the different temperatures of the OGSE BBs. Initial stabilisation of the OGSE BB is about .5 hour, after that for each temperature change 10 minutes (email on November 17 2003 from OGSE godfather M. Groenwegen). Total duration is about 2.5 hours. For both detectors five hours. (Each measurement block (not taking into account the time for BB stabilization) is about 15 minutes).

For PV:
For the standard stars the observing time is the same as in req 4.3.3 (absolute flux calibration). Total time for a $\approx$ 10 Jy source is abit more than 1.5 hours. This is reduced to about 1 hour for a $\approx$ 100 Jy source.

We need measurements on about ten different calibrators.

Calibration Analysis Procedure (CAP)

The output of the measurements are data cubes (25 spatial pixels, 16 wavelength pixels).

```
---25 spatial pixels--- 1
----------------------- 6
.                       w
.                       a
----------------------- v
----------------------- e
```

Determine the flux from the BB (Jy / pixel) for each wavelength and divide the measured signal (flat-fielded) per pixel by that flux. Plot the responsivities as function of input flux.

Output, products

Status/version

Update after PV planning excercise (end July 2008)

```
$Revision: 1.7 $
$Date: 2008/07/31 15:40:06 $
```

Req. 4.3.6 Minimum detectable flux, spectrometer

Objectives

Determine the minimum detectable line (and continuum) flux with the spectrometer. This determination is made empirically. Thus, it provides estimates for the signal-to-noise ratios (SNR) that PACS users can expect in the presence of all sources of noise (whether accounted for in theory-based estimates of SNR or not).

Knowledge about two relationships is required: (i) the SNR vs flux relationship, and (ii) the SNR vs total observation time relationship. The minimum detectable flux for a given observing duration is simply the corresponding flux value for an adopted threshold criterion (SNR) for detection. The second relationship extends this flux limit to other observing times.

Fulfilling or fulfilled by

Partly fullfilled by 4.3.1-5.

Priority

C

When performed / frequency

ILT, PV phase, begining of routine phase. Understanding will grow during mission.

Commissioning:

One possibility is to use the cooling of the telescope mirror as a source of flux difference. Based on the plot of the telescope cooldown[3] I have calculated the ratio $B_\lambda(T)/B_\lambda(85K)$ scaling the curve to an end temperature of 85 K. The table also list the day number after the end of active heating when this temperarure is reached.

T (K)	70 μm	110 μm	170 μm	200 μm	(day after end of acitve heating)
85	1.00	1.00	1.00	1.00	$>$ +20
90	1.16	1.12	1.09	1.08	+11
95	1.33	1.24	1.20		+10
100	1.50	1.36	1.28	1.26	+9
110	1.86	1.60	1.47		+8
120	2.25	1.85	1.66	1.62	+7
130	2.65	2.10	1.86		+6
140	3.06	2.37	2.05	1.98	+5
150	3.48	2.62	2.25		+4
160		2.89			+3
170		3.15	2.64	2.52	+2

If the plot is correct and the end temperature is 100 K, $B_\lambda(T)/B_\lambda(100K)$ becomes

T (K)	70 μm	110 μm	170 μm	200 μm	(day after end of acitve heating)
100	1.00	1.00	1.00	1.00	$>$+20
110	1.24	1.18	1.15		+13
120	1.50	1.36	1.30	1.27	+10
130	1.77	1.54	1.45		+8
140	2.04	1.74	1.60	1.55	+7
150	2.32	1.92	1.76		+6
160		2.12			+5
170		2.31	2.06	1.96	+4
180	3.17	2.52	2.21	2.14	+3

[3] the file telescope_cooldown.pdf in UK mail of 18 July 2007.

To summarize, the telescope cool down provides an interesting and relevant range in flux steps, but the cool down is such that in order to sample this properly the PACS spectrometer needs to be prime very second day for some time atleast.

PV: For continuum sources will be full-filled by Req. 4.3.1-5. That dataset should be sufficient to determine SNR= f(Flux). The dependence on integration time would be a non-standard thing, but could be envisaged as part of AOT testing.

For line sources, additional measurements will be necesary (could be combined with AOT testing). A suitable number of line sources need to be observed in a few sources with different line strengths (e.g. PNe).

Required accuracy

TBD

Inputs, prerequisites

We require knowledge about the input flux. And, knowledge of various detector characteristics, identified below, is needed:

- Detector responsivity.
- Detector spectral response.
- Spectrometer band-pass.

Sources

For in-flight measurement, no special sources are needed; Input data from objects observed during PV and routine phase are likely sufficient.

During the ILT, a line emission source (e.g. lamps), if available, is required to determine the minimum detectable line flux. The EGSE or intercal calibration sources are sufficient for determining the minimum detectable continuum flux.

Calibration Implementation Procedure (CIP)

We adopt a detection with SNR equal to 10 as a criterion for minimal detectivity. A SNR threshold of 10 is preferable because it avoids various statistical biases (e.g. Eddington bias) that are found in the lower, but more widely used, threshold of 5.

It is quite likely that the CIPs already implemented for other calibration activities will generate the data needed to adequately characterize the two relationships identified above. For example, the CIP used to determine detector non-linearity will likely be useful here as well. Specifically, the following data are needed:

- Measurements made for a fixed integration time but for various input flux levels.
- Measurements made for a fixed input flux level but for various integration time.

The number of such measurements depends on the detector non-linearity, if any. In theory, one expects a linear relationship between flux and SNR on a log-log plot:

$$SNR \propto \sqrt{Flux},$$

Thus,

$$\mathrm{Log}_{10}(SNR) \propto 0.5 \times \mathrm{Log}_{10}(Flux)$$

Equation 16.4.14 by Schroeder (D. J. 1987, in *Astronomical Optics*, San Diego: Academic Press, Inc., pg. 324) describes this relationship in more detail. For our purposes, Schroeder's equation can be reduced to:

$$\text{Log}_{10}(Flux) = A + B \times \text{Log}_{10}(SNR)$$

Thus, in theory, one needs only two pairs of (flux,SNR) data points to determine the two unknown constants (A, and B) to fully characterize this relationship. However, the (expected, TBD) presence of fringes in the spectra and any other non-linearities (transients, for instance) will significanly alter this linear relationship. The good news is that complicated theoretical models for fringes or transients, etc. are not necessary for our purposes. We need only to characterize the flux vs SNR relationship empirically at the low-flux end. Using prior experience as a starting point, we assume that the actual relationship is likely to be a combination of a linear and a non-linear component. And, further assume that the non-linear component is adequately fit by a model with 3 parameters. A total of 5 data points (flux,SNR) are, thus, minimally required to do an initial characeterization. The results from this exercise will determine if our assumptions and, hence, the gathered data, are sufficient. This discussion applies to both continuum and line measurements, as described in the CAP below.

The relationship between SNR vs total integration time is mathematically similar to the one for SNR vs flux. Hence, the same arguments can be applied here and we require 5 independent data pairs of (SNR,time) to do an initial characeterization.

Estimated time needed

PV:

For continuum sources no special measurements are needed as the data taken to fulfull req. 4.3.1-5 should suffice.

For line sources one would like to observe a few different lines (covering the spectral orders) in a few sources that have different line strenghts. One can think therefore of 3 lines measured in 5 sources each, or 15 observations (minimum).

The observation can be carried out using the line-scan AOT which takes 8 min. Therefore a total time of 2h is needed.

Calibration Analysis Procedure (CAP)

For a given input flux the SNR is calculated from the data as follows:

Continuum measurements: The error is simply the standard-deviation of the continuum level. This is determined either from a small section of the continuum where simple line (linear)-fitting is sufficient, or over the whole continuum if the continuum can be adequately modeled (eg. via a black body).

Line measurements: For weak lines (for which this CIP is sought), the error on the measured equivalent width is calculated by adding in quadrature the error of each pixel included in the spectral band-bass. This is given by (see, for example, Ramirez et al. 1997, AJ, 113, 1411):

$$\sigma_{line} = \sqrt{2N} \ \times \ \sigma \ \times \text{dispersion}$$

where, N is the number of pixels contained within the defined feature band, and σ is the error per pixel in the continuum measurement. This formula assumes that the rms in the line itself is approximately equal to the rms of the continuum level. This is a valid approach for weak lines in background dominated case because photon noise dominates the magnitude of the error.

Thus, the SNR for a equivalent width, EW, is given by:

$$\text{SNR(line)} = \frac{EW}{\sigma_{line}}$$

The above formulae are used to obtain the SNR vs flux (or time) relationshiop for all points for which the data are available. These are then fitted by an appropriate model to obtain the full SNR vs flux (or time) relationship. The minimal detectable flux value is then, simply, the flux corresponding to SNR of 10.

Output, products

An estimate for the minimum detectable line flux.
An estimate for the minimum detectable continuum flux.

Status/version

Sixth draft version

```
$Revision: 1.8 $
$Date: 2007/10/30 10:40:10 $
```

Req. 4.3.7 Pseudo-noise, spectrometer

Objectives

This requirement aims at charactering sources of noise not directly related to the noise in the electronics. Sources of this so called "pseudo-noise" could be due to:

- **A** timing jitter in the readout,
- **B** timing jitter between the chopper and the readout,
- **C** digitisation noise,
- **D** the effect of data compression,
- **E** mechanical noise of grating movement.

Fulfilling or fulfilled by

Priority

C

When performed / frequency

During ILT when applicable, but in the end has not been characterised. It is extremely difficult to impossible to disentangle these different sources of extra noise. Therefore no dedicated tests are required in PV.

Required accuracy

The pseudo-noise is required to be at a level of less than 20% of the system noise.

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

(A) Unclear how this could be determined.
(B) Unclear how this could be determined.
(C) Unclear how this could be determined.

(D) The effect of data compression can be verified by performing a TBD analysis on compressed and uncompressed data taken under various conditions in terms of point source over background flux and observing modes.

(E) Unclear how this could be determined.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

First draft version

```
$Revision: 1.6 $
$Date: 2007/10/26 13:22:35 $
```

Req. 4.3.8 Relative spectral response function, spectrometer

Objectives

Determine the Relative Spectral Response Function (RSRF)

In principle, the (relative) spectral response function is the product of the (relative) spectral response functions of all components involved, namely, detector, grating, filters, PACS optics, telescope optics. By determining all these RSRFs the full system RSRF could be determined. However, measurements on component level are not available, and some effects are highly dependend on system characteristics (e.g. filter transmission depending on the angle of incidence), so the RSRF needs to be determined accurately on system level.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

ILT, PV, monitoring in routine phase

Required accuracy

Required accuracy depends on the wavelength range. A relative accuracy of better than 1% is needed on the scale of a resolution element in order to preserve line fluxes to the required accuracy. Over a larger wavelength span (a few microns), a relative accuracy of 5% is necessary to allow the detection of solid state features and accurately determine the continuum.

Inputs, prerequisites

The grating needs to be wavelength calibrated (Req. 4.2.1). The basic detector settings (like bias, readout) should be established. Nominal PACS calibration sources performance.

Sources

On-ground: OGSE black bodies In-orbit: Bright sources (¿10 Jy), with well determined (1%) spectral shapes, not necessarily absolute flux calibrated. Bright sources (100Jy), not variable, point-source.

Calibration Implementation Procedure (CIP)

The strategy is to measure the RSRF at very high S/N during the Instrument Level tests, and to verify its validity during PV, and -if necessary- apply corrections to the ILT RSRF based on detailed spectral scans of celestial calibration sources.

The ILT test is done by measuring a full spectral scan of an OGSE blackbody at the optimal temperature to provide a sufficient input flux without saturating the detectors. This measurement is performed with the chopper in a fixed position.

The dependence of the RSRF on chopper position is characterised by repeating the measurements at the 6 chopper positions that correspond to the large, medium and small chopper throws in the AORs.

Spectral leakage is characterised by repeating the measurement at different OGSE blackbody temperatures.

A short but detailed scan of the point source mask behind the external cryostat window (with on and off position) is performed to detect possible fringing that might remain undetected in the RSRF scans on the extended OGSE blackbodies.

The same detailed RSRF scan is also performed on the internal calibration sources.

During PV, the detailed RSRF scan on an internal calibration source is repeated. This gives a first indication on the validity / corrections necessary on the ILT RSRF.

The RSRF is further validated via deep spectral scans on celestial calibration sources for which reliable reference SEDs are available. These can be done similar to the chop/nod range scan AOR at the highest spectral sampling, over the full grating position range. This is repeated on different calibration sources that are chosen not to be affected by the same biases or uncertainties in our knowledge of the spectral shape.

The chopper-dependent difference in shape can be validated by repeating a full SED spectrum of the same bright source (spectral shape not necessarily known very well, as long as it it not variable) at large, medium and small chopper angle in the following 6 combinations: (+S/-S, +M/-M, +L/-L, +L/0, +M/0, +S/0)

Throughout the routine phase, the RSRF is monitored through the observation of detailed, deep spectral scans and shallow full range spectral scans of a non variable, bright source.

Estimated time needed

- ILT RSRF measurement: 5.5 hours per spectral scan; 11hours for all spectral bands
- ILT Broadband validation : 1 hour quick full spectrum in both bands

- PV Internal CS RSRF scan: 11 hours (can be done before the telescope has reached a stable temperature)
- PV Deep chop/nod scan on 2 sources with well know spectral shape : 2x11 hours = 22 hours
- PV Chopper-dependent difference in shape: 6x 1.5 hours = 9 hours

Calibration Analysis Procedure (CAP)

The output of the measurements are data cubes (25 spatial pixels, 16 wavelength pixels), for each step.

```
---25 spatial pixels--- 1
----------------------- 6
.                       w
.                       a
----------------------- v
----------------------- e
```

Determine the flux from the BB (Jy / pixel) for each wavelength and divide the measured signal (flat-fielded) per pixel by that flux. Compare and average the up and down scan.

Output, products

Status/version

Update for the FM ILT

```
$Revision: 1.8 $
$Date: 2007/10/31 14:38:13 $
```

Req. 4.3.9 Flat-field spectrometer internal sources

Objectives

This requirement aims at characterising the pixel-to-pixel variations in gain due to differences in their responsivity (detector flat field) and illumination (optical flat field), using the internal calibrators. In a full-system the two types of flat field can not be distinguished.

Fulfilling or fulfilled by

For QM and FM fulfilled by 4.3.8. Selfstanding for modular detector level tests.

Priority

A

When performed / frequency

During ILT, PV and routine phase.

Required accuracy

TBD percentage. Impact on achievable accuracy in flux determination.

Inputs, prerequisites

QM/FM: Optical distortion map must be known (PACS and test optics). Level of homogeneity and isotropy of the internal and external blackbodies must be known.

Sources

On-ground: Black bodies

Calibration Implementation Procedure (CIP)

ILT detectors only: determine the responsivity of all pixels under various bias and input power conditions. The suitably averaged responsivities give the detector flatfield.

OGSE3: Two internal cryogenic blackbodies are available, which can be put at different temperatures between 20 and 100K (PACS Cryo Test Equipment and OGSE Specification, PACS-ME-DS-002). Contrary to the PACS internal calibrators the emisivity can not be varied (ϵ = 1).

To obtain similar power on the pixels as expected from the telescope background, the OGSE blackbodies need to be operated at considerable lower temperatures than the nominal 80K expected for the telescope. Calculations (by MG) show that at 70 μm the OGSE blackbodies need to be operated at 36 K, at 110 μm at 28 K, at 170 μm at 22 K, and at 210 μm at 19-20 K, to obtain the same fluxes as a blackbody with T = 80 K and ϵ = 0.04.

The test can proceed as outlined in 4.3.8.

PV:

One aspect of the flat-field that has been underrepresented so far is related to the pixel-to-pixel variation using different capacitance values.

Apart from that the FF can be derived from the FoV maps, like in FMILT.

The chopper is stepped from approximately -23500 to +23000, and then back. The step in chopper position is 150 steps, and at each step 5 ramps of 0.25s were taken.

At least during the first test at the beginning of PV, the scan should be made at several wavelengths. Proposed are the key wavelengths at grating positions 300000, 450000, 535000, 600000, 950000.

Estimated time needed

see 4.3.8 for QM/FM tests.

PV:

Time of a single FoV scan as described above is 14 minutes, times 5 key wavelengths implies 70 minutes (For a single capacitance setting).

Initially, the capacitance is set to the largest value (1.1 pF) in red and blue. The data is analysed to check for saturation !

Then the block of 5 x 14 min is repeated (i.e. on another day when the spectrometer is prime) at the next largest capacitance value.

This is repeated until blue and red go into saturation in most pixels.

Calibration Analysis Procedure (CAP)

The output of the measurements datacubes (25 spatial pixels, 16 wavelength pixels), for each step.

```
---25 spatial pixels--- 1
----------------------- 6
.                       w
.                       a
----------------------- v
----------------------- e
```

If the BB were uniform and there were no distortions, and all pixels had the same sensitivity, then each pixel in every row would have the same output (assuming that the flux levels are far above dark current). Different rows would have different output which would follow the input flux BB(T, lambda). The latter effect is small (FOR ONE GIVEN GRATING POSITION), $<0.1\%$.

In a perfect world, the flat field would then be the output map divided by the average over the 25x16 pixels, for each grating position.

In the real world, one had to apply the distortion map for all pixels and all grating positions first.

In the simplest approach the FF is the normalisation of the RSRFs obtained in 4.3.8 over the pixels.

By comparing the FF obtained from the internal and external sources one obtains information on the combined effect of: distortions from the test optics, time variations.

Output, products

Flatfield for every wavelength position, or at key wavelengths only.

Status/version

```
$Revision: 1.9 $
$Date: 2007/10/29 13:53:10 $
```

Req. 4.3.10 Flat-field spectrometer external sources

Objectives

This requirement aims at characterising the pixel-to-pixel variations in gain due to differences in their responsivity (detector flat field) and illumination (optical flat field), using external sources. In a full-system the two types of flat field can not be distinguished.

Fulfilling or fulfilled by

Related to 4.3.9

Priority

A.

When performed / frequency

During ILT, PV and routine phase.

Required accuracy

TBD percentage. Impact on achievable accuracy in flux determination.

Inputs, prerequisites

-Optimal bias voltage

-Chopper extreme positions

Sources

ILT detectors only: determine the responsivity of all pixels under various bias and input power conditions.

CQM and FM-ILT: This test will be covered by the scans over the FoV.

In-orbit: bright point sources, or "cosmological" fields with no bright point sources and no diffuse background.

Calibration Implementation Procedure (CIP)

OGSE set-up

The 'crude' idea (and in the ideal case) is to measure a point source of constant flux at all pixels. Since the input flux is assumed constant, the suitably normalised image of output flux constitutes the flat-field. This idea follows the only practical implementation of this requirement in orbit.

The weaker alternative is to have an extended source of constant and homogeneous illumination. On the ground this would be the external blackbody (but has this constant illumination over the FOV ?), and in orbit an empty skyfield (and how homogeneous is the telescope emission ?)

Problems involved are, (1) the optical distortions (both PACS internal, and in the OGSE optics), (2) the point source nature of the OGSE black-bodies, (3) the brightness of the black-bodies w.r.t. the background signal (provided by the hot plate).

The diffraction limit, 1.22*wavelength/diameter, varies from 4.3 arcsec at 60 micron to 14 arcsec at 200 micron. Any source with a size smaller than this may be considered a point source. The pixel FOV of the spectrometer is 9.4 arcsec.

DL's note from 26-nov-2002 (e-mail 27-nov-2002; PICC-ME-TN-011) regarding the "contrast of observations with punched masks in PACS ILT" illustrates another issue and that is that the ratio of signal-to-background (S/B) is a strong function of wavelength, temperature and size of the punched mask. For example, a hole size of 0.36mm diameter corresponds to 2 arcsec. At 60 micron this maybe considered a point source. For a temperature of the source of 500 K behind the punched hole, and a background of 300K, this corresponds to S/B = 0.074. At 170 micron this has dropped to S/B = 0.010. This implies that in a grating scan with increasing wavelength, one has to change, either the integration time, the size of the hole, or the temperature of the hot source, in order to get the same S/N determination for all wavelengths.

Since very likely the exact differences between different punched hole sizes are not well known, and the temperature control of the hot source is not very accurate (and likely variable in time), it is a-priori suggested to perform the observations for a fixed temperature, and fixed punched hole size.

step 1) choose a hole size of 0.5mm (2.8 arcsec), to ensure a point source behaviour at all wavelengths.

step 2) choose the highest temperature of the hot source (750K following "PACS cryo test equipment and OGSE specification", PACS-ME-DS-002), to maximise the contrast.

Following DL prescription, one can calculated the following S/B for this set-up: 60 micron (0.48), 110 micron (0.12), 170 micron (0.045), 210 micron (0.029). Increasing the hole by a factor of 2 will increase the contrast by a factor of 4.

As one would like to determine the flat field (speak signal) with an accuracy of typically 1%, this implies a S/N of 100 on the signal, which means a S/N of 3000 on the continuum (at 210 mircon), or 2000, 800, 200 at 170, 110, 60 micron. This does not take into account the noise introduced by the background subtraction (when chopping). Nevertheless, it indicates that this test should be carried out in such a way as too achieve the highest S/N.

I have calculated the power on the detector from P = signal * area * pixel * trans1 * trans2, where signal = $\int$ (BB(750)-BB(300)) is the integral of the BB-curve over the bandwidth; area = telescope surface area; pixel = pixel size in sr; trans1 = overall transmission in PACS (assumed 0.15 for spectrocopy); trans2 = factor to take into account OGSE optics.

trans2 = 0.01 since there is a 100x attenuation on the LHe shield. Additionally, there is a filter wheel, but this is kept in the "open" position.

For 9.4 arcsec pixels, one obtains, at 60 micron (2.9 10^{-13} W/pixel), 110 micron (4.9 10^{-14}), 170 micron (1.3 10^{-14}), 210 micron (6.2 10^{-15}).

Based on "PACS Spectral Calibration Requirements for ILT" (PACS-ME-PL-003, appendix), one can expect a S/N of 5000 for a flux level of 1.(-11) W for 1 reset interval of 16 ms. From this assumption, the estimated fluxlevels, and the desired S/N ratios, it then follows that per grating position one would need 1, 5, 150, 600 reset intervals of 16 ms at 60, 110, 170, 210 micron.

If one would step the grating by 2400 units (Nyguist sampling) a grating scan would need 360 steps (in first order). Taking 12 1/4s ramps on source per grating position, chopping, up-and-down scan at the 5×5 spatial pixels would take 30h (one order).

Based on this consideration it seems only feasible to not do a full scan, but smaller scans around the primary and secondary key wavelengths.

In the case of using an extended external source the spatial sampling would become irrelevant (gaining a factor of 25), so that a Nyquist sampled full scan does become feasible.

set-up with point-source:

-set size hole
* 0.5mm (2.8 arcsec) for order 2 and 3
* 1.1mm for order 1

-set temperature of hot source

-command x-y-stage to the position that corresponds to the centre of, say, the upper left spatial pixel.

-Set wavelength to one of the 14 key wavelengths; make a scan of 2 x 2400 grating units centered on these key wavelength.

12 readouts of 1/4s, chop, up-and-down scan.

In the red some on-line reduction is needed as the integration time may need to be increased.

-command the x-y-stage to the next spatial pixel (or position), etc.

set-up with external BB:

-A minimum of 3 high priority measurements are required, with respectively one of the calibration sources and the OGSE BB set to cold & cold, nominal temperature & cold and nominal temperature & 40 K (TBC).

-For each of these measurements a scan is made from the extreme chopper positions -25000 tot +25000, in steps of 500 (corresponding to about 1 spatial pixel), and then back.

- At every chopper position we integrate for 5 seconds (using ramps of 1/4s).

- Every 10 chopper steps, we integrate for 5 seconds on both calibration sources.

- This is repeated at four key wavelengths (grating positions 666000, 535000, 461000, 335000).

PV, In-orbit:

A bright point source is stepped over the spatial pixels.

Although one would like to step by 1/3 or 1/2 pixel this might be too time prohibitive (at least put into one single measurement)

The standard case would be to step by 1 spatial pixel. This then would require 25 measurements, at at least 3 different wavelengths (one per order).

Estimated time needed

(25000 - -25000)/500 * 2 = 200 steps * 5 sec = 1000 sec + 200/10 * 2 * 5 sec calibration = 1200 sec * 4 wavelengths = 4800 sec.

3 times 4800s is 4 hours. Four optional measurements using slightly different set-ups would require an additional 5.3 hours.

PV:

Following HSPOT, a line-scan AOT in mapping mode (raster point step= 9 arcsec, rasterline step= 9 arcsec, number of raster points per line= 5, number of raster lines= 5) takes 8300 sec (2.3h), for one wavelength setting. Therefore a minimum of 7 hours are needed in total to cover 3 wavelengths wih the bare minimum of 1 pixel steps.

Additional measurements later in PV could have larger step sizes and only at one wavelength.

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.13 $
$Date: 2007/10/30 10:46:44 $
```

Req. 4.3.11 Stability telescope background for spectrometer

Objectives

The emission of the telescope will in almost all PACS observations be the dominant source of background flux. The structure in, and the time variation of, the telescope emission is therefore of crucial importance in the finally achievable minimum flux levels, and observing strategies.

Investigate the S/N dependence as a function of chopper mode, chopper frequency and chopper throw.

Investigate for fixed chopper parameters, the influence of the S/N on secondary parameters (for example, the pointing of the telescope relative to the Sun).

Fulfilling or fulfilled by

Priority

A

When performed / frequency

PV phase, as a realistic telescope background is available only then. The absoloute minimum is to perform 2 tests, namely towards the beginning and end of PV to make use of the further cooling and hence change in BG flux level. If the test at the beginning of PV shows significant structure then a more frequent monitoring must be envisaged.

Required accuracy

TBD.

Inputs, prerequisites

Detector settings known. Calibration sources tuned to near-BG levels (to avoid unneccesary transients).

Sources

Choose fields with low sky background and few sources that will have line emission.

Calibration Implementation Procedure (CIP)

PV:

Perform a scan over the field-of-view, similar to those executed during FMILT.

The chopper is stepped from approximately -23500 to +23000, and then back. The step in chopper position is 150 steps, and at each step 5 ramps of 0.25s were taken. In the red the capacitance is set to the largest value (1.1 pF), in the blue to the smallest (0.14 pF).

At least during the first test at the beginning of PV, the scan should be made at several wavelengths. Proposed are the key wavelengths at grating positions 300000, 450000, 535000, 600000, 950000.

Estimated time needed

PV:

Time of a single FoV scan as described above is 14 minutes.

The test at the beginning of PV should cover 5 wavelengths, thus 70 min. total.

Depending on the outcome of this first test, further tests could be planned.

In a worst case, there is a significant structure and it is wavelength dependent. Then, a more frequent monitoring is need, the timescale TBD.

If no significant structure is visible, then a block of 5 times 14 minutes towards the end of PV should suffice.

An alternative way would be to perform a line-scan AOT with non-standard chopper-throws (e.g. (+3 arcmin,0), (0,-3), (3,-3)). Such an observation would take 8 min. per setting and wavelength.

Calibration Analysis Procedure (CAP)

Make the scan, and investigate the spatial pixels. “Things” that move belong to the sky, structures that do not move belong to the telescope background.

Output, products

Status/version

Req. 4.3.12 Instrumental polarization spectrometer

Objectives

Determine the instrumental polarization of the spectrometer. The grating is strongly polarized and this is a strong function of wavelength.

Fulfilling or fulfilled by

Priority

C, as we do not expect to observe strongly polarized sources.

When performed / frequency

PV: TBD. Are there any strong sources with known polarization in the far-IR ?

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Any observations should be differential in time to use the fact that the focal plane has rotated.

Estimated time needed

Calibration Analysis Procedure (CAP)

Output, products

Status/version

Chapter 5

Optimized Observing Strategies for AOTs and Scientific Validation of AOTs

In order to achieve the highest possible calibration accuracy it is not only necessary to properly characterize all instrumental effects and establish the transfer relation between instrumental units and astrophysical flux units, but also to apply the optimal observing strategy in order to minimize systematic effects, enhance the source-to-background or line-to-continuum contrast and increase the S/N ratio. The observing strategy may also depend on the nature of the source (brightness, spatial extension or structure). Another issue is the frequency of internal reference calibrations to cope with instrumental drifts.

We therefore include here this special section in order to ensure that, beside simulations, sufficient real testing of observing modes is performed on well known sources prior to release of Astronomical Observation Templates AOTs. This comprises also consistency checks whether different but comparable observing modes yield consistent results.

These AOT verification measurements will also provide one suitable data set for the scientific validation of the data processing in Standard Product Generation.

One aspect to consider in the verification of the AOTs and their different modes is the priority of the individual modes. According to a statistical assessment of the Guaranteed Time Key Project observing mode requests, the most important PACS AOT modes are

for the photometer:

1) Scan mapping mode
2) Point source photometry
3) Chopped raster mapping mode
4) Small source photometry

and for the spectrometer:

1) Line scan spectroscopy pointed in chop/nod mode
2) Range scan spectroscopy pointed in chop/nod mode
3) Line scan spectroscopy mapping with chop/nod

4) Line scan spectroscopy mapping with wavelength switching
5) Range scan mapping with off-position

5.1 Photometer AOTs

A detailed description of all PACS photometry AOT modes is given in the PACS Observer's Manual (Herschel-HSC-DOC-0832).

The PACS photometry AOT comprises three main submodes:

1) point-source photometry
2) small-source-photometry
3) large area or extended source mapping

The large area or extended source mapping has two technical realisations:

3.1) raster mapping mode including chopping
3.2) scan mapping mode without chopping

Scan mapping can be aligned with the instrument reference frame or with the sky coordinate system.

A statistics performed on the GT and OT Phase 2 AORs gives the following most frequently requested AOT parameters to be considered for calibration:

- Point source
  - repetition factor: 7, 1, 10, 30
- Small source
  - repetition factor: 1, 2, 16
- Raster map
  - repetition factor: 1, 3, 2
  - x-step size: 180, 12, 30, 105
  - y-step size: 45, 90, 30, 52.5
  - no. of raster lines: 2, 3
  - no. of points per line: 5, 2, 3, 4
- Scan map
  - repetition factor: 1, 4, 2, 15
  - scan speed: low, medium
  - scan length ('): 12, 7, 11, 8, 10, 17, 4, 5, 21-25, 81-100
  - cross-scan distance (“): 148.5 (hom. cov.), 25, 20, 210, 51-60, 50
  - map orientation spec: instrument, sky (4:1)
  - orientation angles (deg): 45 (inst), 135 (inst)

Req. 5.1.1 Optimized Observing Strategy for Point Source Photometry AOT

Objectives

Verify and if necessary optimise that the Point Source Photometry AOT gives accurate fluxes for compact point-like sources in all three bands. Check that for a flux range from very bright (≈1000 Jy) down to faint (≈5 mJy) sources, with main emphasis on fainter targets.

- Check it for sources of different spectral shapes (colour correction factors, near-IR leaks).
- Check that dithering and no-dithering give consistent results.
- Check that the chopper amplitude and the chopper frequency is producing the best photometric performance (with respect to the source positioning on the array, the chopper transition times, noise and pipeline aspects).
- Check that it works for SSO objects (tracking).
- Check consistency with other PACS photometric modes (photometry in raster and scan maps).
- Check that the calibration concept works (duration of initial calibration block, repetition of calibration block in-between very long observations).
- Check if the photometric results from low and high gain measurements agree for sources of intermediate brightness (high gain observations are performed with 2-bit SPU onboard rounding).
- Compare the default SPU reduction/compression scheme (average of 4 readouts) with averaging of 8 frames (used in the PACS/SPIRE parallel mode) and averaging of 2 frames (as a possible option for point-source photometry for selected sub-arrays only, and/or the option for faster chopping).
- Check this mode in combination with detector selection tables (to deselect dead/noisy pixels and/or to deselect parts of the array with are not needed for this mode).

Fulfilling or fulfilled by

This AOT may be also used for some full system photometric system calibration tasks:

- req. 2.1.2 to search for filter leaks (different spectral slopes)
- req. 3.2.1 to derive the photometer nominal responsivity
- req. 3.2.3/3.2.4 to establish and calibrate the photometer's non linearity
- req. 3.2.5 to check the relative system response and the colour correction terms

Several observations might also be part of the cross-calibration program (between different PACS modes, between different types of celestial standards, between the Herschel instruments, between Herschel, ISO, Spitzer, Akari, IRAS, . . .)

Priority

A

When performed / frequency

1) During FM-ILT
2) During FS-ILT
3) During PV and Science Validation Phase

4) During Routine Calibration Phase

Required accuracy

- For bright sources around absolute photometric accuracy (5 – 10%).
- For the faintest sources within achievable S/N accuracy.

Inputs, prerequisites

- Cooler recycling
- Optimal bolometer biases (and sequencer) have to be known for the given telescope background.
- Successful technical verification of this mode (OBCP and DMC sequence functioning, timing/synchronisation between instrument and satellite activities, sky source and CS positioning on the arrays, filter operations, SPU configurations, . . .)
- Pointing calibration has to be sufficient to place the source in the centre of a blue matrix (the total of 3×1.33 blue pixel dither pattern has to be placed well within the size of one blue matrix).
- Verification of the chopper calibration (transition times should be well within a bolometer readout of 25 ms).
- Bolometer saturation limits have to be known (Uranus and Neptune will probably exceed the possible limits in the blue and green filter).
- SPU reduction/compression mode has to be consolidated to stay within the data rate bandwidth of 130 kbits/s.
- PACS CS settings have to be established to provide fluxes very similar to the telescope fluxes in all 3 bands.
- Knowledge of the brightness limit for the switch from low to high gain. Knowledge of the saturation limits (AD converter and bolometer output voltage).

Sources

Compact point-like sources:

- Ceres as bright source (and maybe Uranus and Neptune in the red filter)
- Several asteroids and bright fiducial stars as intermediate sources (S/N = 100)
- Several faint stars (S/N $\approx$ 10) and quasars (observed with ISOPHOT/MIPS)
- Several faint stars (S/N $\approx$ 10) from the MIPS 70 μm list (Gordon et al. 2007, PASP 119, 1019)

Calibration Implementation Procedure (CIP)

- Use PACS point source AOR in dither and non-dither mode on all sources in both filter combinations (if meaningful with regard to S/N and saturation).
- Select the integration times to obtain the required S/N-values ($\approx$10, $\approx$100).
- Select observing periods with low confusion backgrounds for the planets and asteroids.
- Use PACS non-standard AORs to execute examplaric observations with the outer parts of the bolometer arrays deselected (the outer 4 matrices in the blue, parts of the red arrays).

- Use PACS non-standard AORs to execute examplaric observations with modified chopper frequency and/or dither patterns.
- Use PACS non-standard AORs to execute observations on the same target in low and high gain (including aspects of the SPU bit-rounding procedure).

Estimated time needed

Test of flux levels and spectral slopes. 4 concatenated AORs per target:
(a) filter A dithered, (b) filter B dithered, (c) filter A non-dithered, (d) filter B non-dithered).

- low flux target 1: (a)+(b)+(c)+(d) = 4 × 1710 s
- low flux target 2: (a)+(b)+(c)+(d) = 4 × 1710 s
- intermediate flux target 1: (a)+(b)+(c)+(d) = 4 × 486 s
- intermediate flux target 2: (a)+(b)+(c)+(d) = 4 × 486 s
- high flux target: (a)+(b)+(c)+(d) = 4 × 333 s

Notes:

- targets 1 and 2 should have different spectral slopes (and/or low/high flux at near-IR wavelengths);
- high flux: several Jy;
- intermediate flux: between 100 mJy and 1 Jy
  (calculation done for 300 mJy);
- low flux: between 10 and 100 mJy
  (calculation done for 30 mJy).

Total time: 5.25 hours

Non-standard AORs on faint/intermediate brightness target to explore the chopper frequencies: 1.25 Hz (16 readouts per chopper plateau = default), 2.5 Hz (8 readouts per chopper plateau), 0.625 Hz (32 readouts per chopper plateau).

- low/intermediate flux target: (a)+(b), chopFreq 1.250 Hz
- low/intermediate flux target: (a)+(b), chopFreq 2.500 Hz
- low/intermediate flux target: (a)+(b), chopFreq 0.625 Hz

Total time: 6 × 486 s = 0.81 hours

Non-standard AORs on intermediate flux target to verify the photometry using high and low gain settings.

- intermediate flux target: (a)+(b), high gain (+ 2-bit rounding)
- intermediate flux target: (a)+(b), low gain (+ no rounding)

Total time: 4×486 s = 0.54 hours

Non-standard AORs on low flux target to investigate the impact of 2-frame averaging (for a sub-array only), 4-frame averaging (default) and 8-frame avergaing (PACS/SPIRE parallel mode) in high gain (+ 2-bit rounding):

- low flux target: (a)+(b), 2-frames averaging (selection of sub-array)
- low flux target: (a)+(b), 4-frames averaging (default)
- low flux target: (a)+(b), 8-frames averaging in the blue channel only (PACS/SPIRE parallel setting)

Total time: 6×1710 s = 2.85 hours

Non-standard AORs to investigate the hold-time aspects (frequency of calibration blocks):

- low flux target: (a)+(b), 4-frames averaging (default), high gain, hold time infinity (default)
- low flux target: (a)+(b), 4-frames averaging (default), high gain, hold time of 330 s (or something similar which would interrupt the AOR after each chop-nod observing entity to perform a calibration block of about 40 s)

Total time: $2 \times 1710\,\mathrm{s} + 2 \times (1710 + 10 \times 40)\,\mathrm{s}$ = 2.12 hours

Total time to validate this mode: 11.57 hours

Calibration Analysis Procedure (CAP)

- Use SPG to process data to Level 2.
- Perform aperture photometry of object (or PSF fitting).
- Perform colour correction.
- Compare with model prediction.
- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check for colour-dependent trends (filter leaks, straylight, . . .).

Output, products

- Release of AOT mode.
- Modification of AOT logic or instrument set-up if needed (e.g. definition and duration of the calibration block, frequency of calibration block execution, dither amplitude, chopper amplitude or frequency, modification of the basic chop-nod observing block, modification in the SPU reduction and compression parameters, better detector selection tables, OBCP/DMC sequence definitions, limits for low/high gain, . . .).
- Warnings/recommendations in the PACS Observers' Manual and on the HSC web-pages for the usage of this mode.

Status/version

```
 updated first ASCII draft,  27/Nov/2007
 updated second ASCII draft, 19/Dec/2007
 updated third ASCII draft,  18/Jan/2008
in CVS:
$Revision: 1.2 $
$Date: 2008/02/29 19:20:03 $
```

Req. 5.1.2 Optimized Observing Strategy for Small Source Photometry AOT

Objectives

Verify and if necessary optimise that the small-source photometry AOT mode gives accurate fluxes for sources with a small spatial extension up to 1.5 arcmin, as well as on compact point-like sources, in all three bands.

- In particular check that Y and Z axis raster step sizes are appropriate and that the observing mode allows a homogeneous coverage, smoothing out the the central gaps between matrices. The current default step sizes are 17" along the Y axis and 8.5" along the Z-axis.
- Check that the principle of 3-position chopping/nodding is efficient in removing both the sky and the telescope background, compared to the 4 positions in point-source mode, with orthogonal chopping and nodding directions.
- Check that the chopping and nodding directions are well aligned and that the nod-on/chop-on and nod-off/chop-off positions coincide, i.e. that chop and nod throws have the same amplitude (3.5').
- Check that chopping frequency (default 1.25 Hz), nodding frequency (default 60 s) and pointing mode are optimal, i.e. produce the best photometric performance with regard to the source positioning on the array, the chopper transition times, noise and pipeline processing aspects.
- Check photometric consistency with point-source mode for a point source and with the large area mapping modes for different flux ranges and spectral shapes.
- Check that the 2 symmetrical chopper positions used in this mode are clean and not contaminated by radiation from the internal calibration sources, i.e. that straylight by these sources is minimal in the sky field or not measurable, otherwise the chopper throw amplitude (3.5') may have to be reduced.

Note : The calibration concept (duration of initial calibration block, repetition of calibration block in between for rather long observations) cannot be tested properly in this AOT mode, but will be tested in other modes.

Fulfilling or fulfilled by

This AOT may be also used for some full system photometric system calibration tasks:

- req. 3.2.1 to derive the photometer nominal responsivity
- req. 3.2.3/3.2.4 to establish and calibrate the photometer's non linearity
- req. 3.2.5 to check the relative system response and the colour correction terms.

Priority

A for the standard AOR observations
B or C for the non-standard AOR observations.
(see Calibration Implementation Procedure for details)

When performed / frequency

1) During FM-ILT (nodding with x-y-stage)
2) During FS-ILT (nodding with x-y-stage)
3) During PV and Science Validation Phase
4) During Routine Calibration Phase

Required accuracy

- For bright sources around absolute photometric accuracy (5 – 10%).
- For the faintest sources within achievable S/N accuracy for point-sources as well as surface brightness.
- Map dynamic range should cover ≈10 mJy up to a few tens of Jy.

Inputs, prerequisites

- Optimal bolometer biases (and sequencer) have to be known for the given telescope background.
- Absolute pointing calibration has to be sufficiently accurate to place a point-source away from the matrix gaps, i.e. in the corner of a blue matrix close to the centre for all four raster positions but not on one of the matrix gaps!
- Verification of the chopper calibration with a 3.5 arcmin chopper throw (transition times should be well within a bolometer readout of 25 ms).
- Independent verification that the 3.5 arcmin chopper throw provides a clean FOV not contaminated by straylight.
- Bolometer saturation limits have to be known (for final assessment of map dynamic range).
- SPU reduction/compression mode has to be consolidated to stay within the data rate bandwidth of 130 kbits/s.
- PACS calibration sources settings have to be established to provide fluxes very similar to the telescope fluxes in all 3 bands.

Sources

- 1 reasonably bright point-like source (fiducial calibration star) for a check of the PSF reconstruction and a comparison of the photometry with the other 3 modes (point-source / raster map and scan maps) on the same source.
- 1 small source, NGC 6543 (planetary nebula), to compare with raster map and scan map mode.
  Flux reference: ”Multi-aperture photometry of extended IR sources with ISOPHOT”, Klaas et al., A&A 452, 523-535 (2006).
- 1 small source, NGC 6286 (galaxy), to compare with raster map and scan map mode. This field was observed regularly by ISOCAM and was known as IRAS TFPR (Total Flux Photometric Reference), its spatial extension matches well the Small Map field-of-view.
  Flux reference: ”The ISOPHOT 170um Serendipity Survey II. The catalog of optically identified galaxies”, M. Stickel, D. Lemke, U. Klaas, A&A 422, 39-54 (2004).
- Beta Pictoris, a Vega like disk, with extended emission that shall be resolved by PACS.
  FIR spatial extent reference: Heinrichsen et al., MNRAS 304, 589-594 (1999).
- A pair of asteroids or other bright stars/galaxy/QSOs to be chosen from ”PACS Sky Fields and Double Stars for Spatial Calibration”, Nielbock et al., 2008, PACS-ME-TN-035.

Calibration Implementation Procedure (CIP)

- Use the PACS small source AOR on all sources in both filter combinations. Choose the integration times such to obtain the required S/N-ratios (≈10 for faint sources, ≈100 for bright sources).

The small source AOT mode executes a small 2 × 2 raster with raster step sizes of 17" along the (long) Y-axis and 8.5" along the (short) Z-axis. The telescope dwells 1 minute on each raster position, chopping is performed to an OFF-position at 1.25 Hz with a chopper throw of 3.5', then the telescope moves to the nod position and also dwells 1 minute there with chopping at the same frequency and with the same throw. The telescope then proceeds to the next raster positions and the same cycle is executed. If the repetition factor is set to >1 the number of nod cycles is correspondingly multiplied on each raster position, before going to the next raster position. The observation principle is therefore a classical 3-position chopping/nodding for each raster position, compared to the orthogonal chopping/nodding in point source mode (refer to the PACS Observer's Manual for more details).

The following observations are envisaged to test if the above observation strategy is the optimum. For this purpose non-standard AORs (which require expert HSpot) are needed to execute observations with different parameter settings to explore if the standard setting is optimum in removing the telescope background and dealing with gain drifts:

- Modified chopper frequency
  The default chopper frequency (in all chopped modes) is 1.25 Hz, i.e. 400 ms per chopper plateau, with 4 averaged readouts of 100 ms each, while the optimum chopping frequency to suppress the 1/f noise seems to be higher as judged from the Allan variance criterion. But it was estimated that 4 readouts per chopper plateau, with one readout possibly affected by the chopper movement was a good compromise.
  ⇒ Exercise 2 higher frequencies, 2.5 Hz and 1.67 Hz (i.e. 2 and 3 averaged readouts per chopper plateau, respectively) and one lower one (0.83 Hz, i.e. 6 averaged readouts) restricted to 2 bands, target: NGC 6543.
  (Option with a low priority, depending on the outcome of the similar exercise in the point source mode, req. 5.1.1, especially the low frequency exploration ⇒ Priority : B)

- Modified nodding frequency
  The default integration time per nod position is 1 min which is defined in the OBCP by the number of chopper cycles per nodding period. By reducing this number, while increasing the repetition factor n accordingly, the nodding frequency is increased and the total integration time on-target is kept constant.
  ⇒ Exercise two higher nodding frequencies, with integration time per nod position of 30 s / n=2 and 10 s / n=6 to check which nodding frequency gives the optimal performance (observations with shorter nodding periods have higher overheads due to more slews to the nod positions). Restrict to 2 bands, target: NGC 6543, Priority: B.

- Modified raster step sizes
  The current envisaged raster step sizes are 8.5" along the Z-axis (small axis of the detector) and 17" along the Y-axis (long axis of the detector, nearly parallel to the chopping direction) in order to cope with a larger gap between the two red detector matrices.
  Depending on the quality and the uniformity of the reconstructed maps some other step size could be exercised, for instance 17" along the Z-axis to have a square sampling pattern resulting in a more symmetrical exposure map. Restrict to 2 bands, target: fiducial star. Priority: C, to be executed only, if default configuration does not give satisfactory results.

- Different pointing mode
  a) nodding-of-raster pointing mode
     The pointing mode used in Small-source photometry mode is the so-called "nodding-in-raster", where nodding is performed on each of the 4 raster positions. ⇒ The "nodding-of-raster" pointing mode shall be exercised and compared to. In this mode the 2 × 2 raster is first performed and then a second 2 × 2 raster at an off position with the required nodding offset. This mode gives a higher efficiency with less slew overheads but the gain drifts may invalidate this observation strategy with a too long time to go to the nodded positions.
     Restrict to 2 bands, target: NGC 6543.
     Priority: B.
  b) repetition of nodded raster map
     The repetition factor n determines the number of nodding cycles per raster position. Instead the nodding raster may be repeated n times resulting in the same number of nodding cycles. ⇒ Investigate whether repeating the 2 × 2 raster map (as implemented in the raster map mode) n times would produce better results with regard to time scales of gain drifts from one raster position to the next than the standard mode. This can be tested by

applying the chopped-raster mode. Restrict to 2 bands, target: NGC 6286, n=4.
Priority: B

Estimated time needed

- Observation of a fiducial star in standard AOT mode in both blue filter channels: 0.5 h
  Expected point-source sensitivity : 10 mJy (5σ) in the 3 bands.
  ⇒ fiducial star with more than 1 Jy (in the 3 bands?) required.
  Priority: A
- Observation of NGC 6543 in standard AOT mode in both blue filter channels: 0.5 h
  Expected PS sensitivity : 10 mJy (5σ) in the 3 bands.
  Priority: A
- Observation of NGC 6286 (TFPR) in standard AOT mode in both blue filter channels: 0.5 h
  Expected PS sensitivity : 10 mJy (5σ) in the 3 bands.
  Priority: A
- Observation of the Beta Pictoris disk in standard AOT mode in both blue filter channels: 0.5 h
  Expected PS sensitivity : 10 mJy (5σ) in the 3 bands.
  Priority: A
- Observation of a pair of objects, ideally asteroids from a list of close encounters/conjunctions prepared by T. Müller, with separation $<$1.5 arcmin and high flux contrast in both blue filter channels: 0.5 h.
  Expected PS sensitivity : 10 mJy (5σ) in the 3 bands.
  Priority: A

Total time: 2.5 hours Priority A

Non-standard AORs:

- Modified chopper frequency: 2.5, 1.67, 1.25 (default), 0.83 Hz in one blue filter band only on NGC 6543:
  4×15 mn = 1 h
  Priority: B
- Modified nodding frequency: 60 (default), 30 and 10 s nodding period in one blue filter band only on NGC 6543:
  3×15 mn = 0.75 h
  Priority: B
- Modified raster step sizes: 17” along the Z-axis in one blue filter band only on fiducial standard star: 15 mn = 0.25 h
  Priority: C
- Different pointing mode: nodding-in-raster (default) and nodding-of-raster in one blue filter band only on NGC 6543:
  2×15 mn = 0.5 h
  Priority: B
- Different pointing mode: repetition of nodding cycles per raster position (default) and sequential repetition of raster with nodding in one blue filter band only on NGC 6286: 2×1 h (with n = 4 repetitions) = 2.0 h
  Priority: B

Total time: 4.25 hours Priority B + 0.25 hours Priority C

Grand Total: 7 hours (2.5 h priority A, 4.25 h priority B, 0.25 h priority C)

Calibration Analysis Procedure (CAP)

- Use SPG to process data to Level 2.
- For nodding-of-raster mode the pipeline processing should recognise that the second raster corresponds to the ”nodded raster” in order to combine the pointings in the appropriate way.
- Perform aperture photometry of object (or PSF fitting).
- Perform colour correction.
- Compare with model prediction.
- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check for colour-dependent trends (filter leaks, straylight, . . .).

Output, products

- Release of AOT mode.
- Modification of AOT logic or instrument set-up if needed (e.g. definition and duration of the calibration block, frequency of calibration block execution, chopper amplitude or frequency, modification of the basic chop-nod observing block, modification in the SPU reduction and compression parameters, better detector selection tables, OBCP/DMC sequence definitions, . . .).
- Warnings/recommendations in the PACS Observers’ Manual and on the HSC web-pages for the usage of this mode.

Status/version

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in CVS:
$Revision: 1.3 $
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Req. 5.1.3 Optimized Observing Strategy for Raster Map Photometry AOT

Objectives

Verify and if necessary optimise that the Raster Map Photometry AOT mode provides the intended dynamic flux range and spatial resolution and gives accurate total fluxes for compact sources up to extended sources within the map size (with a sufficiently large area for background determination).

- Check that for different raster step sizes (user selectable parameter). Recommendations for optimised step sizes should be derived in order to overcome mapping artefacts or deficiencies due to dead/noisy individual or clusters of pixels.
- Check consistency with other PACS photometric modes. Derive criteria when to switch from raster map to scan map mode (overheads, sensitivity, mapping artefacts, ...).
- Check that the calibration concept works (duration of initial calibration block, repetition of calibration block inbetween very long observations).

Fulfilling or fulfilled by

This AOT may be also used for some full system photometric system calibration tasks, TBC.

Priority

A for the standard AOR observations
B for the non-standard AOR observations.

When performed / frequency

1) During FM-ILT (with x-y-stage to simulate the raster pointing mode)
2) During FS-ILT (with x-y-stage to simulate the raster pointing mode)
3) During PV and Science Validation Phase
4) During Routine Calibration Phase

Required accuracy

- For bright sources around absolute photometric accuracy (5 – 10%).
- For the faintest sources within achievable S/N accuracy for point-sources as well as surface brightness.
- Map dynamic range should cover $\approx$10 mJy up to a few tens of Jy.

Inputs, prerequisites

- Pointing calibration of the raster map mode has to be sufficient, in order not to have any resolution degradance in reconstructing the map from images on different raster positions.
- Verification of the chopper calibration (transition times should be well within a bolometer readout of 25 ms).
- Optimal bolometer biases (and sequencer) have to be known for the given telescope background.
- Bolometer saturation limits have to be known (for final assessment of map dynamic range).

- SPU reduction/compression mode has to be consolidated to stay within the data rate bandwidth of 130 kbits/s.
- PACS CS settings have to be established to provide fluxes very similar to the telescope fluxes in all 3 bands.

Sources

- 1 reasonably bright point-like source (fiducial calibration star) for checking PSF reconstrution in fine raster mode and compare with point source photometry.
- 1 small source, NGC 6543 (planetary nebula), to compare with raster map and scan map mode.
  Flux reference: "Multi-aperture photometry of extended IR sources with ISOPHOT", Klaas et al., A&A 452, 523-535 (2006).
- 1 small source, NGC 6286 (galaxy), to compare with raster map and scan map mode. This field was observed regularly by ISOCAM and was known as IRAS TFPR (Total Flux Photometric Reference), its spatial extension matches well the Small Map field-of-view.
  Flux reference: "The ISOPHOT 170um Serendipity Survey II. The catalog of optically identified galaxies", M. Stickel, D. Lemke, U. Klaas, A&A 422, 39-54 (2004).
- 1-2 double (multiple) sources (interacting galaxy, objects with knotty structure ...) with separations close to PACS resolution limit (6 – 9") to check achievable spatial resolution
  sources TBD.
- Extended sources with structures and covering dynamic flux range; their extension should be compatible with the maximum recommended raster map size, otherwise scan map mode has to be used:
  - Cas A SNR 12' $\times$ 12' (morphology changes completely longward of 100 μm!)
    ISOPHOT and Spitzer images are available

Calibration Implementation Procedure (CIP)

Use PACS raster map AORs to

(A) Obtain point source photometry with small raster step sizes reconstructing the PSF (7 $\times$ 7 raster with 2" step size) for bright point like source (S/N $>$ 100).
Offset the source such that it is placed in one matrix as for the point source mode $\Rightarrow$ fix date and hence orientation angle and calculate the offset.

(B) Simulate small source photometry mode (but without nodding) by performing a 2 $\times$ 2 raster with step size of 17" in y-axis and 8.5" in z-axis direction on the two small sources NGC 6543 and NGC 6286.

(C) Perform raster with different raster step sizes on NGC 6543:

  a) 3 $\times$ 3 raster with step size of 3' in S/C-y and 1.5' in S/C-z direction.
  b) 5 $\times$ 5 raster with step size of blue matrix array size (27").
  c) 7 $\times$ 7 raster with 17" step size (twice small map raster step size in S/C-z direction).

(D) Perform large raster map
15 $\times$ 15 raster with step size 51" on CasA.

(E) Perform large raster map with additional internal calibration after completion of each raster leg (exploration of the hold time concept; non standard AOR)
15 $\times$ 15 raster with step size 51" on CasA.

Estimated time needed

(A) 4000 s (1 repetition) $\times$ 2 (both blue filters)

(B) 900 s (2 repetitions) $\times$ 2 (both blue filters) $\times$ 2 (two sources);
30 mJy with S/N = 10.

(Ca) 3700 s (4 repetitions) $\times$ 2 (both blue filters);
30 mJy with S/N = 10.

(Cb) 2500 s (1 repetition) $\times$ 2 (both blue filters);
30 mJy with S/N = 10.

(Cc) 4500 s (1 repetition) $\times$ 2 (both blue filters);
30 mJy with S/N = 10.

(D) 20500 s (1 repetition) $\times$ 2 (both blue filters);
30 mJy with S/N $\approx$ 10
1σ extended fluxes:
2.5 MJy sr^{-1} at 70 μm
2.4 MJy sr^{-1} at 100 μm
0.8 MJy sr^{-1} at 160 μm (after co-addition)

(E) (D) + 15 additional internal calibrations for each repetition
20500 s + (15$\times$50) s = 21250 $\times$ 2 (both blue filters).

Total time: 20.56 hours Priority A + 11.81 hours Priority B
Grand Total: 32.37 hours

Calibration Analysis Procedure (CAP)

Use SPG to process data to Level 2 for (A) - (D) Process semi-automatically(SPG)/interactively (E) type products to Level 2 and perform gain and offset drift correction with intermediate internal calibration measurements

- (A):
  - Perform aperture photometry of object (or PSF fitting)
  - Perform colour correction
  - Compare with model prediction
  - Compare with point source mode result
- (B):
  - Perform aperture photometry of object
  - Perform colour correction
  - Compare with reference photometry
  - Compare with small source mode result
- (C):
  - Perform aperture photometry of object
  - Perform colour correction
  - Compare with reference photometry
  - Compare with small source mode result

  - Intercompare results with different step sizes

- (D) + (E):
  - Obtain total flux of object
  - Perform colour correction
  - Compare with total fluxes of reference results
  - Check dynamic range and S/N of faintest levels
  - Check resolution of compact features over the whole map area
  - Compare morphological features with reference results
  - Compare with scan map mode results
  - Compare photometric results and morphological features for maps with standard and more frequent internal calibrations

- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check for colour-dependent trends (filter leaks, straylight, ...). Check pointing information of individual raster points (reference and instantaneous pointings).

Output, products

- Release of AOT mode.
- Modification of AOT logic or instrument set-up if needed (e.g., definition and duration of the calibration block, frequency of calibration block execution, recommendation for preferred raster step sizes, raster dwell times? ...).
- Warnings/recommendations in the PACS Observers' Manual and on the HSC web-pages for the usage of this mode.

Status/version

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 ASCII draft 1, UK, 06 December 2007
 ASCII draft 2, UK, 26 February 2008
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$Date: 2008/03/04 11:15:46 $
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Req. 5.1.4 Optimised Observing Strategy for Scan Map Photometry

Objectives

Verify and if necessary optimise the in-orbit performance so that the Scan Map Photometry mode provides the intended dynamic flux range and spatial resolution and gives accurate total fluxes for compact sources up to extended sources within the map (with a sufficiently large area for background determination).

- Check that the observing mode is robust against detector drifts and telescope temperature variations.
- Check that for different scan speeds and access the impact on the PSF shape.
- Check resulting flat-field quality due to narrow and coarser scan leg separation:
  a) Cross scan steps of only a few arcsec yield a homogeneous map coverage and possibly the best flat-field accuracy.
  b) 51” is a recommended intermediate cross-scan size independent of position angle, which is also used in the raster map validation.
  c) The option of homogeneous map coverage in the instrument reference frame uses a cross scan step size of 149.5”.
- Check that the recommended array orientations in the instrument reference frame give the optimum result with regard to coverage and sampling interval perpendicular to the scan direction.
- Check resulting image quality, if map is taken in instrument reference frame versus map is taken in sky coordinates, including cross-scans (orthogonal coverage).
- Check consistency with other PACS photometric modes.
- Check that the calibration concept works (duration of initial calibration block, repetition of calibration block inbetween very long observations).

Dithering of scan maps by varying the map centre in repeating the map according to a defined scheme is up to the observer.

Fulfilling or fulfilled by

This AOT is also used for some full system photometric system calibration tasks:

- req. 3.1.3 Photometer Field of View Distortion
- req. 3.1.4 Photometer Point Spread Function ⇔ CIP A
- req. 3.1.5 Photometer Ghosts
- req. 3.1.6 Photometer Straylight

Priority

A
B (CIP A)

When performed / frequency

1) During FM-ILT (continuous x-y-stage raster scans)
2) During FS-ILT (depends on bolometer availability & completeness for FS)

3) During PV and Science Validation Phase
4) During Routine Calibration Phase

Required accuracy

- For bright sources around absolute photometric accuracy (5 – 10%).
- For the faintest sources within achievable S/N accuracy for point-sources as well as surface brightness.
- Map dynamic range should cover ≈10 mJy up to a few tens of Jy.

Inputs, prerequisites

- Pointing calibration of the scan map mode has to be sufficient, in order not to have any resolution degradance in reconstructing the map from images on different scan legs.
- Optimal bolometer biases (and sequencer) have to be known for the given telescope background.
- Bolometer saturation limits have to be known (for final assessment of map dynamic range).
- SPU reduction/compression mode has to be consolidated to stay within the data rate bandwidth of 130 kbits/s.
- PACS CS settings have to be established to provide fluxes very similar to the telescope fluxes in all 3 bands.

Sources

- 1 reasonably bright and isolated point-like source for checking PSF shape depending on scan speed with fine separation of scan legs and compare with point source photometry.
  - fiducial calibration star
- 1 extended source with structures and covering dynamic flux range to compare with raster map mode
  - Cas A SNR 12' × 12' (morphology changes completely longward of 100 μm!)
    ISOPHOT and Spitzer images are available.
- 2 large sources with structure and large dynamic range
  - Helix Nebula (NGC 7293, PN) 25' × 25'
    ISOPHOT 90 and 180 μm P22 maps
  - NGC 6946 (galaxy) 12' × 12'
    visible all time, ISOPHOT P32, Spitzer MIPS 24 and 70μm images
    Flux references:
    "ISOPHOT Maps of NGC 6946 in the range lambda 60-200 μm", Tuffs et al., A&A 315, L149-L152 (1996)
    "Photometric mapping with ISOPHOT using the "P32" Astronomical Observation Template", Tuffs & Gabriel, A&A 410, 1075-1088 (2003)
- 1 heavily structured area
  - Draco cloud $2^o \times 0.6^o$
    (centre of map not identical with Draco cloud SIMBAD positions (RA: 16:48:17.04, DEC: +60:11:49.2, 2000)
    ⇒ RA: 16:45:00, DEC: +60:12:00
    ISOPHOT Serendipity Sky Atlas Maps
    Flux reference:
    "The ISOPHOT 170 μm Serendipity Survey. IV. The far-infrared sky atlas", Stickel et al., A&A 466, 1205-1210 (2007)

- 1 empty field to check noise behaviour

  - GOODS-S (cosmological field for deep surveys)
    17' $\times$ 5' (only part of field)
    Spitzer images

Calibration Implementation Procedure (CIP)

Use PACS scan map AOR photometry in all three bands (if not restricted) to

(A) Obtain point source photometry with narrow scan leg separation (2-4") in the three scan speeds 10"/s, 20"/s and 60"/s to assess impact on the PSF shape and point source photometry for bright point like source (S/N $>$ 100).
Map size: 30' leg length, 15 legs with 4" scan leg separation in instrument reference frame with 45 deg array orientation.

(B) Perform scan map with intermediate scan leg separation (51") in scan speed 10"/s on Cas A to compare with raster map photometry.
Map size 15' $\times$ 15', perform orthogonal scan map, too.
Perform maps in

a) instrument reference frame
b) sky coordinates

PV planners should check that orientation of both map types is not absolutely identical!

(C) Perform 2 scan maps with scan speed 10"/s on large sources (NGC 7293, NGC 6946) with structure and large dynamic range in instrument reference frame with 45 and 135 deg array orientation.
Map sizes square 12' $\times$ 12' and 25' $\times$ 25'.
Perform maps with

a) scan leg separation of 25"
b) homogeneous map coverage. Adjust repetition factor w.r.t. achieved depth of more finely sampled scan map (a).

C1a) NGC 7293: 25' scan leg length, 60 legs with 25" scan leg separation
C1b) NGC 7293: 25' scan leg length, homogeneous coverage, square map
C2a) NGC 6946: 12' scan leg length, 28 legs with 25" scan leg separation
C2b) NGC 6946: 12' scan leg length, homogeneous coverage, square map

(D) Perform 1 scan map with scan speed 10"/s on large source (NGC 6946) with structure and large dynamic range in instrument reference frame with 15 and 105 deg array orientation.
Map size square 12' $\times$ 12'.
Perform map with 25" scan leg separation. Repetition factor should give the same depth as (C2a). Restrict to 70 μm and 160 μm filter.

(E) Perform very large scan map with medium scan speed of 20"/s on extended galactic structure (Draco cloud) with intermediate scan leg separation (51") in sky coordinates. Map size $2^o\times 0.6^o$.
120' scan leg length, 44 legs with 51" scan leg separation, 125^o orientation on sky.
Restrict to 100 and 160 μm (cirrus emission).

(F) Perform scan map with lowest scan speed of 10"/s on cosmological field with fine scan leg separation (4").
Map size 17' $\times$ 5'
17' scan leg length, 75 legs with 4" scan leg separation, in instrument reference frame with 45 deg array orientation.
Restrict to 70 μm (Spitzer reference) and 160 μm filter.

(G) Perform 1 scan map with scan speed 10"/s on large source (NGC 6946) with structure and large dynamic range in instrument reference frame with 45 and 135 deg array orientation (C2a) and additional internal calibrations.
Restrict to 25" scan leg separation in instrument reference frame:
12' scan length / 10"/s = 72 s execution time for each scan
Set hold time such, that internal calibration is performed every 4th out of 28 scan legs, i.e. about every 288 s or 5 min. This gives 7 additional internal calibrations.
Restrict to one blue filter.

(H) Perform very large scan map with medium scan speed of 20"/s on extended galactic structure (Draco cloud) with intermediate scan leg separation (51") in sky coordinates including additional internal calibrations:
2^o scan length / 20"/s = 360 s execution time for each scan
Set hold time such, that internal calibration is performed every 4th out of 44 scans, i.e. about every 1440 s or 24 min. This gives 11 additional internal calibrations.
Restrict to 100 and 160 μm filters (cirrus emission).

(I) Perform scan map with lowest scan speed of 10"/s on cosmological field with fine scan leg separation (4") in instrument reference frame with 45 deg array orientation and additional internal calibrations:
17' scan length / 10"/s = 102s execution time for each scan
Set hold time such, that internal calibration is performed every 5th out of 75 scans, i.e. about every 510 s or 8.5 min. This gives 15 additional internal calibrations.
Restrict to 1 blue filter.

Estimated time needed

(Aa) 3250 s (1 repetition) × 2 (both blue filters) × 1 (map orientations)

(Ab) 1950 s (1 repetition) × 2 (both blue filters) × 1 (map orientations)

(Ac) 1350 s (1 repetition) × 2 (both blue filters) × 1 (map orientations)

Total time (A): 13100 s = 3.7 h

(Ba) 2450 s (1 repetition) × 2 (both blue filters) × 2 (map orientations)

(Bb) 2450 s (1 repetition) × 2 (both blue filters) × 2 (map orientations)

Total time (B): 9800 s = 2.8 h

(C1a) 10700 s (1 repetition) × 2 (both blue filters) × 2 (map orientations)
S/N = 7 for 25 MJ ysr^{-1} at 70 μm
S/N = 6 for 20 MJ ysr^{-1} at 100 μm
S/N = 7.5 for 12 MJ ysr^{-1} at 160 μm

(C1b) 8400 s (4 repetitions) × 2 (both blue filters) × 2 (map orientations)
S/N = 6 for 25 MJ ysr^{-1} at 70 μm
S/N = 5 for 20 MJ ysr^{-1} at 100 μm
S/N = 6.5 for 12 MJ ysr^{-1} at 160 μm

(C2a) 5650 s (2 repetitions) × 2 (both blue filters) × 2 (map orientations)
S/N = 4.5 for 12 MJ ysr^{-1} at 70 μm
S/N = 5.5 for 15 MJ ysr^{-1} at 100 μm
S/N = 16.5 for 20 MJ ysr^{-1} at 160 μm

(C2b) 4550 s (8 repetitions) $\times$ 2 (both blue filters) $\times$ 2 (map orientations)
S/N = 4 for 12 MJ ysr^{-1} at 70 μm
S/N = 5 for 15 MJ ysr^{-1} at 100 μm
S/N = 14.5 for 20 MJ ysr^{-1} at 160 μm

Total time (C): 117200 s = 32.6 h

(Da) 5650 s (2 repetitions) $\times$ 1 (short blue filters) $\times$ 2 (map orientations)
S/N = 4.3 for 12 MJ ysr^{-1} at 70 μm
S/N = 16.3 for 20 MJ ysr^{-1} at 160 μm

Total time (D): 11300 s = 3.2 h

(Ea) 34700 s (2 repetitions) $\times$ 1 (long blue filter) $\times$ 1 (map orientations)
S/N = 9 for 20 MJ ysr^{-1} at 160 μm

Total time (E): 34700 s = 9.7 h

(Fa) 9500s (1 repetition) $\times$ 1 (short blue filter) $\times$ 1 (map orientations)
S/N = 5 for 8 mJy at 70 μm
S/N = 12 for 10 mJy at 160 μm

Total time (F): 9500 s = 2.7 h

(Ga) 5650 s (2 repetitions = (C2a)) $+ 2 \times (7 \times 50\,\mathrm{s}) \times 1$ (1 blue filter) $\times$ 2 (map orientations)

Total time (G): 12700 s = 3.6 h

(Ha) 34700 s (1 repetition) $+ 2 \times (11 \times 50\,\mathrm{s}) \times 1$ (1 blue filter) $\times$ 1 (map orientations)

Total time (H): 35800 s = 10.0 h

(Ia) 9500 s (1 repetition) $+ 1 \times (15 \times 50\,\mathrm{s}) \times 1$ (1 blue filter) $\times$ 1 (map orientations)

Total time (I): 10250 s = 2.9 h

Grand Total = 71.2 h

Calibration Analysis Procedure (CAP)

Use SPG to process data to Level 2 for (A) - (F) Process semi-automatically(SPG)/interactively (G) - (I) type products to Level 2 and perform gain and offset drift correction with intermediate internal calibration measurements

- (A):
  - Assess 2-dimensional PSF width depending on angle relative to scan direction
  - Perform aperture photometry of object
  - Perform colour correction
  - Compare with model prediction

  - Intercomapre for the three different slew speeds
  - Compare with point source mode result

- (B) - (I):
  - Obtain total flux of object
  - Perform colour correction
  - Compare with total fluxes of reference results
  - Check dynamic range and S/N of faintest levels
  - Check destriping depending on scan leg separation, array orientation and instrument or sky reference
  - Check resolution of compact features over the whole map area (e.g. HII regions in NGC 6946)
  - Compare morphological features with reference results
  - Compare with raster map mode results
  - Compare photometric results and morphological features for maps with standard and more frequent internal calibrations
  - Intercompare results of various co-addition reduction algorithms/schemes, like MadMap, Mopex, etc. in order to check for possible artefacts introduced by the processing.

- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check for colour-dependent trends (filter leaks, straylight, . . .). Check pointing information of individual scan legs (reference and instantaneous pointings)

Output, products

- Release of AOT mode.
- Modification of AOT logic or instrument set-up if needed (e.g., definition and duration of the calibration block, frequency of calibration block execution, recommendation for preferred scan leg separations, array-to-scan orientations? . . .).
- Warnings/recommendations in the PACS Observers' Manual and on the HSC web-pages for the usage of this mode.

Status/version

```
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```

Req. 5.1.5 Optimised Observing Strategy for SPIRE/PACS Parallel Mode

Objectives

Verify and if necessary optimise the in-orbit performance so that the parallel mode provides the intended dynamic flux range and spatial resolution and gives accurate total fluxes for compact sources up to extended sources within the map.

- Verify that point-like sources of 100 mJy can be detected in the blue channel and of 150 mJy in the red channel (5 sigma) at the high scan speed (60"/s).
- Check that the observing mode is robust against detector drifts and that the orthogonal coverage improves reconstructed map quality and PSF.
- Check that the resulting map and exposure map is homogeneous, with the fixed cross scan step used in this mode.
- Check that the PACS parallel mode scan maps at the two scan speeds give photometry that is consitent with each other.
- Derive PSF profile for the two parallel mode scan speeds and on-board averaging, and compare to predictions. NB: *This objective is related to the specific req. 3.1.4 on the PSF. Under the assumptions described there (e.g. no special detector biases tuned to the parallel mode), the only dedicated parallel mode PSF check is through the scans of a fiducial calibrator described below.*
- Check consistency with other PACS photometric modes, taking into account the on-board averaging of 8 frames for the blue channel, instead of 4, for point sources of different fluxes.
- Check that the calibration concept works (duration of initial calibration block, repetition of calibration block in between very long observations). TBC: *actually, is provision made for repeated internal calibrations for PACS in parallel mode ? If so, how can it be synchronized with PCAL calibrations ? The duration and frequency of PCAL cal. measurements is very important, coordination needed with SPIRE !*
- Check that the parallel SPIRE observations/operations have no influence on the PACS scan map observations obtained in this mode.
- Investigate an alternative SPU readout mode with averaging on-board 1 frame or 4 frames out of 8 in the blue and 3 out of 4 in the red band, instead of the default averaging of 8 and 4 frames, respectively. It should yield higher (sharper) spatial resolution at the expense of lower sensitivity.

Fulfilling or fulfilled by

The parallel mode is currently not used by other PACS calibration requirements.

Priority

A and B , see CIP

When performed / frequency

1) During FM-ILT (scan speed in combination with SPU mode, both filters)
2) During FS-ILT (depends on bolometer availability & completeness for FS)
3) During FM-IST (mutual interference, data rate, operation of 2 instruments)
4) During PV and Science Validation Phase
5) During Routine Calibration Phase

Required accuracy

- For bright sources around absolute photometric accuracy (5 – 10%).
- For the faintest sources within achievable S/N accuracy for point-sources as well as surface brightness.
- Map dynamic range should cover a few tens of mJy up to a few tens of Jy.

Sources

- Cooler re-cycling for the two instrument (simultaneously or consecutively) is successful and the hold time longer than one observational day.
- Pointing calibration of the scan map mode has to be sufficient, in order not to have any resolution degradations in reconstructing the map from images on different scan legs.
- Optimal bolometer biases (and sequencer) have to be known for the given telescope background, and possibly adjusted to the high scan speed (60"/s) for faster response time of the detectors.
- Bolometer saturation limits have to be known (for final assessment of map dynamic range).
- SPU reduction/compression mode has to be consolidated to stay within the data rate bandwidth of 130 kbits/s.
- PACS CS settings have to be established to provide fluxes very similar to the telescope fluxes in all 3 bands.
- Common agreement on calibration block duration with SPIRE (hold time).
- For the special sampling mode, the configuration of the SPU to select a certain number of frames out of 8(4) must be possible and verified.

Sources

- 1 reasonably bright and isolated point-like source for checking PSF shape depending on scan speed with fine separation of scan legs and comparison with point source mode (and other modes) photometry.
  - PACS fiducial calibration star
- 1 large source with structure and large dynamic range
  - NGC 6946 (galaxy) 12' $\times$ 12'
    visible all time, ISOPHOT P32, Spitzer MIPS 24 and 70μm images
    Flux references:
    "ISOPHOT Maps of NGC 6946 in the range lambda 60-200 μm", Tuffs et al., A&A 315, L149-L152 (1996)
    "Photometric mapping with ISOPHOT using the "P32" Astronomical Observation Template", Tuffs & Gabriel, A&A 410, 1075-1088 (2003)
- 1 heavily structured area
  - Draco cloud $2^o \times 2^o$
    (centre of map not identical with Draco cloud SIMBAD positions (RA: 16:48:17.04, DEC: +60:11:49.2, 2000)
    $\Rightarrow$ RA: 16:45:00, DEC: +60:12:00 i.e. same center as the rectangular map in PACS photo scan map mode.
    ISOPHOT Serendipity Sky Atlas Maps
    Flux reference:
    "The ISOPHOT 170 μm Serendipity Survey. IV. The far-infrared sky atlas", Stickel et al., A&A 466, 1205-1210 (2007)
- 1 galactic field with a high density of bright sources

- A representative Hi-GAL field (early science demonstration ?)

- A relatively empty cosmological field, but with some bright sources:
  - XMM-LSS field centered on the VVDS (VIMOS Very Deep Survey) area, with deep Spitzer coverage in all bands for cross-identification for PACS and SPIRE. (*to be agreed with HERMES SPIRE GT team*)
  - otherwise GOODS-S (cosmological field for deep surveys, PEP) 17' × 17', that has also Spitzer images available, targeted under req. 5.1.4 to check the noise behaviour.
  - or Lockman Hole (PEP)
  - or any of the H1K (Herschel Kilo degrees survey) KP OT fields

Calibration Implementation Procedure (CIP)

Use the standard parallel mode AORs on the following fields:

(A) Fiducial calibration star, with high and low scan speed
Field: 30' × 30' (Note: 30' length is the minimum allowed by HSpot), single pass, no orthogonal coverage
blue and green bands.
Priority: A

(B) NGC6946, with low speed (20"/s)
Field 30' × 30', orthogonal coverage
blue and red filter band only (highest spatial resolution)
Priority: A

(C) Galactic Hi-GAL (representative) field, with high speed (60"/s)
Field $1^o \times 1^o$, with orthogonal coverage
blue and red filter band only
Priority: A

(D) Draco Cloud, with high scan speed (60"/s)
Field $2^o \times 2^o$, centered on the same coordinates as the rectangular scan map (req. 5.1.4), with orthogonal coverage
green and red filter band only (cirrus emission)
Priority: A

(E) XMM-LSS, cosmological field, with low (20"/s) scan speed Field $1^o \times 1^o$, with orthogonal coverage
blue and red filter band only (the blue band is selected for a direct comparison with SWIRE (Spitzer))
Priority: B (very time consuming, to be executed during science demonstration phase only?)

Use XHspot to:

(F) Investigate the potential benefit of different sampling mode (e.g. 1 frame out of 8 in blue filter)
on the Hi-GAL-like field, with orthogonal coverage.
Use XHspot to change the SPU on-board averaging to 1/8 sampling in the blue channel. Priority: B

Estimated time needed

(A) (2325 s (high speed) + 4077 s (low speed)) × 2 (both blue filters) × 1 (map orientations)

Total time (A): 12850 s = 3.6 h

(B) 4100 s × 1 (short blue filter) × 2 (map orientations)

Total time (B): 8200 s = 2.3ḣ

(C) 4600 s × 1 (short blue filter) × 2 (map orientations)

Total time (C): 9200 s = 2.6ḣ

(D) 11200 s × 1 (long blue filter) × 2 (map orientations)

Total time (D): 22400 s = 6.3ḣ

(E) 9400 s × 1 (short blue filter) × 2 (map orientations)

Total time (E): 18800 s = 5.3ḣ

(F) =(C) 4600 s × 1 (short blue filter) × 2 (map orientations)

Total time (F): 9200 s = 2.6ḣ

Grand Total = 22.7 h, i.e. close to 1 Observational Day
Priority A: 14.5 h
Priority B: 7.7 h

Calibration Analysis Procedure (CAP)

Use SPG to process data to Level 2 producing maps using MadMap. The pipeline takes the whole detector timeline and, using maximum likelihood methods, derives the pixelized map. For some observations, filtering and direct mapping may also be adequate.

- (A) - (F):
  - Extract 3 maps: cross-linked, nominal and orthogonal one:
    Check de-striping. Compare the photometry on all of them as a consistency check.
    Derive the gain in terms of signal-to-noise and faint source detection (1/f noise effect) in each case.
  - Assess 2-dimensional PSF width depending on angle relative to scan direction. Check resolution of compact features over the whole map area.
  - Compare morphological features with reference results.
  - Compare with PACS (only) scan map mode results.
  - Perform aperture photometry of object.
  - Perform colour correction.
  - Compare the photometry for the two slew speeds and with scan map mode.
  - Compare the photometry with other observing modes and with Spitzer 160 μm SWIRE maps (available at HSC).
- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check for colour-dependent trends (filter leaks, straylight, . . .). Check pointing information of individual scan legs (reference and instantaneous pointings)

Output, products

- Release of AOT mode.
- Modification of AOT logic or instrument set-up if needed (e.g., definition and duration of the calibration block, frequency of calibration block execution, modification in the SPU reduction and compression parameters . . .).
- Warnings/recommendations in the PACS Observers' Manual and on the HSC web-pages for the usage of this mode.

Status/version

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```

5.2 Spectrometer AOTs

A detailed description of all PACS spectroscopy AOTs and their modes is given in the PACS Observer's Manual (Herschel-HSC-DOC-0832).

There are two PACS spectroscopy AOTs:

1) line scan spectroscopy
2) range scan spectroscopy

Line scan spectroscopy offers the following main modes:

1.1) standard chopping-nodding mode
1.2) bright lines chopping-nodding mode
1.3) wavelength switching mode

Range scan spectroscopy offers the following main modes:

2.1) raster mapping
2.2) range scan
2.3) SED mode

Spectra can be sampled with different sampling frequencies. It is possible to define an off-position for background determination.

A statistics performed on the GT and OT Phase 2 AORs gives the following lines and the number/type of observing requests for line spectroscopy to be considered for validation/calibration:

Table 5.1: Key Projects line spectroscopy statistics.

#	Line Id	Rest Wave [μm]	# of line requests	comment	# bright line mode included in col 4
1	CII	157.741	406	strong line, mostly emission	90
2	NII 121	121.898	394	weak to medium, emission, important	5
3	NII 205	205.178	208	weak emission, difficult wavelength, but important	3
4	N III 57	57.317	102	weak to medium, important, emission	4
5	OI 63	63.183	700	strong line, mostly emission	15
6	OI 145	145.525	333	weak, but important, emission	4
7	O III 52	51.815	10	medium strong, emission, only for z>0.06 (e.g. SHINING), observed e.g.@64.88	
8	OIII 88	88.356	322		13
9	Si I	68.473	11	KPOT_aedge_1, observed at medium redshifts in green band (e.g. @88.92)	
10	H2O 6250-5140	65.166	3	absorption / emission	
11	H2O 3300-2210	66.437	18	absorption / emission, e.g. KPGT_pharto01_1, KPGT_evandish_1	
13	H2O 3310-2200	67.089	3	absorption / emission	
14	H2O 321-212	75.380	5	absorption / emission	
16	H2O 6160-5050	82.030	3	absorption / emission	
17	H2O 221-110	108.073	49	absorption / emission	
19	H2O 414-303	113.537	37	absorption / emission	
20	H2O 404-313	125.353	46	absorption / emission	
21	H2O 313-202	138.527	46	absorption / emission	
22	H2O 303-212	174.626	52	absorption / emission	
23	H2O 212-101	179.527	102	absorption / emission	
24	H2O 221-212	180.488	38	absorption / emission	
25	HD 2675GHz	112.073	1	KPGT_vossenko_1	
26	CH4	119.69	2	Uranus and Neptune, KPGT_pharto01_1	
27	OH b	79.12	43	several blended, should be range mode?	
28	OH	84.6	76	several blended, should be range mode?	
29	OH 119 micron	119.34	1	several blended, should be range mode? KPGT_vossenko_1	
30	OH/CO 16-15	162.97	43	several blended, should be range mode?	
31	CO 24-23	108.763	33		
32	CO 14-13	185.999	38	KPGT_evandish_1	

Notes:
dithered lines: OI 63 (many), OIII 88 (2), OI 145 (1);
OIII 88 and OI 145 are from KPGT_smadde01_1;
pointed lines: all of the lines
mapped lines: all of the lines
bright lines: - all 7 lines in bright mode are observed in SHINING (low met part);
- 6 of the bright OI 63 lines are from KPOT_tmegeath_2;
- some of the bright CII lines are from KPGT_cwilso01_1;
- most bright line requests are pointed or mapping with chop/nod
- the 6 KPOT_tmegeath_2 OI 63 bright lines are in dithered mode

Req. 5.2.1 Optimized Observing Strategy for Chopping/Nodding Line Spectroscopy

This requirements comprises the following line spectroscopy sub-modes:

- Chopping/nodding (pointed, pointed with dither, mapping)
- Chopping/nodding for bright lines (pointed, pointed with dither, mapping)

Objectives

Verify and if necessary optimize that the Line Spectroscopy AOT gives accurate spectra, including reliable continuum and line flux densities, and line profiles (resulting then in well calibrated line fluxes) over the full accessible wavelength range.

The point-like and small extended sources should be located in the vicinity of clean background/off-source positions. This mode is only foreseen for nominal lines (narrow, unresolved lines), but not for very extended broad lines with more than several hundred km/s FWHM (the full 16-pixel spectral coverage at the longest wavelength in each grating order is only about 600-800 km/s!).

Verify that this mode provides sufficient redundancy allowing to reconstruct the full line profile with regard to sampling density, line peak, line wings and continuum under the in-orbit radiation environment.

- Check that spacecraft dithering and no-dithering give consistent line fluxes for all the positions (note, the dithering central position conincides with the no-dithering position).
- Check that the chopper frequency and the number of chopper cycles per grating position produces the best performance (with regard to the on-off signal determination, noise, impacts by glitch events affecting ramps and inducing detector repsonsivity drifts).
- Check that it works for SSO objects (tracking).
- Verify that the capacitance settings are optimal!
- Check the consistency between results of normal and bright line mode, including the different SPU reduction/compression schemes.
- Check that the three chopper amplitudes give consistent results (for sources without gradients in the background).
- Check explicitly at very long wavelenths (per grating order) if this mode provides sufficient coverages of the line wings in nominal and bright line mode (this could then trigger a new recommendation in the PACS Observer's Manual to use range scan mode instead for these wavelength ranges).
- Check that the calibration concept works (duration of initial calibration block, repetition of calibration block inbetween very long observations, key wavelength concept).
- Verify that all 5 $\times$ 5 spatial pixels in the prime channel provide sufficient data to reconstruct the spectral information for the full 0.78' $\times$ 0.78' FOV and that the line fluxes are similar if a point-source centroid is moved around the 25 spatial pixels.
- Verify the impact of pointing accuracy on data quality (part of the spatial calibration where sources are placed at various positions on and inbetween pixels and systematic test in req. 4.2.5).
- Check S/N and line fluxes in nominal 3rd order vs. extended 2nd order (this is currently not an option in line spectroscopy but it would be worth to characterize the differences; the extended 2nd order is currently only available in range scan mode.)
- Verify that this mode works for emission lines as well as for absorption lines.

- Verify that this mode works for several lines of different brightness (different repetition factors) in one single AOR.
- Check the advantages/disadvantages of ”line repetition factor” vs. ”repetition of nod cycles”.
- Verify the AOTs long-term robustness (flux repeatability over days and weeks):
  $\Rightarrow$ should either be part of the routine calibration plan on a monitoring source (like wavelength monitoring on NGC6543) with high visibility or part of a new requirement!
- Verify via PACS PHOT Small-source photometry (effective core map size 3.12’x1.56’) or with a PHOT raster AOT or PHOT scan map AOT the vicinity for all SPEC chop-nod line scan targets
  (chopper amplitudes in SPEC mode: small: 1’; medium: 3’; large: 6’).

Fulfilling or fulfilled by

Priority

A

When performed / frequency

1) During FM-ILT
2) During FS-ILT
3) During PV and Science Validation Phase
4) During Routine Calibration Phase

Required accuracy

The achieved resolution should be in the range $c \cdot \frac{\Delta\lambda}{\lambda} \approx 55 - 320$ km/s (or $\frac{\lambda}{\Delta\lambda} \approx 940 - 5500$), with the instantaneous 16 pixel spectral coverage between 600 to 2900 km/s, corresponding to 0.15 – 1.0 μm wavelength coverage. The best 5 σ/1 h sensitivity in the first order should be around 140 mJy for the continuum, 2×10^{-18} W m^{-2} for the line sensitivity and roughly a factor 2.5 worse in the 2nd and 3rd order (but there is hope that also in 2nd and 3rd order one could reach the 140 mJy under ideal conditions).

Inputs, prerequisites

- Simulations should be performed for the nominal and bright line scans on realistic line profiles in the full accessible wavelength range to verify the currently selected number of grating steps and the grating step sizes. Can all the line profiles be reconstructed? Are there at least 3 samples per FWHM for an unresolved line at all wavelengths?
- Established calibration concept and data processing concept (i.e., availability of a working pipeline) in order to check easily and fast the advantages/disadvantages of a certain observation configuration.
- Pointing calibration has to be sufficient to place the source in the centre of the 5×5 array and to execute meaningful dither patterns.
- Verification of the chopper calibration (transition times should be well within an envisaged subramp length of 8 readouts = 31 ms).
- Verification of the grating calibration (transition times for the small grating steps in the line scan mode should be within an envisaged subramp length of 8 readouts = 31 ms or for the larger grating steps, like in the spectrometer calibration blocks, well within 2 sub-ramps).
- Verification of the signal derivation process: flagging and de-selecting of sub-ramps which are affected by chopper or grating movements should be well tested and understood in the signal derivation process (validation also via the raw channels).

- PACS CS settings have to be established to provide fluxes as similar as possible to the telescope fluxes in all 3 grating orders (part of the req. 2.5.4 on the emissivity of the PACS calibration sources).
- Optimal spectrometer biases have to be established for the given in-orbit radiation environment.
- The default capacitor settings and ramp lengths for both channels and for faint and bright lines have to be known (with regard to sensitivity and saturation).
- Established RSRF and definition of key wavelengths.
- The allowed SPU reduction/compression schemes to stay within the 130 kbit/s limit have to be known.
- Successful technical verification of this mode (OBCP and DMC sequence functioning, timing/synchronisation between instrument and satellite activities, sky source and CS positioning on the arrays, filter operations, SPU configurations, . . .).
- Results from the spatial calibration sequence are needed as input for all dithering and small mapping modes in SPEC.

Sources

The source list comprises compact point-like sources and slightly extended sources with faint and bright intrinsic narrow and broader emission/absorption lines covering the full accessible wavelength range.

Calibration Implementation Procedure (CIP)

- Current default configuration (OBCP27, DMC seq. 12):
  Both scan modes use the same default bias and one default capacitor for the blue and one for the red channel. The nodding takes place after the completion of the grating up-/down-scan.
  - normal lines:
    64 readouts per ramp, 16 samples per subramp, sub-ramp mean values,
    number of grating steps and step sizes
    48/168(3rd), 46/188(2nd) 43/240(1st order);
    1 chopper cycle per grating position (2 ramps on-source, 2 ramps off-source, 1 ramp for the grating movement, the first ramp on each chopper plateau is affected by the chopper movement)
  - bright lines:
    32 readouts per ramp, slope fitting,
    number of grating steps and step sizes
    16/168(3rd), 16/188(2nd) 16/240(1st order);
    1 chopper cycle per grating position (2 ramps on-source, 2 ramps off-source, 1 ramp for the grating movement, the first ramp on each chopper plateau is affected by the chopper movement)
  - both options are possible in combination with ”pointed”, ”pointed with dither” and ”mapping” mode.

A) Standard AORs

  - Use PACS spectrometer nominal line scan AOR in satellite dither and non-dither mode on different sources with several faint lines in all 3 grating orders.
    Select the repetition factors for the grating up-/down-scans to obtain the required S/N-values (≈10, ≈100).
  - Use PACS spectrometer nominal line scan AOR on one source with different lines (faint and intermediate line fluxes), reachable in one filter setting.
    Selection of the corresponding line repetition factors for the different lines to obtain similar S/N values for each line.
  - Use PACS spectrometer nominal line scan AOR on a broader line with a FWHM around 5 – 8 spectral pixels, no satellite dithering.

- Use PACS spectrometer bright line scan AOR in satellite dither and non-dither mode on different sources with several bright lines in all 3 grating orders.
  Select the repetition factors for the grating up-/down-scans to obtain the required S/N-values ($\approx$10, $\approx$100).
- Use PACS spectrometer bright line scan AOR in combination with all 3 chopper amplitudes.
- Use PACS spectrometer bright line scan AOR on a solar system object with an apparent sky motion between 10 and 80"/h.
- Use PACS spectrometer bright line scan AOR in mapping mode on a (5 $\times$ 5) raster (step size: 9.5", roughly the size of one spatial pixel of 9.4") to validate the pointing mode in combination with the grating line scan on a resonably bright line for a point-source. Also to validate that the reconstructed line fluxes are the same for all 25 modules.

B) Non-standard AORs

- Use PACS non-standard AORs to execute:
  - nominal line scans but with 32 readouts per ramp and 2 chopper cycles per grating position, no dithering;
  - nominal line scans with 64 readouts per ramp, but 2 chopper cycles (one ramp on each chopper plateau) per grating position (OBCP23 without synchronisation ramps for chopper and grating movements);
  - bright line scans with 32 readouts per ramp, but 2 chopper cycles (one ramp on each chopper plateau) per grating position (OBCP23 without synchronisation ramps for chopper and grating movements).
- Use PACS standard AORs to investigate the optimal observing strategy with regard to grating scan and nodding aspects and to investigate hold-time aspects (frequency of calibration blocks):
  - nominal line scan on a faint line with 10 nodding cycles and with a line repetition factor of 1 (one calibration block during target acquisition);
  - nominal line scan on a faint line with 1 nodding cycle and with a line repetition factor of 10 (one calibration block during target acquisition):
  - 10 concatenated observations with 1 nodding cycle and with a line repetition factor of 1 (10 calibration blocks in total, one per AOR);
  - intermediate size raster with/without hold-time interruption.
- Use PACS non-standard AORs to investigate the impact of flux changes caused by the switch from the calibration block at a key wavelength to the first line in a multi-line AOR:
  - nominal line scan on a line which is far away from the key wavelength in that band;
  - nominal line scan on a line with a preceeding calibration block at the same wavelength (to avoid signal transients due to large flux jumps).

C) Long term issues

- Use PACS standard AORs to investigate the impact of the role angle, i.e. polarisation effects, for the line profile reconstruction and the continuum flux; observations of a bright line for a point-source.
  (See also the req. 4.3.12 on instrumental polarization.)
- Use PACS standard AORs to investigate the possible degradation effects: repeated observations of a bright line for a point-source under the same role angle, i.e. separated by half a year. (e.g., monitoring wavelengths of bright PNe lines)

Estimated time needed

TBD

Calibration Analysis Procedure (CAP)

- Use SPG to process data to Level 2.

- Perform separate analysis of the grating up- and down-scans to characterize the signal deviations due to transient effects.
- Perform an analysis of the line profiles and the line strengths.
- Compare with theoretical profiles and/or with results from other projects.
- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check the impact of signal transients in the resulting products.

Output, products

- Release of AOT mode based on success criteria: TBD
  (what are the criteria to judge if a line scan in a specific instrument configuration is better than from the "default" configuration? Are there success criteria which depend on the wavelength? or on the grating order? or on the glitch rate? or on the detector history? or on the time since the last curing/biasing? If we determine different line fluxes through different techniques: what is the correct answer? Is the background/off-position clean? is there a dependence on role angle? . . .)
- Modification of AOT logic or instrument set-up if needed (e.g., definition and duration of the calibration block, frequency of calibration block execution, satellite dither steps, chopper amplitude or frequency, modification of the basic chop-nod observing block, modification in the SPU reduction and compression parameters, detector selection tables, OBCP/DMC sequence definitions, saturation limits, . . .)
- Warnings/recommendations in the PACS Observer's Manual and on the HSC web-pages for the usage of these modes (e.g., on the combination of lines in one AOR, the combination of faint and bright lines in one AOR, on the repetition factors vs. the repetition of nodding cycles, on pros and cons of the nominal and the bright line modes, . . .)

Status/version

```
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                            during ICC co-location meeting in March 2008
 sixth draft,  17/Apr/2008, after telecon with BA, RV
 7th draft,    14/May/2008, raw pixel and calibration block, hold-time
 8th draft,    02/Jun/2008, comments by AC, ES, new target/line lists;
                            first words in "success criteria"
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```

Req. 5.2.2 Optimized Observing Strategy for Line Spectroscopy in Wavelength-Switching Mode

This requirements comprises the following line spectroscopy sub-modes:

- Wavelength switching (raster-mode with off-position)

Objectives

Verify and if necessary optimise that the wavelength-switching mode gives accurate line-profiles and line-fluxes over the full accessible wavelength range. The extended sources should be located in the vicinity of clean off-source positions.

Verify that this mode provides sufficient redundancy allowing to reconstruct the full line profile with regard to sampling density, line peak and line wings under the in-orbit radiation environment.

- Check that the grating amplitude, the grating frequency and the sevenfold shift of the grating pattern produce the best performance (with regard to the on-off signal determination, noise, impacts by glitch events affecting ramps and inducing detector repsonsivity drifts).
- Check the consistency between wavelength-switching technique and nominal (chopped/nodded) line scans for a point-source or small extended source.
- Verify that the capacitance settings are optimal.
- Check that the calibration concept works (initial calibration block at nearby key wavelength + repetition of the wavelength-switching pattern on a clean off-position).
- Verify that all 5×5 spatial pixels in the prime channel provide sufficient data to reconstruct the spectral information for the full 0.78' $\times$ 0.78' FOV.
- Verify that this mode works for unresolved and slightly resolved emission and absorption lines.
- Check the pros and cons for the wavelength-switching concept vs. a very fast repeated grating up-down scan (unchopped) for extended sources where chopping is not possible.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

1) During FM-ILT
2) During FS-ILT
3) During PV and Science Validation Phase
4) During Routine Calibration Phase

Required accuracy

TBD

Inputs, prerequisites

- Simulations should be performed for realistic line profiles in the full accessible wavelength range to verify the currently selected number of grating steps and the grating step sizes. Can all the line profiles be reconstructed?
- Established calibration concept and data processing concept (i.e., availability of a working pipeline) in order to check easily and fast the advantages/disadvantages of a certain observation configuration.
- Pointing calibration has to be sufficient to place the source in the centre of the 5×5 array.
- Verification of the grating calibration (transition times for the large grating steps in the wavelength-switching mode should be within an envisaged short ramp of 32 readouts = 125 ms).
- PACS CS settings have to be established to provide fluxes very similar to the telescope fluxes in all 3 grating orders.
- Optimal spectrometer biases have to be established for the given in-orbit radiation environment.
- The default capacitor settings and ramp lengths for both channels and for faint and bright lines have to be known (with regard to sensitivity and saturation).
- Established RSRF and definition of key wavelengths.
- The allowed SPU reduction/compression schemes to stay within the 130 kbit/s limit have to be known.
- Successful technical verification of this mode (OBCP and DMC sequence functioning, timing/synchronisation between instrument and satellite activities, sky source and CS positioning on the arrays, filter operations, SPU configurations, ...)

Sources

Small extended and fully extended sources (with clean off-positions) with intermediate and bright lines (emission and absorption lines) covering the full accessible wavelength range [TBD].

Calibration Implementation Procedure (CIP)

- Current default configuration (OBCP32, DMC seq. 18):
  (Full description in PACS-ME-LI-005, issue 1.6.)
  The smallest possible AOR contains a 2×1 raster on-source in combination with an off-position (to be specified by the observer).
  This pointing mode with off-position starts and ends always with an off-position which means that the smallest possible AOR has in fact 4 pointings:
  offPosition - (rasterPoint1 - rasterPoint2 - offPosition);
  If the observer will give a repetition factor of 2, the pointing pattern will be:
  offPosition - (rasterPoint1 - rasterPoint2 -offPosition) -
  (rasterPoint1 - rasterPoint2 -offPosition);
  and so on ...

  The smallest possible AOR takes about 718 s:

  - 1×70 s rasterPoint1
  - 1×70 s rasterPoint2
  - 2×70 s offPosition
  - 180 s target aquisition
  - 4×9 s OBCP overhead
  - 1×8 s for a 2 arcsec slew within the raster

- 2×107 s for a 1 deg slew from and to the off-position
  Note, that the slew times depend on the slew length and far-away off-positions contribute a significant overhead within the AOR (e.g., a 2 deg slew would take 128 s).

With one single 70 sec block containing:

- 5 grating cycles (onLine-offLine1-onLine-offLine2)
- on each grating position half a second integration time (2 ramps of 1/4 s or more likely 4 ramps of 1/8 s), i.e., a 1 Hz signal modulation
- 7 repetitions of this wavelength-switch pattern, each time shifted by about 3/4 of a spectral pixel

The 2×1 raster can be specified with a minimum raster step size of 2 arcsec which means that effectively the same sky position is seen twice and the corresponding rms value drops by $\sqrt{2}$.

Detailed parameters for OBCP32 (as given in Cal-U ”OBCP32params”):
The line is placed at -1600 and +1600 grating units away from the central position on the 16 spectral pixels (2 positions on the array). We do 5 grating cycles [$5 \times$ (on-off-on-off)] with half a second on each position (about 10 s in total), then the whole pattern is shifted by 300 grating units and repeated, then shifted by 300 and repeated, . . . (7 wavelength-switch patterns, shifted by 300 grating units each).

The grating movement durations are the following (based on FM-ILT tests):

- grating step sizes of 3200 units (8 spectral pixel) : 170.0 ms
- grating step sizes of 1600 units (4 spectral pixel) : 140.0 ms
- grating step sizes of 800 units (2 spectral pixel) : 100.0 ms
- grating step sizes of 400 units (1 spectral pixel) : 75.0 ms

This compares to the duration for:

- 1 readout : 3.9 ms
- 1 short sub-ramp (8 readouts) : 31.3 ms
- 1 long sub-ramp (16 readouts) : 62.5 ms
- 1 short ramp (32 readouts) : 125.0 ms
- 1 long ramp (64 readouts) : 250.0 ms

The FWHM of an unresolved line has the following widths in pixels:

1st order:	105	158	175	210	micron
	1.78	2.43	2.65	3.11	pixel
2nd order:	72	105			micron
	1.42	1.78			pixel
3rd order:	55	72			micron
	1.26	1.42			pixel

Grating step sizes of 3/4 of a pixel (300 grating units) guarantee at least 3 samples in 1st order at wavelengths beyond 150 micron.
Grating step sizes of 1/2 of a pixel (200 grating units) guarantee at least 3 samples in 1st and 2nd order at wavelengths beyond 75 micron.
Grating step sizes of 2/5 of a pixel (160 grating units) guarantee at least 3 samples at all wavelengths.

Default pointing mode: raster (minimum 2x1) with off-position.
Alternative pointing mode: beam-switching (this would allow to have a single pointing on the sky to perform n-times the wavelength-switch pattern in combination with one off-position with a different dwell-time).

GT KP and OT KP statistics on this mode:
(* to be updated after phase 3 of the proposal entry)

- how many AORs? *
- raster options?
- repetition factors?
- separation between raster center and off-position?
- what kind of targets?
- what kind of lines (emission, absorption, weak, intermediate, bright lines, ...)?
- distribution of the lines within the 3 grating orders?
- how many lines per AOR?
- . . .

A) Standard AOR with: raster (minimum: 2x1) + off-position, smallest raster step size of 2”:

- Use PACS spectrometer wavelength-switch AOR on different sources with several intermediate and bright lines in all 3 grating orders. Select the repetition factors to obtain the required S/N-values ($\approx$10, $\approx$100).
- Use PACS spectrometer wavelength-switch AOR on one source with different intermediate and bright lines (reachable in one filter setting). Selection of the corresponding line repetition factors for different lines (also for direct comparison with the results from chopped-nodded line scans maybe on the same target?).
- Use PACS spectrometer wavelength-switch AOR on one broader line (FWHM around 5-8 spectral pixels).
- Use PACS non-standard AORs on one extended target, for one bright line, keeping the 7-fold grating pattern and with always the same total integration time. Modifications of ramp length, grating movement frequency and grating cycles:
  - wavelength-switch AOR with 64 readouts per ramp and 2 ramps per grating position and 10 full grating cycles per wavelength (default setting);
  - wavelength-switch AOR with 64 readouts per ramp and 4 ramps per grating position and 5 full grating cycles per wavelength (slower grating movements);
  - wavelength-switch AOR but with 32 readouts per ramp and 4 ramps per grating position and 10 full grating cycles per wavelength (shorter ramp option);
  - wavelength-switch AOR but with 32 readouts per ramp and 2 ramps per grating position and 20 full grating cycles per wavelength (shorter ramp option with faster grating movements);
  - wavelength-switch AOR but with 32 readouts per ramp and 8 ramps per grating position and 5 full grating cycles per wavelength (shorter ramps, slower grating movements).
- Use PACS spectrometer wavelength-switch AOR on a source for a bright line in combination with an intermediate size raster (raster could also be sparsely sampled) with off-position, line repetition factor of 1.
- Use PACS spectrometer wavelength-switch AOR on a source for an intermediate line in direct comparison with the chopped/nodded line-scan mode (on the same source and very close in time).

B) Standard AOR with a single pointing with off-position:

- Use PACS spectrometer wavelength-switch AOR on different sources for a bright line in all 3 grating orders with a repetition factor of 1, 2, 4, 8.
- Use PACS spectrometer wavelength-switch AOR on an extended source for an intermediate line in direct comparison with a very fast repeated grating up-down scan (unchopped)
  (to see the result in direct comparison with the wavelength-switch mode and the chop/nod line scan mode).
- Exercise the current OBCP32 twice:
  - once in positive grating direction,

  - once in negative grating direction

  (similar to the grating up-/down-scan in the chop/nod-mode).

- Establish the frequency of "off-position" observations
  (similar to the hold-time concept in other modes)
- There is also an option "nodding_pointing mode" which offers the possibility for single pointing + OFF, but the largest nod amplitude is 7200 arcsec, i.e., 2 deg. which seems to be too small for many projects with pointings in the to galactic plane.

C) Non-standard AORs:

- Use PACS non-standard AORs on one extended target, for one bright line, keeping the 7-fold grating pattern and with always the same total integration time. Modifications of grating amplitude (smaller than the 3200 grating units) and grating movement frequency/grating cycles (note that even for the small grating amplitudes of 4 pixels the grating movement duration exceeds the duration of a short ramp of 32 readouts or 2 sub-ramps of 16 readouts!). This should also reduce the signal jumps due to the smaller movements along the RSRF:
  - wavelength-switch AOR with 64 readouts per ramp and 2 ramps per grating position and 10 full grating cycles per wavelength (default setting), but for smaller grating amplitude of 1600 grating units (i.e., 4 spectral pixels instead of 8);
  - wavelength-switch AOR with 32 readouts per ramp and 2 ramps per grating position and 10 full grating cycles per wavelength (default setting), but for smaller grating amplitude of 1600 grating units (i.e., 4 spectral pixels instead of 8).
- Use PACS non-standard AORs on one extended target, for one line of intermediate brightness, but with higher spectral sampling:
  - wavelength-switch AOR with 64 readouts per ramp and 2 ramps per grating position and 5 full grating cycles per wavelength, for the nominal grating amplitude of 3200 units (8 spectral pixels), but for a 9-fold repetition of the grating pattern (instead of 7), each time shifted by 2/3 of a spectral pixel (better matched to the FWHM of an unresolved line in the intermediate wavelength range of 1st order);
  - wavelength-switch AOR with 64 readouts per ramp and 2 ramps per grating position and 5 full grating cycles per wavelength, for the nominal grating amplitude of 3200 units (8 spectral pixels), but for an 11-fold repetition of the grating pattern (instead of 7), each time shifted by 1/2 of a spectral pixel (better matched to the FWHM of an unresolved line in 2nd order);
  - wavelength-switch AOR with 64 readouts per ramp and 2 ramps per grating position and 5 full grating cycles per wavelength, for the nominal grating amplitude of 3200 units (8 spectral pixels), but for a 13-fold repetition of the grating pattern (instead of 7), each time shifted by 2/5 of a spectral pixel (better matched to the FWHM of an unresolved line in 3rd order)

Estimated time needed

TBD

Calibration Analysis Procedure (CAP)

- Use SPG to process data to Level 2.
- Perform an analysis of the line profiles and the line strengths.
- Compare with theoretical profiles and/or with results from other projects.
- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check the impact of signal transients in the resulting products.

Output, products

- Release of AOT mode,
- Modification of AOT logic or instrument set-up if needed (e.g., off-position concept, combination of raster positions, impact of the calibration block on the PACS internal CSs, grating amplitudes and movement frequencies, ramp lengths, modification in the SPU reduction and compression parameters, detector selection tables, number of repetitions of the grating pattern, displacement of the grating patterns, OBCP/DMC sequence definitions, saturation limits, . . .).
- Warnings/recommendations in the PACS Observer's Manual and on the HSC web-pages for the usage of these modes.

Status/version

```
 first draft,  18/Mar/2008, TM
 second draft, 28/Mar/2008, TM, several additions after
                                ICC co-location meeting
 third draft,  16/Apr/2008, comments by MB, RV, AlPog, update
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```

Req. 5.2.3 Optimized Observing Strategy for Range Spectroscopy

This requirements comprises the following line spectroscopy sub-modes:

- Range scan in chopping/nodding pointed, pointed with dither, mapping) in "Nyquist sampling" and in "high sampling density"
- Range scan in "mapping with off-position" (no chop/nod)

Objectives

Verify and if necessary optimize that Range Spectroscopy AOT gives accurate spectra, including reliable continuum and line flux densities, and line profiles (resulting then in well calibrated line fluxes) over the full accessible wavelength range.

Range mode specific issues are performance for broad lines and continuum, longer and variable time scales of measurement blocks depending on the range width, variable grating density, parallel mode data and the use of the off-position.

- Check that spacecraft dithering and no-dithering give consistent continuum flux densities for all three positions over the full spectral range.
- Check that it works for SSO objects (tracking).
- Verify that order dependent grating step sizes in Nyquist sampling provide the optimum performance (w.r.t. to homogeneous coverage of a spectrum at a given wavelength, overheads, bad pixel map, spectral resolution).
- Check that the chopper frequency and the number of chopper cycles per grating position produce the best performance in Nyquist sampling (w.r.t. on-off signal determination, chopper and grating transition times, noise, glitch statistics). This has to be verified over the full wavelength range.
- Verify that the capacitance settings are optimal. Compare performance in all 4 integrating capacitors covering the full spectra range on continuum sources. Verify if a single capacitor setting is sufficient for the full range coverage in a given band. Verify that flux limits triggering a capacitance change are optimal.
- Check the consistency of continuum flux density and line fluxes in Nyquist sampling vs. high sampling density scans. Verify for emission lines as well as for absorption lines.
- Check the consistency of line profiles obtained in Nyquist sampling vs. high sampling density scans for narrow and broad lines. Verify if line wings are present in Nyquist sampling mode.
- Check the optimum observing strategy to detect the full line profile of a bright unresolved line (S/N $\geq$ 3 for the 3rd minimum) in terms of repetition factors and verify profile reconstruction accuracy.
- Check continuum and line S/N ratio in 3rd order vs. extended 2nd order (parallel) data in Nyquist and high sampling density settings.
- Check the consistency of the continuum levels in the overlapping part of the 2nd and 3rd order ranges.
- Check the consistency of up- and down-scans over various time scales (range widths).
- Check the applicable longest time scale for a single high sampling density scan without degradation in performance. Verify the consistency of continuum flux densities obtained in a full spectral coverage vs. a number of consecutive short range coverages (with attention to measurement duration, overheads, glitch statistics, pipeline issues).
- Check the applicability of chopped frames for long-term response monitoring and calibration.
- Verify the impact on the performance of a full range scan by a curing block executed prior to the scan.
- Check that the three chopper amplitudes give consistent continuum flux denities and S/N (for sources without gradients in the background).

- Verify the impact of pointing accuracy (SRPE) on data quality, especially for long observations. This has to be mainly assessed prior to AOT validation, but some of the validation measurements will be useful for an additional verification of the pointing performance.
- Check the impact of the S/C roll angle on continuum flux densities and line fluxes. This is a long term routine calibration task.
- Compare the performance of mapping with off-position with nodding in raster for an isolated point-like source covered by a mini-raster.
- Compare the performance of nodding in a raster with nodding of a raster for an isolated point-like source covered by a mini-raster.
- Check, if there is any systematic correlation between grating position and measured point source centroid position on the 5×5 matrix. This check has to be repeated on the same point source along different roll angles. It should be part of the spectrometer spatial calibration PV and Routine Phase calibration plans.
- Verify the AOTs long-term robustness (flux repeatability over days and weeks):
  $\Rightarrow$ should be part of the routine calibration plan.
- Verify the impact of calibration reults on the AOT design (spectral purity, spectrometer ghosts, alignment issues, . . .)
  $\Rightarrow$ need to sort out if certain aspects can be improved by the AOT design.
- Verify the fastest possible strategy to cover the full wavelength range in Nyquist sampling mode considering both nominal/parallel channel data.

Low priority objectives:

- Compare the performance in the parallel channel with the nominal channel for the appicable spectral domain. Verify the impact of the non-standard sampling density / oversampling factor in the parallel channel
- Check the performance of mapping with off-position for a point source embedded in a crowded field.
- Check the performance of mapping with off-position for extended diffuse emission.
- Check the performance of mapping with off-position for an isolated point source, if the freqeuncy of visiting the off-position is increased/decreased.
- Check the advantages/disadvantages of the “range repetition factor” vs. the “repetition of nod cycles” for various representative range widths.
- Check that the calibration concept works (duration of initial calibration block, repetition of calibration block inbetween very long observations, key wavelength concept).

Fulfilling or fulfilled by

Some of the range spectroscopy validation aspects are covered by req. 5.2.1. The related objectives are not listed above.

Spectrometer flux calibration observations (reqs. 4.3.x) apply standard range spectroscopy AOTs.

Priority

A

When performed / frequency

1) During FM-ILT

2) During FS-ILT
3) During PV and Science Validation Phase
4) During Routine Calibration Phase

Required accuracy

Sensitivity in range/Nyquist sampling modes: TBW
Spectral resolution/FWHM sampling density in range/Nyquist modes: TBW

Inputs, prerequisites

- Model of the instrumental profile for the three grating orders providing the following information:
  - Expected spatial resolution as a function of wavelength
  - Profile width as a function of wavelength
    (definition of width: intensity falls below 1 % of the line peak flux)
- Simulations:
  - Establish minimum number of grating steps to cover the model instrumental profile width in range/Nyquist sampling modes
    (note: in line spectroscopy the goal is to verify the correct FWHM coverage)
  - Establish minimum number of grating steps to cover the model instrumental profile width for briad lines ⇒ number of grating steps as a function of line width.
  - Verify range widths required for a full line detection of an unresolved line (including line wings up to the 3rd minima at least) in high sampling density mode.
- Established calibration concept and data processing concept (i.e., availability of a working pipeline) in order to check easily and fast the advantages/disadvantages of a certain observation configuration.
- Pointing calibration has to be sufficient to place the source in the centre of the 5×5 array and to execute meaningful dither patterns.
- PACS CS settings have to be established to provide fluxes as similar as possible to the telescope fluxes in all 3 grating orders (part of the req. 2.5.4 on the emissivity of the PACS calibration sources).
- Optimal spectrometer biases have to be established for the given in-orbit radiation environment.
- Established RSRF and definition of key wavelengths.
- Successful technical verification of this mode (OBCP and DMC sequence functioning, timing/synchronisation between instrument and satellite activities, sky source and CS positioning on the arrays, filter operations, SPU configurations, . . .).
- Results from the spatial calibration sequence are needed as input for all dithering and small mapping modes in SPEC.

Sources

Continuum sources (point-like and extended) and line sources (absorption and emission) with various line-to-continuum contrasts and line widths.

- strong continuum point source for full range scans in high sampling density and Nyquist sampling modes, e.g. NGC 7027

Calibration Implementation Procedure (CIP)

- Current default configuration
  TBW

A Standard AOTs to verify the default settings and logic

- Full Range scans in high sampling density mode:
  The full range coverage in high sampling density mode may introduce irrealisticly long time scales between up/down scans and between nodding cycles. It is highly desirable to fragment the full range into individual AORs such that the duration of a fragment in a single repetition should not exceed the duration of the SED mode in the given order (see under Shorter Range scans). The duration of a single SED up/down scan can be considered as the longest calibratable unit for the PACS Spectrometer between a nodding A-B switch. There are no calibration efforts planned (at least during the PV phase) to assess longer time scales, but for reference a long full range scan at high sampling density needs to be executed.
  - 1st+2nd order combination, single repetition factors, full range, high sampling density, pointed mode, small chopper throw;
  - 1st+3rd order combination, settings as for 1st+2nd order combination.
- Full Range scans in Nyquist sampling mode
  - 1st+2nd order combination, apply nodding repetition factor to obtain the required S/N ($\approx$10 – $\approx$100), pointed mode, small chopper throw;
  - 1st+3rd order combination, settings as for 1st+2nd order combination;
  - 1st+2nd order combination, apply nodding repetition factor to obtain the required S/N ($\approx$10 – $\approx$100), pointed with dither mode, three chopper throws (3 AORs);
  - 1st+3rd order combination, settings as for 1st+2nd order combination;
  - 1st+2nd order combination, apply nodding repetition factor to obtain the required S/N ($\approx$10 – $\approx$100), 3×3 raster with 9.5” step size, large chopper throw
- Shorter Range scans in high sampling density mode
  - 1st+2nd order combination, single repetition factors, shorter ranges with durations as close as possible to the SED duration [n AORs are required to cover the entire order], pointed mode, small chopper throw;
  - 1st+3rd order combination, settings as for 1st+2nd order combination;
  - 1st+2nd order combination on one source with several different broad lines, the range width should be defined as the IP width (see definition in prerequisites) at the line wavelength. Selection of the corresponding range repetition factors for the different lines to obtain similar S/N values for each line, small chopper throw;
  - 1st+3rd order combination on one source with several different broad lines, settings as for 1st+2nd order combination;
  - 1st+2nd order combination on several sources with few broad lines (same wavelengths for each AOR), the range width should be defined as the IP width (see definition in prerequisites) at the line wavelength. Selection of the corresponding range repetition factors for the different lines to obtain similar S/N values for each line, small chopper throw. The number of lines could be less than for the two previous validation items.
  - 1st+3rd order on several sources with few broad lines, settings as for 1st+2nd order combination;
  - two AORs in the 1st+2nd and 1st+3rd order settings to cover the overlaping wavelength range between the 2nd and 3rd orders. Pointed mode, small chopper throw, on strong continuum source.
- Shorter Range scans in Nyquist sampling mode
  - 1st+2nd order combination on one source with several different broad lines, the range width should be defined to cover the IP width with a homogeneous oversampling factor, this requires a broader range to define than in high sampling density mode. Selection of the corresponding range repetition factors for the different lines to obtain similar S/N values for each line, small chopper throw;

- 1st+3rd order combination, settings as for 1st+2nd order combination;
- 1st+2nd order combination on several sources with few broad lines, the range width should be defined to cover the IP width with a homogeneous oversampling factor, this requires a broader range to define than in high sampling density mode. Selection of the corresponding range repetition factors for the different lines to obtain similar S/N values for each line, small chopper throw;
- 1st+3rd order combination, settings as for 1st+2nd order combination;
- two AORs for which the number of grating steps is minimized but the entire PACS wavelength range is covered considering data from the 3 nominal orders and the extended second order. Selection of range repetition factors to obtain similar S/N values for each range, small chopper throw.

B Non-standard AOTs to verify alternative settings and complement all objectives
TBW

C Long-term verification of AOT concept
TBW

Estimated time needed

Calibration Analysis Procedure (CAP)

- Use SPG to process data to Level 2.
- Perform separate analysis of the grating up- and down-scans to characterize the signal deviations due to transient effects.
- Perform an analysis of the line profiles and the line strengths.
- Compare with theoretical profiles and/or with results from other projects.
- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check the impact of signal transients in the resulting products.

Output, products

- Release of AOT mode based on success criteria: TBD
- Modification of AOT logic or instrument set-up if needed (e.g., definition and duration of the calibration block, frequency of calibration block execution, satellite dither steps, chopper amplitude or frequency, modification of the basic chop-nod observing block, modification in the SPU reduction and compression parameters, detector selection tables, OBCP/DMC sequence definitions, saturation limits, . . .)
- Warnings/recommendations in the PACS Observer's Manual and on the HSC web-pages for the usage of these modes

Status/version

```
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in CVS:
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Req. 5.2.4 Optimized Observing Strategy for SED modes

This requirements comprises the following line spectroscopy sub-modes:

- SED scan in chopping/nodding (pointed, pointed with dither, mapping) in ”Nyquist sampling”;
- SED scan in ”mapping with off-position” (no chop/nod).

Objectives

Verify and if necessary optimize that the SED mode of the Range Spectroscopy AOT gives accurate spectra, in particular reliable continuum flux densities, over the full accessible wavelength range.

- Verify the consistency of data obtained in up- and down scans in the three SED modes.
- Compare the resulting performances for increasing the range repetition with increasing the number of nodding cycles
(range repetition cannot be changed in the current SED implementation).
- Compare resulting continuum and line S/N for SED blue vs. SED blue high sensitivity mode.
- Verify continuum and line S/N in combined 3rd order and extended 2nd order data (w.r.t. pipeline aspects).
- Check performance if applying alternative sequencing scenarios:
  - chain sub-range up-down scans and check performance vs. single up- down scan;
  - chain sub-range up-down scans and do nodding for each sub-range, check performance vs. single up- down scan.
- Check performance applying additional calibration measurements in hold-time blocks.
- Check performance applying alternative scanning scenarios:
  - nominal 71-98 μm in the second order, parallel 142-196 μm in the 1st order;
  - nominal 102-142 μm in the first order, parallel 60-71 μm in the extended 2nd order;
  - nominal 55-73 μm in the 3rd order, parallel 165-210 μm in the first order.
- Verify performance in the fastest possible full range coverage mode:
grating step size is equal to the instantaneous coverage.
(Grating positions in up-down scans should be shifted by 8 pixels?)
- Compare the performance of mapping with off-position with nodding in raster for an isolated point-like source covered by a mini-raster.
- Compare the performance of nodding in a raster with nodding of a raster for an isolated point-like source covered by a mini-raster.
- Check the performance of mapping with off-position for a point source embedded in a crowded field.
- Check the performance of mapping with off-position for extended diffuse emission.
- Check the performance of mapping with off-position for an isolated point source, if the freqeuncy of visiting the off-position is increased/decreased.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

1) During FM-ILT
2) During FS-ILT
3) During PV and Science Validation Phase
4) During Routine Calibration Phase

Required accuracy

TBW

Inputs, prerequisites

- Established calibration concept and data processing concept (i.e., availability of a working pipeline) in order to check easily and fast the advantages/disadvantages of a certain observation configuration.
- PACS CS settings have to be established to provide fluxes as similar as possible to the telescope fluxes in all 3 grating orders (part of the req. 2.5.4 on the emissivity of the PACS calibration sources).
- Optimal spectrometer biases have to be established for the given in-orbit radiation environment.
- Established RSRF and definition of key wavelengths.

Sources

strong continuum point source with emission lines, e.g. NGC 7027

Calibration Implementation Procedure (CIP)

- Current default configuration
  TBW

A Standard AOTs to verify the default settings and logic

- SED red and blue scan
  - all three different chopper throws,
    small, medium, large
    on compact source
  - dithering in combination with large chopper throw
  - 3×3 raster, step size 9”
    large chopper throw
- SED blue high sensitivity scan
  - pointed mode with large chopper throw

B Non-standard AOTs to verify alternative settings and complement all objectives
TBW

C Long-term verification of AOT concept
TBW

Estimated time needed

TBD

Calibration Analysis Procedure (CAP)

- Use SPG to process data to Level 2.
- Perform separate analysis of the grating up- and down-scans to characterize the signal deviations due to transient effects.
- If there are deviating results:
  Analyse the data interactively and check whether AOT set-up, internal calibration frequency imply insufficient calibration or whether exceptional events like unexpected glitch behaviour are the cause for the deviation. Check the impact of signal transients in the resulting products.

Output, products

- Release of AOT mode based on success criteria: TBD
- Modification of AOT logic or instrument set-up if needed (e.g., definition and duration of the calibration block, frequency of calibration block execution, satellite dither steps, chopper amplitude or frequency, modification of the basic chop-nod observing block, modification in the SPU reduction and compression parameters, detector selection tables, OBCP/DMC sequence definitions, saturation limits, ...)
- Warnings/recommendations in the PACS Observer's Manual and on the HSC web-pages for the usage of these modes.

Status/version

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Chapter 6

Cross-Calibration

This chapter addresses the cross-calibration possibilities of PACS with itself (photometry versus spectroscopy mode, consistency of the different observing modes), with the other two Herschel instruments SPIRE and HIFI, and with instruments on other space observatories in this wavelength regime, like Planck-HFI, Spitzer-MIPS, ISO-ISOPHOT, ISO-LWS, and IRAS.

6.1 PACS internal cross-calibration

Internal cross-calibration of PACS refers to comparison of calibrated flux or flux density values amongst the following combination:

- Broad-band "blue" filter and Spectrometer Order 3
- Broad-band "blue" filter and the extended Spectrometer Order 2
- Broad-band "green" filter and Spectrometer Order 2
- Broad-band "red" filter and Spectrometer Order 1
- Spectrometer Order 3 and the extended Spectrometer Order 2 overlap region.
- Photometer in scan map mode and Photometer in chopped mode

The purpose of PACS internal cross-calibration between photometric and spectroscopic detectors and among different observing modes of the same detector is to ensure that observations of a source using the different PACS channels or observing modes are internally consistent. If the results do not agree then the calibration procedure for each channel must be re-examined to identify the causes of inconsistencies and to trigger/recommend further work and propose solutions.

With a source SED, conventionally expressed as $f_{\nu,s}(\lambda)$ [Jy] in the FIR, and the relation $\nu\ f_\nu = \lambda\ f_\lambda, i.e.\ f_\lambda = \frac{c}{\lambda^2}\ f_\nu$, the flux in a PACS photometer band can be expressed as $F_{\rm photband}[W] = T\ A\ \int_{\lambda_1}^{\lambda_2} \frac{c}{\lambda^2}\ f_{\nu,s}(\lambda)\ S(\lambda)\ d\lambda$
with T being the product of reflection losses by the optical mirrors, A being the effective telescope area and S(λ) being the relative photometer system response of the PACS photometer band.

By introducing the the flux density at the band reference wavelength λ_0, $f_{\nu,s}(\lambda_0)$,

$$F_{\rm photband}[W] = T\ A\ f_{\nu,s}(\lambda_0)\ \frac{1}{f_{\nu,s}(\lambda_0)} \int_{\lambda_1}^{\lambda_2} \frac{c}{\lambda^2}\ f_{\nu,s}(\lambda)\ S(\lambda)\ d\lambda$$

For the PACS photometer, the convention is, that the flux density at the reference wavelength $f_{\nu,s}(\lambda_0)$ is determined for the reference SED $f_{\nu,1} = \nu^{-1}$, i.e. $f_{\nu,1}(\lambda) = \frac{\nu_0}{\nu}\ f_{\nu,1}(\lambda_0) = \frac{\lambda}{\lambda_0}\ f_{\nu,1}(\lambda_0)$, hence

$$F_{\rm photband}[W] = T\ A\ f_{\nu,1}(\lambda_0)\ \frac{c}{\lambda_0} \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda}\ S(\lambda)\ d\lambda$$
$$f_{\nu,1}(\lambda_0) = \frac{F_{\rm photband}}{T\ A\ \frac{c}{\lambda_0} \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda}\ S(\lambda)\ d\lambda} = F_{\rm photband}\ C_{\rm conv}$$
with
$$C_{\rm conv} = \frac{1}{T\ A\ \frac{c}{\lambda_0} \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda}\ S(\lambda)\ d\lambda}$$
and effective bandwidth
$\Delta\nu_0 = \frac{c}{\lambda_0} \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda}\ S(\lambda)\ d\lambda$, as tabulated in calTree.photometer.responsivity.

If the source SED $f_{\nu,s}(\lambda)$ is known, the true photometer source flux is determined as

$$f_{\nu,s}(\lambda_0) = \frac{f_{\nu,1}(\lambda_0)}{K_{cc}}$$
with K_{cc} being the appropriate color correction factor as described in document "PACS Photometer Passbands and Colour Correction Factors for various source SEDs", PICC-ME-TN-038.

For the computational prescription of the comparison between photometer and spectrometer observations of a celestial standard with known source SED, the definition of the color correction factor K_{cc} is the starting point:

$$K_{cc} = \frac{f_{\nu,1}(\lambda_0)}{f_{\nu,s}(\lambda_0)} = \frac{\frac{F_{\rm photband}}{T\ A}\ \frac{\lambda_0}{c\ \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda}\ S(\lambda)\ d\lambda}}{\frac{F_{\rm photband}}{T\ A}\ \frac{f_{\nu,s}(\lambda_0)}{c\ \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^2}\ f_{\nu,s}(\lambda)\ S(\lambda)\ d\lambda}} = \frac{\lambda_0}{f_{\nu,s}(\lambda_0)}\ \frac{\int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^2}\ f_{\nu,s}(\lambda)\ S(\lambda)\ d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda}\ S(\lambda)\ d\lambda}$$

, hence,

$\int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^2}\, f_{\nu,s}^{\mathbf{spec}}(\lambda)\; S(\lambda)\; d\lambda = K_{cc}\; f_{\nu,s}^{\mathbf{phot}}(\lambda_0)\; \frac{1}{\lambda_0} \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda}\; S(\lambda)\; d\lambda = f_{\nu,1}^{\mathbf{phot}}(\lambda_0)\; \frac{\Delta\nu_0}{c}$
$\int_{\lambda_1}^{\lambda_2} \frac{c}{\lambda^2}\, f_{\nu,s}^{\mathbf{spec}}(\lambda)\; S(\lambda)\; d\lambda = f_{\nu,1}^{\mathbf{phot}}(\lambda_0)\; \Delta\nu_0$

In this case the photometer measurement is independent of the exact source SED, since the total inband flux is compared.

An alternative comparison is to compare the resulting flux densities at the reference wavelength:

$f_{\nu,s}^{\mathbf{spec}}(\lambda_0) = \frac{f_{\nu,1}^{\mathbf{phot}}(\lambda_0)}{K_{cc}}$
In this case the source SED must be known in order to calculate an accurate color correction factor from the photometer flux.

The relative photometer system response of each PACS photometer band is obtained as the convolution of the PACS filter transmissions (including dichroics), contained in calTree.photometer.FilterTransmission, and the detector absorption, contained in calTree.photometer.absorption.

Req. 6.1.1 Compare point-source fluxes between spectrometer and bolometer

Objectives

Compare flux measurements of the same sources with the PACS spectrometer and bolometer arrays according to the prescription above.

Fulfilling or fulfilled by

Fulfilled by req. 3.2.4 for the photometer, except a few sources with specific SEDs.

Priority

B

When performed / frequency

In Routine Science Phase, see [RD5].
After achievement of consistent full-system spectrometer and bolometer calibration.

Required accuracy

Set by the spectrometer and bolometer calibration accuracy. Since this is a comparison, the measured values are expected to be similar within the derived photometer and spectrometer uncertainties. The spectrometer flux accuracy depends strongly on the assessment of the pointing and the beam correction.

Inputs, prerequisites

Flux calibration source SEDs
PACS photometer band spectral system responses
PACS-P and -S beam profiles
Spectrometer RSRF

Sources

Any source with high S/N for the spectrometer measurement can be used in case the total inband flux is compared. Sources should be non-variable. In case of asteroids, the photometer and spectrometer measurements should be close in time. The comparison should be based on a variety of sources covering a range of fluxes. Repeated measurements on the same source will give an assessment of the reproducibility accuracy.

Calibration Implementation Procedure (CIP)

The spectral scan has to cover the bandwidth of the photometer filter. The PACS spectrometer SED mode is ideally suited for this requirement.

Estimated time needed

About 80 h, see [RD5], PACS Routine Calibration Plan, mainly for spectrometer SED scans.

Calibration Analysis Procedure (CAP)

The introduction to this chapter summarizes the general procedures required to produce sensible comparative values. In short, the fully calibration point source flux measurement from the bolometers is compared with values one derives by predicting the broad-band flux from the observed spectrum.

Output, products

The output is expected to be a document describing the comparison.

Status/version

$Revision: 1.4 $
$Date: 2014/11/28 12:45:00 $

Req. 6.1.2 Compare point-source fluxes between photometer mini-scan map and chopped/nod mode

Objectives

Compare flux measurements in mini-scan map mode and chopped/nod mode of the same sources with the PACS photometer for any systematic differences. Due to the different signal modulation of both observing modes, detector frequency dependent effects can result in different detector responvities under the same illumination level. The main PACS photometric calibration is based on mini-scan maps of celestial standards, consistent with the scan map mode being the major and final PACS-P science observing mode. There are a number of early science observations and pointing calibration observations in chop/nod mode. Consistent calibration observations in chop/nod mode were obtained for the full mission. Parallel observations in mini-scan map mode and chop/nod mode allow to disentagle external and environmental effects impacting both observing modes in the same way.

Fulfilling or fulfilled by

Fulfilled by reqs. 3.1.2 and 3.2.4 for the photometer.

Priority

C

When performed / frequency

In Routine Science Phase, see [RD5].
After achievement of a consistent bolometer calibration, independently for mini scan map mode (prime) and chop/nod mode.

Required accuracy

Set by the bolometer calibration accuracy (few %). The comparison should give the same fluxes for a statiscally meaningful sample, using comparable aperture photometry. In case of a systematic flux offset of the chopped mode, this yields the observing mode dependent correction term. Chop/nod photometry has a limited field size due to the chopper throw and the location of positive and negative chopper beams on the array.

Inputs, prerequisites

Photometer responsivities from celestial standard measurements
PACS-P beam profiles and aperture corrections
Corrections for external and environmental effects (evaporator temperature, time after detector biasing, telescope background flux)

Sources

Photometer fiducial standard sources.

Calibration Implementation Procedure (CIP)

Standard mini-scan maps on fiducial standard stars
Chop/nod observations on same fiducial standards, quasi-simultaneous
see [RD5], PACS Routine Calibration Plan, for details

Estimated time needed

No extra time needed, fully covered by standard photometric program, comprising both observing modes.

Calibration Analysis Procedure (CAP)

Standard ipipe processing to produce

1) standard photometer scan map data products
2) standard photometer chop/nod data products

Aperture photometry with appropriate aperture correction.

Output, products

PACS-ICC flux calibration report.

Status/version

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$Revision: 1.2 $
$Date: 2014/11/28 12:50:00 $
```

6.2 Herschel internal cross-calibration

Herschel internal cross-calibration refers to the verification of a consistent line and continuum flux calibration between the PACS-S spectrometer and the SPIRE-S and HIFI spectrometers, taking into account the different spectral resolutions and beam sizes in the common wavelength areas. Furthermore it refers to consistent source SEDs between PACS-P and SPIRE-P photometery.

Herschel internal cross-calibration is a Herschel Science Centre responsibility and described in Herschel Cross-Calibration Plan and Use Cases, HERSCHEL-HSC-DOC-1720 and Herschel Cross-Calibration Plan Supplement: Additional Observations Proposal, HERSCHEL-HSC-DOC-1879.

Req. 6.2.1 Cross-calibration PACS photometer versus SPIRE photometer: consistency of source SEDs

Objectives

The goal is to verify a consistent SED shape of sources observed with PACS-P and SPIRE-P. There are no, common wavelengths, however, the ratios observed vs. modelled flux will clearly highlight any inconsistency.

Fulfilling or fulfilled by

Priority

B

When performed / frequency

In Routine Science Phase.
After achievement of consistent full-system calibration of the two photometers.

Required accuracy

Set by the photometer calibration accuracies and the uncertainties of beam corrections. Also slightly dependent on the selected standard model and its accuracy. Expected to be better than 5%.

Inputs, prerequisites

PACS-P responsivities
Aperture corrections
Color corrections

Sources

Common celestial standards from primary standard star, asteroid and planet list, see [RD5], PACS Routine Calibration Plan, for details. Note, that some of the primary standard stars may have significant chromospheric emission, not taken into account in the models and mainly affecting the SPIRE wavelengths.

Calibration Implementation Procedure (CIP)

- PACS-P scan maps in all filters for mainly point-like celestial standards.

Estimated time needed

No extra time needed for PACS, covered by PACS-P standard photometric program in scan map mode (ID 3.2.4), see [RD5], PACS Routine Calibration Plan, for PACS part.

Calibration Analysis Procedure (CAP)

Standard ipipe processing to produce standard photometer scan map data products. Aperture photometry with appropriate aperture correction. Color correction.

Output, products

Herschel cross-calibration report, HERSCHEL-HSC-REP-1935.

Status/version

```
$Revision: 1.2 $
$Date: 2014/11/28 12:52:00 $
```

Req. 6.2.2 Cross-calibration PACS spectrometer versus SPIRE-S and HIFI in overlapping wavelength ranges

Objectives

The goal is to establish and verify a consistent line and continuum flux calibration between the PACS spectrometer and the SPIRE and HIFI spectrometers, taking into account the different spectral resolutions and beam sizes. This can be verified in the common wavelength areas which are

- 156 – 219 μm between PACS-S and HIFI
- 194 – 210.6 μm between PACS-S and SPIRE-S

Note, that a significant part of this wavelength regime, in particular the whole PACS-S – SPIRE-S overlap area, is affected by spectral leakage into PACS band R1, which must be corrected for. 2 lines, which are outside the leakage range in PACS band R1 and which are inside the HIFI wavelength regime, hence allow clean line flux comparison, are the CII line at 157.7 μm and the CO (16–15) line at 162.8 μm. This calibration item also includes photometric mapping of the target sources, if not covered by science programs, in order to have a detailed two-dimensional picture of the spatial extent of emission regions for proper beam corrections.

Fulfilling or fulfilled by

Priority

B

When performed / frequency

In Routine Science Phase, for PACS-S part see [RD5].
After achievement of consistent full-system calibration of the three spectrometers.

Required accuracy

Set by the spectrometer calibration accuracies and the uncertainties of beam effects. Since this is a comparison, the measured values are expected to be similar within the derived uncertainties. The PACS spectrometer flux accuracy depends strongly on the assessment of the pointing and the beam correction. At the longest wavelengths, i.e. the complete wavelength overlap with SPIRE-S, the proper leakage correction of the red band is another uncertainty for the finnaly achieved accuracy.

Inputs, prerequisites

PACS-S beam profiles
Spectrometer RSRF
Red band leakage correction

Sources

Post-AGB stars and planetary nebulae with CO, [CII] and [NII] lines, see [RD5], PACS Routine Calibration Plan, for details.
Prime planet calibrators Uranus and Neptune for continuum fluxes.

Calibration Implementation Procedure (CIP)

- Chopped range scans in Nyquist sampling (standard AOT)
- Chopped line spectroscopy (standard AOT)
- PACS-P scan maps in red filter for non point-like targets

Estimated time needed

About 40 h, see [RD5], PACS Routine Calibration Plan, for PACS part.

Calibration Analysis Procedure (CAP)

Standard ipipe processing to produce standard spectrometer data products. Convolution of spectra to minimum resolution of compared spectra. Flux corrections for pointing offsets. Leakage correction for PACS-S.

Output, products

Herschel cross-calibration report, HERSCHEL-HSC-REP-1935.

Status/version

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$Revision: 1.2 $
$Date: 2014/11/28 12:54:00 $
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6.3 Cross-calibration against instruments of other observatories

As with the previous chapter, this chapter will be a place holder for the proper references summarizing the on-going discussions on this topic at the Herschel Calibration Steering Group meetings.

- Herschel Calibration Concept Document. Available via livelink. DocRef: HERSCHEL-HSC-DOC-0399

Req. 6.3.1 Cross-calibration Herschel versus Planck: consistency of bright standard source SEDs between PACS-P, SPIRE-P and Planck-HFI

Objectives

The Planck HFI instrument will be absolutely calibrated against the COBE FIRAS instrument which had an absolutely calibrated blackbody onboard. There is no wavelength overlap between PACS and the Planck HFI instrument. However, there is a reasonable/very good wavelength overlap between HFI 545 and 850 GHz bands (feed horns 13,14) and the SPIRE 500 and 350 μm bands. This offers the possibility to get accurate fluxes of the planets and bright asteroids, when observed with Planck HFI and carefully extracted from the total flux in the beam, which can lead to improvement of their models. In this sense also PACS can benefit in its flux calibration from an upgrade of the SSO flux standard models.

Fulfilling or fulfilled by

Priority

B

Required accuracy

Set by the photometer and Planck-HFI calibration accuracies and the uncertainties of beam corrections. Also dependent on the achievable accuracy of the updated standard model. Expected to be better than 5%. For the most accurate cross-calibration, it is required that SPIRE and PACS observe the cross-calibration targets within $\pm$ one week of the Planck observation.

Sources

Common celestial standards from asteroid and planet list, see [RD5], PACS Routine Calibration Plan, for details. Fluxes at 350 μm should be above 0.5 Jy (i.e. about 5 Jy at 100 μm).

Calibration Implementation Procedure (CIP)

- PACS-P scan maps in all filters for bright asteroid and planet standards, coordinated with Planck sightings of this target.

Estimated time needed

No extra time needed for PACS, complementary with PACS-P standard photometric program in scan map mode (ID 3.2.4), see [RD5], PACS Routine Calibration Plan, for PACS part.

Calibration Analysis Procedure (CAP)

Standard ipipe processing to produce standard photometer scan map data products. Aperture photometry with appropriate aperture correction. Color correction. Comparison with model after Planck-HFI feedback and SPIRE-P photometry for SED consistency.

Output, products

Status/version

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$Revision: 1.2 $
$Date: 2014/11/28 12:57:00 $
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Chapter 7

Telescope

7.1 Optical Quality

The final optical quality of the Herschel telescope is a determining factor for image sharpness, resolution, and sensitivity. In particular the final focus position of the SiC primary reflector - hexapod assembly - secondary reflector telescope is essential, since Herschel has no focusing mechanism.

Req. 7.1.1 Herschel telescope focus verification

Objectives

When cooling Herschel to the operational temperature in L2, the resulting Herschel telescope focus position should be within the specified range in order to feed a sharp image into the entrance pupil of the PACS instrument. If this were not the case, the resulting image quality and hence also the contrast, which is strongly related to sensitivity, would be degraded.

Fulfilling or fulfilled by

Since Herschel has no focusing mechanism to adjust the telescope focus, fulfilled for the PACS wavelength regime by Req. 3.1.4 (PACS photometer) and Req. 4.1.3 (PACS spectrometer) measuring the convolution of the telescope PSF with the instrument aperture.

Priority

A

When performed / frequency

- [1] During Commissioning/PV Phase

Required accuracy

as for Req. 3.1.4 and Req. 4.1.3 (PACS wavelength regime).

Inputs, prerequisites

Cool-down of telescope mirror completed.
Herschel cryostat cover open.
PACS photometer bias voltages optimized for telescope background conditions.
For reference ground ILT-tests with telescope simulation optics and model calculations to establish references.

Sources

Bright point-like sources

Calibration Implementation Procedure (CIP)

The telescope focus position was checked repeatedly during cool-down cycles of the Herschel telescope on ground. The correct focus position was adjusted by shimming. The final optical quality of the Herschel telescope focus can only be determined in orbit together with the FIR/submm instruments over the wavelength range of the Herschel Observatory. The resulting image quality has to be checked against the predicted performance with regard to roundness of point source images, FWHM of the PSF and encircled energy.

Estimated time needed

No extra time on top of the PACS PSF measurements for photometer and spectrometer for PACS wavelength regime.

Calibration Analysis Procedure (CAP)

See CAPs of Req 3.1.4 and Req. 4.1.3 (for PACS wavelength regime). Resulting FWHM in S/C z and y , encircled energy values are compared against ground test results and the modelled specifications (cf. Herschel Telescope Specification, SCI-PT-RS-04671).

Output, products

1) Report: PACS photometer point spread function (as measured), PICC-ME-TN-033

2) Report: Herschel/PACS modeled point spread functions, PICC-ME-TN-029
3) PSF library and associated products like FWHM tables and pixel efficiency factors.

Status/version

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$Revision: 1.2 $
$Date: 2014/05/09 11:50:00 $
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7.2 Thermal telescope background

The Herschel telescope is passively cooled and will settle in L2 to a final “equilibrium” temperature in the range 85 – 90 K with a seasonal variation amplitude of $\approx \pm 1$ K. This results in a significant thermal background level which determines the limiting lower in-band power onto the PACS detectors and which is as bright as the brightest celestial photometric standards. Therefore, the telescope background has a large impact on the set-up selection for the detectors with regard to bias settings and read-out cycles/integration capacities and on the curing strategy, since it should provide sufficient self-curing. Also the PACS internal calibration source output needs to be adjusted for a comparable illumination during the detector response reference calibrations.

On the other hand, the telescope background can be used as a relatively stable flux reference which varies only slowly and systematically.

The second important factor, beside the telescope temperature T_{tel}, determining the absolute level of the telescope background is the telescope emissivity $\varepsilon_{\mathrm{tel}}$. It can be approximated by the following relation
$\varepsilon_{\mathrm{tel}} = 2 \times \alpha$, with $\alpha(\lambda) = 0.0336 \times \lambda^{-0.5} + 0.273 \times \lambda^{-1}$ (λ in μm),
Fischer et al. 2004, Applied Optics, Vol. 43, No. 19.

Req. 7.2.1 Monitor the Herschel telescope background during the cool-down phase and the mission

Objectives

The Herschel telescope is passively cooled. During the transit to L2 the telescope cools down from ambient temperature (it is actually actively heated at 170 K for the decontamination period) to the final operational temperature. This means that the background level needs to be monitored in order to optimise the PV schedule with regard to the final photometric calibration measurements, which should be representative for Routine Phase, combined with the final adjustment of the internal calibration source settings. Also the final telescope background will not be stable. It will undergo seasonal changes due to different solar illumination and the mirror emissivities will slightly alter with time. Since the telescope background can be taken as a reference signal in chopped measurements, a detailed spectral telescope background model should be established.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- 1) During Commissioning Phase in the steep temperature gradient.
- 2) During Routine Phase about every 180 ODs (0.5 year) around minimum and maximum solar illumination.

Required accuracy

- 1) A first stability level is achieved, if the extrapolated temperature trend indicates less than 5 K from the final temperature. The final temperature is expected to stay within $< \pm 1$ K due to the seasonal changes and telescope mirror emissivity alteration.
- 2) For the purpose of absolute spectrophotometric calibration, absolute accuracy $<10\,\%$.

Inputs, prerequisites

- 1) Telescope temperature HK information.
- 2) Cool-down model of telescope.
- 3) Wavelength dependent telescope mirror emissivities.

Sources

- 1) Dark sky field.
- 2) Prime spectrophotometric standards (planets and asteroids)

Calibration Implementation Procedure (CIP)

- 1) Commissioning Phase and early PV Phase: The trend of the telescope temperature sensor data should be already quite indicative and serve as guideline for scheduling decisions. Iterative adjustments of detector settings and calibration source heating powers may be necessary.

- 2) Dedicated medium resolution SED scans with PACS spectrometer covering the spectral ranges B2A, B2B and B3A and applying all 3 main chopper throws small, medium and large to cope with temperature gradients over the PACS differential FOV. These are done on a dark field. Alternative measurements are chopped SED scans of celestial standards, which are covered by Req. 6.1.1.

Estimated time needed

- 1) Commissioning and early PV Phase cool-down: The monitoring of the telescope temperature curve does not require any additional time. Tests for the proper set-up of the detectors are described e.g. under Reqs. 1.1.1 or 1.2.1/1.2.3. The adjustment of the internal calibration sources is described by Req. 2.5.4. These requirements give the time need for relevant tests, which may have to be repeated a number of times until the final settlement of the telescope temperature.
- 2) One set of SED scans with the 3 chopper throws takes 5.0 h (Routine Phase set-up). In total 7 measurements during the mission take 35 h. During Commissioning Phase there were 3 shorter scans (with 1 chopper throw only) with 1 h each (hence 3 h in total).

Calibration Analysis Procedure (CAP)

- 1) Telescope cool-down: Since the exact final telescope temperature cannot be predicted pre-launch, the real telescope temperature trend should be compared with the model trend. Also from the temperature gradients per day it should be possible to make a solid prediction of the end temperature.
- 2) Use chopped SED measurements on spectrophotometric standards to derive absolute telescope background spectra at fixed dates. The temperature HK data and frequent monitoring of a secondary flux standard (Req. 4.3.4) are used to establish the seasonal variation model including changes of the telescope mirror emissivity. The chopped SED scans on the dark field can be used to establish the background asymmetry in the two chopper beams.

Output, products

- 1) Prediction of the telescope temperature being in the final range for calibration planning and time scales of certain temperature ranges.
- 2) Telescope background model for absolute calibration of chopped PACS spectrometer measurements.

Status/version

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$Revision: 2.0 $
$Date: 2014/11/27 18:00:00 $
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Req. 7.2.2 Homogeneity of the Herschel telescope background

Objectives

Since the Herschel telescope is only passively cooled and its final equilibrium temperature causes a significant thermal background in the FIR and submm regime, differential measurements have to be performed by chopping in order to cancel out this background contribution. Since the chopper "off-source"-position has to be slightly spatially displaced "on-source"- and "off-source"-beam may contain slightly different background contributions, if there are temperature gradients. Such a chopping-offset would lead to too much or too less background subtraction and falsify the resulting source flux.

Fulfilling or fulfilled by

Related to Reqs. 3.2.9 and 4.3.11 which focus also on small scale structures inside the field-of-view.

Priority

A

When performed / frequency

- [1] In-flight at any phase when performing differential measurements including telescope nodding.

Required accuracy

A not properly cancelled chopping offset has direct impact on the final absolute photometric flux accuracy in form of a systematic uncertainty.

Inputs, prerequisites

The specification is that the maximum temperature difference along the S/C Y axis is < 1 K

Sources

Accurate faint photometric flux standards

Calibration Implementation Procedure (CIP)

One method to overcome possible chopping offsets is the method of telescope nodding, i.e. repeating a rectangular chopped sequence with the "on-source"- and "off-source"-beam exchanged with regard to positive and negative chopper deflections. Hence, any systematic offset between positive and negative chopper beam should cancel out. Since the PACS chopper deflection is fixed with regard to the S/C y-axis, any permanent background gradient should become statitistically significant when evaluating the on-off differences of chop-nod sequences of dedicated point source measurements. If the method is fully successful, then the flux of faint flux standards should be fully recovered.

Estimated time needed

No extra time required on top of observations of faint photometric standards.

Calibration Analysis Procedure (CAP)

Systematic comparison of chop on-off differences for two telescope nod positions with "on-source" and "off-source"-beam associated both with the positive and negative chopper deflection inside the sky filed-of-view of PACS.

Output, products

Level of chopping offset relative to total telescope background.

Status/version

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$Revision: 1.1 $
$Date: 2007/10/31 19:24:54 $
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7.3 Straylight Suppression

By a combination of telescope design (shun shade, baffles) and pointing constraints with regard to super bright infrared sources the straylight level by scattered light should be suppressed to less than 1% of the thermal telescope background (cf. Herschel Straylight Calculation Results, HP-2-ASED-TN-0023).

Straylight suppression as part of the optical system design of the telescope is verified and optimised by industry with the help of ray tracing straylight models. Another important step is the check of the built telescope components versus their design with regard to straylight susceptibility.

The pointing constraints are (cf. Herschel Telescope Specification, SCI-PT-RS-04671):

1) Between the line-of-sight of the telescope (X-axis) and the Sun there must be a minimum angle of 60.6^o (Sun constraint). (The maximum constraint of 119.4^o is with regard to sufficiently illuminate the solar arrays on the backside of the sun shade). The spacecraft Z-axis must be within $\pm 3^o$ pointing towards the Sun.

2) The most unfavorable angle Sun – S/C – Earth with regard to straylight is 37^o. From the S/C orbit the Earth appears with a diameter of $\approx$30', hence the Earth constraint is about 23^o.

2) The most unfavorable angle Sun – S/C – Moon with regard to straylight is 47^o. From the S/C orbit the Moon appears with a diameter of 8', hence the Moon constraint is about 13^o.

A homogeneous straylight component is not detectatble due to the differential measurement technique for subtracting the telescope background. Therefore, any homogeneous straylight component does not harm the photometric accuracy.

There is the possibility of specular reflections of bright sources at the hexapod and secondary mirror structures at around 10 – 25^o distance from the line-of-sight of the telescope. Sources include the Moon, which is always inside the area of pointing constraints, or bright planets, like Jupiter or Saturn, which pass through the allowed pointing area.

Conditions of specular straylight were analysed by a dedicated Herschel Straylight Working Group beyond the industrial studies in deeper detail (cf. RD1). For that purpose the Herschel Straylight Working Group developed its own ray tracing model. The calibration strategy was then to verify for the the most significant straylight spots how much the measured patterns correspond to the predicted ones. This was achieved by dedicated observations during the Performance Verification Phase (cf. RD4). Then the straylight model spot geometry was implemented inside the Herschel Science Mission Planning System to indicate and avoid as much as possible pointings potentially affected by specular straylight of the sources Moon, Venus, Mars, Jupiter and Saturn.

Req. 7.3.1 Verification of Sun straylight rejection

Objectives

Determine whether the straylight specification for the Herschel focal plane is met when the Sun is between 60^o and 120^o of the telescope line-of-sight and within the allowed $\pm 3^o$ rotation angle around the Sun vector. Since the telescope is protected against direct Sun illumination by its sunshade, scattered Sun light can only enter the focal plane by diffraction at the sunshade edge.

Fulfilling or fulfilled by

Priority

C

When performed / frequency

Before launch.

Required accuracy

In order to assess the straylight level quantitatively the measurement accuracy must be much better than 1% of the telescope background level.

Inputs, prerequisites

1) Ray tracing study of scattered Sun light.

Sources

n/a

Calibration Implementation Procedure (CIP)

The level of scattered straylight was estimated by an industrial study (HER.NT.0017.T.ASTR, issue 4, 12-Dec-2006), which showed that the expected level of scattered straylight was far below the specification of 1 % of the telescope self-emission.

Estimated time needed

No observing time required.

Calibration Analysis Procedure (CAP)

n/a

Output, products

No measurable Sun straylight expected.

Status/version

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$Revision: 2.0 $
$Date: 2014/11/27 13:00:00 $
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Req. 7.3.2 Verification of Earth straylight rejection

Objectives

Determine whether the straylight specification for the Herschel focal plane is met, when the Earth comes as close as 23^o to the telescope line-of-sight. Also a search for specular reflections by the hexapod should be done.

Fulfilling or fulfilled by

Priority

C

When performed / frequency

Before launch.

Required accuracy

In order to assess the straylight level quantitatively, the measurement accuracy must be much better than 1% of the telescope background level.

Inputs, prerequisites

1) Ray tracing study of scattered Earth light.
2) Herschel specular straylight model.
3) Earth ephemerides relative to Herschel orbit.

Sources

n/a

Calibration Implementation Procedure (CIP)

The level of scattered straylight was estimated by an industrial study (HER.NT.0017.T.ASTR, issue 4, 12-Dec-2006), which showed that the expected level of scattered straylight was far below the specification of 1 % of the telescope self-emission.

The specular straylight study resulted in the finding, that the Earth would never hit one of the model straylight spots relative to any allowed telescope pointing.

Estimated time needed

No observing time required.

Calibration Analysis Procedure (CAP)

n/a

Output, products

No measurable Earth straylight expected.

Status/version

```
$Revision: 2.0 $
$Date: 2014/11/27 12:30:00 $
```

Req. 7.3.3 Verification of Moon straylight occurrence in straylight spot F

Objectives

At its most extreme solar elongations, the Moon can reach straylight spots F,G and E,H (cf. documents listed in (RD1) for the naming convention) relative to a telescope boresight pointing inside the allowed pointing area close to the Sun constraint of 60.6^o. Verify detection of specular Moon straylight due to straylight spots F or G and compare with predictions of the specular straylight model.

Fulfilling or fulfilled by

Related to Req. 7.3.4 with regard to specular reflection measurements of bright IR sources outside the Herschel telescope field-of-view.

Priority

A

When performed / frequency

- Ideally in PV Phase, when Moon is at extreme solar elongation. Otherwise early in Routine Phase.

Required accuracy

The relative intensity of the extended straylight spots F/G is predicted to be vary between 7.6×10^{-5} and 1.6×10^{-4}. Moon straylight (in the order of 10,000 Jy/7"⊘ beam) should be easily detectable in the scan map.

Inputs, prerequisites

1) Herschel specular straylight model.
2) Moon ephemerides relative to Herschel orbit.

Sources

Ideally an empty field with no bright IR sources. The position must be close to the Sun constraint of 60.6^o and located such that the Moon is in one of the straylight spots F or G relative to this pointing.

Calibration Implementation Procedure (CIP)

Identify a date when Moon is at its most extreme solar elongation which falls into a parallel mode or PACS only PV observation slot. Perform a scan map of size $\approx 1^o \times 1^o$ around the expected position of straylight spot F or G. Apply high (60"/s) scan speed. Select scan map orientation of 45^o. No cross-scan map is needed. Select filter combination 70+160 μm. For observational details, cf. (RD4), for planning details cf. (RD1).

Estimated time needed

0.5 h per scan map.

Calibration Analysis Procedure (CAP)

Evaluate the scan map in a standard way (e.g. high pass filtering with filter width adapted to an extended signal). Check to which degree the measured straylight pattern matches the model prediction. Straylight spots F/G are extended and the Moon is a relatively extended (7') source, so that a relatively large area of the map should be covered by straylight. For an overview of results cf. (RD1).

Output, products

Verification of Moon straylight occurrence in straylight spot F/G as predicted by the out-of-field sources straylight model. Feedback to the spot geometry of the graphical straylight warning system inside the Herschel Science Mission Planning System indicating science pointings potentially affected by specular straylight.

Status/version

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$Revision: 2.0 $
$Date: 2014/11/27 12:00:00 $
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Req. 7.3.4 Sensitivity to bright out-of-field sources inside or outside the Herschel focal plane

Objectives

The Herschel telescope FOV has a diameter of 30'. The PACS FOV is offset from the centre by about 10' in negative Z-direction. The spatial sensitivity of the PACS instrument within or outside the Herschel FOV due to scattering, diffraction effects and/or stray reflections shall be investigated.

Fulfilling or fulfilled by

Straylight assessment inside the Herschel FOV and close to the PACS FOV is fulfilled by Reqs. 3.1.6 for PACS photometer and 4.1.5 for PACS spectrometer, respectively. This Req. concentrates on investigating specular reflections of bright sources outside the Herschel telescope field-of-view, by the hexapod and secondary mirror structures at relative angles to the line-of-sight of about 10^o - 25^o (cf. documents listed in (RD1) for a description of the related straylight model).

Priority

A

When performed / frequency

- In PV Phase, when very bright IR sources like Jupiter and Saturn are visible and a PACS/SPIRE parallel mode observation slot is scheduled.

Required accuracy

In general telescope straylight levels should be below 1% of the telescope background level. The relative intensity of straylight spots A/B/C/D/I/J is predicted to be 1.5×10^{-3} (brightest compact straylight feature), the relative intensity of straylight spots E/H/K/M/O/Q varies between 2.5×10^{-4} and 3.3×10^{-4}. Jupiter straylight (in the order of 15,000 Jy/7"⊘ beam) should be easily detectable in the scan map.

Inputs, prerequisites

1) Herschel specular straylight model.
2) Jupiter, Saturn, Mars ephemerides relative to Herschel orbit.

Sources

A very bright IR source, which can be resolved. The planets Jupiter (maximum diameter from Earth = 49") and Saturn (maximum diameter from Earth = 20") are best suited for this investigation. The telescope pointing should be ideally on an empty field with no bright IR sources. It must be located such that the very bright source is in one of the straylight spots A/B/C/D/I/J or E/H/K/M/O/Q relative to this pointing.

Calibration Implementation Procedure (CIP)

Schedule PACS/SPIRE parallel mode scan maps of size $\approx 2^o \times 2^o$ around the expected position of straylight spots A/B/C/D/I/J and E/H/K/M/O/Q. Due to the telescope symmetry one spot of each group (finally selected ones were I and E) is sufficient. Do 4 scan maps, offset by ≈39", for a proper sampling of the straylight zone. Apply high (60"/s) scan speed. Select filter combination 70+160 μm. For observational details, cf. (RD4), for planning details cf. (RD1).

Estimated time needed

Each parallel mode scan map takes 3.2 h. In total 8 parallel mode scan maps require 25.6 h.

Calibration Analysis Procedure (CAP)

Evaluate the scan maps in a standard way (e.g. high pass filtering with filter width adapted to an extended signal) and superimpose the 4 offset maps. Check to which degree the measured straylight pattern matches the model prediction. For an overview of results, cf. (RD1).

Output, products

Verification of Jupiter straylight occurrence in straylight spot A/B/C/D/I/J and E/H/K/M/O/Q as predicted by the out-of-field sources straylight model. Feedback to the spot geometry of the graphical straylight warning system inside the Herschel Science Mission Planning System indicating science pointings potentially affected by specular straylight.

Status/version

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$Revision: 2.0 $
$Date: 2014/11/27 15:40:00 $
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7.4 Focal Plane Geometry

The Focal Plane Geometry assessment establishes the relative location of the PACS photometer and spectrometer array field-of-views in the Herschel telescope focal plane (S/C Y-Z coordinate plane) and the pointing offset with regard to the S/C X-axis. The approximate pointing offset of the PACS photometric camera is $\approx$10' in -Z-direction. The Focal Plane Geometry is related with the telescope versus startracker alignment. The pointing offsets derived include virtual aperture pointings, e.g. for rectangular chopping the mid-point between "on"- and "off"-position.

Req. 7.4.1 Relative location of PACS photometer and spectrometer field-of-views in the Herschel Focal Plane

Objectives

The Focal Plane Geometry assessment ensures that a pointing request to a target for PACS results in this target being centered in or being at a virtual pointing offset inside the PACS photometer and spectrometer field-of-views, respectively. The virtual pointing position may be the midpoint between the "on"- and "off"-position of a rectangular chopped measurement.

Fulfilling or fulfilled by

Implicit in successful execution of *both* photometer and spectrometer central pointing position (3.1.1 and 4.1.1) with regard to a common spatial alignment reference.

Priority

A

When performed / frequency

- [1] Related tests during ILT
- [2] As early as possible after release of the cryo-cover and adjusting the detectors to the in-orbit and illumination conditions. In principle the "first light" (from sky) measurement is part of it.

Required accuracy

The larger value of absolute measurement error of the telescope pointing system and 1/5 of a spectrometer pixel.

Inputs, prerequisites

The attitude and orbit control system of the S/C must be checked out. The telescope versus startracker alignment must have been achieved, although for PACS this may be a combined effort with the Focal Plane Geometry. The telescope background must be acceptable for detector operation. First in-orbit settings for the detectors must have been found.

Sources

- ILT: XY stage and single hole, raster
- In orbit: The bright PN NGC 6543 is a possible first target - bright although somewhat structured at PACS resolution. It is close to the Ecliptic North Pole, hence always visible. It is compact (optical diameter about 14", not resolved by ISO/ISOPHOT at 60 μm; A&A 452, 523) and has a total flux of 140 Jy at 60 μm ($\approx$18 Jy at 160 μm). For further sources see req. 4.1.1 (brighter fluxes needed than for req. 3.1.1).

Calibration Implementation Procedure (CIP)

- ILT: XY stage data obtained for photometer/spectrometer central pointing position and FOV distortion. See section 3.1.1 of FMILT test report
- In-orbit: The Focal Plane Geometry is an iterative process starting with coarse scans or rasters to locate the target until pinpointing the target at the required position on the array. The relative alignment of photometer versus spectrometer is known from ground tests, so that a successful localisation of the target in the photometer field-of-view should already allow to derive a relatively reliable pointing offset for the spectrometer field of view. See reqs. 3.1.1 and 4.1.1 for details.

Estimated time needed

Calibration Analysis Procedure (CAP)

- ILT: See section 3.1.1 of FMILT test report.
- In-orbit: Determine the centroid of the target and its offset in S/C Y- and Z-coordinates with regard to the expected nominal position for the given type of observation. This offset correction has to be added to the instrument offset information in the S/C Focal Plane Geometry file SIAM (Spacecraft/Instrument Alignment Matrix). In the iterative process the offset should approach the pointing system absolute measurement error limit, or the limit of 1/5 of a spectrometer pixel (req. 4.1.1).

Output, products

Accurate instrument field-of-view pointing offsets with regard to the telescope line-of-sight (X-axis) and the startracker in the SIAM (Spacecraft/Instrument Alignment Matrix).

For details of analysis and results cf. (RD1).

Status/version

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$Revision: 1.3 $
$Date: 2014/11/06 14:45:00 $
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Chapter 8

Space Weather Effects

This chapter addresses all aspects of space weather impact on instrument operations and data quality. Space weather effects can become significant in case of solar activity producing energetic protons which can penetrate the S/C and instrument shielding or generate secondary particles. Among the most energetic events are also individual cosmic ray particles. The flow of cosmic ray particles is anticorrelated with solar activity.

The Herschel mission falls in Solar Cycle 24. The Herschel launch was close to solar minimum and the maximum number of sunspots stayed far below the original prediction. In that respect the Herschel mission faced mild space weather conditions.

8.1 Statistics and Trends

Space Weather can have an impact on space instrument operations by causing single event upsets in the instrument electronics by cosmic ray hits, thus spoiling automatic command sequence execution. In the most unfavorable cases it may even affect the health and safety of the instrument. EDAC (Error Detection and Correction) protection can repair affected memory addresses. Nevertheless, it is important to monitor the impact of cosmic ray hits on the instrument electronics. In case of single event upsets, a curing method is a power cycling of the instrument.

Under active space weather conditions, e.g. solar flares, also the data quality may be affected due to high glitch rates and thus lower achievable signal-to-noise ratios. Analysis of glitch rates and responsivity variations, in particular for the Ge:Ga detectors, during active space weather periods is mandatory to estimate the degradance of the data quality. For the PACS spectrometer raw data ramps of 3 pixels are transmitted together with the onboard processed full array data stream which allows investigations on glitch frequency and strength.

There is a Standard Radiation Environment Monitor (SREM) onboard Herschel which can be used as reference wrt. the energetic characterization of the Space Weather events. Calibrated SREM proton flux weekly summary plots are available under
http://proteus.space.noa.gr/ srem/herschel/data/.

Req. 8.1.1 Monitor the EDAC mapping of the addresses of single memory failures

Objectives

PACS on-board computer memory is EDAC (Error Detection And Correction) protected. By continuous monitoring of the addresses of single memory failures it can be deduced, whether these are completely random or whether a defect in a certain area of the on-board memory is building up.

Fulfilling or fulfilled by

Self-Standing.

Priority

A, important for instrument health and safety.

When performed / frequency

In-flight, during whole Routine Science Phase, once per 14 day cycle.

Required accuracy

–

Inputs, prerequisites

–

Sources

–

Calibration Implementation Procedure (CIP)

The addresses of single memory failures, which are stored automatically on-board by the EDAC, shall be regularly mapped into the configurable HK. This is possible for 10 addresses. For flexibility in the address mapping, the absolute address, which is at present 0x0005476A and an incremental offset N can be specified as AOT parameters.

Estimated time needed

6 s per individual measurement. Less than 0.2 h in total.

Calibration Analysis Procedure (CAP)

Inspect the addresses recorded in the configurable HK.

Output, products

Monitor when 10 EDAC events have happended and the incremental offset must be increased. Note, that in case of power cycling of the instrument, the storage is cleaned and re-started from the original start address.

Status/version

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$Revision: 1.2 $
$Date: 2014/10/05 13:40:00 $
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Chapter 9

Inter-Instrument Interferences

This chapter considers (unexpected) interferences by HIFI, SPIRE or the PACS bolometer on the nominal spectrometer operation, and by HIFI, SPIRE or the PACS spectrometer on the nominal bolometer operation. Also the thermal self-emission of the PACS subinstruments are considered.

Early on in the Herschel mission it was noticed that the operation of the SPIRE DCU on the Herschel service module had significant impact on the HIFI WOV laser temperature stability, so that it had to be finally avoided to schedule HIFI observations after a SPIRE block.

9.1 Photometer

Req. 9.1.1 Influence SPIRE on bolometers

Objectives

Investigate the possible influence of SPIRE operations on the operation of the PACS bolometers, in terms of increased noise, etc. The influence should be highest in case of the parallel operation of both instruments.

Fulfilling or fulfilled by

Related to requirement 1.1.12 (Noise Equivalent Power) where noise properties are determined.

Priority

C. Any influence is expected to be small. In case of significant effects the common operations mode must be revised and modified.

When performed / frequency

First possibility to test this is during EQM test. Another opportunity on ground under quite realistic conditions are the SOVT tests. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

Required accuracy

No significant noise enhancement due to parallel observations should be observed.

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

The best strategy is to compare parallel mode observations with PACS photometer only observations on the same target and with comparable PACS instrument set-up. Note that for parallel mode observations the compression for the PACS blue detector is different from the PACS only mode. The compared observations should be timely detached from cooler recycling and orbit prologue (detector biasing) operations, since these can influence the detector stability for 1 - 2 h, too.

Estimated time needed

These tests can be accomodated in the context of PACS photometer and parallel mode AOT validation (cf. section 5).

Calibration Analysis Procedure (CAP)

Evaluate the parallel and PACS only scan maps and compare their noise behaviour.

Output, products

Status/version

```
$Revision: 1.0 $
$Date: 2014/11/04 12:30:00 $
```

Req. 9.1.2 Influence HIFI on bolometers

Objectives

Investigate the possible influence of HIFI operations (either during a previous operational day, or on the same operational day) on the operation of the bolometers, in terms of increased noise, etc. Another aspect is the advanced switch-on and stabilization of the HIFI Local Oscillator during phases when PACS photometer is prime.

Fulfilling or fulfilled by

Related to requirement 1.1.12 (Noise Equivalent Power) where noise properties are determined.

Priority

C. Any influence is expected to be small. Revision of priority possibly, if this turns out not to be the case.

When performed / frequency

First possibility to test this is during EQM test. Another opportunity on ground under quite realistic conditions are the SOVT tests. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

Required accuracy

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

The best strategy is to compare two identical observations, one being close to a HIFI operations block and the other one more timely detached. The compared observations should be timely detached from PACS cooler recycling and photometer orbit prologue (detector biasing) operations, since these can influence the detector stability for 1 - 2 h, too. Normally, PACS and HIFI observations are scheduled into larger time blocks (several ODs), but the ideal case would be a HIFI block scheduled into a PACS photometer period, so that the effects by cooler recycling and detector biasing can be best decoupled.

Estimated time needed

These tests can be accomodated in the context of PACS photometer AOT validation scheduled in a PACS photometer block following a HIFI operations block.

Calibration Analysis Procedure (CAP)

Evaluate and compare the noise behaviour of the two comparison observations.

Output, products

```
$Revision: 1.1 $
$Date: 2014/11/04 12:45:00 $
```

Req. 9.1.3 Influence photoconductors on bolometers

Objectives

Investigate the possible influence of previous PACS spectrometer operations (either during a previous operational day, or the same operational day) on the operation of the PACS photometer bolometers, in terms of increased noise, etc.

Fulfilling or fulfilled by

Related to requirement 1.1.12 (Noise Equivalent Power) where noise properties are determined.

Priority

C. Any influence is expected to be small. Revision of priority, if this turns out not to be the case.

When performed / frequency

During ILT test. Repeat during EQM and SVOT tests. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

Required accuracy

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

The best strategy is to compare two identical observations, one being close to a PACS spectrometer operations block and the other one more timely detached. The compared observations should be timely detached from PACS cooler recycling and photometer orbit prologue (detector biasing) operations, since these can influence the detector stability for 1 - 2 h, too. The ideal case would be a PACS spectrometer block scheduled into a PACS photometer period, so that the effects by cooler recycling and detector biasing can be best decoupled.

Estimated time needed

Calibration Analysis Procedure (CAP)

Evaluate and compare the noise behaviour of the two comparison observations.

Output, products

Status/version

```
$Revision: 1.1 $
$Date: 2014/11/04 13:00:00 $
```

9.2 Spectrometer

Req. 9.2.1 Influence SPIRE on photoconductors

Objectives

Investigate the possible influence of previous SPIRE operations (either during a previous operational day, or the same operational day) on the operation of the PACS photoconductors, in terms of increased noise, dark current, etc.

Fulfilling or fulfilled by

Related to requirement 1.2.10 (Noise Equivalent Power) where noise properties are determined.

Priority

C. Any influence is expected to be small. Revision of priority possibly, if this turns out not to be the case.

When performed / frequency

First possibility to test this is during EQM test. Another opportunity on ground under quite realistic conditions are the SOVT tests. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

PV: During Routine Phase every AOT is coupled to a calibration block observation. This not being the case during PV, the best way to monitor the changes in noise properties, etc, is to carry out regular stand-alone calibration block observations in the red and blue detector. Monitoring the properties will be important in general, but specifically should reveal if there is any influence by SPIRE, HIFI or the PACS bolometers.

Such a calibration block should be carried out as quickly as possible after PACS spectrometer becomes prime, and at two intervals after. These intervals need not to be strictly periodic and can be interwoven with regular PV observations. The time interval needed between such blocks will probably be better known after commissioning phase.

Required accuracy

Not applicable.

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Analysis of noise determinations (and possibly other TBD quantities) as a function of time after the switch-off of the SPIRE photometer or the SPIRE spectrometer and the switch-on of the PACS photoconductors, respectively, in the case of parallel mode, the switch-off of SPIRE and the PACS photometers, and the switch-on of the PACS photoconductors. SPIRE (and the PACS bolometer) should be operated in such a way as to produce the highest heat dissipation expected under normal operating conditions.

Estimated time needed

PV: The calibration block could be identical to that carried out during normal AOT observations, and be carried out at 3 key wavelengths (one per order).

The duration of a calibration block for 1 key wavelength is about 0.1 h, hence 0.3 h for all 3 key wavelengths.

Calibration Analysis Procedure (CAP)

Output, products

Status/version

$Revision: 1.1 $
$Date: 2014/11/04 10:45:00 $

Req. 9.2.2 Influence HIFI on photoconductors

Objectives

Investigate the possible influence of HIFI operations (either during a previous operational day, or on the same operational day) on the operation of the photoconductors, in terms of increased noise, dark current, etc. Another aspect is the advanced switch-on and stabilization of the HIFI Local Oscillator during phases when PACS spectrometer is prime.

Fulfilling or fulfilled by

Related to requirement 1.2.10 (Noise Equivalent Power) where noise properties are determined.

Priority

C. Any influence is expected to be small. Revision of priority possibly, if this turns out not to be the case.

When performed / frequency

First possibility to test this is during EQM test. Another opportunity on ground under quite realistic conditions are the SOVT tests. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

Required accuracy

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Analysis of noise determinations (and possibly other TBD quantities) as a function of time after switch-off of HIFI and the switch-on of the PACS photoconductors.

PV: See req. 9.2.1 for a description.

Estimated time needed

PV: See req. 9.2.1.

Calibration Analysis Procedure (CAP)

Output, products

Status/version

```
$Revision: 1.1 $
$Date: 2014/11/03 12:00:00 $
```

Req. 9.2.3 Influence bolometer on photoconductors

Objectives

Investigate the possible influence of previous PACS bolometer operations (either during a previous operational day, or the same operational day) on the operation of the PACS spectrometer photoconductors, in terms of increased noise, dark current, etc.

Fulfilling or fulfilled by

Related to requirement 1.2.10 (Noise Equivalent Power) where noise properties are determined.

Priority

C. Any influence is expected to be small. Revision of priority, if this turns out not to be the case.

When performed / frequency

During ILT test. Repeat during EQM and SVOT tests. Should be repeated in PV phase. First indications of any possible influence due to thermal memory effects could come from a thermal model of telescope+cryostat+three instruments.

Required accuracy

Inputs, prerequisites

Sources

Not applicable.

Calibration Implementation Procedure (CIP)

Analysis of noise determinations (and possibly other TBD quantities) as a function of time after switch-off of PACS photometer and the switch-on of the PACS photoconductors.

PV: See req. 9.2.1 for a description.

Estimated time needed

PV: See req. 9.2.1.

Calibration Analysis Procedure (CAP)

Output, products

Status/version

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$Revision: 1.1 $
$Date: 2014/11/03 11:20:00 $
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Req. 9.2.4 Thermal self-emission of the spectrometer

Objectives

Check for thermal self-emission of spectrometer components including the cryo harness. Investigate the effect of filter wheel and grating movements on dark current and sensitivity of the detectors. The effect on the dark current may be less important as it is normally canceled out by the differential measurements.

Fulfilling or fulfilled by

Self-standing

Priority

When performed / frequency

EQM, PV.

PV: appararently not a priority, as no similar ground tests have been carried out so far.

Required accuracy

Inputs, prerequisites

Sources

Calibration Implementation Procedure (CIP)

Dark current:

Turning the filter wheel:
Keep the grating in a fixed position and let the wheel turn. Small steps as well as full turns should be made. Staring measurement on dark position (on cold internal calibrator). The measurement should be sufficiently long to get a stabilized signal.

Moving the grating:
Keep the filter fixed and move the grating with 1) few steps and 2) a significantly longer scan. Staring measurement on dark position (cold internal calibrator). The measurement should be sufficiently long to get a stabilized signal.

Sensitivity:
Similar as above but now observing the heated internal source.

If the above effects turn out to be important, further measurements should be performed for typical observations for every AOT that will be offered to the community.

Estimated time needed

Calibration Analysis Procedure (CAP)

Plot the dark current or measured signal as a funtion of observing time. Perform trend analysis.

Output, products

Status/version

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$Revision: 1.8 $
$Date: 2014/11/03 11:15:00 $
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Chapter 10

Characterization of the PACS Ground Calibration Facility

The PACS ground calibration facility OGSE (Optical Ground Support Equipment) contains several optical elements which serve to

1) simulate the telescope beam into the PACS instrument
   a) mirrors M1 and M2 for external stimulators
   b) mirrors M1, M2, M3, M4, M5 for FIR laser
   c) mirrors M1, M2, M3, M4, M6 (chopper wheel), M7, M8 for BB1
   d) mirrors M1, M2, M3, M4, M9, M10 for BB2
2) feed several stimulators into the PACS entrance aperture
3) provide a satellite representative thermal environment

An overview on the whole OGSE optics is given in PACS-ME-DS-002 (PACS Cryo Test Equipment and OGSE Specification).

10.1 OGSE Chopper

The OGSE internal chopper serves to star on one of the two extended emission OGSE BBs 1 and 2 or to modulate the radiation coming from them (it is not possible to chop between both radiation sources with the PACS internal chopper). The chopper wheel is a vane shaped mirror which either reflects BB1 radiation (via mirrors M7 and M8) or transmits BB2 radiation (via mirrors M9 and M10).

Req. 10.1.1. OGSE Chopper Positioning

Objectives

The OGSE chopper is also used to position the beam on one of the two BBs for staring observations. Since the BBs are extended emitters the position must be such accurate that all PACS arrays are fully illuminated. Assess the time need to re-position the wheel.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- CQM-ILT
- FM-ILT
- FS-ILT

for all detector characterizations requiring staring observations of a well known absolute emitter (Responsivity/NEP).

Required accuracy

± 30 deg (each sector has 90 deg, the BB beam roughly 15 deg)
positional reproducibility ± 1 deg

Inputs, prerequisites

- Test Equipment Controller must allow to command the wheel position and return the HK info (cf. PICC-ME-GS-001).

Sources

n/a

Calibration Implementation Procedure (CIP)

Perform dedicated positioning of OGSE chopper on BB1 or BB2 with various temperatures (e.g. BB1 on , BB2 off) and check by means of bolometer signals that correct BB has been selected. For details of test cf. PICC-ME-TR-005 "OGSE Characterization during CQM/FM-ILT".

Estimated time needed

see FM-ILT test logs

Calibration Analysis Procedure (CAP)

1) Check HK packets of type PACS_ILT_EGSE_* for Optics_CW_Sensor and Optics_CW_Mode data and plot timeline. In positioned mode Optics_CW_Mode = "fixed" and Optics_CW_Sensor = "1" or "2".
2) Check bolometer signals and correlate signal evoution with Sensor HK timeline.
3) Verify that positions and signals are as expected by commanding.

Output, products

- Verification of correct HK feedback
- Establishment of settling times on selected positions

For details of analysis and results cf. (RD1).

Status/version

```
$Revision: 2.0 $
$Date: 2014/09/26 18:40:00 $
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Req. 10.1.2. OGSE Chopper Frequency

Objectives

The OGSE wheel chopper shall produce chopper frequencies that are representative for typical detector characterizations. Establish the reliable frequency range. Verify that the rotation frequency remains stable over typical characterization test durations. Due to the shape of the chopper mirror with 90 deg segments, one full wheel rotation corresponds to two chopper cycles, hence the chopping frequency is twice the rotation frequency of the wheel.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- CQM-ILT
- FM-ILT
- FS-ILT

for all detector characterizations requiring modulated signals of well known absolute emitters.

Required accuracy

$\pm$ one averaged bolometer signal (4×25 ms = 100 ms) $\pm$ one short spectrometer ramp (32 readouts $\times$ 1/256 s = 125 ms)

Inputs, prerequisites

- Test Equipment Controller must allow to command the wheel to various constant speeds and return the HK info (cf. PICC-ME-GS-001).

Sources

n/a

Calibration Implementation Procedure (CIP)

Operate the OGSE chopper in the cold cryostat via SCOS2000. Command a range of input frequencies.

Estimated time needed

TBD

Calibration Analysis Procedure (CAP)

Evaluate modulated detector signal and establish relationship between commanded frequency and measured signal modulation frequency.

Output, products

Reported results, cf. (RD1).

Status/version

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$Revision: 2.0 $
$Date: 2014/09/26 16:30:00 $
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Req. 10.1.3. OGSE Chopper Duty Cycle

Objectives

Establish the duty cycle of the OGSE wheel chopper, taking into account the move of the OGSE BB beam over the edges of the vane shaped mirror, i.e. determine the fraction of the rotation period when one of the two BB beams is mirrored onto the detector. (There may be time shifts between the two extreme sides of the beam.)

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- CQM-ILT
- FM-ILT
- FS-ILT

for all detector characterizations requiring modulated signals of well known absolute emitters.

Required accuracy

$\pm$ one averaged bolometer signal (4×25 ms = 100 ms) $\pm$ one short spectrometer ramp (32 readouts $\times$ 1/256 s = 125 ms)

Inputs, prerequisites

- Test Equipment Controller must allow to command the wheel to various constant speeds and return the HK info (cf. PICC-ME-GS-001).

Sources

n/a

Calibration Implementation Procedure (CIP)

Operate the OGSE chopper in the cold cryostat via SCOS2000.

Estimated time needed

n/a

Calibration Analysis Procedure (CAP)

Evaluate modulated detector signal. Assess relative length of plateaux and transition times.

Output, products

Reported results, cf. (RD1).

Status/version

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$Revision: 2.0 $
$Date: 2014/09/26 16:22:00 $
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10.2 OGSE Blackbodies

Absolute flux calibration, relative spectral response function and detector flat-fielding are ILT applications to be performed close to realistic observation scenarios. For those cases two cryogenic blackbodies are used. One provides the calibrated source flux and the other the calibrated background flux. A cryogenic mechanism (chopper wheel) is chopping between the two sources or staring at one of them. These blackbody devices were designed, built and calibrated at MPE. Their 18mm opening of the cavity is adapted to the pupil sizes inside the test optics. The nominal operational temperature range is from 4.2K to 80K. The OGSE contains also optics to simulate the telescope f-ratio to illuminate the detectors.

Required OGSE temperature range

Document PICC-KL-TN-004 "Flux estimates (in-orbit and OGSE)" specifies the power onto a detector pixel from the telescope as:

$$P_{tel} = \Omega \cdot A_{tel} \cdot Tr_{tel} \cdot \int_{\lambda_1}^{\lambda_2} \varepsilon_{tel} \cdot B_\lambda(T_{tel}) d\lambda \quad [W] \tag{10.1}$$

where $A_{tel} = \pi \cdot (\frac{D_{eff}}{2})^2$ is the effective telescope collecting area with D_{eff} being the effective telescope diameter taking into account the central obscuration, D_{eff} = 3283 mm, and $\Omega = (\frac{pix["]}{206265["/rad]})^2$ is the solid angle of a pixel. The relation for the solid angle Ω can be written using the physical size of the pixel $pix[mm]$ as $\Omega = (\frac{pix[mm]}{D_{eff}[mm] \cdot f/\#_{tel}})^2$, with $f/\#_{tel}$ = 8.68 being the telescope f-ratio. Hence, the product

$\Omega \cdot A_{tel} = (\frac{pix[mm]}{D_{eff}[mm] \cdot f/\#_{tel}})^2 \cdot \pi \cdot (\frac{D_{eff}}{2})^2 = \frac{\pi}{4} \cdot (\frac{pix[mm]}{f\#_{tel}})^2$

is independent of telescope diameter D_{eff}.

Therefore, the illumination of the detector pixel by the crogenic OGSE blackbodies can be written as

$P_{OGSE} = \frac{\pi}{4} \cdot (\frac{pix[mm]}{f\#_{OGSEtelsim}})^2 \cdot Tr_{OGSE} \cdot \int_{\lambda_1}^{\lambda_2} \epsilon_{OGSE} \cdot B_\lambda(T_{OGSE}) d\lambda \quad [W]$

Hence, for a resonable small wavelength interval $\Delta\lambda$, OGSE illumination can be matched to the telescope illumination, as described in PICC-KL-TN-004, by:

$$\epsilon_{OGSE} \cdot B_\lambda(T_{OGSE}) = \varepsilon_{tel} \cdot B_\lambda(T_{tel}) \tag{10.2}$$

adopting ε_{OGSE} = 1 and ε_{tel} = 0.04 and T_{tel} = 80 K. Table 2 in PICC-KL-TN-004 provides the corresponding T_{OGSE} for various λ of the PACS wavelength range.

Uncertainty estimates

From Eqn. 10.1, it can be deferred that the accuracy of the flux estimate depends on the following parameters with the percentage:

1) $\frac{dP}{dpix} \propto \frac{d\Omega}{dpix} = 2 \cdot (\frac{1}{206265["/rad]})^2 \cdot pix = \frac{\Omega}{pix}$
$(\frac{dP}{P})_x = 2 \cdot \frac{dpix}{pix}$
For a pixel scaling uncertainty of 0.1" and a nominal pixel size of 3.2", the uncertainty in illumination power is in the order of 6%.

2) $(\frac{dP}{P})_\epsilon = \frac{d\epsilon}{\epsilon}$
The uncertainty in illumination power is directly propotional to the uncertainty in the telescope emissivity. Note that the telescope emissivity is not grey, but shows some wavelength dependence.

3) $\frac{dB_\lambda(T)}{dT} = \frac{2\,h\,c^2}{\lambda^5} \cdot \frac{1}{e^{\frac{h\,c}{\lambda\,k\,T}} - 1} \cdot -e^{\frac{h\,c}{\lambda\,k\,T}} \cdot -\frac{h\,c}{\lambda\,k\,T^2}$

$\frac{dB_\lambda(T)}{B_\lambda(T)} = \frac{h\,c}{\lambda\,k\,T^2} \cdot e^{\frac{h\,c}{\lambda\,k\,T}} \cdot \frac{1}{e^{\frac{h\,c}{\lambda\,k\,T}} - 1}\,dT = \frac{\lambda^4}{2\,c\,\lambda\,k\,T^2} \cdot e^{\frac{h\,c}{\lambda\,k\,T}} \cdot \frac{2\,h\,c^2}{\lambda^5} \cdot \frac{1}{e^{\frac{h\,c}{\lambda\,k\,T}} - 1}\,dT = \frac{\lambda^4}{2\,c\,\lambda\,k\,T^2} \cdot e^{\frac{h\,c}{\lambda\,k\,T}} \cdot B_\lambda(T)\,dT$

If the telescope mirror temperature varies by 5 K (relative to the level of 80 K) due to final equilibrium level or seasonal variations, the flux difference is ≈18%. The absolute temperature level accuracy of the OGSE of 20 mK at 20 K means a photometric accuracy better than 1%.

Req. 10.2.1. OGSE BlackBody Stability

Objectives

Determine the stabilization times for a certain temperature level of the two cryogenic OGSE blackbodies and the level of temperature variation once the final temperature has been reached.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- CQM-ILT
- FM-ILT
- FS-ILT

Required accuracy

1) Determine stabilization times for ± 10 mK, ± 5 mK and ± 1 mK variation (≈ 1 h).
2) Thermal stability goal is $< \pm 1.25$ mK at 30 K and $< \pm$ 5 mK at 50 K.

Inputs, prerequisites

- Temperature control is implemented by means of a calibrated Cernox CX-1070 with controller LS370.

Sources

n/a

Calibration Implementation Procedure (CIP)

Command the respective cryogenic OGSE BB to the desired controler setting.

Calibration Analysis Procedure (CAP)

Record the OGSE BB temperature reading and its trends into the stable phase. Investigate the amplitudes on the set temperature level.

Output, products

Reported results, cf. (RD1).

Status/version

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$Revision: 1.0 $
$Date: 2014/09/29 17:40:00 $
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Req. 10.2.2. OGSE BlackBody Flux Calibration

Objectives

For ILT calibration of photometer response and spectrometer relative spectral response function the geometry, bandpass and throughput of the cryogenic OGSE blackbody illumination into the detector focal plane must be estimated.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- CQM-ILT
- FM-ILT
- FS-ILT

Required accuracy

Uncertainties involved with the OGSE BB flux estimate are discussed in the introduction to this section. The uncertainty of the OGSE BB flux due to absolute temperature uncertainty is better than 1%. Driving factors of uncertainty are more the deviation of the final telescope temperature from the assumed 80 K reference as well as uncertainties in the emissivity of the source and the telescope.

1) For the photometer estimate illumination per pixel in pW with an accuracy of ±20%.
2) For the spectrometer estimate illumination per pixel in Jy with an accuracy of ±20%.

Inputs, prerequisites

- The design of the thermal heat sink and the combination of a calibrated Cernox CX-1070 with controller LS370 provide an absolute temperature calibration accuracy of ±20 mK at 20 K and ±35 mK at 50 K.

Sources

n/a

Calibration Implementation Procedure (CIP)

n/a

Calibration Analysis Procedure (CAP)

n/a

Output, products

Reported results, cf. (RD1).

Status/version

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$Revision: 1.1 $
$Date: 2014/10/10 14:20:00 $
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10.3 OGSE External Sources

Beams of external sources can be fed into the OGSE to simulate point sources or as wavelength reference.

1) A hot black body combined with a punched hole mask serves as a point source simulator. This source can be moved relative to the focal plane by means of a x-y-stage for a fine PSF scan and for distortion assessment.
2) A water vapor cell (evaporated and filled) serves as wavelength reference

Req. 10.3.1. Characterize OGSE Point Source Simulator

Objectives

Images of FIR point sources are realized in the OGSE by means of pin holes in a black painted surface in front of an external hot blackbody (300 – 1000 K). Characterize this facility with regard to required hole diameters and achieved contrast.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- CQM-ILT
- FM-ILT
- FS-ILT

for PSF and focal plane distortion assessment of both the photometer and the spectrometer.

Required accuracy

- Apertures with different diameters are located on an aperture wheel. The centers of aperture coincide to within $\pm 20\,\mu$m for the different wheel settings (0.1" for scale 5.55 "/mm).
- For masks with a grid of holes, the centroid of each hole should be known with an accuracy of <0.2" (36 μm).

Inputs, prerequisites

- Specifications for hole masks are given in PACS-ME-DS-003.
- External BB is operated manually. Obey stabilization times.
- Focus sequence is needed.
- X-Y-stage to simulate nodding for double differential image.

Sources

n/a

Calibration Implementation Procedure (CIP)

Calibration Analysis Procedure (CAP)

Output, products

Specifications and reported results, cf. (RD1).

Status/version

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$Revision: 1.0 $
$Date: 2014/10/16 17:15:00 $
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Req. 10.3.2. Characterize OGSE Raster Simulator (X-Y-Stage)

Objectives

The OGSE point source simulator (external black body and pin hole mask) is mounted on a x-y-stage to simulate the movement of a point source over the detector array as achieved with the real telescope by executing a spacecraft raster. Define the x-y-coordinates of the optical zero point (central pointing). Characterize the raster performance.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- CQM-ILT
- FM-ILT
- FS-ILT

for PSF and focal plane distortion assessment of both the photometer and the spectrometer and for alignment measurement of spectrometer relative tp photometer.

Required accuracy

- Absolute position accuracy due to mounting/dismouting of x-y-stage and driving to recommended "beam center": ± 0.1 mm, corresponding to ± 0.55" (scale: 0.1802 mm/")
- Reproducibility of position: $\pm 20\,\mu$m

Inputs, prerequisites

- Centering procedure. Central positions and corner positons, scale.
- Transfer of HK packages.

Sources

n/a

Calibration Implementation Procedure (CIP)

Commanding of absolute positions as well as execution of rasters and nodding can be done by CUS.

Calibration Analysis Procedure (CAP)

Output, products

Specifications and reported results, cf. (RD1) and PACS-ME-DS-003. See also reports wrt. req. 3.1.1 (FM-ILT).

Status/version

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$Revision: 1.1 $
$Date: 2014/10/24 10:15:00 $
```

Req. 10.3.3. Characterize OGSE Wavelength Reference (H_2O Cell)

Objectives

The water vapour cell in front of a hot plate provides proper absorption lines over the complete wavelength range of PACS and covering the complete field-of-view. Model spectra are calculated for the applied pressure. A vacuum measurement serves to provide the continuum level.

Fulfilling or fulfilled by

Priority

A

When performed / frequency

- CQM-ILT
- FM-ILT
- FS-ILT

for PACS spectrometer wavelength calibration.

Required accuracy

- Temperature stability of hot plate: ± 1 K

Inputs, prerequisites

- Molecular data of H_2O and all its isotopes are taken from the HITRAN2001 data base. Line by line optical depths are calculated taking into account individual line strengths, pressure broadening and pressure induced line shifts for composing the respective Voigt profiles. These profiles are convolved with a Gaussian instrumental profile corresponding to the predicted PACS resolution for the respective wavelength range and including an additional slit convolution for an extended source.

Sources

n/a

Calibration Implementation Procedure (CIP)

Record a vacuum reference spectrum of the hot plate continnum. Fill cell with H_2O under the appropriate pressure and record the absorption line spectrum on top of the hot plate continuum. Typical pressures are in the range 10 - 25 mbar.

Calibration Analysis Procedure (CAP)

Output, products

Specifications and reported results, cf. (RD1) and PACS-ME-DS-002. See also reports wrt. req. 4.2.1 (FM-ILT).

Status/version

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$Revision: 1.1 $
$Date: 2014/10/24 11:30:00 $
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