| LRM-ENS<br>HIFI | Calibration<br>Plan | Hifi no.: LRM-ENS/HIFI/PL/2000-001<br>Inst no: LRM-ENS<br>Issue: 1.01<br>Date: 22 January 2004<br>Category: 2 |
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# TITLE: CALIBRATION PLAN FOR HIFI

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## DOCUMENT CHANGE RECORD

| **Date** | **Issue / revision** | **Page** | **Change** |
|---|---|---|---|
| 27 October 2000 | Draft 0.1 | All (First Working Draft) |  |
| 3 November 2000 | Draft 0.2 |  | Minor changes |
| 2 February 2001 | Draft 0.3 |  | II.1.a, II.2, II.2.b, II.3.c.2, III.1.b, III.2.a.1, III.3.b |
| 8 March 2001 | Draft 0.4 |  | II., II.1., II.1.a |
| 11 July 2003 | Pre-Issue 1 | All | Completion of many sections/paragraphs. Deletion of requirements given elsewhere. Equations now agree with calibration framework. |
| 15 October 2003 | Issue 1 |  | Minor changes (mainly typo's) on pages 10, 12, 20, 24 |
|  |  | p. 24/25 | Inclusion of priorities within AIV/ILT |
| 22 January 2004 | 1.01 | p.41 | Correct frequencies for CII and NII given |
|  |  | p 19 | AR coating HEB's added |

# I. Introduction

## I.1. Purpose

The purpose of this document is to present a general view of the calibration concepts and work planned for the HIFI instrument. It describes all the necessary steps needed to fulfil the instrument specifications. The task breakdown as described in the present document is believed to match the permanent need to consider the calibration as a whole operation- and analysis chain that should evolve in time. Consequently, this document is a living document. It should also allow a smooth implementation of the calibration operations, both pre-launch and in-orbit, inside the general instrument performance test plan.

## I.2. General Document Overview

The Calibration Plan consists of the merge of three main documents, namely, the overall calibration strategy, the specific calibration requirements, and the operational calibration plan in itself. The calibration strategy presents the challenges implied by the calibration work on HIFI and recalls the organisation and technical contexts where it is applied. It connects the top-level calibration effort to other calibration activities. Figure 1 gives an overview of the calibration activity flows. The calibration requirements should gather the calibration-related information to be collected during the dedicated measurement period. It is the direct reference to establish the operational calibration plan where detailed sequencing and planning for pre-launch and in-orbit measurements are given.

In this document the top-level strategy is outlined. A description will be given of the basic calibration chain from the intensities of hot and cold load (and blank sky) to the absolute calibration of the spectra. However, next to this top-level document there will be a frame work document describing the theoretical model of the HIFI instrument. Also a requirements document, consisting of use cases, is written. Whereas the frame work document is expected to be a little static, the use case document will be very dynamic, updated every time new information becomes available.

## I.3. References

### *I.3.a. Applicable documents*

AD-01 HIFI Instrument specification, SRON-G/HIFI/SP/1998-001
AD-02 FIRST Operation Scenario Document, Version 1.0
AD-03 AIV Plan, SRON-G/HIFI/PL/1999-01
AD-04 Science Implementation Plan for the HIFI ICC, HIFI-ICC-1998-001

### *I.3.b. Reference documents*

RD-01 FIRST-Planck IID-A, SCI-PT-IIDA-04624
RD-02 HIFI IID-B, SCI-PT-IIDB/HIFI-02125
RD-03 Project Management Plan, SRON/HIFI/PL/1999-001
RD-04 Calibration Sources Requirements for Herschel/HIFI, LRM-ENS/HIFI/SP/2000-001
RD-05 Science User Requirement Document, SRON-G/HIFI/SP/2000-001
RD-06 Realisation of a gas cell for tests of Herschel/HIFI, IAS-LERMA/HIFI/AIV/2002-01
RD-07 Chopper Wheel Calibration Method on HIFI, LRM-ENS/HIFI/CAL/2000-02

RD-08 The need of an internal cold load, HIFI/ICC/CAL/2000-11
RD-09 Analysis inputs on Standing Waves - KOSMA Data, LRM-ENS/HIFI/TECH/2001-001
RD-10 The intensity calibration framework for HIFI,V.Ossenkopf, 2003, ALMA memo 442.1
RD-11 Design Description of the HIFI Calibration Source Assembly – SRON-U/CSA/RP/2003-001
RD-12 Spatial Response – Contribution to the framework document of the HIFI/Herschel calibration group – HIFI/ICC/2003-30
RD-13 HIFI Observing Modes Document – SRON-ICC/2002-001
RD-14 HIFI Calibration Use Cases – SRON-ICC/2001-005
RD-15 HIFI Observing Mode Descriptions Document – SRON-ICC/2003-008
RD-16 HIFI Observing Modes Calibration Document –SRON-ICC/2003-010
RD-17 Solar Bodies as calibration Sources – L3AB/HIFI/CAL/2003-01
RD-18 End-Users Requirements Document – SRON-ICC/2001-004
RD-19 HIFI Observing Modes Implementation Document – SRON-ICC/2003-009
RD-20 Frequency calibration framework document, L3AB/HIFI/CAL/2003-02
RD-21 Detailed test plans of HIFI ILT, SRON-G/HIFI/PL/2001-001

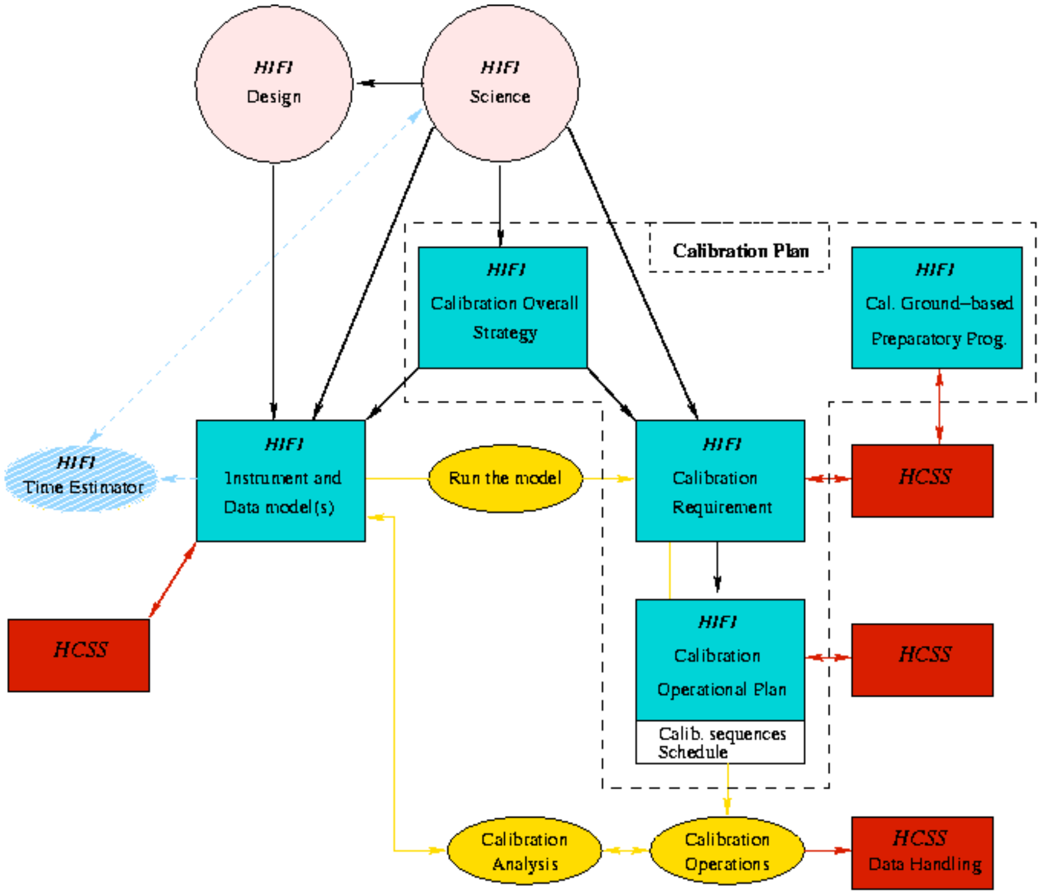

Figure 1.: HIFI Calibration activities and connections

### I.4. Used acronyms and definitions

| | |
|---|---|
| AGB | Asymptotic Giant Branch |
| AIV | Assembly, Integration and Verification |
| CSA | Calibration Source Assembly |
| CSO | Caltech Submillimetre Observatory |
| DBS | Double Beam Switch |
| DSB | Double Side Band |
| Far-IR | Far Infrared Red |
| FIRST | Far Infra Red and Sub-millimetre Telescope (renamed Herschel) |
| FPU | Focal Plane Unit |
| EGSE | Electrical Ground Support Equipment |
| GBPP | Ground-Based Preparatory Program |
| HCSS | Herschel Common Science System |
| HEB | Hot Electron Bolometer |
| HIFI | Heterodyne Instrument for Far-Infrared |
| HRS | High Resolution Spectrometer |
| HK | HouseKeeping |
| ICC | Instrument Control Centre |
| ICU | Instrument Control Unit |
| IF | Intermediate Frequency |
| ILT | Instrument Level Tests |
| ISM | Interstellar Medium |
| JCMT | James Clerk Maxwell Telescope |
| LOSU | Local Oscillator Source Unit |
| LO | Local Oscillator |
| LSB | Lower Side Band |
| PPNe | Proto-Planetary Nebulae |
| Odin | Swedish Submillimetre Wave Satellite for Astronomy and Aeronomy |
| RF | Reference Frequency |
| S/C | Space-Craft |
| SIS | Superconductor-Isolator-Superconductor |
| S/S | Sub-System |
| SWAS | Sub-millimetre Wave Astronomy Satellite |
| TBC | To Be Confirmed |
| TBD | To Be Done |
| USB | Upper Side Band |
| $V_{LSR}$ | Velocity relatively to the Local Standard of Rest |
| WBS | Wide Band Spectrometer |

## II. Calibration Strategy

This chapter aims to provide a comprehensive overview of the HIFI calibration process at an early design stage. Although the overall process will be iterative and flexible, the guidelines are not expected to evolve dramatically during the project. The objectives of the calibration operations derive from the scientific user's requirements. But how these objectives can be reached derives from the instrument scientist's understanding of the instrument. Calibration is also closely connected to the instrument operations: it partly drives the operations, and operational modes, but also uses the operational environment to its highest capabilities (instrument commanding, data flow control, data processing and analysis, archiving capabilities). Altogether it is a complex aspect of the preparation of the mission, which needs interaction with all partners of the project. This makes it an effective place to develop common concepts and vocabulary, and host part of the long term memory of the project.

The main objectives of calibration and the underlying challenges are described in the first section of this chapter. The calibration background and needed resources are then detailed. A description of the main steps envisaged to reach the calibration objectives are derived in the last section of this chapter.

## II.1. Objectives

There are several ways to approach the calibration work. The scientifically useful point of view consists in considering the calibration task as a *calibration of the science data*. This corresponds to the "scaling" of the instrument data to physical units. A complementary point of view aims at understanding and controlling of the instrument performances and their stability (we call it the *instrument calibration*). The calibration of the science data is driven by the main scientific objectives of the instrument, and conditioned by our ability to use, astrophysical sources as calibrators. The calibration of the instrument on the other hand is closely related to the engineering assessment of the instrument: it needs a high level of cooperation with integration and system tests and check-out: this cooperation is in principle beneficial to both testing and calibration. In a sense calibration interfaces science and engineering.

The objectives of both science data calibration and instrument calibration are detailed in the following sub-sections. How both approaches merge in the implementation of the calibration will become clear in the subsequent sections.

### *II.1.a. Calibration of science data*

Calibration is nothing more than the determination of the "instrument equation" which relates the output samples to the distribution of the cosmic sky brightness: the sky brightness is a function of direction, frequency, and possibly time and polarization state. The crudest step is the determination of a scaling factor relating the data numbers to the incoming power: this scaling factor is the radiometric calibration temperature. Quite a few difficulties are hidden behind this simple scaling. A prerequisite is the ability to properly stamp the sampling axis (angle, frequency, time and polarization). Immediately follows the need to accurately know the sampling function (the instrument response function). Further, no physical measurement should avoid a proper assessment of the noise contamination. These issues are successively examined.

### Calibration signal and calibration temperature

Mm/submm observatories have followed the remarkably simple and effective method introduced by Penzias & Burrus (1973) for deriving the photometric "temperature" scale of modulated spectroscopic measurements using a differential "load" minus "blank sky" measurement. With various degrees of refinement (Ulich & Haas 1976, Kutner & Ulich 1981), this method leads to antenna temperatures corrected for atmospheric absorption ( $T_A^*$ ) equivalent to the power received in the forward diffracted beam pattern in one spectral resolution element, expressed as Rayleigh-Jeans temperature "out of atmosphere" (see RD-7 for details.). The power of this simple technique comes from the weak dependence of $T_{cal}$ (see RD-7) on the atmospheric transmission.

For a double side-band instrument, all signals are, by definition, double side-band quantities, and are frequency (channel) dependent. On the other hand $T_{cal}$ has to be adjusted to the signal side-band for spectral measurements, but is only weakly dependent on frequency within the analysed spectral range, provided that the calibration load temperature, the effective atmospheric emission temperature and the so called ambient temperature (effective radiation temperature of the telescope loss terms) are close to each other. For a space-borne telescope, this condition simplifies to similar load and loss temperatures.

This peculiar situation makes the accuracy of the calibration of HIFI with a standard load depend strongly on the assumption that the relative sideband response is much more stable than the overall response. It is certainly important to assess as early as possible the respective contributions of the various upstream and downstream (relative to mixing) fluctuations in the reception chain, namely: local oscillator power (and frequency, although there will be no Doppler tracking), standing waves, contamination through the loss terms, calibration load(s), mixer response, amplification gain, and ... spectrometers.

Despite of all the effects given above that need characterization, modelling and understanding. The combination of cold load, hot load and empty sky, will serve as the intensity scale. Absolute calibration, i.e., tie HIFI into a well accepted astronomical frame-work, will be done on Uranus. This is all crucially depending on all kind of coupling efficiencies that also have to be determined.

The scientists have identified one key issue for spectroscopy in the submillimetre range with HIFI, namely the ability to accurately measure the underlying continuum emission, which is usually higher than in the millimetre wavelength range, and by no way unimportant: not only is the intensity of the continuum background needed to derive opacities in absorption spectroscopy, but also continuum photons may play a significant role in the emission line formation. Continuum measurements in space with an heterodyne spectrometer should not be a problem indeed if the chain enough (special attention should be given to the cold-IF HEMT amplifiers), if the standing waves are well enough understood, if the modulation system provides an accurate zero-mean measurement (e.g. identical optical paths for the different positions of the chopper, or exact compensation though dual, chopping when applicable, but see RD-10 for other solutions). These conditions need to be evaluated as early as possible, as part of the AIV and calibration joint performance assessment, in order to prepare adequate hardware, procedural and software solutions. Especially the establishment of the different stability times for the instrument is important, since this drives the observing modes of HIFI (and their calibration). The requirement on the measurement of continuum emission can be used as a test bench for this purpose (not the only one, but a critical one).

### Calibration of frequency, position, polarisation and time

An obvious prerequisite is the availability of accurate and precise tags of the data samples in the fundamental coordinate space. This obviously involves the instrument, and the telescope, but also the spacecraft and ground-link.

- Position and coupling to the sky

As HIFI has very limited imaging capabilities, the position accuracy relies essentially on the telescope pointing system and its calibration accuracy. The stability of the optical alignment, and the repositioning accuracy of the moving parts may be additional concerns. On this last point it should be emphasized that we have very few control on the telescope parameters.
A good knowledge of the beam profile (i.e. the antenna diagram or the point spread function) is mandatory for calibrating the data. Of primary importance are the parameters of the main diffraction beam: the half power beam width (HPBW) and its relative power. It is, however, also important to know the widths and relative power of any extended error beams which HIFI/Herschel may have. This is of great importance especially when observing extended sources: emission detected through the error beams may add to the emission detected through the main beam. This can be corrected for only if the beam profile is accurately known. In addition, optical errors may show up in the beam profile which may thus deviate from axial symmetry. Finally the change of the beam as a function of frequency will influence the deconvolution of spectral scans (see Comito & Schilke 2002). Accurate knowledge of the position and the beam-sizes is mandatory.

- Time:

In the HIFI case especially the On-The-Fly mapping mode (OTF) depends on careful tracking of time. It indeed is a shared responsibility of the instrument and spacecraft engineers to make sure that no inaccuracies are included in the time recording(s), and that appropriate verifications are made.

- Frequency:

The frequency accuracy will rely on the stability of the reference oscillators, on the thermal stability of the temperature sensitive spectrometer components and on the accuracy of frequency calculations and frequency tuning. Calculations are used in the translation of frequencies between the Local standard of rest and the Observatory. Careful set-ups allow an ample sufficient accuracy (better than 10 kHz). Because of the extra up-converter in HIFI’s band 6, special attention will be given to the frequency determination and monitoring in this band (see RD-20).

- Polarimetric parameters

Mixers respond to the electric field component parallel to one axis. Two orthogonally polarized mixers allow the determination of the total intensity and partial information on the polarization state. The accuracy is limited by the knowledge of the instrumental polarization and it will be very difficult to disentangle instrumental polarization from other differences in gain between two orthogonal mixers. It is not foreseen to use HIFI as a polarimeter.

### Instrument response function (freq., angle, polar., time) and non-linearities

Since HIFI, which avoids the disturbing atmosphere, is expected to be more accurate than any other single-dish submillimeter telescope, the chopper wheel method, as worked out first by Penzias & Burrus (1973) and improved by many others, is not directly applicable. Indeed a refinement was found to be necessary, which resulted in the HIFI frame-work document. Here a detailed description of the bandpass, the frequency scales and the beam profile is given. Whenever possible, relations to the classical descriptions are given. As far as possible non-linearities will be discussed in the frame work document, polarization will only be discussed as soon as instrument tests show this to be important.

### Noise terms

While on Earth, at submm frequencies, the atmospheric conditions are the main source of noise, HIFI's main source of noise are the detectors, the mixers, themselves. This noise is mainly determined by the system temperature. A more refined description of all noise terms will be given in a table based on the noise budget described in AD-01 (HIFI specification) to be appended to this document. This table will be updated when more information is available, especially in-orbit.

### *II.1.b Calibration of the instrument*

### Performance verification and their permanence (overlap with AIV and sub-systems)

To improve the calibration and to avoid extra analysis software development, the HIFI-ICC tries to have the AIV-phase and the in-orbit calibration phase as uniform as possible. This attitude has resulted in as much overlap as possible in the detailed test-plan for AIV and the HIFI calibration Use Cases. Also the operation of the instrument within Instrument Level Tests and in-orbit observations will be made as uniform as possible (although there exist possibilities to define special observation sequences through the Common Uplink System). This basic approach guarantees that similar observations on the ground and in-orbit are executed in a similar fashion. Note that these procedures almost every time make use of calibrating through the cold (and hot) load(s). We expect these measurements thus to be carried out over about 7 years in a uniform fashion, allowing the performance verification to be uniform over this time as well. Having this uniformity for the basic calibration observations is an absolute necessity, but it doesn't guarantee success. Time limitations make that a complete in-orbit characterization is impossible. Here we have to rely on the thorough characterization done in ILT. A strong requirement is *that every frequency setting can and need to be scanned in ILT,* and then later compared with "critical" frequencies in-orbit. Permanence therefore relies on these critical frequencies.

### Analysis of the instrument behaviour and discrepancies (overlap with system engineering)

The analysis of the instrument behaviour is an on-going effort from the sub-system teams and the HIFI System Engineering Team (SET). The build-up of the HIFI ICC, with sub-system specialists and SET members guarantees that this knowledge and the used models will smoothly make the transition into the ICC and Herschel Common Science System.

### Error analysis

The best warranty for highest quality return from the calibration effort is to connect all this information through sets of comprehensive models, that we call instrument and data models. These models need to be grounded to instrumental physics, but also include empirical ingredients, at various levels of sophistication, with a great deal of adaptivity to targets, plus iterativity throughout the mission.

The main objectives of the modelling efforts are:

- consistently derive sensitivity of output to various inputs (w.r.t. instrument understanding and w.r.t. time),
- make connections between optical, thermal, electronic aspects,
- work out critical parameters to monitor/measure problems to cure and devise optimal observing procedures,
- detect discrepant data as quickly as possible (instantaneous or trend),
- put forward common vocabulary and schemes through the whole HIFI project (from construction to data processing),
- serve as common basis to calibration-related developments (time estimator, data simulator, data processing, etc...).

These objectives have resulted in a frame-work document for HIFI, where all the main relevant equations are given. Extra models for detailed problems will be developed ad hoc. From the given equations a thorough error analysis can be easily performed.

## II.2. Context

### *II.2.a. Chopper wheel calibration method*

This is worked out in much more detail in the framework document (RD-10) and in RD-07. Below a summary is presented with some of the main aspects.

### Principles

The chopper wheel method consists in relating the backend counts of a differential (*on-off*) source observation to the output of a hot (also called the *chopper*) stable temperature load that was compared to a colder one. In the procedure first introduced by Penzias & Burrus (1973), the cold measurement is done on the (assumed) blank sky in similar conditions as the observations (i.e. the *off* position).

The astronomical signal is then retrieved from the calibration measurements using the simple equation:

$$T_A^{*j} = \frac{c^j_{source} - c^j_{sky}}{c^j_{hot} - c^j_{cold}} \quad J_{cal}$$

In the above equation, the j indices mean per channel *j* of the spectrometer. $J_{\mathrm{cal}}$ is the main factor to calibrate in the chopper wheel method. Its calculation involves several parameters depending on the telescope design and the instrument stability. Its expression depends on whether the cold measurement is done either on the blank sky or on an internal cold load. This issue is of critical importance for the final design of the internal calibration box and of the calibration procedure. The base line is to use the internal cold load.

### Calibration of the 'loss' terms, and effective temperature

The equation giving the calibration factor is presented in III.1.a. It involves various temperatures corresponding to internal loads (hot and cold) or contributions from the outer world (cosmic background, environment temperature). In particular, when measuring the cold signal on the sky, one has to account for losses due to the rearward component of the telescope beam. This means that a fraction of the signal arises from the temperature of the satellite environment. Since the thermal behaviour of the satellite in the L2-point area is still partially unknown, it is of great importance to make sure that the temperature distribution of all parts possibly contributing to loss terms is monitored. The contribution to this component arising from the different temperature levels of the cryostat is still to be assessed.

In the HIFI frequency domain, effective temperatures need to be given by their Rayleigh-Jeans expression. This implies that physical temperatures are higher than the effective one, especially at high frequencies. This drives somehow the requirements on e.g. the hot load temperature and the hot load design.
As mentioned further in the calibration plan, the final aim of the calibration is to derive a telescope independent temperature scale, i.e. the main beam brightness temperature. To first order it is:

$$J_{\nu,mb}(T) = \frac{\eta_l}{\eta_{mb}} \quad T_A^*$$

with $\eta_l$ and $\eta_{mb}$ being respectively the forward and main beam efficiencies (in the Kutner & Ulich formalism, 1981). These efficiencies calibrate loss terms that are also crucial to be known, whatever the calibration procedure is.

### Single side-band measurements with a double side-band instrument

The first expression given above illustrates that one has to calibrate the various signal contributions in both the image and the signal bands. A critical parameter is the side-band ratio $G_{ssb} / G_{isb}$ (ratio of the band respective gains) that needs to be measured at some point. Since this gain depends on the LO frequency, the measurement of a line injected successively in the LSB and USB will not help because it will require two different tunings. A scanning line will help if its power as a function of frequency is precisely known. A technique making use of an absorption cell is also envisaged, as was for SWAS. For further details we refer to the AIV plan and RD-06. Getting spectral information with a Double Side-Band system implies the use of specific observing strategies and restoring software in order to be able to reconstruct the final spectra. *Knowledge of the side-band ratio is thus mandatory.*

### Standing waves, optical path balance, questions

Reflections at the various interfaces between the FPU, the LOU and the outer world will very likely create standing waves. Their effects on the photometric calibration can be non negligible. This has critical consequences for e.g. absorption measurements where the continuum level needs to be very stable. Some quite high requirements (90 dB) on the absorption level of these ripples have been derived on the total power emission and the question of how this effect will propagate in the differential measurements implied by the calibration procedure is posed. Since the ripple frequencies depend on the optical paths between the reflective surfaces, it is interesting to assess the advantages of comparing measurements done with more or less precisely balanced path lengths and/or similar emissivity. In particular the two procedures described in the principle subsection are expected to exhibit different behaviours in terms on standing waves. This item is developed in section III.1.b and worked out in great detail in RD-10.

### Absolute photometry of spectral lines

It is of great importance to decide on which kind of source one will rely to derive the absolute photometric scale to be applied to each measurement. HIFI is expected to provide a calibration-accuracy much better than what is available on the ground, especially outside the sub-mm atmospheric windows. In particular, the use of astronomical sources as primary calibrator finds its drawbacks at the highest frequencies where the expected emission of astronomical calibration bodies can only be modelled. For HIFI, the primary calibrators will very likely be planets (Mars, Uranus) or asteroids, for which models are available in the submm and far-IR ranges (see section II.2.d.). These primary calibrators are required to assess the telescope efficiencies and check the internal load levels, but the day-to-day *absolute* scaling will be given by the internal calibration procedure. In that sense, regular astronomical measurements can only provide *relative* calibration corrections.

Assuming that observations of the astronomical primary calibrators have provided the required instrument parameters, the chopper wheel method sets the intensities. This antenna temperature scale is in principle not directly comparable to measurements done with other telescopes. To get to the *real* source brightness temperature one has to account for correct source coupling with the telescope beam. If the source is more extended than the beam a fraction of the signal is picked up by the error beams. In that sense the widely used scaling to the *main-beam brightness* temperature is not correct if the source does not perfectly match the main beam size. Nevertheless, for a small telescope as on Herschel, the first error beams are expected to arise several arcminutes away from the beam axes and their intensities may not be too high. Still they need to be measured. Several methods exist to correct from these losses but are not described here (see e.g. Bensch et al. A&A 2000). Note, that while we apply the above procedure to find the spectral line intensity scale, there will be no absolute intensities from well-known spectral lines. In this sense the above method is more absolute photometry from and through continuum emission.

### Absolute photometry of continuum emission

Are there possible advantages in implementing dedicated detectors to measure the total power of the IF independently of the spectrometers? A technical note by N. Whyborn describes an extensive analysis of the need for such an additional hardware and concludes that the use of the spectrometers will suffice to provide the IF total power, and allows for estimating the continuum level required for absorption line studies. Note that the 1/f noise of the HEMT amplifiers may disturb the picture. Although this may be alleviated by higher chop frequencies, the chopper has an upper limit of about 4 Hz. It is strongly believed that careful dedicated continuum observations and applying different calibrations to the different side-bands would alleviate part of this problem.

### Conclusions

From the above we derive a.o. the following strong requirements:

- Every frequency setting needs to be scanned in ILT
- Every coupling and efficiency as defined in RD-10 and RD-12 needs to be determined, either during ILT or in-orbit
- Knowledge of the side-band ratio is mandatory
- Standing wave behaviour needs to be determined as soon as possible
- Intensity scale will be defined on Uranus, asteroids and the internally derived scale from the Hot and Cold Black Body in the Calibration Source Assembly.

### *II.2.b. Understanding of supraconductive mixing devices*

This section aims at reminding some of the mixer issues that could be involved in the calibration concerns. It is obviously strongly connected to the main challenges the mixer groups are facing.

#### II.2.b.1. General overview of heterodyne mixers for HIFI

The heterodyne mixers used for HIFI will contain several key components, including: an antenna that generates a quasi-optical beam that can be coupled to a telescope beam with low signal losses, a highly non-linear mixing device to generate the IF signal, an RF tuning circuit that couples radiation from the antenna to the mixing device, and an IF matching circuit to couple the IF signal from the mixer to the IF amplifier chain.

The HIFI mixers will incorporate two types of antenna. In bands 1, 2,3 and 4 a waveguide antenna with a corrugated horn will be used. This combination should produce a beam with > 97% coupling to the telescope beam and > 99% polarization purity. In bands 5-6b, a quasi-optical planar antenna plus lens will be used. This combination should produce a beam with > 95% coupling to the telescope and > 99% polarization purity.

Two types of superconducting mixer are being developed to yield the highest possible sensitivities in each of the 7 HIFI mixer bands. Superconductor-Insulator-Superconductor (SIS) tunnel-junction mixers will be used in bands 1-5 (480-1250 GHz), although the mixers used in each band will be independently optimized. The mixers in bands 6a and 6b (1410-1910 GHz) will be Hot-Electron Bolometer (HEB) mixers.

### II.2.b.2. Critical issues for SIS Mixers

#### RF bandwidth and Side-band Ratio

It is generally not possible to design a SIS tuning circuit with an arbitrarily wide RF bandwidth. The 3-dB bandwidth of a well-optimized SIS mixer is typically 15-20 % of the centre frequency. Furthermore, the sensitivity of an SIS mixer is rarely independent of frequency within the mixer band. Extra bandwidth can be obtained by allowing dips in sensitivity in the middle of the RF band. Thus, it is expected that the side-band ratio of each HIFI SIS mixer will be strongly frequency dependent. This will be particularly true at 8 GHz IF, as the 16 GHz separation of the signal and image frequencies will be a significant portion of the RF bandwidth of these mixers.

#### Sensitivity to operating conditions

Optimized bias voltages can be found in which either the noise or the gain of an SIS mixer is maximised. In these bias positions, the optimized parameter (noise or gain) should not be too dependent upon small variations in bias voltage or LO power. However, the second parameter will generally still be dependent upon the bias conditions. The optimum bias conditions will be both frequency and device dependent, and must thus be separately determined for each mixer.

Few measurements of the temperature stability of SIS mixers have been published. One report indicates that although the IF output of a SIS mixer is highly temperature-dependent around 4.5 K, this temperature-dependence drops at low temperatures, and is negligible below ~ 2.5 K (when compared with the temperature-dependence of the gain of the IF amplifier used). Note that the mixer noise generally increases, while the gain decreases, with increasing temperature.

#### IF Output Power Spectrum

The shape of the IF output signal of an SIS mixer is strongly affected by the IF circuit used to couple the mixer to the 2 K isolator. This IF circuit contains a DC to IF coupler for coupling the DC bias voltage into the mixer and coupling the IF signal out of the mixer. In principle, this circuit may also be used for impedance matching the mixer to the 50Ω impedance of the IF system. However, this is made difficult in practice by the fact that the differential resistance of the junction changes with $F_{LO}$. An isolator is thus used to suppress the formation of standing waves between the mixer and the IF amplifier. In practice, some standing waves may still be formed, however, it is difficult to predict their strength or periodicity at this time. Thus, until representative mixers, cables, and isolators can be tested as an integrated unit, it will be difficult to predict the exact shape of the IF output signal from the mixers.

**SIS Mixer Saturation**

Past work has shown that saturation in a SIS receiver is usually attributable to one of two factors: saturation of an IF amplifier or detector (this can be avoided in HIFI by using an adjustable IF attenuator), or saturation of the SIS mixer. Saturation of the SIS mixer can take on two forms: gain compression and the generation of higher-order mixing products from one or two relatively strong RF signals. Both of these effects occur when the total IF output power of the mixer becomes large enough that the resulting IF voltage amplitude, $V(t)-V_0$, is no longer a small perturbation of the bias voltage, $V_0$. When this occurs, the mixer gain and noise become a function of input signal power.
From a simple modelling analysis, it is estimated that ~ 150 pW of signal power could lead to 1 % gain compression. Although this is much higher than the typical signal powers that will be detected by HIFI, it should be noted that $k_BT$ at 100 K is 1.4 pW per GHz of RF bandwidth. Thus, depending upon how efficiently the HIFI mixers down-convert RF radiation from outside of the image and signal bands, some saturation effects may be observed (because the full RF band-width of a mixer may be ~ 200 GHz, the total available signal power may be ~ 300 pW at 100 K and 1 nW at 300 K).
One additional point to consider with respect to saturation is that during astronomical observations, the diplexer will direct thermal (~ 100 K) radiation from the LO port to the mixer at frequencies outside of the image and signal bands. Thus, although this radiation will not be seen in the 4-8 GHz IF output of the mixer, it may lead to partial saturation of the mixer.

### II.2.b.2. Critical issues for HEB Mixers (*needs further inputs from people at Chalmers)*

### RF bandwidth and Side-band Ratio

Because an HEB is essentially a resistor, it is possible to match the detector impedance to the antenna impedance over a fairly broad RF bandwidth. Thus the RF sensitivity of the HEB mixers in HIFI should be much less frequency-dependent than in the SIS mixers, yielding a side-band ratio closer to 1 over most of the RF band. A deviation from this behaviour may result if an anti-reflection coating is applied to the silicon lens to reduce optical reflection losses at the air-Si interface the coating will be optimized for the centre of the RF band, and will be less effective at the band-edges.

### Sensitivity to operating conditions

HEB mixers are generally less stable with respect to variations in their operating conditions than SIS mixers. In particular, variations in temperature and LO power will change the optimum bias conditions of the HEB. Furthermore, changes of any of temperature, LO power, or bias position will modify the IF bandwidth both types of HEB. This may be of particular significance in HIFI, as the 3-dB IF bandwidth of both types of HEB will fall close to or within the 4-8 GHz IF band used in HIFI.

### Lack of anti-reflection coating

Because waveguides and corrugated horns become increasingly difficult to manufacture at high frequencies, the HEBs being developed for HIFI are quasi-optical structures incorporating a planar antenna mounted on a silicon lens. These are anti-reflection coated to reduce the ~ 30% reflection loss present at an air-Si interface. The coating is found to be 95% effective.

### Saturation effects

Gain saturation in HEB mixers has not been studied in great detail at this time, although one report of measured results (Yagoubov et al.) indicates that the gain compression is < 1 dB below for $P_{sig} < 0.1 \cdot P_{LO}$ (this would translate to $P_{sat} \sim 1$ nW if $P_{LO} \sim 200$ nW for < 1 % gain compression). Although this saturation level is much higher than predicted above for a 1 THz SIS mixer, gain saturation may still be significant in the HEB mixers, since the total RF band-width of the HEB mixers will most likely be much larger than in the SIS mixers.

### *II.2.c. Understanding of microwave spectrometers*

#### II.2.c-1 General overview of the Wide Band Spectrometer (WBS)

The WBS subsystem is based on 2 acousto-optical 4-channel Array-spectrometers including IF processing and data acquisition. Each spectrometer consists of two separate units: an optical (WBO), and an electrical (WBE).

In the WBO the pre-processed IF signals are analysed with the acousto-optical technique. The WBE IF section processes the Intermediate Frequency signals (4-8 GHz) from the FPU to the four input frequency bands of the WBO (4 x 1.55-2.65 GHz). The WBE electronic section controls the subsystem, the data acquisition and the communication with the Instrument Computer (ICU).

#### II.2.c-2 Critical issues of WBS

### Frequency calibration

The precise frequency calibration of each subband spectrum is done by analysing a comb-spectrum. A zero measurement should already be subtracted from the comb spectrum. In addition, the frequency of the centre comb line, the comb line spacing and the approximately pixel number of the centre comb line are needed. See the frequency framework document (RD-20) for more details.

The repetition rate of the frequency calibration measurement depends strongly on the temperature stability of the WBO. With a stability of 1 K per hour for the WBO a comb measurement is required at least every 20 minutes to guarantee a frequency calibration better than 100 kHz. Integration times of 1 second with the comb input signal are sufficient. Together with a comb measurement we recommend a zero measurement for correction of the comb data and as part of the health check of the WBS. After switching signals in the WBE IF-unit (zero, comb, signal) a minimum dead time of 100 msec (KOSMA/WBS/SID –WBS specifications and interfaces) before starting the measurement is required to guarantee a stable input signal at the WBO.

### Platforming

The WBS shows platforming effects in case of big continuum offset levels (ON & OFF position). This effect comes mainly from the compression of IF amplifiers at large amplification. The IF processor non-linearity will be measured and it will be used as input for a software correction of the individual spectra in order to reduce platforming.

### Influence of Bragg cell heating on baseline stability

The baseline stability of the WBS will be degraded in case of a calibration measurement. This is caused by large power changes of RF signals (HOT/COLD-load) fed into the Bragg cell. When high baseline stability is required (OTF, long total power observations, etc.) in order to avoid such effects a dead time of approx. 20 sec should be implemented after calibration.

### II.2.c-3 Essentials of the HRS

The bandwidth of the input signal is 4-8 GHz, and the nominal power level at input is –95 dBm/MHz. The concept is such that the HRS provides the capability to analyse up to 4 sub-bands per polarisation, placed anywhere in the 4 GHz input bands coming from the FPU. The number of auto-correlation channels is 4096 per polarisation. The power level on each sub-band can be tuned with a programmable attenuator (0-15.5 dB by step of 0.5 dB) to optimise the analogue to digital conversion.

The HRS sub-system is made of 2 identical boxes: the FHHRV (HRS vertical polarisation) and the FHHRH (HRS horizontal polarisation). Each box is made of 3 sections:

- the IF electronics down-converts the RF input signal from 4-8 GHz in an acceptable range for the autocorrelator. The Local Oscillator (LO) module contains Image Rejection Mixers (IRM), some local oscillators (10.5 GHz, 1.25 GHz, 4x13-17 GHz) and the 10 MHz distribution. This section also contains the interfaces with the AutoCorrelation Spectrometer (ACS) module. It also contains the low-noise amplification, half of the matrix switch, IF up and down conversion. The IF provides adjustable attenuators for setting the correct signal level in each of the sub-bands

- the ACS section. This section samples at 550 MHz and digitizes with a 2 bit / 3 level code the 8 analog signals coming from the IF section. It computes the auto-correlation functions of either 1, 2, 4 or the 8 digitised signals, it sends the autocorrelation functions to the Instrument Control Unit (ICU), it generates the housekeeping (HK) data and sends them to the ICU
- the DC/DC converter providing power to both IF and ACS sections.

One HRS unit shall provide, as a minimum, the modes listed in table below:

| **Mode** | **Number of bands per polarisation x bandwidth** | **Number of lags** | **Number of offset channels** | **Spectral resolution (kHz) -Hanning type apodisation-** | **Channel spacing (kHz)** |
|---|---|---|---|---|---|
| High resolution | 1 × 250 MHz | 1 × 4080 | 16 | 135 | 67 |
| Nominal Resolution | 2 × 250 MHz | 2 × 2040 | 16 | 270 | 134 |
| Low resolution | 4 × 250 MHz | 4 × 1020 | 16 | 539 | 270 |
| Wide band | 4 × 500 MHz | 4 × 2 × 510 | 16 | 1078 | 540 |

The HRS is a tuneable spectrometer:

- it is possible to set each sub-band frequency independently anywhere in the 4 GHz input range
- the HRS can be used in 4 different modes regarding the resolution (0.14, 0.27, 0.54 or 1.1 MHz).

Frequency calibration of the HRS is described in detail in the frequency frame-work document (RD-21). The principle is that the local oscillators in the HRS are locked to the master oscillator in the LO system, thus providing electronic knowledge on the frequency.

### *II.2.d. Astronomical sources in the sub-mm (Inputs taken from RD-04).*

Herschel/HIFI will observe many types of astronomical sources, from bright planets to weak distant galaxies. The calibration sources must sample the variety of targets to measure the performances of the instrument for all types of observations.
The sources shall be chosen in order to fulfil the calibration check requirements presented in III.2. and III.3. They can be separated in four types, which cover most of the future targets for HIFI (see RD-05):

- Solar system sources
- Evolved stars

- ISM sources: hot cores and photo-dissociation regions
- Starburst galaxies

To choose calibration sources in each type, we shall first try to answer the following questions:

- How many sources can /need to be used as calibration sources?
- How well are these sources known from previous observations and/or models?
- Which strong lines are expected in their submm spectrum?
- Is it possible to perform ground-based observations with the current submm telescopes to gather the missing data and prepare an astronomical calibration database?

In the following we give an overview of what is available in the submm range for each of the four source types listed above.

## Solar system sources

The solar system sources are described in detail in RD-17. From the discussion in this document *Uranus and asteroids are the main candidates for establishing HIFI's intensity scale* (together with internal loads). Other planets like Mars could be used outside the strong atmospheric lines. Most solar system objects can be used for beam-maps. RD-12 contains all information on the beam-properties that can be derived from solar system objects observations. Note that PACS and SPIRE will also use Uranus and asteroids as calibrators for their spectrometers. Visibility of all solar system objects may pose a problem early in the mission.

## Evolved stars

Evolved stars (including AGB, post-AGB, PNe, PPNe) are used as pointing sources on many ground based telescopes. They show strong lines with a simple geometry. Thermal lines of CO, SiO, $H_2O$, HCN, CS are expected in these objects, although not all species will be visible in the same object. Some of the sources exhibit a very rich spectrum, and can be used as line calibrator for spectral line survey. Appendix A gives a list of the main lines to be expected in the submm range.

In general, AGB and post-AGB objects show a great variety of excitation conditions, corresponding to inner/outer regions, shocked/quiescent media, molecular/PDR gas, etc. Variations in $T_k$ between >1000 K and <10 K exist in every object. Information on the variability and the source extent at high-J transitions is scarce. Some models exist, predicting for instance that the extent must be roughly inversely proportional to J, but they cannot yet be compared with observations. However, in almost all AGB stars, the envelopes show spherical symmetry and remain unresolved for most submm single-dish facilities. These sources are very well suited to exercise Astronomical Observation Templates (AOTs) and to verify that HIFI indeed measures spectral lines in agreement with ground observations. The fact that few lines will be observed often during the mission also allows for health monitoring of HIFI and finally for trend-analysis in these settings.

It is likely that a few among these stars could be used to check the pointing accuracy. Some $H_2O$ (and HCN) lines are masing. These maser lines are variable and will not be usable for calibration, only for pointing. Whether they can serve to check polarisation performances is still to be assessed.

The list gathered in Appendix B presents the main candidates identified so far in the submm range. This sample is expected to grow up with additional southern targets that still need to be identified (see preliminary list in Appendix B.2). Some of the sources exhibit a very rich spectrum, and can be used as line calibrator for spectral line survey.

### Hot cores and other spectral line sources

Hot cores are the ISM sources with the richest spectra. In these sources, a young star (protostar) illuminates the surrounding dense gas. Organic molecules are formed in the hot dense gas (200 K) envelopes, giving rise to a complex and intense submm spectrum. The brightest source, Orion-IRc2 has been surveyed up to 900 GHz, with bright molecular lines. There are 10 similar sources, which can be observed in the Galaxy. Work on these sources is in progress with ground-based radio telescopes.

The main problem is the sensitivity of the observed spectrum to pointing since physical conditions rapidly vary on small scales in these sources. These sources will be well suited to measure the side band ratio, but may not be the first choice for frequency calibration.

These sources have also very intense submm continuum emission. Absorption lines may be seen in addition to emission lines. One could take advantage of these narrow features to calibrate the spectral resolution of the HRS (see also RD 04).
Most of these sources are associated with ultra-compact HII (UCHII) regions. Recombination lines are expected to be present in their spectrum (see list in appendix A). There is no prediction yet on the intensity of these lines. If they are strong enough, they would provide a good list of frequencies for calibration since the intensity ratio can be accurately predicted, and the line shape is the same for all lines. A preliminary list is given in appendix B.

### Starburst galaxies

It is important to include starburst galaxies in the calibration source list as galaxies will be observed intensively with HIFI. Also, the line shape is different in galaxies, which have broader lines than stars and ISM sources. It is important to check the performances on such sources, especially with regard to platforming of the spectrometers, when observing broad faint lines. An additional argument is the different distribution in the sky since galaxies avoid the Galactic Plane generally. The main lines to be observed will be the CO lines, and possibly water and HCN. The expected line width is about 300 km/s, corresponding to 1 GHz at a frequency of 1 THz, so the lines will cover a significant fraction of the backend, particularly in band 6. Note that this figure is just illustrative, and that some galaxies very important for HIFI (e.g. Arp220) have much broader lines. This kind of calibration check may be restricted to the brightest galaxies where integration time remains reasonable to get reliable data. However, similar information may be available from the monitoring of regular science observation in-orbit or through measurements of asteroids, whose continuum mimics the broad extragalactic lines.

The source sizes vary from a few arcsec to 1 arcmin, and may depend on frequency. Most galaxies will be unresolved or marginally resolved with HIFI. As for hot cores, most galaxies are expected to have continuum flux. These sources could be used to monitor the line to continuum ratio as they are not variable. A preliminary list is given in Appendix B, including 18 sources, of which 5 have already provided many data at several submm frequencies and appear in bold face.

## II.3. Resources

### *II.3.a. Teams and management*

Most elements related to the management of Calibration Group are presented in AD-04. The Calibration Group consists of its Calibration Manager and the institutes contributing to several levels of the calibration effort. Its relation to the other components of the ICC is illustrated in the Science Implementation Plan (SIP, AD-04).

### *II.3.b. Documentation*

The calibration plan is the top-level document to be delivered by the Calibration Group. The document distribution is currently managed through a web-based document server at LRM-ENS (http://www.lra.ens.fr/hifi-icc/, registration required). It gathers documents in their draft or official versions, as well as internal notes. In the future it is expected to be included in the HCSS. References to physics/astrophysics documents are listed as an appendix in the Calibration Plan.

### *II.3.c. Test facilities*

#### II.3.c.1. General AIV/ILT concerns

In principle the ground-calibration is completely done in the AIV programme. Any specific requirements of the in-orbit calibration on ground measurements will be performed through AIV and thus makes use of the AIV/ILT test facilities. Below a list of prime topics to be covered for the DM is given. For a description of the facilities we refer to AD-03. Specific equipment needs do, nevertheless, arise as measurement requirements get refined. One of them is the absorption cell described in details hereafter.

### *II.3.d. Test procedures (concepts & compliance with AIV/ILT)*

Test procedures concepts are outlined in the AIV plan (AD-03). Here only the priorities for calibration are given:

### Characterization of standing waves

The tests have to enable a first measurement based modelling of the standing waves in all optical paths within the DM and the following models.

As the standing waves can be measured only as difference between standing waves and we find always a superposition of the combination of the standing wave in the LO path and the signal path, a number of cross comparisons is required to determine the role of single standing waves.

The comparisons have to include changes of the LO frequency in small steps and changes of the position of the LO relative to the mixer unit measuring for each step the signal to the internal loads and the outer shutter. The number of steps has to enable a sufficiently clear picture of the standing waves in each branch. The tests have to be performed for more than one band (e.g. band 1 and band 5) because they use a completely different design for the LO path.

By changing the temperature of a thermal source in the signal path it has to be discriminated between the additive and the multiplicative contribution of the standing waves.

### Stability characterization

The stability measurements have to provide a first impression for the overall stability of the instrument as measured in terms of the Allan time and they have to give clear guidelines for the ratios between the different stability times which determine the operation of the instrument (observing modes).

Thus they have to include normal Allan variance measurements where the signal is dumped over a long period in regular intervals (every second) without any changes to the system and they have to include difference Allan variance measurements measuring the mutual drift between two signals. The difference Allan variance measurements have to include a time series for the difference between the two internal loads (band pass stability time), a time series for the difference between the cold load and the cold shutter (chop standing wave stability time), and a time series for the difference in the signal between two slightly different LO frequency settings (frequency switch standing wave stability time).

### System alignment

As the optical alignment is a crucial key for the overall instrument performance, the DM tests have to verify that the planned alignment procedures work reliably and result in reproducible configurations close to the theoretical optimum.

### Bandpass characterization

In the planned measurements of the instrument band pass it has to be made sure that always all spectrometer channels are considered and that the characterization may not be based on average values. This guarantees that no spurious signals and effects may be hidden. Moreover a possible nonlinearity (compression) has to be determined.

All spectra taken during these measurements should be stored in an annotated database allowing a clear interpretation of the measurements.

### Absorption cell

During the AIV/ILT tests an absorption cell will be used. A complete description of the current envisaged design and of the operation principles can be found in RD-06. The objectives of this gas cell are twofold: *(i)* it should allow an accurate measurement of the side-band ratio along the HIFI spectrum at frequencies of interest, and *(ii)* it will provide a unique source of representative molecular spectra similar to the ones HIFI will have to deal with once in orbit. A great number of instrumental capabilities are thus expected to be probed using this test hardware.

When the gas cell becomes available, the possible interference between the standing waves and the sideband ratio has to be determined. This means that the sideband ratio has to be considered as a function of the IF frequency and of the LO frequency. This can be determined only by scanning both the LO frequency and the LO position within a restricted range.

We propose two modi to test the variation of the sideband ratio due to standing waves: The first is a dense scanning of the LO frequency and partly of the LO position for saturated lines. The second mimics the procedure of frequency surveys for samples with many lines, where a range of several GHz is covered by frequency changes in the order of several hundred MHz. This provides a test both for the practical understanding of the standing wave influence as determined with the first method and for ability of the sideband deconvolution algorithms to deal with varying gain ratios.

### Characterization of the internal thermal loads

By changing the temperatures in the focal plane unit the thermal cross talk between the two loads should be estimated.

### Compliance with AIV/ILT

Compliance with AIV/ILT and in-orbit calibration is necessary in order to avoid duplication or neglect of measuring crucial parameters. Below we present the overlap between the AIV-plan (AD-04), the AIV detailed test plan (RD-21) and the current Use Case Document (RD-14). This table, although directed at compliance at high level, is subject to change when more instrument parameters are known.

| UC number | Where in AIV detailed test plan |
|---|---|
| 1.1.1 – Measure Instrument Sensitivity | Section 9 - Radiometry |
| 1.1.2. – Determine Instrument Response Times | -- ; from S/Ss |
| 1.1.3 – Determine Instrument Intensity Stability | (Section 9 – Radiometry)<br>Section 11 – HIFI System Stability |
| 1.1.4 – Make Long Duration Integrations | Section (9/)11 |
| 1.1.5 – Measure Platforming | Section 11 |
| 1.1.6 – Measure Baseline ripple | (Section 9)<br>Section 10 – Spectral tests<br>(Section 11) |
| 1.1.7 – Measure Continuum Emission | Section (9)/10/(11) |
| 1.2.1 – HIFI Focal Plane Geometry | From S/S |
| 1.2.2 – Beam patterns | Section 8 – Beam pattern measurements |
| 1.3.1 – Frequency Calibration | Section 10 + S/S |
| 1.3.2 – Measure Instrument Line Profile | Section 10/(11) + S/S |
| 1.3.3 – Measure Spectral Purity | Section 10 |
| 1.3.4 – Measure Side Band Ratio | Section 10 |
| 1.3.5 – (Measure Diplexer Performance) | -- |
| 1.3.6 The influence of Bragg cell heating… | -- |
| 1.4.1 – Measure Internal Calibrator Radiometric Properties | Section 9 |
| 1.4.2 – Measure Internal Calibrator Coupling | -- |
| 1.4.3 – Measure Telescope Aperture Efficiency | -- |
| 1.4.4 – Intensity Calibration | Section 9/(11) |
| 1.4.5 – Measure Dynamic Range | Section 10 |
| 1.4.6 – Measure Non-Linearity | Section 10 |
| 1.5.x – Validation of Observing Modes | -- |

### *II.3.e. Software environment (HCSS) and tools*

For the downlink systems Interactive Analysis (IA) provides the environment and the basic analysis tools. Several analysis systems will be built on top of IA: Quick Look Assessment (QLA), Calibration Analysis (CA), Trend Analysis (TA), Standard Product Generation (SPG) and Science Analysis (SA). The Real Time Analysis system (RTA) will be based on SCOS2000.

The baseline software environment:

- The HIFI ICC systems will be design to operated (at least) under the Linux operating system
- The HIFI ICC systems will be developed using the TogetherJ UML tool

- The HIFI ICC systems that are interacting with or part of the HCSS will be implemented in Java and/or Jython

IA is the environment in which all ICC systems will be embedded. It will contain facilities to select and retrieve data from the HCSS and will provide display facilities. IA will provide utilities to decode HIFI telemetry, to perform unit conversions, to perform basic arithmetic on HIFI data etc. Also it will allow users to store results from analysis in the HCSS.

QLA will be built as part of the IA environment, supporting all (near) real-time test functionalities especially needed during the ILT and IST phase. QLA must give the IT the ability to have a good idea how his test is evolving. QLA will only thread (near real-time) science data by displaying it in its original format and/or after some simple processing (e.g. FFT of HRS data, subtraction and division of scans and/or spectra, etc.). Further data analysis will take place under IA.

RTA will use the standard interface facilities to retrieve and display (instrument) data from the HCSS. RTA will contain tools to analyse housekeeping data to allow monitoring of the instrument's behaviour. HIFI ICC and instrument team members will use it extensively during instrument test and assembly. It is very likely that RTA will be based on the ESA SCOS-2000 system.

Calibration Analysis (CA) software consists of a set of tools built in the IA environment. They inherit all standard functionality available there. Each of the calibration analysis tools is designed to analyse a specific (set of) calibration observation(s) to yield a certain (set of) calibration parameter(s). The tools will be prototyped, developed and tested within the IA environment.

Trend Analysis (TA) software will be used to study trends in instrument behaviour based on housekeeping data and science data. Like CA, TA will be designed and tested in IA.

Calibration results are stored in the calibration database. Within the Herschel Common Science System. The initial database is the result of the pre-launch calibration and will be completed by dedicated in-orbit and observers' data. It should concern both raw calibration data as directly produced by HIFI, and the further processed calibration files for which specific software is needed. This software is to be designed in close contact with the backend teams. The baseline format for any HIFI output data is defined in RD-18.

Reduction tools shall be available, as described above. The calibration database in the HCSS will not only consist of data and calibration files, but also e.g. the calibration reports.

## II.4. Timeline, development, and interfaces

### *II.4.a. Implementation lines*

The Calibration measurement strategy cannot be separated from the model philosophy adopted by the HIFI Project. It can be seen as a hybrid approach containing a Development program (DP), a Qualification program (QP) and a Flight program (FP). The QP should then apply both on the

Development Model (DM) and the Proto-Flight Model (PFM) by distinguishing test programs according to the levels they apply to; no real Qualification Model is expected. The Flight Model as a flying instrument can be seen as the S/C mounted PFM. It is anticipated that the Calibration Plan operations shall be conducted on the PFM before delivery but test procedures should be developed at an earlier stage. How this breaks down between pre-launch and in-orbit items is not the purpose of the present part (see IV).

The measurements levels are hierarchically nested according to the HIFI product tree. They provide the key-parameters to the Instrument and Data model. To make further discussions easier, we adopt the same instrument level breakdown as stated in other top-level documents, namely: Parts, Components, Sub-Units (S/U) or Assemblies, Units, Sub-systems (S/S), Instrument, and telescope mounted Instrument, designated as Proto-Flight Instrument (FI). Among the measurement levels for the Calibration tests and operations are (non exhaustive list, see requirements):

- Sub-system level tests: this includes the sub-systems and lower levels. The tests are to be started at an early phase of the development in order to better prepare specific requirements to the concerned institutes. This could imply a preliminary calibration campaign during DM program (see above) and inclusion of results from sub-system tests even if the main campaign should apply on the PFM. This also depends on the work progress achieved at this stage.
- Instrument level tests: complete tests shall be performed on the PFM before integration into the Proto-Flight Instrument. The measurement plan works together with the calibration data processing concerns. This should be used to make test procedures evolve to more mature versions after completion of each test campaign. Specific in-orbit sequences should be qualified at this stage.
- Flight Instrument level: this concerns the in-orbit calibration but procedures should have been exercised during pre-launch test campaigns (see above). Short- (commissioning, I/O check-out) and long (routine operations) term measurement plans shall be provided. Long-term procedures are expected to be adjusted in the course of the mission. They assume the delivery of a calibration source list (see section III.3.b.).

The calibration measurements strategy is aimed to provide a sufficiently over-determined measurement network. This means that one parameter shall be measured more than once.

### *II.4.b. Strategic choices*

- Close coupling with the system engineering team
- Close coupling with AIV activities, etc. especially within the ILTs
- Importance of HCSS as shared info repository from the beginning on
- Use instrument breakdown (product tree) and naming identical to project whenever possible
- Strong coupling between test + operations + data processing and calibration analysis and modelling.
- Model philosophy and programs (DM, PFM,...)

- Iterative and time-evolutionary process
- Close coupling to observing modes, AOTs and end-user requirements

### *II.4.c. Relation to other sub-systems, teams, and operations*

The calibration process is included inside the overall instrument test and performance verification activities. Any scheduling or planning shall be designed accounting for the baselines stated in hierarchically higher documents such as AD-04. Nevertheless their content shall be supplemented when very specific plan documents have to apply (e.g. Calibration Plan). The calibration work should also provide new elements to account for in the Critical Items identification.

# III. Calibration requirements

## III.1. Analysis of calibration objectives

### *III.1.a. Spectrophotometry calibrated with a chopper wheel*

From the simple equation given in II.2.a. one derives the calibration factor expression. As stated previously, the cold measurement can be done either on the blank sky or an internal cold load. However, following RD-10 it makes more sense to use the Cold Black Body in the CSA for the cold measurement and an OFF measurement for removal of standing waves. A complete discussion is given in the frame work document (RD-10), where also an error analysis is presented.

**Accuracy of the measured quantities:**

This contribution deals with the errors arising in the signals when performing the measurement. They affect the whole spectra. We have so far identified two main components to this error: ***(i)*** standing waves due to reflection on the various surfaces (see description in II.2.a), ***(ii)*** spectral contribution to the sky measurement if the (not so) blank sky is used as cold load.

- *Standing wave analysis (see frame-work document RD-10)*

Standing waves are unavoidable in on-axis telescopes such as the one chosen for Herschel. The ripples created in the total power measurements are expected to show up in the differential signals and thus in the calibrated spectra as expected from the equation in II.2. The reason why standing waves appear and disappear (as observed in most on-axis ground-based radio telescopes) is so far reasonably well understood and depends on stability of the system and stability of the continuum creating atmosphere. Some stability parameters need to be determined a.o. in ILT. The double side-band nature of the observations is one of them. Indeed, the amplitude of the ripple resulting from the combination of both side-bands is directly dependent on the synthesizer frequency and varies according to the ratio between the LO and the standing wave frequency (see RD-09 and RD-10 for details). This theoretical behaviour and its consequences on possible techniques to attenuate the ripples still need further tests. Nevertheless it is clear that the synthesizer frequency should **not** be changed between an ON and an OFF measurements (technique usually known as *Doppler tracking*), except for frequency switching.

The standing waves observed in the differential signals are also expected to vary according to the optical path lengths involved in the measurements and the emissivity of the surfaces they originate from. From a practical point of view, if the cold load is taken on the sky, the optical path between the sky measurement (reflection on the secondary mirror) and the hot (reflection from the integrated sphere) are quite different and ripples may be enhanced. The use of an internal cold load located at a similar distance as the hot load will probably help in that sense, but significant differences in surface emissivity may bring up other problems.

A preliminary analysis (see RD-09) conducted on data taken at KOSMA and CSO confirms that the main contributions to the standing wave contamination arise from reflections on the secondary mirror, the loads and the receiver horns. For HIFI, the corresponding ripple frequencies are of the order of 20-100 MHz. It is so far not clear how this depends on the signals emitted from the sources (sky or loads) and the receiver (noise, LO).

- *Purity of the blank sky (see RD-08/10 for further details)*

While HIFI will rely on its hot and cold load for calibration, the cold sky may be used to improve the calibration, either by acting as a second cold load or to derive extra calibration parameters. While the latter point will be worked out in the frame work document, the first is addressed in this section. The critical issue then is to know whether or not the sky is empty enough to serve as a cold load for the calibration procedure. From previous surveys of the sky at sub-mm frequency (e.g. COBE with a 7° resolution) one knows that apart from specific regions the sky background effective temperature is nearly zero at the HIFI frequencies. The situation is more complex close to the Galactic plane and in active star forming regions where the continuum emission is maybe not negligible. To this may add line emission (mostly [CII] and [NII]), which could affect the final data when subtracting the calibration measurement. In these areas the sky emission is thus much harder to estimate and consequences on the calibration can become very significant. A preliminary important work is to estimate the expected level of emission in the frequency range considered (see RD-08). If some sky areas indeed cannot provide close (within a chopper throw) sufficiently blank points one could think of moving the telescope to an adequate position to perform the sky measurement. Given the current plans for nodding capabilities of the S/C, more than a minute will be necessary to move by 3° in the sky, which is unacceptable if one wants to keep the calibration procedure reasonably short (say 10-20 sec.). The 3-point observing modes described in RD-13 and RD-15 may be sufficient.

### *III.1.b. Criticality*

One of the elements of the calibration work is to assess a level of criticality to the parameters we are dealing with. This criticality is connected to its direct contribution to the error budget on the astronomical signal (see previous section), but also more indirectly to a more general view of how components and their parameters influence each other. This analysis should be facilitated by tools such as a data model and scientific instrument model as described in II.1.

### *III.1.c. Permanent, trend, and event parameters*

Results of calibration operations are expected to deliver a wide range of information depending on the test level. In a simple view, one could distinguish between (terms are subject to changes):

- *Permanent* parameters that should not change during the complete mission, unless e.g. accident. This should concern design parameters like the frequency range or the telescope dimensions. This also deals with parameters that will not be directly measurable in-orbit and that will be frozen after launch.
- *Trend* parameters that monitor the degradation or improvement of the Flight Instrument both on high levels (e.g. telescope surface quality) and lower ones (e.g. mixer performances). Their behaviour shall be interpreted with respect to an ideal "launch instrument" that refers to the instrument state after the last pre-launch calibration.
- *Event* parameters that reflect special effects detected on scientific or calibration processed data. They might be of systematic (gain drifts in electronic), periodic (thermal effects on the structures) or random (particles) nature. Experience should allow some of those effects to be further treated as *trend* behaviours and naturally implemented in the data processing.

The criticality and content of each of these will be addressed in the calibration Use Case document.

### *III.1.d. Data accessibility*

One should always keep in mind that not all parameters will be available at every stages of the calibration operations. Typically, there are parameters which are not available on the ground (but in some cases can be modelled) and, obviously, some of the measurements conducted pre-launch will not be feasible in-orbit and the corresponding parameters will thus be frozen for the whole mission time. The calibration effort must include this analysis and identify the set of variables that need particular attention. This should drive what needs to be done on the ground to freeze parameters with a sufficient level of confidence. This also applies to parameters available in-orbit but that could not be as fully and frequently tested as prior to the launch. These parameters will be detailed in the Phase Verification (PV) and operational plans.

## III.2. Calibration measurements requirements

The calibration measurements should provide an estimate of the instrument quality as a spectroscopic photometer. For the in-orbit phase, this is to be connected to the health monitoring activities. It deals with problems such as stability, sensitivity, spectral response, IF chain quality and optical performances and alignment. Output of the internal calibration source shall also be known for any frequency band and calibrator temperatures. The main issues addressed here are:

- instrument noise
- flux and frequency calibration,
- beam pattern,
- standing waves for different chopper positions,
- noise and gain variation with time.

### *III.2.a. At component level*

Since HIFI can only function when both the up-conversion chain and the down-mixing and IF-chains are present (combined with at least 1 spectrometer), there is hardly any component that needs special attention. It is expected that the combined specifications, design descriptions and data-packages will be more than sufficient for unexpected troubleshooting. More important are requirements on instrument level.

### *III.2.b. At sub-system level*

All sub-systems have their own test and qualification program, in which many parameters are derived or characterized. The in-orbit calibration needs are described through the Calibration use cases (RD-14).

### *III.2.c. At instrument level (pre-launch)*

#### Nominal

It is already expected that the calibration tests will require a likely better precision than for the general performance and validation ones. This is driven by the need of a better understanding of the sources used and of their stability, as well as a better representation of the in-orbit conditions (background level, optic, thermal), but also since the science requirement is set to be less than 10% (base-line), with a goal value of 3%.

#### Influence of environment

Effects from the HIFI environment deal with the temperature behaviour of the integrated system, as well as with the external environment in which the satellite will evolve.

Temperature fluctuations are expected to have non-negligible effects on the data calibration. These issues are somehow related to a thermal model of the instrument and the telescope. They should analyse effects of thermal coupling between stages and assess the losses associated. It should be pointed out that the temperature dependence apply both to the losses function in itself and to the total power the telescope collects. Parameters addressed here are the time constants involved in the temperature establishment, the stability and the power dissipation to derive the thermal budget. Its effect on the ambient temperature (see I.2.a), together with the influence of the satellite environment, may be of great importance in the internal calibration procedure, whichever adopted.

This is a way to monitor the relative changes in the system.

Alignment accuracy is directly concerned by mechanical displacements due to temperature gradients. The thermal behaviour of the telescope in itself is related to surface accuracy consideration and effects such as astigmatism, coma, or vignetting should be analysed since they modify the complete diffraction beam. Sensitivity to standing-waves is another important issue.

The issues addressed in the external environment concerns are the Electro-Magnetic (*FIRST-Planck EMC Requirement Specification* document still awaited) and particles contamination from the outer world, plus the thermal radiation proceeding from the other instruments, the payload and ``close'' astronomical bodies (Earth, Moon, etc).

**In operational context**

Some of these requirements are directly related to the Herschel S/C. In principle all observing modes need to be exercised prior to integration (ILT). However, this is impossible for some and tests will concentrate on the ones feasible in the tests. One purpose is to qualify their efficiency to provide the best spectral baseline. This applies e.g. to the internal and external calibration procedures that are to be optimised as tests proceed. Scientific e*nd-to-end* test procedures shall be tested to check the availability of essential calibration parameters. Obviously, such requirements also apply to the in-orbit operation phase.

#### *III.2.d. At system level (PV phase)*

The knowledge of the mechanical behaviour after launch (and possible displacements) is of great importance for alignment. This includes the internal calibration source assembly, the polarisers and the LO window for the RF injection. Although this should have been addressed pre-launch with dedicated vibrational tests, checks should be done on the beam polarisation where mechanical pieces are involved (whether Martin-Pupplet or beam splitter). Checks on issues such as telescope de-center, defocusing or tilt are required to assess consequences on the telescope side-lobes and efficiencies, and the stray light contamination. It is a strong requirement to derive very accurately the telescope main beam and forward efficiencies**.** The assessment of these parameters will need specific methods that may very likely differ for the pre-launch and in-orbit phases. Techniques based on observations of suitable calibrators are usually used for ground-based facilities and may be adapted for the space borne conditions. Quasi-optical modelling is foreseen for the whole optical system including the aperture efficiency. Of course the overall sensitivity and ripple-sensitivity will need to be determined and/or characterized.

#### *III.2.e. At system level (routine)*

Unlike the pre-launch tests that may be conducted during dedicated and limited test campaigns, the in-orbit calibration shall present a more periodic scheduling with observing periodicity varying from the scan calibration level to the monthly sensitivity check, as anticipated in AD-04. Some of these activities are expected to be combined with the instrument health monitoring.

## III.3. Derived requirements

### *III.3.a. Calibration source requirements (inputs from RD-04)*

One of the key calibration issues is the preparation of a list of astronomical sources. This includes:

- Photometric calibration: absolute scale, and relative calibration in time (day-to-day *relative* calibration),
- Photometric cross-calibration with PACS and SPIRE,
- Spectroscopic calibration: side band ratio, accuracy of the frequency scale, frequency resolution and profile of the spectrometers,
- Pointing calibration.

Also, for all types of sources, which will be studied by HIFI, we will need a few bright templates to be used as calibration sources (or references), in order to monitor the instrument and be able to detect and identify any failure of the system. Ideally, these template sources will be used for calibration of some of the performances of the system also.

The requirements on the calibration sources for these objectives are clearly different:

- Photometric calibration

- a bright continuum source, with no(few) line emission,
- good pointing (peaking up),
- knowledge of the beam shape (in flight).

- Frequency calibration

- compact sources with a rich submm spectrum,
- simple line shape with the same radial velocity for all emission lines,
- simple spatial structure, e.g. point source at any HIFI frequency.

- Side band ratio

- at least 2 settings per LO band
- same requirements as for frequency calibration.

- Spectral resolution

- sources with simple line profiles, narrow lines or straight edges to calibrate the performances of the backends.

- Source distribution

- A common requirement to all sources is the homogeneity of their distribution on the sky. Due to constraints on the Sun-S/C and Earth-S/C angles, the sky viewing for a given date will be restricted and not all sources visible simultaneously.

Given these requirements, evolved stars and solar system sources will be the basic calibration sources for HIFI. The Solar System Objects are studied through a collaboration initiated by the Herschel calibration Steering Group. Hot cores and galaxies will be used as second calibrators for specific purposes. Ground based observations connected to these concerns are described in the following section. This calibration work is best done in synergy with the science program.

### *III.3.b. HIFI Calibration Source Ground-Based Preparatory Program*

(See RD-04 for a detailed description)

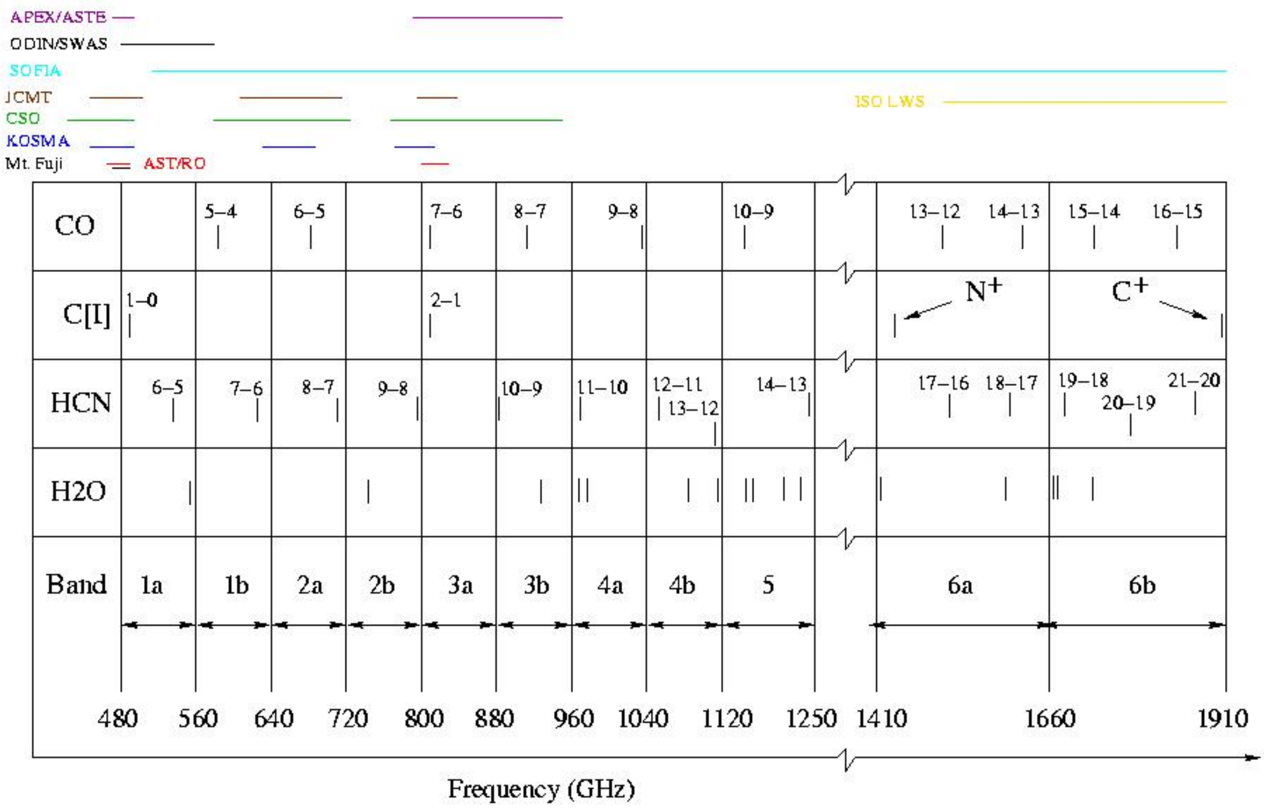

Figure 2.: Main available lines and telescopes in the HIFI range

The preparation of a suitable calibration source list for HIFI requires some observations to be conducted prior to launch. This ground-based preparatory program shall be conducted concurrently to some of the preparatory work that has been identified by the HIFI Science Group (see RD-05). The outcome of this preparatory program should serve as input for the modelling effort to be performed by the Science Group. An important issue is related to the modelling of solar system bodies, which is of critical importance for the absolute photometric calibration in flight. A dedicated working group will focus on this task.

Obviously, this effort should focus on the specific calibration-oriented concerns in order to avoid duplicate works. All data collected in that framework will add to other existing submm database and may be used for any modelling work.

This work implies a preliminary selection of the sources among the available lists and according to what is missing in terms of calibration-related requirements. In particular, most existing data do not provide the sufficient spatial information to restore the expected signals to the HIFI beams and assess the source extent at the considered frequencies. The submm detectors have known great improvement in the last few years and the high frequency windows are now available with unprecedented sensitivity. It is also important to search for variability in the submm line and continuum emission of the target sources, given the duration of the mission. Finally, most of the southern sky is very poorly known in the HIFI range due to the lack of submm facilities in the south hemisphere. The use of AST/RO and of the first prototype antennas for ALMA, APEX & ASTE, will hopefully allow to start this exploratory work before SOFIA flies. The use of the JCMT archive should also help deriving the priorities for the higher frequencies.

The current basis for such ground-based observing proposals are:

- mapping observation of a core of homogeneously-distributed targets in continuum and in a series of submm lines (see Figure 2)
- spectral line surveys of a few dedicated sources
- continuum mm and submm observations of strong asteroids for modelling in the submm/FIR domain
- search for potential secondary calibrators in the southern sky

Given the high pressure to get observing time on submm telescopes such as CSO or JCMT this calibration work should provide side-products to the community. First of all, the scientific outcomes of such observations need to be put forward. There will obviously be new material to feed scientific issues such as evolved star envelopes and mass-loss rate, O-rich star variability in the submm, detection of new spectral features, etc. Moreover, it would be of great interest to conduct a cross-calibration analysis of data proceeding from different telescopes in order to better understand the discrepancies observed in previous database and hopefully use the benefits of these analysis for the HIFI calibration. Pioneering campaigns are expected to be conducted in order to demonstrate the outcomes of preparatory ground-based observations in the submm windows. An example for such a pioneering campaign is described in RD-04. Contact was also taken between the Herschel Project Scientist and the directors of the main submm observatories observed to date.

### *III.3.c. Data analysis requirements*

Although many of the standard functionalities contained in the Interactive Analysis (IA) environment would already allow simple reduction operation on the calibration data, specific Calibration Analysis (CA) tools need to be designed. Together with the Real-Time Analysis (RTA) facilities, it will provide dedicated calibration parameters and flux-calibrated data for further science analysis. Calibration data format need to be designed according to commonality and portability concerns. In general the software requirements are described in the End-user Requirements Document (RD-18), the Calibration Use Cases (RD-14), and the subsystem Use

Cases.

### *III.3.d. Modelling requirements*

One purpose of the pre-launch calibration work deals with the design of an accurate instrument and data model characterising the instrument behaviour according to a set of parameters (temperature, time, polarisation, position, observing mode). The modelling concern is fed by the HIFI Science and the instrument design. This should result in a first cascade-like chain of components that do not necessarily stick to the product tree, depending on the analysis accuracy. In particular, simplified models may be needed for in-orbit data analysis as less parameters are generally available.

Contribution to the cascade components shall arise from all the HIFI community as much modelling effort is expected from all groups involved in designing tasks. The complete instrument and data modelling implies an early compilation of these *sub-models* and a close contact with the institutes for efficient upgrade. This should be facilitated by the use of the Herschel Common Science System (HCSS). In return, all contributors to the model shall have access to the current model version and benefit from its use at any stage of the construction. Understanding the interfaces between sub-models is not the responsibility of the calibration group but it is anticipated that it will take an important part in this work.

One should insist on the fact that the Instrument and Data model shall *not* been seen as a *perfect simulator* for the HIFI instrument. It will in no case replace any hardware model but rather allow an early detection of how the instrument components influence on each other at various levels and thus point out (sometimes) unsuspected interface behaviours to put special efforts on during the tests.

## III.4 Verification of AOTs and calibration of basic modes

Verification of AOTs (Astronomical Observation Templates) is an important issue to assure that different basic observing modes provide the same results within the required accuracy of the instrument.

Basic observing modes are described in the observing modes document (RD-13 & RD-15). They are combinations of pointing modes, reference schemes, chopper speed and back-end settings. Stability of the HIFI instrument is an important issue, which leads to several instrument settings within the basic modes. However, when these settings are chosen optimally the basic modes should produce results, which are consistent among the different modes. Verification of the basic modes therefore consists of measuring a set of celestial sources in selected frequencies. In Phase Verification (PV) the above-described settings should be found such that consistency is present. For the continuum the Solar System Objects (Uranus and asteroids) can serve for verification. For line measurements evolved stars with strong CO (and HCN) line emission can be used. After verification in PV similar measurements will be scheduled regularly which will be used for trend-analysis and health monitoring. Details of the AOT verification will be written in the AIV detailed test-plan (RD-20), the observing modes time-line document (Comito & Schilke 2002), the PV plan, the operational plan, and in the Calibration Use Case (RD-14).

# IV. Calibration operational plan(s)

The calibration operational plans consist of the Phase Verification (PV) plan and the daily operational plan. While the first is aimed at the first months of the mission in which the calibration of HIFI should be established, the latter aims at improving the calibration towards the goal value, to schedule regular calibration observations, monitor the instrument, do trend analysis and optimise the observing modes. These plans will be written after more is known about the HIFI instrument tests on the Development Model (DM) and will mature after the Cold Qualification Model (CQM) instrument level tests.

## Measurement sequences and Time lines

In general the HIFI-ICC will use the standard AOTs to derive as many instrument settings as possible, however, some dedicated observations will be made through the Common Uplink System (CUS) that will not be offered to general users but are special for calibration or general ICC work. The number of special observations should be kept as low as possible. Details on the measurement sequences are worked out in the observing modes time-line document and in the PV and operational plan.

## Inputs

As inputs to the operational plans serve the outputs of the Instrument Level Tests with in particular those on the CQM. Also improved knowledge through the quasi-optical modelling of the HIFI Focal Plane Unit (including the Calibration Source Assembly) and improved knowledge on the telescope are important. It is expected that improved modelling of Solar System Objects and evolved stars can be used to improve the calibration accuracy and optimise the calibration strategy.

## Data processing

Data processing results from calibration and science requirements on the Herschel Common Science System (HCSS). The calibration requirements on data-processing are given by the calibration use cases (RD-14), which are based on the HIFI calibration frame-work document (RD-10). The whole HIFI calibration will be done in the HCSS software environment, but since some parameters can only be derived from more sophisticated analysis and user interaction (e.g. side-band deconvolution) special software needs to be developed or installed (e.g. GILDAS-CLASS). Details will be worked out within the general HIFI-ICC context.

## Products

Products of the in-orbit calibration are (a.o.):

- Flux and frequency calibrated spectra for the general astronomers
- Knowledge on the different gains and couplings in the instrument and with the telescope
- Knowledge on stability of the instrument
- Knowledge on standing-waves
- Knowledge on side-band ratio’s
- Knowledge on the beam pattern
- Knowledge on plat-forming

- Trends and time analyses for many parameters

The complete products are described in the frame-work document (RD-10) and in the HIFI calibration Use Cases (RD-14)

# Appendix

## A. Main lines for the calibration

A number of atomic, ionic and molecular parameters are given below to be used as a quick reference. Details on their use will be given in the HIFI Use Cases. Details on their exact values and uncertainties can be found in e.g. the Cologne Database for Molecular Spectroscopy (CDMS).

### A.1 Hydrogen alpha recombination lines

| | | |
|---|---|---|
| H15α | 1769.610820 GHz | Band 6b |
| H16α | 1466.610151 GHz | Band 6a |
| H17α | 1229.033572 GHz | Band 5b |
| H18α | 1040.131063 GHz | Band 4a |
| H19α | 888.047035 GHz | Band 3b |
| H20α | 764.229558 GHz | Band 2b |
| H21α | 662.404172 GHz | Band 2a |
| H22α | 577.896461 GHz | Band 1b |
| H23α | 507.175490 GHz | Band 1a |

### A.2 Molecular and Atomic lines

CO:

| Frequency (MHz) | El ($cm^{-1}$) | Transition | Band |
|---|---|---|---|
| 576267.9305 | 38.4481 | 5-4 | 1b |
| 691473.0763 | 57.6704 | 6-5 | 2a |
| 806651.8060 | 80.7354 | 7-6 | 3a |
| 921799.7000 | 107.6424 | 8-7 | 3b |
| 1036912.3930 | 138.3904 | 9-8 | 4a |
| 1151985.4520 | 172.9780 | 10-9 | 5a |
| 1496922.9090 | 299.7656 | 13-12 | 6a |
| 1611793.5180 | 349.6975 | 14-13 | 6a |
| 1726602.5066 | 403.4612 | 15-14 | 6b |
| 1841345.5060 | 461.0545 | 16-15 | 6b |

Carbon:

| Frequency (GHz) | El ($cm^{-1}$) | Species | Band |
|---|---|---|---|
| 492.1607 | 0.00 | CI(1-0) | 1a |

| | | | |
|---|---|---|---|
| 809.3435 | 16.4168 | CI(2-1) | 3a |
| 1900.5369 | | C+ | 6b |

Nitrogen:

| Frequency (GHz) | El (cm$^{-1}$) | Species | Band |
|---|---|---|---|
| 1461.134 | | N+ | 6a |

$H_2O$:

| Frequency (MHz) | El (cm$^{-1}$) | Transition | Band |
|---|---|---|---|
| 556936.0020 | 23.7944 | $1_{01}-1_{01}$ | 1b |
| 752033.2270 | 70.0908 | $2_{11}-2_{02}$ | 2b |
| 916171.5820 | 285.2193 | $4_{22}-3_{31}$ | 3b |
| 970315.0220 | 383.8425 | $5_{24}-4_{31}$ | 4a |
| 987926.7640 | 37.1371 | $2_{02}-1_{11}$ | 4a |
| 1097364.7910 | 136.7617 | $3_{12}-3_{03}$ | 4b |
| 1113342.9640 | 0.0000 | $1_{11}-0_{00}$ | 4b |
| 1153126.8220 | 134.9016 | $3_{12}-2_{21}$ | 5a |
| 1158323.7430 | 610.3412 | $6_{34}-5_{41}$ | 5a |
| 1162911.5930 | 173.3658 | $3_{21}-3_{12}$ | 5a |
| 1207638.7140 | 275.4970 | $4_{22}-4_{13}$ | 5b |
| 1228788.7720 | 95.1759 | $2_{20}-2_{11}$ | 5b |
| 1410618.0740 | 399.4575 | $5_{23}-5_{14}$ | 6a |
| 1602219.1820 | 222.0528 | $4_{13}-4_{04}$ | 6a |
| 1661007.6370 | 79.4964 | $2_{21}-2_{12}$ | 6a |
| 1669904.7750 | 23.7944 | $2_{12}-1_{01}$ | 6b |
| 1716769.6330 | 79.4964 | $3_{03}-2_{12}$ | 6b |

CS:

| Frequency (MHz) | El (cm$^{-1}$) | Transition | Band |
|---|---|---|---|
| 489751.040 | 73.5268 | 10-9 | 1a |
| 538688.830 | 89.8631 | 11-10 | 1a |
| 587616.240 | 107.8318 | 12-11 | 1b |
| 636531.841 | 127.4326 | 13-12 | 1b |
| 685434.764 | 148.6650 | 14-13 | 2a |
| 734323.997 | 171.5286 | 15-14 | 2b |
| 783198.519 | 196.0231 | 16-15 | 2b |
| 832057.299 | 222.1477 | 17-16 | 3a |
| 880899.299 | 249.9022 | 18-17 | 3b |
| 929723.470 | 279.2858 | 19-18 | 3b |
| 978528.750 | 310.2981 | 20-19 | 4a |
| 1027314.070 | 342.9383 | 21-20 | 4a |
| 1076078.345 | 377.2058 | 22-21 | 4b |
| 1124820.480 | 413.0999 | 23-22 | 5a |
| 1173539.367 | 450.6199 | 24-23 | 5a |

| | | | |
|---|---|---|---|
| 1222233.882 | 489.7649 | 25-24 | 5b |
| 1416745.273 | 662.5792 | 29-28 | 6a |
| 1465300.578 | 709.8367 | 30-29 | 6a |
| 1513824.457 | 758.7139 | 31-30 | 6a |
| 1562315.677 | 809.2096 | 32-31 | 6a |
| 1610772.984 | 861.3229 | 33-32 | 6a |
| 1659195.107 | 915.0525 | 34-33 | 6a |
| 1707580.753 | 970.3972 | 35-34 | 6b |
| 1755928.612 | 1027.3560 | 36-35 | 6b |
| 1804237.351 | 1085.9275 | 37-36 | 6b |
| 1852505.615 | 1146.1103 | 38-37 | 6b |
| 1900732.030 | 1207.9033 | 39-38 | 6b |

HCN:

| Frequency (MHz) | El (cm$^{-1}$) | Transition | Band |
|---|---|---|---|
| 531716.35 | 44.3440 | 6-5 | 1a |
| 620304.0952 | 62.0802 | 7-6 | 1b |
| 708877.2081 | 82.7713 | 8-7 | 2a |
| 797433.6638 | 106.4169 | 9-8 | 2b |
| 885971.4087 | 133.0164 | 10-9 | 3b |
| 974488.4000 | 162.5693 | 11-10 | 4a |
| 1062982.6043 | 195.0747 | 12-11 | 4b |
| 1151452.0030 | 230.5320 | 13-12 | 5a |
| 1239894.5896 | 268.9403 | 14-13 | 5b |
| 1505041.6397 | 401.8620 | 17-16 | 6a |
| 1593357.2244 | 452.0648 | 18-17 | 6a |
| 1681636.2074 | 505.2135 | 19-18 | 6b |
| 1769876.6871 | 561.3068 | 20-21 | 6b |
| 1858076.7832 | 620.3436 | 21-20 | 6b |

## B. Calibration source lists

### B.1 Evolved stars anticipated as calibrators for health monitoring and trend-analysis (variability still to be assessed)

| ***Source Name*** | ***R.A.*** | ***Declination*** | ***$V_{LSR}$ (km/s)*** |
|---|---|---|---|
| O Ceti | 02:19:20.8 | -02:58:39.5 | 47 |
| IRC+10420 | 19:26:48.1 | 11:21:17.0 | 70 |
| IRC+40540 | 23:34:28.0 | 43:33:02.0 | -15 |
| IK Tau | 03:53:28.6 | 11:24:20.0 | 46 |
| Chi Cyg | 19:50:33.9 | 32:54:50.6 | 10 |

| | | | |
|---|---|---|---|
| CRL618 | 04:42:53.8 | 36:06:52.0 | 46 |
| V Cyg | 20:41:18.3 | 48:08:28.8 | 10 |
| OH231.8+2.4 | 07:42:16.8 | -14:42:52.0 | 20 |
| CRL2688 | 21:02:18.8 | 36:41:38.0 | -38 |
| IRC+10216 | 09:47:57.3 | 13:16:44.0 | -26 |
| NGC7027 | 21:07:01.7 | 17:11:35.0 | 20 |
| CIT 6 | 10:16:02.0 | 30:34:19.0 | -2 |
| CRL3068 | 23:19:12.4 | 17:11:35.0 | -30 |
| RX Boo | 14:24:11.6 | 25:42:13.4 | -10 |
| R Cas | 23:58:24.9 | 51:23:19.7 | 25 |
| HD56126 | 07:16:10.3 | 09:59:48.0 | 72 |
| R Leo | 09:47:33.5 | 11:25:43.6 | 3 |
| VY CMa | 07:22:58.3 | -25:40:12.5 | 10 |
| CRL865 | 06:04:00.0 | 07:26:18.0 | 42 |
| A Ori | 05:56:10.3 | 07:24:25.4 | 3 |
| R Hya | 13:29:42.8 | -23:16:52.8 | -10 |
| W Hya | 13:49:02.0 | -28:22:03.5 | 41 |
| V Hya | 10:51:37.3 | -21:15:00.3 | -16 |
| X Her | 16:02:39.2 | 47:14:25.3 | -72 |
| R Aql | 19:06:22.3 | 08:13:48.0 | 47 |
| Y Cvn | 12:45:07.8 | 45:26:24.9 | 20 |
| TX Cam | 05:00:50.4 | 56:10:53.0 | 15 |
| IRAS15194-5115 | 15:23:05.0 | -51:25:59.0 | -15 |
| MWC 349 | 20:32:45.6 | 40:39:37.0 | |
| NML Cyg | 20:46:25.7 | 40:06:56.0 | -1 |

## B.2. Southern stars potentially suitable as calibration sources for health monitoring and trend-analysis

| ***Source name*** | ***R.A.*** | ***Declination*** | ***$V_{LSR}$ (km/s)*** |
|---|---|---|---|
| R Hor[B] | 02:53:52.8 | -49:53:22.7 | |
| R Dor[B] | 04:36:45.6 | -62:04:37.8 | |

| | | | |
|---|---|---|---|
| AFGL4078[B] | 07:45:25.7 | -71:12:18.0 | |
| V341 Car [B] | 07:56:50.9 | -59:07:32.8 | |
| IRAS09203-5220 [A] | 09:21:59.2 | -52:33:51.8 | |
| IRAS09513-5324 [C] | 09:53:06.7 | -53:38:54 | |
| AFGL4098 [B] | 09:52:29.9 | -75:22:26 | |
| IRAS10056-5300 [A] | 10:07:32.8 | -53:15:36.5 | |
| IRAS11318-7256 [C] | 11:33:57.9 | -73:13:17 | |
| IRAS13442-6109 [A] | 13:47:45.9 | -61:24:27 | |
| AFGL4183 [C] | 13:51:29.0 | -65:46:56 | |
| AFGL4202 [C] | 14:52:24.3 | -62:04:20 | |
| AFGL4211[B] | 15:11:41.9 | -48:20:01 | |
| IRAS15194-5115 [A] | 15:19:26.9 | -51:16:19.0 | |
| IRAS15287-5811 [A] | 15:32:47.6 | -28:21:10 | |
| IRAS15576-5400 [A] | 16:01:32.9 | -54:08:05 | |
| IRAS16006-5257 [A] | 16:04:30.8 | -53:05:28 | |
| 16079-4812 [C] | 16:11:35.1 | -48:19:53 | |
| NGC6072 [B] | 16:12:58.8 | -36:13:38 | |
| OH338.1+6.4 [B] | 16:14:02.6 | -41:13:03 | |
| IRAS16340-4634 [A] | 16:37:41.1 | -46:40:41.0 | |
| NGC6302 [B] | 17:13:44.4 | -37:06:11.2 | |
| IRAS17163-3907 [A] | 17:19:48.6 | -39:10:37 | |
| 17446-4048 [C] | 17:48:12.3 | -10:49:36 | |
| CRL2135 [A] | 18:22:34.7 | -27:06:29 | |
| RZ Sgr [B] | 20:15:28.4 | -44:24:37.5 | |

[A]: from the Valinhos-ESO survey, Epchtein et al. 1987, sources with F(12:m) > 200 Jy
[B]: from Loup et al. 1993, sources with T(CO(1-0)) or T(CO(1-0)) > 0.5 K
[C]: from Groenewegen et al. 1996, sources with T(CO(1-0)) or T(CO(1-0)) > 0.5 K

### B.3. Hot cores, UCHII, and PDRs potentially suitable as frequency calibration sources

| *Source name* | *R.A.* | *Declination* | *$V_{LSR}$ (km/s)* |
|---|---|---|---|
| W3(OH) | 02:27:04.1 | 61:52:22.0 | -40 |
| G343 | 16:54:43.8 | -42:47:32.4 | |
| NGC6334I | 17:20:55.0 | -35:47.5:00.0 | |
| G5.89 | 17:57:26.8 | -24:03:56.0 | |
| G10.62 | 18:07:30.7 | -19:56:29.1 | |
| G34.3 | 18:53:18.5 | 01:14:58:2 | |
| G45.1 | 19:13:22.0 | 10:50:53.4 | |
| K3-50A | 20:01:45.6 | 33:32:43.5 | |
| ON-1 | 20:08:09.9 | 31:22:42.3 | |
| W75N | 20:28:35.9 | 42:37:22.0 | |
| NGC7538 | 23:13:46.3 | 61:28:10.6 | |
| HL Tau | 04:31:38.4 | 18:13:57.9 | |
| LkHalpha234 | 21:43:06.7 | 66:06:54.6 | |
| GL490 | 03:27:38.8 | 58:47:00.7 | |
| L1551-IRS5 | 04:31:34.1 | 18:08:05.1 | |
| Orion-KL | 05 35 14.17 | -05 22 23.1 | 9.0 |
| Orion Bar | 05 35 22 | -05 24.6:00 | 9.0 |
| IRAS16293-2422 | 16 32 22.8 | -24 28 33 | 4.2 |
| Sgr-B2(N) | 17 47 20.4 | -28:22:19 | 61 |
| G10.47 | 18:08:38.2 | -19:51:49.7 | |
| G10.62 | 18:10:28.6 | -19:55:49.7 | 0.2 |
| M17 | 18:20:26 | -16:10:36 | 20.0 |
| W51E1-E2 | 19:23:44 | 14:30:30 | |

## C. References to physics/astrophysics documents

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