HIFI Observing Modes Document

Version DRAFT 0.41 of 30/01/03, by V. Ossenkopf

Abstract

This document contains a description of the modes in which the HIFI instrument will be used in normal astronomical observations together with a summary of the main constraints and time limits for the different modes.

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Prepared by:	Volker Ossenkopf	30 January, 2003
Checked by:		
Authorised by:		

Distribution

ESA:

P. Estaria	ESTEC

HIFI steering committee

Th. de Graauw	SRON

HIFI project:

H. Aarts	SRON
C. Wafelbakker	SRON

Revision history

Version	Date	Changes	(in Section)	Author
DRAFT 0.1	02/04/02	First version		V. Ossenkopf
DRAFT 0.1.1	02/12/02	Computation of integration times now for baseline system temperatures from AD6	2.5	V. Ossenkopf
		Note on standing waves for frequency switched modes	3.2.3	
		Efficiency of map vs. OTF now for a single scan	3.5	
		Updated paragraph on chop direction	3.2.2, A1,A3	
DRAFT 0.2	02/13/02	Several changes throughout all parts of the text to get a more precise outline		V. Ossenkopf (contributions from D. Teyssier and C. Kramer)
		Clarification of the topics concerning frequency surveys	2.2.3.	
		Added specified Allan times	2.3	
		Major rewriting of the section on observing efficiencies	3.5	
		More comprehensive description of frequency surveys	4.2	
		Added discussion on the combination of mapping and chopping	4.3	
		Added new appendix summarising the constraining parameters	A	
		List of questions updated	B	

DRAFT 0.3	02/28/02	Small changes throughout all parts of the text for a further clarification		V. Ossenkopf (contributions from N. Whyborn)
		Restructuring of the text for the definition of the observing modes and their efficiencies	3., 4.	
		New slew specification using a physically possible acceleration	2.1.1 B.3	
		Added paragraphs on spectrometer stabilisation	2.2.2 2.2.3	
		Corrected slow chop and frequency switch timings	2.1.2 2.2.4	
		Note on integration time limits	2.5,B.2	
		Add the possible need for additional load calibrations in frequency surveys	2.2.5 4.2.4	
		Changed the discussion on the efficiency of chopped and frequency switch modes	3.4.2 3.4.3	
		Added load chopped modes	3.2.3 4.1	
		Add modes with frequency switch and OFF for baseline calibration	4.1	
		Preliminary priority list	4.1	
		Added requests for terrestrial test of modes	4.1, B.4	
		Added high−level modes with temporary reference	4.2.1	
		Removal of the high−level mode for symmetric dual frequency switch because of low significance	4.2	
		List of questions updated	B	

DRAFT 0.31	03/07/02	Small changes throughout all parts of the text		V. Ossenkopf
		Improved discussion on integration times and noise	2.5	
		Updated thermal Bragg cell time	2.2.2	
		Update of open questions	B	
DRAFT 0.32	05/23/02	Removal of many typos and small adjustments throughout the whole text		V. Ossenkopf (contributions from M. Gerin and F. Helmich)
		Clarification on the used system temperatures	2.5	
		Added paragraph on LO frequency	3.4	
		Readd simple chop mode for frequency surveys	4.2.4	
DRAFT 0.35	07/02/02	Extension of the stability considerations	2.3	V. Ossenkopf (contributions from T. Prusti)
		Clarification of different Allan times	2.3.2 A	
		Removed mapping modes in total power without OFF due to bandpass calibration considerations, added chop modes in maps with OFF	4.1	
		Discussion of timing parameters for pointing and reference modes	3.1 3.2	
		Added paragraph on load calibration efficiency	3.5.1	
		New considerations on jiggle mode observations	3.5.3	
		Priorities updated	4.1	

DRAFT 0.39	09/24/02	Remove possibility to use the burst data rate	2.4 A, B3	V. Ossenkopf (contributions from F. Herpin and D. Beintema)
		Introduced clear distinction between OFF position and REF measurement	all parts	
		Section on observational timeline as precursor for AOT timing and time estimator	3.5	
		Updated priority list	4.1	
		List of open questions updated	B	
DRAFT 0.395	10/24/02	Introduced lower pointing time limit of 10s	2.1.1, 3.1,3.5	V. Ossenkopf (contributions from D. Beintema)
		Clarified pointing mode limitations	3.6.3, B.2	
		List of open questions updated	B.2	
DRAFT 0.4	12/13/02	Corrected integration times for single−sideband noise	2.5	V. Ossenkopf
		Clarify the equivalence of different Allan times	2.3.2	
DRAFT 0.41	01/30/03	Correction of several minor typos		V. Ossenkopf

Applicable documents

Doc. ref.	Title
AD1	Herschel/Planck Instrument Interface Document − IID PART A: SCI−PT−RS−07725
AD2	Herschel/Planck Instrument Interface Document − PART B − “HIFI”: SCI−PT−IIDB/HIFI−02125
AD3	End User Requirements for HIFI Interactive Analysis: ICC/2001−004
AD4	HRS specification: CESR−HRS−SP−316−043
AD5	WBS Specifications and Interfaces: KOSMA/WBS/SID/1000
AD6	HIFI Instrument Specification: SRON−G/HIFI/SP/1998−001

Reference Documents

Doc. ref.	Title
RD1	R. Schieder, C. Kramer, Optimization of heterodyne observations using Allan variance measurements, A&A 373 (2001), 746
RD2	Proposal for the ICU processing of the WBS data rate in different observing modes, 07/16/2001, V. Ossenkopf
RD3	Observing Modes: Typical examples and tentative time estimates for HIFI, 07/23/2001, C. Kramer
RD4	Technical Note on HIFI Observing modes − Template beam sy nthesis observations, 10/16/2000, D. Teyssier
RD5	Standing wave analysis for KOSMA data, 08/02/2001, D. Teyssier, C. Kramer
RD6	Time Estimates for Line Surveys, 12/21/2001, P. Schilke, C. Comito
RD7	The intensity calibration framework, 09/01/2002, V. Ossenkopf

Contents

1 Introduction

For astronomically useful observations with the HIFI instrument, standard observing modes have to be defined, specifying the general strategy and the pointing and timing constraints that apply to a particular observation. The modes have to be found within the operating space spanned by the technical constraints of the spacecraft and the instrument. Moreover the modes should be selected to cover all kinds of astronomical observations which are intended for HIFI on the one hand and to be technically as simple and as few as possible on the other hand. The need for a small number of observing modes results from the fact that all modes have to be verified and calibrated independently. Within the range of technically possible modes the most important modes and the modes which will be used by most observers have to be categorised and prioritised.

For the different observing modes the main input parameters and instrumental constraints have to be listed so that it is possible to define astronomical observation templates (AOTs) from the observing modes. Moreover, they have to be investigated with respect to an efficient implementation and the resulting requirements on uplink, calibration and data reduction.

2 Instrumental and satellite constraints

The selection and optimisation of the different HIFI observing modes is constrained by the capabilities of the satellite and the instrument.

2.1 Timing limits from the telescope

2.1.1 Telescope slews

Changes in the telescope pointing are performed by slews. The slewing time t_{slew} depends on the distance between subsequent pointings $\Delta\phi$ and provides a main constraint to many observing modes. The slewing time consists of three contributions which are (partially implicitly) defined in AD1:

$$t_{slew} = t_{fix} + t_{acc} + t_{rate}$$

The constant contribution t_{fix} is specified as being 10s with a goal of 5s. It contains the settling to the new position. The contribution from the acceleration and deceleration t_{acc} is specified as $\sqrt{2\Delta\phi_{acc}}$ ['’] seconds with a goal of $\sqrt{\Delta\phi_{acc}}$ ['’] seconds. Here $\Delta\phi_{acc}$ is the length over which the telescope may accelerate and decelerate. Acceleration is possible up to a speed limit which is specified to be at least 7°/min. From this value we obtain a maximum length for acceleration and deceleration $\Delta\phi_{acc,max}$ of 24.5° at the specified acceleration rate and 12.25° at the goal rate. At smaller angular distances the full slew length is used for acceleration and deceleration. If the total slewing length $\Delta\phi$ exceeds $\Delta\phi_{acc,max}$ the additional slewing is performed with the constant speed limit rate. Using 7°/min results in $t_{rate} = (\Delta\phi - \Delta\phi_{acc,max})/420''$ in seconds. The following table shows some example slew times:

$\Delta\phi$	***10''***	***3'***	***10'***	***20'***	***1°***	***20°***	***90°***
t_{slew} at specified slew	15 s	29 s	45 s	59 s	95 s	6.5 min	<16.5 min
t_{slew} at goal slew	9 s	19 s	30 s	40 s	65 s	<4.7 min	<14.7 min

As the number at 90° using the specified rates is inconsistent with the requirement to finish a 90° slew within less than 15 min also specified in AD6, the constant speed limit will be increased probably to about 8.5°/min allowing to meet this requirement.

A slew of 10'' corresponds to the change between neighbouring steps in a fully sampled raster map for HIFI band 5, i.e. The given slewing times will appear as dead times in corresponding observations. The slew of 3' will be typically used in double beam switch observations. All values given here refer to minimum slewing times. Slower slewing rates are always possible.

A special telescope motion is the turnaround between subsequent lines in line scanning (OTF) observations. The time needed for the turnaround t_{turn} is composed of contributions from the deceleration, turnaround, and acceleration to small velocities. The turnaround time is not yet specified but as the distance between subsequent lines will be small, t_{turn} is to be expected to fall only slightly above the slewing times given for the 10'' slew.

Beyond the pure slewing time the telescope motion sets another timing constraint provided by the fact that only after about 10s the noise in the star tracker image reaches a sufficiently low level to allow an accurate pointing determination. Thus all ESA pointing modes as introduced in Sect. 3.1 have a lower limit for the pointing at one position of 10s.

2.1.2 Chopper motion

The instrument has a focal plane chopper to switch the telescope between the astronomical source and a nearby reference so that the difference between the two positions can be measured. The chopper throw is adjustable with a maximum of 3'. The direction of the chopper throw is determined by the satellite coordinate system. Thus a selection of different chop directions is only possible by defining certain time windows for the observations where the chop direction in the satellite coordinates matches the chop direction that is needed on the sky. Moreover, for observations in the ecliptic plane the satellite system is fixed within a few degrees relative to the sky so that the chop direction cannot be varied for objects close to the ecliptic plane. Thus, the free selection of a chop direction is not a general option.

The chop frequency is specified in AD6 between1/3 and 5 Hz. To reduce the relative contribution of the chopper dead time combined with a simple readout in a 1s raster it would be favourable to increase the maximum chop cycle to 4s. As slower chopping does not impose any technical problem, the chop frequency of ¼ Hz is included here. Corresponding to different backend limitations we distinguish two chop modes:

- **Slow chop**: chop frequencies f_{chop} of 0.5 and 0.25 Hz
- **Fast chop**: chop frequencies f_{chop} between 2 and 5 Hz (typically $f_{chop} = 4$ Hz)

The dead time due to the moving mirror $t_{chop-dead}$ is not yet specified. Recent predictions indicate a dead time of 0.025s for each motion. This implies a reduction of the observing efficiency by the chopper motion down to 75% for an observation chopped with 5 Hz. Thus fast chop should only be used if unavoidable.

2.2 Timing limits from the instrument

2.2.1 WBS readout

The WBS readout is performed in two different ways affecting the observing modes. In a normal mode used for total power, OTF, and slow−chop observations the WBS adds the data up in one memory bank while the data in the second memory bank can be transmitted to the ICU. The WBS can be read out after a minimum time $t_{min-data}$ of 1 s (shorter times possible for total power observations will not be used). Thus one full set of channels can be transmitted in each second of observations. The maximum time between subsequent readouts $t_{max-data}$ is 80 s.

In fast−chop mode both chopper cycles are added up independently in the WBS but after the end of the integration 2 seconds are lost for the switching due to data transfer of the two WBS banks after switching. The two full channel sets are transmitted in two readout seconds. For a reasonable efficiency of this mode the time between subsequent readouts $t_{min-data}$ should not fall below 10 s (This would mean 4 s integration on the source, 4 s integration on the chopped position, and 2 s for the readout process). The maximum time between subsequent readouts $t_{max-data}$ is 160 s.

2.2.2 WBS stabilisation

Switching different IF signals to the WBS requires some settling time $t_{s,WBS}$ before a reliable spectrum can be taken. In AD5 there are settling times given for switching on the comb, terminating to zero or for setting different attenuators. They are estimated to about 0.1s. No exact number is specified yet.

Beyond the IF settling time a thermal settling of the Bragg cell has to be taken into account. As the IF input power results in a considerable heating of the Bragg cell, different levels of the input power will result in different equilibrium temperatures and thus in changes of the spectral characteristics of the WBS. Thus a thermal settling time $t_{s,Bragg}$ has to be taken into account when switching between sources with strong differences in the continuum spectrum. The effect will be negligible in higher bands where the noise from the receiver always dominates the signal, but in band 1 it might be important even when switching between the cold load and the blank sky as this results in a 20% change of the IF power. It should be taken into account for all calibration measurements using the cold load and the hot load so that it enters the calibration time. Preliminary tests have shown that a change of the input power by more than about 20% requires a thermal settling time for the Bragg cell $t_{s,Bragg}$ of 10−15s. Hence, load calibration measurements will be relatively time consuming.

2.2.3 HRS stabilisation

The IF handling in the HRS will also require some settling times $t_{s,HRS}$ when switching different signals to the spectrometer, similar to the specified times for the WBS. They are not yet considered in AD4. According to the design of the HRS they are not expected to exceed the corresponding times for the WBS so that one can assume values of 0.1s . As there is no thermally critical element in the HRS we expect no settling time for switching between different levels of input power. Hence, stabilisation times in the HRS do probably not constrain the observations.

2.2.4 Frequency switch

Frequency switch can be used in observations to obtain a reference which is shifted in frequency and not in spatial coordinates with respect to the source. Here, the LO setting is changed by a small value $\Delta\nu_{fs}$ which does not require any retuning of the mixer unit. The frequency throw $\Delta\nu_{fs}$ is adjustable in steps between 0 and >90 MHz. The dead time for a frequency switch t_{fs} is specified in AD6 to fall below 0.1s. The frequency of the frequency switches f_{fs} in the observations is specified between 1/3 and 1 Hz. To increase the observing efficiency with respect to the frequency switch dead time longer periods are useful. Thus frequency switch frequencies f_{fs} of 0.5 Hz and 0.25 Hz should be foreseen. Modes with 1/6, 1/8 or 1/10 Hz might further reduce the relative contribution of the dead time.

2.2.5 Frequency change

For frequency surveys a change in the LO frequency $\Delta\nu_{fc}$ by some tens of MHz up to at most 2000 MHz will be necessary. Each frequency change will result in a slightly modified system response. Thus step sizes exceeding $\Delta\nu_{recal}$ need a new hot−cold calibration. The time for the calibration t_{cal} is composed of the contributions from the hot and the cold load, switching times and the thermal settling time of the WBS

$t_{s,Bragg}$. With typical load times of 8s (AD3), the calibration time t_{cal} will fall at about 20s. The step size $\Delta\nu_{recal}$ will depend strongly on the exact calibration scheme that is used for the particular observation.

Frequency changes exceeding some size $\Delta\nu_{retune}$ need a retuning of the mixers with respect to the LO power, the mixer bias, and possibly the magnetic field strength. The retuned mixer has then to be calibrated by a pair of hot−cold measurements using the calibration time t_{cal}. The whole time for a frequency change t_{retune} is not yet known but will be in the order of 1 minute.
Thus, for single frequency changes $\Delta\nu_{fc}$ below $\Delta\nu_{retune}$, where the calibration scheme of the observation does not need a new absolute calibration, the time for the frequency change t_{fc} will be identical to the frequency switch time t_{fs}. For frequency changes or a series of frequency changes covering $\Delta\nu_{recal}$ but below $\Delta\nu_{retune}$ the time for the calibration t_{cal} has to be added. For frequency changes exceeding $\Delta\nu_{retune}$ or a series of frequency changes which cover in total $\Delta\nu_{retune}$ the retuning time t_{retune} has to be added as dead time instead.

Frequency surveys may include switches between different HIFI bands. Within this switch the LO of one band has to be powered off and the LO of the next band has to be powered on. The subsequent stabilisation of the system requires a large amount of time which is not yet known. The total band switch time t_{bc} will be in the order of 15−20 min. Thus band switching will not be foreseen within one observing mode.

2.3 Stability

2.3.1 Instabilities

The instrumental response of HIFI will not be constant in time but will suffer from various drift effects. This will modify the response function of the instrument with respect to the input signal, the coupling to the warm surfaces in the telescope and the contribution of instrumental noise in time. We have to distinguish two types of drifts: a drift in the instrumental gain with respect to the input signal and a drift of the contributions added in the instrument.

Variations in the instrumental gain are translated as a linear factor into the resulting astronomical data, so that a variation by 1 to a few percent is acceptable for the intended calibration accuracy of HIFI. The variation in the gain has to be taken into account by frequent load−calibration measurements, i.e. the observation of a hot and a cold source in the focal plane unit. The stability of the gain is not yet known, so that the time between subsequent load measurements $t_{load-cycle}$, given by a variation of the gain by about 1% is still to be determined. Calibration sources with a strong continuum radiation should be used to measure $t_{load-cycle}$. Experience from ground−based SIS receivers suggests stability times $t_{load-cycle}$ of 10−20 min.

The contribution of drift terms added to the signal is much more critical as they are typically several hundred times stronger than the astronomical signal. Thus they are treated by a differencing scheme, where mutual differences are formed in a sequence of astronomical and reference observations. Possible reference schemes are discussed in detail in Sect. 3.2. As long as the drift behaviour is linear in time, this approach can completely remove the additive drift contributions. If these drift contributions change non−linearly between subsequent reference measurements their influence typically shows up as distortions in the baseline of the observation − baseline ripples. HIFI will see two major additive contributions, the receiver noise and the radiation from parts of the telescope within the beam. As the backward efficiency is low, the contribution from the telescope term will be about 50 to 500 times lower than the contribution from the receiver.

A main source of instabilities are path length variations in the instrument modifying the pattern of standing waves occurring between the different (partially) reflecting surfaces in the instrument. They are determined mainly by the mechanical stability of the instrument and the telescope with respect to low−frequency vibrations and thermal deformations. The standing waves modulate the gain of the instrument depending on frequency and the coupling to the telescope structure. A drift in the standing wave pattern thus results in a nonlinear change of the system response for any given frequency. The relative influence of the standing wave variation on the receiver temperature contribution to the backend signal and on the signal gain is not yet clear. Thus it might turn out that the telescope radiation term is still more important for the drift behaviour than the receiver temperature term. Whereas the receiver temperature contribution is mainly modified by changes in the LO−mixer path and drifts in IF chain, the telescope contribution is as well modified by changes in the path to the subreflector.

If the differencing scheme applied to correct for the drift of the additive term shows itself slight differences in the standing wave behaviour between the two phases used, the relative drift of the two response functions has to be considered as well. This holds e.g. for chop observations where the path to the subreflector is different for the two chopper positions. Then the relative drift of the two standing waves has to be taken into account when planning observations which correct for the standing waves by symmetric chopping (dual beam switch, see Sect. 3.1.3).

2.3.2 Allan time

To quantify the stability time for the additive drift contributions one can use the Allan variance. It allows to compare the error due to the instrumental drift with the radiometric noise in the astronomical observation. The minimum of the Allan variance is the Allan time t_A indicating the turn−over from the dominance of the radiometric noise to the dominance of drift effects. The radiometric noise depends on the fluctuation bandwidth $\Delta\nu_{fluct}$ of the spectrometer which is in general more than 50% larger than the resolution bandwidth $\Delta\nu_{res}$. Assuming that the ratio between the fluctuation bandwidth and the resolution bandwidth is constant, one can still express the Allan time t_A as a function of the resolution bandwidth $\Delta\nu_{res}$. As the drift noise typically has an spectrum between $1/f^2$ and $1/f^3$ the Allan time at a given resolution bandwidth behaves inbetween $t_A \propto \Delta\nu_{res}^{-1/2}$ and $t_A \propto \Delta\nu_{res}^{-1/3}$. When the Allan variance is measured at the resolution bandwidth of 1 MHz, lower limits for the Allan time at the resolution bandwidth $\Delta\nu_{res}$ are given by:

$$t_A = t_A\,(1\text{ MHz}) / \sqrt[3]{\Delta\nu_{res}[\text{MHz}]} \qquad \text{for } \Delta\nu_{res} < 1\text{MHz}$$
$$t_A = t_A\,(1\text{ MHz}) / \sqrt{\Delta\nu_{res}[\text{MHz}]} \qquad \text{for } \Delta\nu_{res} > 1\text{MHz}.$$

The stability time of the system is not yet known. The amplitude stability specification from AD6 given at the total bandwidth of the backends and at the HRS resolution is consistent with a noise characteristics inbetween $1/f^2$ and $1/f^3$ and can be translated into a time for the minimum of the Allan variance t_A at the resolution bandwidth of 1 MHz of about 50s at 460 GHz and 70s at 1.9 THz. Using the experience from SWAS as an estimate the Allan time at 1 MHz would be 150 s corresponding to a minimum Allan time at 0.14 MHz of 400 s. Instabilities due to the Helium circuit and the higher complexity of Herschel may result in a smaller Allan time whereas the stable environment may be taken as an argument for longer Allan times compared to SWAS.

The implication of the Allan time for the planning of observations has been comprehensively discussed in RD1. The Allan time t_A provides an estimate for the optimum time in which one complete cycle with source and reference should be finished. However, depending on the observing mode different factors apply in the translation of t_A into this optimum time:

$$t_{cycl} = f_{mode} \times t_A$$

In general the cycle time can be written as

$$t_{cycl} = t_{ref} + t_{dead} + N \times t_{on}$$

where t_{on} is the time spent on each of the N source positions within one cycle, t_{ref} is the time spent on the reference, and t_{dead} is the dead time due to slews, frequency or chopper switches.

In observations using the same time on the source and on the reference and N=1, as used typically in pointed observations, the factor f_{mode} depends only on the dead time between the reference and the source observation. If the data are read out twice per position, i.e. in a REF−ON/ON−REF mode, the dead time is given by one motion between source and reference and one obtains approximately

$$f_{mode} \approx (t_{dead}/t_A)^{0.25} + t_{dead}/t_A$$

At shorter times the observation is dominated by radiometric noise and the relative amount of dead times is larger than required. At longer times the difference between the source signal and the reference signal is dominated by the instrumental drift so that systematic errors may occur.

For mapped observations the optimum cycle time for a given number of source positions in one cycle N can be approximated by

$$f_{mode} \approx (N^{0.31} + N^{-0.19}) \times 0.53(t_{dead} / t_A)^{0.23} + t_{dead} / t_A$$

where the time spent on the reference position t_{ref} is $\sqrt{N}$ times the time spent on any source position t_{on} which is the most efficient mode for mapping. From the viewpoint of the observing efficiency the removal of dead times between subsequent source positions by continuous (On−The−Fly) observations is always favourable. To map large regions it is also favourable to use long scans with N as high as possible taking into account that the time on each source position $t_{on} \approx N^{-0.69} \times 0.53(t_{dead} / t_A)^{0.23} \times t_A$ has to be larger than the minimum readout cycle limited by the hardware constraints. Then the total cycle time can be considerable larger than the Allan time. In these computations one has to keep in mind that the Allan time t_A is always a function of the final velocity resolution Δv_{res}.

If the two phases of the referencing scheme show a slightly different instrumental response due to different standing waves, the relative drift of these two contributions has to be quantified as well. This can be done in terms of a standing waves Allan time $t_{A,sw}$. The standing wave difference Allan time can be measured equivalent to the normal Allan time when using the difference of the instrumental output between the two phases of the observation of a well defined source in a time series. The different reference schemes discussed in Sect. 3.2 have in general all different standing wave Allan times as different optical paths contribute. For the relative drift of the standing waves between the two chopper positions, we expect the standing waves Allan time $t_{A,sw-chop}$ to be much larger than the global Allan time t_A due to the carbon−fibre construction for the subreflector mount, but no numbers are specified yet. $t_{A,sw-chop}$ determines the cycle time for double beam switch observations. The same estimates as given above for the cycle between source position and reference position can be used for the cycle between the two positions taken to correct for the standing wave bandpass ripple.

As the Allan times will not be definitely known before launch, the planning of the optimum observing cycle for each observation has to be adaptable to the actual stability of the instrument by a flexible scheduling.

2.4 Data rates

The maximum data rate produced by any observation is constrained by the combination of bus traffic limits, on board mass memory, downlink rate, and the ICU capabilities. The mass memory is designed to hold 48 hours x 140 kb/s and the downlink will transfer 24 hours x 140 kb/s in 1 hour. At 140kb/s 50% of the CPU in the ICU are needed for adding up of channels and normal transfer operations. Thus, all limits are compliant with a bus rate of 140 kb/s so that this is the only data rate that will be made available to the user.

The downlink data rate limit has to be compared to the maximum output data rate provided by the spectrometers. They produce N_{pol} * N_{chan} * N_{bit} bits of data per read cycle, where N_{pol} is the number of polarisations, N_{chan} is the number of channels per polarisation, and N_{bit} is the number of significant bits per channel.

In all observing modes which do not use a fast chopping, the WBS can be read out every second providing 2 polarisations with 8192 channels each containing 24 bits, i.e. 393,216 bit/s. On integration times up to 4 seconds only 16 of these 24 bits are significant, so that the data rate may be dropped to 262,144 bit/s if the ICU provides a bit shift to extract the relevant 16 bits from the 24 bits that are delivered by the WBS. On integration times above 4 seconds more than 16 bits are significant so that the full 24 bits have to be used, but than the data rate is reduced by the longer integration time, e.g. to 78,643 bit/s for 5 seconds integration. In the fast chopping modes the data for both chop cycles are read out in a 2 seconds window after the integration. To reduce this dead time to at most 20% the mode should be used only for integrations of at least 8 seconds, leading to a data rate of 78,643 bit/s.

The HRS consists of subbands which can be combined in a flexible way to treat different resolutions adding up always to 4096 channels in 2 polarisations. Here, a dynamic range of about 20 bits may contain significant information in the auto−correlation function. However, the distribution of significant bits varies within the subband so that a variable bit shift in the ICU may probably reduce the data rate also by about one third as for the WBS. This has to be further investigated. The HRS can be read out in compliance with the fast−chop mode, i.e. 8 times per second but the data will be pre−integrated to at least 1 second in the ICU. In case of fast−chopped observations and 24 bit data this results in a data rate of 393,216 bit/s, for all other observations the maximum rate is 196,608 bit/s, which can be further reduced to 131,072 bit/s if a compression in the ICU is possible.

This results in the following limitations for the different configurations (assuming that compression of HRS data in the ICU is possible):

- **WBS only (slow chop):**
  – all channels can be stored in 2s
  – 8750 channels, i.e. ≈½ of the WBS can be stored in 1s

- **HRS only (slow chop):**
  – all subbands can be stored in 1s

- **WBS+HRS (slow chop):**
  – all channels can be stored in 3s
  – 8750 channels, i.e. ≈1/3 of all channels can be stored in 1s

- **WBS only (fast chop):**
  – all channels of both cycles stored in 2 × 4s (faster modes not useful)

- **HRS only (fast chop):**
  – all subbands of both cycles can be stored in 2s
  – ½ of the HRS can be stored in 1s

- **WBS+HRS (fast chop):**
  – all channels of both cycles stored in 2 × 4s (faster modes not useful)

If no compression of the HRS data is possible, the HRS limitations will fall between the values given above for the HRS and the values for the WBS.

The data rate problem in fast observations can be avoided by selecting sections of channels within the WBS and/or subbands of the HRS. For the WBS this means that channel ranges (at most 4) can be defined within the AOT, so that only the data within these ranges are transferred. For the HRS only complete subbands can be selected. This means that in the high−resolution mode only a complete half the spectrometer, and in the normal and low−resolution mode quarters of the spectrometer can be discarded to save data rate.

2.5 Integration times

The integration time per source position is determined by the desired noise level T_{rms}. For white noise it follows from the radiometer formula for the system temperature T_{sys} by

$$t_{on,tot} = (T_{sys}/T_{rms})^2 / \Delta\nu_{res}$$

if the integration time on the reference is much longer than on the source position (as will be the case for long line scans in OTF observations with a separate OFF position). Here $\Delta\nu_{res}$ is the resolution bandwidth of the observations. In general the integration time has to be increased relative to this value to compensate for the noise contribution from the reference measurement:

$$t_{on,tot} = (1 + t_{on,tot}/t_{ref,tot}) \times (T_{sys}/T_{rms})^2 / \Delta\nu_{res}$$

If the integration time is the same for the source and the reference position the on−source integration time thus is given by

$$t_{on,tot} = 2\,(T_{sys}/T_{rms})^2 / \Delta\nu_{res}$$

Small corrections to these formula are to be applied if either the source or the reference position has a strong continuum contribution. In observations using the optimum cycle time the total uncertainty of the intensity within the resolution bandwidth $\Delta\nu_{res}$ is composed to about equal parts from the rms white noise and instrumental drift effects (see 2.3 above), i.e. only half of the total uncertainty is given by the noise. In general the drift contribution does not show up as increased noise level but as distortions (ripples or shifts) to the base line.

The equations above assume that the system temperature and the noise temperature are defined on the same total bandwidth. However, for line observations only the noise in the signal sideband is relevant whereas the system temperature is measured from radiation in both sidebands. Thus, the equations hold only for observations of continuum sources which contribute equally in both sidebands. If the noise is measured as T_{rms}(SSB) but the system temperature as T_{sys}(DSB), the ratio T_{sys}/T_{rms} has to be increased by the ratio between the total gain and the gain in the signal sideband $1/G_{ssb}$. For a receiver with approximately the same sensitivity in both sidebands this corresponds to a factor 2.

Using this factor 2 and the double−sideband temperatures defined as the baseline for the instrument in the different HIFI bands (AD6) results in the following time estimates for observations with negligible noise from the reference:

Freq.	***T_{sys} (DSB)***	***T_{rms} (SSB) in 1s at $\Delta\nu_{res}$=1 MHz***	***T_{rms} (SSB) in 1s at $\Delta\nu_{res}$=0.14 MHz***	***$t_{on,tot}$ for T_{rms}=0.1K at $\Delta\nu_{res}$=1 MHz***	***$t_{on,tot}$ for T_{rms}=0.1K at $\Delta\nu_{res}$=0.14 MHz***
480 GHz	82 K	0.16 K	0.44 K	3 s	19 s
640 GHz	127 K	0.25 K	0.68 K	7 s	46 s
800 GHz	178 K	0.36 K	0.95 K	13 s	91 s
960 GHz	227 K	0.45 K	1.21 K	21 s	147 s
1120 GHz	275 K	0.55 K	1.47 K	30 s	216 s
1250 GHz	583 K	1.17 K	3.12 K	136 s	971 s
1410 GHz	748 K	1.50 K	4.00 K	224 s	1599 s
1910 GHz	771 K	1.54 K	4.12 K	238 s	1698 s

where the difference of a few K between the instrument temperature and the system temperature due to the coupling to the 80K telescope structure (coupling efficiency ≈2%) is neglected. For observations using the same integration time on the source and the reference position, all times have to be doubled or the rms temperatures have to be increased by a factor √2, respectively.

Unfortunately, the definition of pointing modes in AD1 does not foresee any pointings of less than 10s. Consequently the shorter integration times which are completely sufficient for some observations in the lower bands cannot be used in modes using fixed pointings but only in line−scanning (OTF) modes.

3 Composition of observing modes

The basic observing modes are determined by the possible operational modes of the instrument partially restricted by the hardware capabilities of the HIFI backends and partially by the slewing modes of the telescope.

3.1 ESA pointing modes

The possible motions of the telescope within the basic observing modes are defined by the ESA pointing modes given in the Instrument Interface Document (AD1). The pointing mode description there specifies all parameters characterising the mode from the telescope point of view. Here, they are translated into corresponding parameters from the viewpoint of the observation.

Pointing mode parameters describing the scheduling within an observation are split from parameters describing the coordinates because most of timing parameters are determined by the stability times t_A, $t_{A,sw}$, and $t_{load-cycle}$ which are not yet known. A comprehensive discussion of the timing of the observations is given in Sect. 3.5.

3.1.1 Staring

Staring was only mentioned as ''Fine pointing'' in Section 5.12.4 of the IID−A (AD1) but not listed in the appendix containing the detailed definitions of the Herschel pointing modes. It is obvious that it has to be used, e.g. together with frequency switch, and that it is easy to implement. Hence, it will be used here as the most simple pointing mode.

Pointing mode parameters:	coordinates l,b coordinate system (may contain an epoch)
Free timing parameters:	total integration time for the selected point t_{point}

3.1.2 Position switching

The mode is defined to be periodically switching between a source and a reference position. The distance between both points may not exceed 2°. The integration times on each position may fall between 10s and 30min.

Pointing mode parameters:	coordinates l_{on},b_{on}, l_{off},b_{off} coordinate system (may contain an epoch)
Free timing parameters:	source integration time during one cycle $t_{on,point}$ OFF integration time during one cycle $t_{off,point}$

number of cycles N_{pos}

3.1.3 Nodding

Nodding is known as dual beam switch (DBS) on ground−based radio telescopes. The telescope changes its position periodically to move the source from one instrument chop position to the other chop position. The change of the pointing direction thus coincides with the chopper throw.

Pointing mode parameters:
coordinates l,b
coordinate system (may contain an epoch)
length of chopper throw d_{chop} (≤3')

Free timing parameters:
integration time t_{dbs} per telescope move
number of telescope forward+back moves N_{dbs}

3.1.4 Normal raster pointing

The normal raster pointing as a series of pointed observations of equal duration in equal spacing without separate OFF position used for maps covering the full extent of the emission so that certain pixels within the map may be used for reference. Subsequent rows of pointings are scanned in opposite direction to minimise the slewing overhead. The minimum integration time on each position is 10s.

Pointing mode parameters:
coordinates $l_{on,center}$,$b_{on,center}$
coordinate system (may contain an epoch)
angle of raster row direction θ
distance between raster columns and rows d_1,d_2
(2''≤ d_1,d_2 ≤ 8')
number of raster columns and rows N_1, N_2
(N_1, N_2 ≤ 32)

Free timing parameters:
source integration time per raster point $t_{on,point}$
total number of raster scans N_{raster}

The normal raster pointing does not foresee any particular point to be used to calibrate the difference in the system response between the source and the reference. Thus these modes are very sensitive to standing wave problems.
In some cases the difference calibration can be done if each raster line starts at a point free of emission, so that this point can be used for calibration. Nevertheless this mode is not favourable from the viewpoint of bandpass calibration as an optimum calibration scheme uses different integration times for the standing wave calibration and the source observation.

3.1.5 Raster pointing with OFF−position

This pointing mode is equivalent to the normal raster pointing except that after a certain number of pointings on the source the telescope slews to an OFF position for a reference or calibration observation. According to AD1, the number of source positions between two reference observations can be any number between 2 and the map size, but it is obvious that also a reference measurement after each source point should be possible. There is no requirement that the number of source positions has to be an integer multiple of the length of the rows in the map.

Pointing mode parameters:
coordinates $l_{on,center}$,$b_{on,center}$, l_{off}, b_{off}
coordinate system (may contain an epoch)
angle of raster row direction θ
distance between raster columns and rows d_1,d_2
number of raster columns and rows N_1, N_2

Timing parameters:
source integration time per raster point $t_{on,point}$
integration time on the OFF position $t_{off,point}$
time between subsequent OFFs $t_{off-off}$
(translates into number of pointings between OFF pointings N_{on-off})
total number of raster scans N_{raster}

3.1.6 Normal line scanning

Line−scan is normally known as On−The−Fly (OTF) mapping. The only difference to the normal raster pointing mode is the continuous slew to scan rows (lines) in the map. Whereas in normal raster pointing the telescope stops at each pointing before the integration, the telescope moves in the line scanning mode continuously along the lines providing pointed observations by dumping the spectrometers in a regular interval. The scan direction is reversed in every second line to reduce the slewing overhead. The scan velocity can be varied between 0.1''/s and 1'/s in steps of 0.1''/s.

Pointing mode parameters:
coordinates $l_{on,center}$,$b_{on,center}$
coordinate system (may contain an epoch)
angle of line direction θ
distance between lines d_2
number of lines N_2 ($\leq$ 32)
distance between subsequent dumps d_1

number of dumps N_1

Free timing parameters:

source dumping time $t_{on,point}$
(d_1/t_{on} determines the scan velocity)
total number of map scans N_{OTF}

The normal line scanning does not foresee any particular point to be used to calibrate the difference in the system response between the source and the reference. Thus the same restrictions as for the normal raster pointing apply.

3.1.7 Line scanning with OFF−position

This pointing mode is equivalent to the normal line scan (OTF) except that after a certain number of lines the telescope slews to an OFF position for a reference or calibration observation. An integer multiple of full lines has to be scanned between subsequent OFF positions.

Pointing mode parameters:

coordinates $l_{on,center}$,$b_{on,center}$, l_{off}, b_{off}
coordinate system (may contain an epoch)
angle of line direction θ
distance between lines d_2
number of lines N_2 ($\leq$ 32)
distance between subsequent dumps d_1
number of dumps N_1

Timing parameters:

source dumping time $t_{on,point}$
(d_1/t_{on} determines the scan velocity)
integration time on the OFF position $t_{off,point}$
time between subsequent OFFs $t_{off-off}$
(translates into number of lines between OFF pointings N_{on-off})
total number of map scans N_{OTF}

3.1.8 Tracking of solar system objects

The tracking of solar system objects is a pointing mode superimposed to the other pointing modes. It is not considered as a separate observing mode because it is implied already by the selection of a parameter for the coordinate system of the observations in the parameters for the other pointing modes. This coordinate system may be moving and can be taken from a solar system object data base.

3.2 Selection of reference

All heterodyne observations need to compare the spectrum measured on the source with a spectrum on a reference because the output power from the spectrometers is dominated by contributions intrinsic to the instrument (described by system temperature) varying in time due to various drift processes. Thus only differencing can reveal the contribution from the source.

For all observations applying the same integration time on the source and on the reference it is preferable from the viewpoint of stability to use two readouts within each position so that each observation is calibrated as an REF−ON−ON−REF observation. This reduces the dead time within each cycle containing ON and REF by a factor 2.

3.2.1 Total power

Total power observations use the normal integration at a certain telescope pointing as reference value. This is used e.g. in position switch observations where the telescope is moved to a distant OFF position for reference REF. In maps covering the full extent of the emission, a point within the map may be used for reference if the full map is observed within about the Allan time t_A. The minimum noise level per total integration time is obtained if the integration time on the reference position t_{ref} is $\sqrt{N}$ times the integration time on the source position t_{on} when N different source positions are to be compared to the same reference position.

Reference parameters: none

3.2.2 Chopped observations

If the emission is restricted to a small angular region on the sky, the reference may by taken by chopping with the focal plane mirror from the source position to a slightly shifted position. The maximum offset provided by the chopper is 3’. Chopping is much faster than position switch observations as no telescope slew is required. However, the chopper direction is always fixed to the satellite coordinates so that the chop throw reaches different REF positions in observations at different times. It will be possible to specify the pointing modes in the satellite coordinates, so that it is e.g. possible to set up a map direction relative to chop direction, but it is not possible to specify arbitrary chop directions. For objects at high latitudes above the ecliptic plane a certain chop direction can be forced by selecting a particular time window for the observation, but it is not yet clear to which accuracy the observational scheduling will allow to select the chop direction in the astronomical observing templates. With additional input on scientific reasons for an accurate selection of the chop direction the accuracy and flexibility of the procedure for the selection of a certain chop direction in sky coordinates by an appropriate scheduling has to be further specified.

According to the different backend readout behaviour two different chop modes are distinguished:

- **Slow chop**: $f_{chop} \leq 0.5$ Hz
- **Fast chop**: $f_{chop} \geq 2$ Hz

Fast chop is only required if observations with a very large effective resolution bandwidth are to be carried out in case of a small system stability time t_A.

As the optical path in the instrument is changed by the motion of the chop mirror, the standing waves in the system will differ between two chop directions resulting in an imperfect cancellation of the baseline pattern between the two positions. To obtain flat baselines it is thus preferable to combine chopping with nodding so that the standing wave difference is once added and once subtracted from the difference between the source position and the reference position (DBS). The slew to the second chopper position needs not to be done frequently if the standing wave pattern is relatively stable. This dual beam switch approach also results in an exact cancellation of linear drifts in the radiometer output.

For chop observations, as well as for load−chop and frequency switch observations, the optimum chop cycle is determined by the system Allan time t_A according to the equations given in Sect. 2.3.2. After the corresponding Allan time for the standing wave drift $t_{A,sw}$ the standing wave difference should be determined again at an OFF position.

Reference parameters: chopper throw d_{chop}
chop frequency f_{chop}
(chop direction θ_{chop} by selecting the observing date)

3.2.3 Load chop

In case of the lack of a nearby position without emission the internal cold load may be used as reference. As this implies two completely different optical paths in the observation the difference signal will be heavily influenced by the difference in the standing wave patterns. Thus, the standing wave pattern of load chop observations has to be calibrated on a separate OFF position. This implies that the standing wave pattern is very stable, so that it can be determined by rare slews to the OFF position.

As the cold load provides in general a continuum level which is large compared to the sky level, the thermal settling of the Bragg cell in the WBS might constrain the load chop time in the lower bands. If the difference in the IF level is negligible with respect to the thermal behaviour of the Bragg cell, load chop can be performed as fast as normal chop.

Reference parameters: load chop frequency f_{lchop}

3.2.4 Frequency switch

In case of the lack of a nearby position without emission the reference may be obtained by switching to another frequency at the source position. The frequency switch has to be small compared to the total bandwidth of the spectrometers so that the mixer behaviour is not changed due to the frequency switch and the observed lines are visible for both frequency settings within the bandwidth of the spectrometer. The subtraction of the two spectra then results in shifted negative lines in the spectrum of positive lines. For most observations the original spectrum can be computed by adding the shifted spectra, but in case of many spectral lines or a possible blending of the lines the computation of the true source spectrum may require a more sophisticated analysis. As frequency switch modes combine two spectra from the same position they can be in principle the most efficient observing modes.

Frequency switch also results in a standing wave problem as chopping does. Although the optical path is not changed in this case, the standing wave pattern will shift due to the frequency shift. This shift of the standing wave pattern is often linear for very small frequency changes but becomes chaotic at large changes. At the current stage it is not known how strong the baseline problem will be in frequency switched modes and whether it can be easily corrected. If the standing wave pattern is very stable it can be determined in rare slews to an emission−free OFF position. Additional tests on ground−based telescopes should be performed to find acceptable ways to correct for the baseline ripples.

Reference parameters: frequency throw $\Delta\nu_{switch}$
frequency switch frequency f_{fsw}

3.3 Backends

The HRS may be used in 3 different modes regarding the resolution:

– Hires mode:

Resolution FWHM = 0.14 MHz,

2 polarisations

1 subband (with 4096 channels) per polarization

– Normal mode:

Resolution FWHM = 0.27 MHz,

2 polarisations

2 subbands (with 2048 channels) per polarization

– Lowres mode (emergency mode):

Resolution FWHM = 0.54 MHz,

2 polarisations

2 subbands (with 2048 channels) per polarization

Moreover, it is possible to reduce the total data rate by selecting a certain subband from the HRS which may either by restricted to a polarization or a frequency section.

Backend parameters: resolution $\Delta\nu_{res}$
subbands to read

The WBS uses always a fixed resolution. Here, one can reduce the effective data rate by selecting at most 4 windows of channels.

Backend parameters: first and last frequency of the channel windows $\nu_{1,i}$, $\nu_{2,i}$

3.4 LO frequency

A main parameter for the observation is the exact frequency coverage in the two sidebands of the receiver. The width of this coverage is determined by the backend selection above, but the location of the central frequencies is determined by the LO frequency. The LO setting has to guarantee that the specified frequency is mixed down to an intermediate frequency of 6 GHz.

The LO setting has to be computed on the base of the sky frequency of a considered transition which is different from the rest frequency by the Doppler correction from the velocity frame of the astronomical object relative to the velocity frame of the telescope. Typical velocity frames for the telescope are the local standard of rest (LSR) in the L2 orbit or the heliocentric standard of rest. Velocity frames of the astronomical object may be given as some know line−of−sight velocity with respect to the telescope rest frame or as the velocity frame of a solar system object.

Moreover, there is always the choice of the receiver sideband which is to be used. In many cases an observer will not have a particular preference for the sideband. Then the system should recommend the optimum sideband from the known spectral receiver characteristics to minimise the noise from the second sideband. In many cases, however, the observer will insist on a particular sideband either to avoid blending with known lines from the other sideband or to obtain information about lines in the two selected sidebands in a single observation.

LO frequency parameters: rest frequency of the central channel ν_{rest}
sideband for the selected frequency
velocity frame of the telescope v_{tel}
velocity frame of the object v_{obj}

3.5 Time estimates for the observing modes

The timing of the observing modes is determined by three classes of timing parameters:

I. Integration times
II. Dead times
III. Stability times

The physical constraints for all timing limitations were discussed in Sect. 2. Only the total time for the observation t_{tot} should be specified explicitly by the astronomer. Taking the instrumental constraints given by the dead times and the stability times this translates into the exact timing parameters for the selected observing mode. They consist of the timing parameters for the pointing mode and the reference frame. They form the schedule for a specific observing mode and indicate the actual integration time spent on a specific astronomical source position. On has to keep in mind that many timing parameters depend on the desired frequency resolution of the observation (see Sect. 2.3 and 2.5) so that the timing can vary within one observing mode.

3.5.1 Integration times

The integration times are primarily determined by the total time spent on the source which should be specified by the observer. We have to distinuish the integration time for the source observation t_{on} and for the reference observation t_{ref}. In all observing modes where each source measurement has one corresponding reference observation equal integration times are to be used for both measurements, $t_{on}=t_{ref}$. Although a small modification to this rule should be applied in principle for the most efficient observation of sources with a strong continuum in the lower HIFI bands the small number of such astronomical objects does not justify to implement this increased complexity into the design of the observing modes, so that we apply $t_{on}=t_{ref}$ for all such observations. In observing modes where one reference observation is used for several source observations the most efficient relation between the two integration times is $t_{ref}=\sqrt{N}\, t_{on}$, when N is the number of source measurements per reference measurement (RD1).

The total integration time spent on a given point may be split into a number of integrations. Thus we have to distinguish the total integration times $t_{on,tot}$ and $t_{ref,tot}$ which determine the noise of the resulting data set as discussed in Sect. 2.4., the integration times per data dump from the ICU to the satellite $t_{on,data}$ and $t_{ref,data}$, the times spent on a given sky position as used in the pointing modes $t_{on,point}$ and $t_{ref,point}$, and the actual integration times used in a single exposure $t_{on,exp}$ and $t_{ref,exp}$. In chop observations the exposure integration time can be shorter than the data dump time as severel chop cycles can be pre−integrated in the ICU. For total power observations the actual integration time can be larger than the dump time.

Lower limits to the actual exposure integration time are set by the chop frequency. The upper limits are determined by the system Allan time for the desired frequency resolution and observing mode (see 2.2.6 and 3.5.3). The actual integration time should be selected always as large as possible taking the limitations from the Allan variance and the total integration time into account to increase the observing efficiency. The actual integration times also form a lower limit to the pointing times. In pointed observations, i.e. non−scanning modes, another lower limit to the pointing integration time is given by the 10s requirement from Sect. 2.1.1. Their upper limit is given by the standing wave Allan time requiring a recalibration of the reference scheme on an OFF position after $t_{A,sw}$. A lower limit to integration times per data dump is set by the satellite data rate as discussed in Sect. 2.3. Because the data storage is available anyway and a quick data dump is also desirable for monitoring purposes it makes no sense to use dump times exceeding the minimum dump times, so that in fact only dump times of 1, 2 or 3s will be used. One exception is given by the fast−chop modes which are characterized by long readout dead times asking for longer dump times (10s and above) for a reasonable efficiency.

Depending on the reference frame we find thus the following limiting conditions to the different integration times:

Reference mode	***Relations between integration times***	***Absolute times***
total power	$t_{on,data} \leq t_{on,exp} = t_{on,point} \leq t_{on,tot}$	$t_{on,data}=[1,2,3]s$
fast−chop	$t_{on,exp} << t_{on,data} \leq t_{on,point} \leq t_{on,tot}$	$t_{on,exp}=1/2f_{chop}-t_{dead,chop}$ $t_{on,data}=4...40s-t_{dead}$
slow−chop, load−chop, frequency switch	$t_{on,exp} \leq t_{on,data} \leq t_{on,point} \leq t_{on,tot}$	$t_{on,exp}=1/2f_{chop}-t_{dead,chop}$ $=[1,2,3]s-t_{dead,chop}$ $t_{on,data}=[1,2,3]s-t_{dead}$

Here, the time $t_{dead,chop}$ represents the dead time for one switch within the chop cycle (either focal plane chopper switch or frequency switch), whereas t_{dead} stands for the sum of these times within one readout−cycle. Only in total power measurements the integration times on the reference position t_{ref} may deviate from the integration times on the source position according to the relations given above, so that $t_{ref,exp} \leq t_{on,exp}$ there. For all other observations the times as given in the table above are identical for the reference.

3.5.2 Dead times

The sources of the different dead times provided by the instrument are discussed already in Sect. 2. We can summarize three kinds of dead times:

I. Reference switch times
II. Additional dead times
III. Calibration times

The reference switch times occur during each observation when switching between the source and the reference. They may be given by the chopper dead time $t_{chop-dead}$, the frequency switch time t_{fs} or the slew time to the reference position t_{slew}. These times always have to be added to the exposure integration times $t_{on,exp}$ and $t_{ref,exp}$ in the estimate for the total observing time.

In a number of observing modes additional dead times cannot be avoided. These are in particular slew times between the two chop angles in dual−beam switch (nodding) observations, slew times between different positions and between subsequent lines in raster and line−scanning modes, and the dead time for frequency changes t_{retune} in frequency surveys. The frequency of the actions leading to these additional dead times is constrained by the system stability but can be chosen arbitrarily above the corresponding lower limits. The best choice leading to a minimum amount of dead times within the observation poses a nontrivial optimization problem. Some guidelines how to approach this problem are discussed in Sect. 3.6.

The thrid class of dead times is provided by the need for frequent calibration measurements as integral part of the observing modes. Two different kinds of calibration measurements are needed: the bandpass calibration based on the observation of the two internal thermal loads, and the reference calibration where a difference in the system response between the source and the reference observation is measured by observing a sky position free of emission with the same reference frame as used in the astronomical observation. The latter can be used to avoid typical baseline problems when the reference frame contains two different system response functions. We have to consider two cases: **i)** total power observations or observations of very narrow lines where baseline ripples play no role for the scientific result; **ii)** frequency switch, chopped, and load−chop observations which are to be corrected for system response differences.

In case **i)** only the bandpass calibration time enters as dead time. The integration times on the two thermal loads are determined by the frequency resolution of the observations. Using the specified system temperatures as discussed in Sect. 2.4 we the following integration time per load:

Backend resolution (MHz)	***LO frequency (Ghz)***							
	480	640	800	960	1120	1250	1410	1910
1.0	1s	1s	1s	1s	1s	2s	3s	4s
0.54	1s	1s	1s	1s	1s	3s	5s	7s
0.27	1s	1s	1s	1s	2s	6s	10s	13s
0.14	1s	1s	2s	2s	3s	11s	19s	25s

The total dead time for the calibration is then twice the value from the table above increased by 4s for the frequency calibration and by another $2 \times t_{s,Bragg}$ for the thermal settling of the WBS if this is used as backend. The bandpass calibration can be carried out while the telescope is slewing to another position, so that the calibration dead time enters the observing mode only if it exceeds the time for a slew that is already foreseen in the pointing mode.

In case ii) the calibration of the system response difference requires an additional integration time on an OFF position to measure the actual system response difference. Although there are still several uncertainties about this difference due to the influence of standing waves (RD7) we can derive an upper limit for the integration time for each chop phase on the OFF position. It is given by the integration time on the source position multiplied by the ratio between the frequency resolution of the observation and the frequency resolution required to measure the standing wave ripple in the system response $t_{OFF} = t_{on} \times \Delta\nu_{obs} / \Delta\nu_{sw}$. In mapping observing modes the difference calibration can be used for several map points. As it can be considered as a second order reference the same relation between the OFF integration time and the integration time on the astronomical source as derived in Sect. 3.5.1 for the reference integration time can be used when corrected for the resolution ratio $\Delta\nu_{obs} / \Delta\nu_{sw}$. The frequency of this difference calibration measurements depends on the stability time of the standing waves $t_{A,sw-chop}$. Although this difference calibration may provide the longest dead time in an observing mode when used, it can help to increase the overall efficiency of an observation which would otherwise be performed in a total power mode suffering from very long slew dead times.

3.5.3 Stability times

The sequence of observations, reference measurements, load calibration measurements, and system response difference measurements is determined by the different stability times of the system. Taking current system knowledge we expect a sequence $t_A < t_{load-cycle} < t_{A,sw}$, but the standing wave stability times for the different reference modes $t_{A,sw-chop}$, $t_{A,sw-load}$, and $t_{A,sw-fs}$ are not yet known. Taking the different Allan times the optimum cycles for a reference measurement, a load calibration measurement, and an OFF calibration measurement can be computed using the equations from Sect. 2.2.6. In general we obtain a hierarchy of three calibration cycles where the time for the calibration of one quantity enters as dead time in the next longer loop.

3.5.4 Timing relations for the different observing modes

3.5.4.1 Pointed observations

Observations of a single point may be carried out either in staring mode, in dual beam switch (nodding) or in position switch mode depending on the reference frame and the need for a baseline calibration in the reference frame. Staring is only reasonable for chopped observations and frequency switch observations when baseline problems are no concern for the observation. Then the integration times follow $t_{on,exp} \leq t_{on,data} \leq t_{on,point} = t_{on,tot}$ where the first relation is determined by the ratio between the system Allan time t_A constraining the chop or frequency switch cycle, and the dump time constrained by the data rate limitation for the selected backend. In most cases $t_{on,exp}$ and $t_{on,data}$ will agree as the reference cycle can be selected shorter than t_A. The load−cycle is given by $t_{load-cycle}$ which is the main limitation for the overall efficiency of the mode.

Dual beam switch is a special approach to calibrate the baseline difference between the two chopper positions combining reference and source observations in both chopper positions. Hence, no dead time is lost for the baseline difference calibration. The chopper motion has to correct for the general drift of the instrument in t_A. The timing for a slew to the second chop position is determined by the stability of the standing waves in the path between the subreflector and the receiver $t_{A,sw-chop}$. If this stability time is longer than the total integration time, only one slew in the middle of the integration time is required.

In the observation of single points a slew to a reference position (position switch) may be used either for the reference measurement (total power observation) or for calibrating the system response difference in chopped, load−chop, or frequency switch observations. In the first case a slew to the OFF position is necessary within the system Allan time t_A and the integration time on the OFF position agrees with the integration time on the source. In the second case such a slew is only required within the standing wave Allan time $t_{A,sw}$ and the time spent on the OFF position can be smaller than the source integration time. As the time spent here on the OFF position enters as additional dead time there is no general rule which mode is to be preferred. This depends on the actual dead time for the slew, i.e. the distance between the source and the OFF position, the frequency resolution determining the baseline difference calibration time, and the stability times of the system.

3.5.4.2 Mapping observations

The normal raster pointing and the normal line−scanning modes do not foresee any particular point to be used as reference or to calibrate the difference in the system response between the source and the reference. Hence, these modes are only useable in chopped, load−chop or frequency switch observations when the standing wave baseline ripple is ignored.

In some cases the difference calibration could be done when each map line starts in a region free of emission, so that these points can be used for calibration. However, as the optimum calibration scheme requires a fixed ratio between the integration times for the source points and for the bandpass calibration, this approach is in general not favourable.

Baseline problems can be avoided only in mapping modes with an OFF position. In total power observations the OFF position is used as reference and because only one optical path and frequency setting is used no difference calibration is required. The time for a cycle to the OFF position is given by $t_{cycl} = t_A(N^{0.31} + N^{-0.19}) \times 0.53(t_{dead} / t_A)^{0.23} + t_{dead}$, where the number of source pointings within one cycle N is mainly constrained by the data dump limitation. In most cases the optimum integration time is given by the dump time $t_{on,data}=t_{on,exp}=t_{on,point}$ as this maximises the number of source points per reference measurement and $t_{ref}=\sqrt{N}\ t_{on,exp}$ (RD1). This general rule may be violated, however, when the overhead due to slewing times grows above the reduction of the reference integration time. Unfortunately, the rule can also not be used for raster maps, because the minimum pointing time is given by 10s there. Hence, they suffer from a drastically reduced efficiency. The load cycle should be adjusted to give an integer multiple of the reference cycle, so that the slew times to the OFF position can be used for the load calibration measurement.

In chopped, load−chop, and frequency switch observations the OFF position can be used to measure the difference in the standing wave pattern between source and reference. Here, the cycle time is given by the corresponding Allan time for the standing wave difference $t_{A,sw-chop}$, $t_{A,sw-load}$, or $t_{A,sw-fs}$. The integration time on the OFF position used for the baseline difference calibration depends on the frequency resolution of the observation and the dominant standing waves. Here, we find the full hierarchy of timing loops $t_{on,exp}=1/f_{chop} \le t_{on,data} \le t_{on,point} < t_{load-cycle} < t_{OFF-cycle} = t_{A,sw} \le t_{tot}$.

3.6 Observing mode efficiencies

Both when selecting a particular observing mode and when selecting the timing parameters within an observing mode the total efficiency of the observation has to be considered. This includes a comparison of the dead times due to telescope slew, chopper motion, and frequency switch. As most of the quantities needed for the efficiency estimator are not yet accurately known one can only give some general rules at present. This list should be extended when more information on the system stability and on the dead times become available.

3.6.1 Load calibration measurements

All observing modes have to include measurements on the internal calibration loads (load measurements) to determine the bandpass and receiver temperature of the instrument. Both parameters vary with time so that this measurement has to be repeated after a time $t_{load-cycle}$. As load measurements imply dead times in the order of 30s they should not be carried out more often than required from the instrument stability and preferentially overlapping with dead times already enforced by telescope slews.

3.6.2 Slewing

Telescope slews result in the longest dead times in the observations, thus they should be used as rarely as possible.

This implies a preference of OTF modes relative to raster maps, as line scans do not show any dead time between subsequent points in a line. While many OTF maps will be much larger one can consider as an extreme example a fully−sampled 3×3 map at 1.9 THz. The specified slewing time between the raster points offset by 6'' is 14s. Assuming a turn−around time between subsequent lines in an OTF map of 20s this results in a total dead time of 112s for a single raster map and of 40s for the corresponding single OTF map, ignoring all dead times coming from the observation of a reference position. Similar numbers are obtained in the case of the small raster proposed in AD6 for peaking up on the source so that a cross line scan is more efficient than a raster in the peak−up mode. For all larger maps the relative reduction of the dead times when switching from raster maps to OTF observations is still considerably larger. Thus all mapping observations should rather use the OTF modes instead of raster modes, so that it has to be discussed whether the raster modes can be dropped completely from the list of basic modes which will be made available to the general observer. They may have some value, however, for calibration and monitoring purposes.

In nodding (DBS) observations the slew to the second position is the main part of the total dead time. Thus it should only be performed once in the Allan time of the standing wave pattern $t_{A,sw}$ or the total integration time − if the latter is shorter. As an example one can consider observations of galaxies showing broad lines, with a required spectral resolution of 20km/s at 1.9 THz using a chopper throw of 3'. If the standing wave Allan time $t_{A,sw}$ at a frequency resolution of 1 MHz is 150s, like the total instrumental Allan time on SWAS, the corresponding Allan time at $\Delta\nu_{res}$=127 MHz is 13.3s whereas the slewing time between the two telescope positions is 29s at the specified rate and 19s at the goal rate. Even in fast observations spending most time in slewing and being thus very inefficient baseline problems due to drifts would probably show up which may make the scientific outcome questionable. If the standing wave Allan time is ten times larger, the slew should be done once within about 0.8 $t_{A,sw}$ resulting in a dead time overhead of 27% and 18%, respectively.

3.6.3 Chop

The dead time due to the moving chopper $t_{chop-dead}$ is much smaller than the slewing time. It will fall in the order of 0.025s which have to be taken into account. Using the fast chop−mode at 5Hz with the WBS read out every 10s, providing an additional 2s dead time, the total observing efficiency is reduced by 40%. Thus the chop cycle should be as long as possible and the fast−chop mode should be omitted if avoidable.

As chopped observations will in general suffer from the difference of the standing wave pattern in the two chop directions it is always favorable to use a dual beam switch approach where the same source point is observed in both chop directions so that the different baselines cancel out each other. Then the efficiency is, however, again limited by the slews. In case of map observations the efficiency of the dual beam switch approach can be increased in principle by using a DBS slew which is already part of the mapping of a source. If the slew between the two chop positions is identical to a map slew no additional dead time occurs. Moreover, the general efficiency is increased by a factor 2 when both chop cycles fall on the source.

This approach is obvious for the mapping of extended sources where the chop throw falls inside the observed map except for some boundary points which should be free of emission. If the chop direction is e.g. parallel to the direction of the line scans in an OTF map, a differencing signal along the line is measured where each point contributes once in both chop phases. The original spectrum can be easily computed from the differencing signal and the standing wave problem is solved. This mode is often used for bolometer observations. For heterodyne observations this approach is, however, not generally useable because the differencing between different points of the map increases the radiometric noise in each point. This noise explosion can be circumvented in the data reduction by restricting the data to finite positive contributions, but this prevents the use of this mode for sources with absorption lines or a strong continuum. The approach should be tested on a ground−based telescope before it is implemented for HIFI because it has not yet been used at ground−based telescopes for heterodyne observations.

For the mapping of sources without continuum and absorption lines the mode may turn out as the most efficient approach. But it also imposes severe requirements to the scheduling of the observations. As the chop direction cannot be selected arbitrarily, the orientation of the most efficient map on the sky is determined by the date of the observation and the ecliptical latitude of the source. An arbitrary map direction which is determined by the satellite coordinate system and not by the source geometry may be acceptable for some sources but for many sources a certain map direction will be required. For sources at high latitudes this can be obtained by a sophisticated scheduling procedure for this type of observations guaranteeing a good match of the satellite direction with the required map direction on the sky. As an alternative one can use a more complex observing mode where the two chop phases do not fall on the same line of a map. Depending on the stability of the standing wave pattern this may require an inhomogeneous spacing in the temporal scan of the different lines in a map which is not foreseen in the ESA pointing modes so that it would have to be set up as composed observing mode consisting of interlacing maps. Moreover, it requires a more sophisticated data analysis to disentangle the two chop phases. The selection of the best approach to this efficiency problem needs further discussion.

3.6.4 Frequency switch and load chop

Frequency switch and load chop can be used to observe sources without a nearby position which is free of emission. In principle they should always be preferred to position switch observations. However, both approaches have to rely heavily on the nature and stability of the standing wave pattern. If frequency switch observations are only weakly affected by standing waves or the standing wave pattern can be easily corrected they provide the most efficient observing mode as they spend all observing time on the source and have relatively small dead times. If the standing wave pattern cannot be neglected in frequency switch observations but it is stable over a long time, it can be determined on a separate OFF position. This holds as well for the load chop observations which also need a calibration with respect to the standing waves. Here, additional slew times to the OFF position have to be taken into account.

From the viewpoint of the observing efficiency frequency switch is the best mode for most observations as long as standing waves are stable over a long time. At ground−based telescopes it works for small frequency throws when observing narrow lines. However, it still has to be proven, that the standing wave baseline can be easily handled in this approach. For maps where the dual beam slew falls into the mapped region, chopped observations may turn out as the most efficient mode. Frequency switch observations may also fail in regions with line confusion. If there is no nearby position free of emission available load chop might be the most efficient way for these cases.

With the restricted current knowledge on the standing wave behaviour, no definitive conclusion on the preference for a particular reference scheme in a particular observation can be given yet. In case of rapidly varying standing waves the traditional dual beam switch approach or the position switch pointing, which are both well tested on the ground but slow on HIFI, may turn out as the only reliable modes. In case of an well understood and stable standing wave behaviour, almost all observations could be done in frequency switch mode. Unfortunately this uncertainty results in tremendous differences for the efficiency of frequency surveys, as they do not need long integration times for each frequency setting and are sensitive to baseline ripples. Hence, one can estimate for the same frequency survey efficiencies between 5% and 70% depending on the nature of the standing baseline ripples and the resulting observing mode.

4 Observing modes

4.1 Basic observing modes

Basic observing modes are defined as a simple combination of an ESA pointing mode with a reference mode and the selection of a backend. In principle all pointing modes may be combined with all modes for the reference and both backends but several combinations are not useful so that the total number of combinations is reduced by mutual exclusions.

It is e.g. not reasonable to use load chop observations in pointing modes without a separate OFF position, because this OFF position is required for the calibration of the baseline. As fast chop is intended to be used on wide lines it is probably not useful in observations with the HRS although it is possible. Moreover, reference modes with long dead times are a problem in the frame of OTF observations as they produce “gaps” in the data, so that they limit the scanning velocity. Therefore the combination of line scan observations with the fast−chop mode and the WBS was excluded because the WBS has a readout dead time of 2 seconds. Several other combinations, however, should be further discussed. As such the list of basic observing modes is still preliminary and should be further discussed. It is summarised in the table below:

		Herschel pointing mode							***Reference***					***Back−end***		
Observing options ***Basic observing modes***	Preliminary Priority	Pointed observation	Position switching	Nodding (Double Beam Switch)	Raster pointing with OFF	Raster pointing without OFF	Line scanning (OTF) with OFF	Line scanning without OFF	Total power	Fast wobbler chop	Slow wobbler chop	Frequency switch	Load chop	Only HRS	Only WBS	Both backends
Staring − fast chop	1	✘								✘				?	✔	?
Staring − slow chop	5	✘									✘			✔	✔	✔
Staring − frequency switch	5	✘										✘		✔	✔	✔

		Herschel pointing mode							***Reference***					***Back–end***		
Position switch	8		✘						✘					✔	✔	✔
Position switch – fast chop	1		✘							✘				✔	✔	✔
Position switch – slow chop	5		✘								✘			✔	✔	✔
Position switch – frequency switch	5		✘									✘		✔	✔	✔
Position switch – load chop	4		✘										✘	✔	✔	✔
DBS – fast chop	2			✘						✘				**?**	✔	**?**
DBS – slow chop	9			✘							✘			✔	✔	✔
Raster map with OFF	4				✘				✘					✔	✔	✔
Raster with OFF – fast chop	1				✘					✘				**?**	✔	**?**
Raster with OFF – slow chop	4				✘						✘			✔	✔	✔
Raster with OFF – frequency switch	4				✘							✘		✔	✔	✔
Raster with OFF – load chop	2				✘								✘	✔	✔	✔
Raster without OFF – fast chop	0					✘				✘				**?**	✔	**?**
Raster without OFF – slow chop	2					✘					✘			✔	✔	✔
Raster without OFF – freq. switch	2					✘						✘		✔	✔	✔
OTF map with OFF	9						✘		✘					✔	✔	✔
OTF with OFF – slow chop	5						✘				✘			✔	✔	✔
OTF with OFF – frequency switch	7						✘					✘		✔	✔	✔
OTF with OFF – load chop	5						✘						✘	✔	✔	✔
OTF without OFF – fast chop	1							✘		✘				**?**		
OTF without OFF – slow chop	4							✘			✘			✔	✔	✔
OTF without OFF – frequency switch	4							✘				✘		✔	✔	✔

✘ –Combination of options defining the observing mode

✔– Possible and reasonable usage of backends within the observing mode

? – Backend usage is technically possible but probably not useful. There is no obvious application for this backend combination.

The priority numbers run from 0 (lowest priority) to 10 (highest priority). They are preliminary and reflect only the opinion of the few people that have discussed the document until now. Several objective factors enter the priority of a mode:

- *General observing efficiency:* Modes which are inherently more efficient as they do not have long dead times or they use both switch cycles on the source got a higher priority. Various efficiency aspects are discussed in Sect. 3.6.
- *Scientific relevance:* The priority of modes without an obvious astronomical application is reduced.
- *Known robustness with respect to baseline problems:* Modes which are insensitive with respect to standing waves or bandpass drifts have an increased priority.
- *Ground−based experience:* Modes which are well tested on ground−based telescopes are set to a higher priority. For proposed modes which have not yet been used at terrestrial telescopes, but can be tested there, corresponding runs should be performed in the future.
- *Technical simplicity:* Modes which are technically somewhat more challenging, like the fast−chop modes, were reduced in their priority.
- *Calibration effort:* Modes requiring a higher effort and longer times for their calibration are reduced in their priority relative to modes with a smaller calibration requirements

In a discussion with the science community the priority list has to be further iterated. In the final priority list some basic observing modes should drop out because of their low efficiency and relevance so that the total list of observing modes can be reduced to keep the validation and calibration effort small. It seems e.g. questionable whether the fast chop modes are necessary and why to offer any raster modes when corresponding OTF modes are more efficient. The final list should cover all scientifically required modes but being as small as possible.

4.2 High−level observing modes

The astronomical observations will also use some standard modes which do not correspond to a single pointing mode of the telescope but represent a combination of several basic observing modes.

4.2.1 Maps with temporary reference

As slew times to a distant OFF position will provide the main dead times when the mapping many astronomical objects it is preferable to use a reference position which is close to or within the map to be observed, even if this point is not free of emission. Then the emission at the reference point has to be determined in an independent step. The high−level observing modes for maps with a temporary reference are thus composed of two basic observing modes: a mapping mode with OFF position and a position switch mode to determine the spectrum at the OFF position. The position switch observation to determine the emission from the temporary reference has to be long relative to the normal integration time on the OFF position so that the increase of the noise due to the intermediate step is negligible but small compared to the observing time for the map to result in an actual improvement of the observing efficiency. We obtain two different modes:

- *Raster map with OFF and temporary reference*
  Preliminary priority: 5
- *OTF map with OFF and temporary reference*
  Preliminary priority: 8

4.2.2 Cross scan

A common technique to study point−like sources are cross scans. They will consist of two line scans perpendicular to each other with only one line in each of them. They may use all reference schemes available for the OTF modes and both backends. This results in 4 reasonable modes:

- *Cross scan with OFF*

  Preliminary priority: 6
- *Cross scan without OFF*

  Preliminary priority: 3
- *Cross scan without OFF − slow chop*

  Preliminary priority: 4
- *Cross scan without OFF − frequency switch*

  Preliminary priority: 4

4.2.3 Staring with load chop

For staring observations using the cold load as reference, the standing wave pattern has to be calibrated on an OFF position. The time for the calibration of the baseline can be short compared to the integration time on the source. Thus this mode does not fit into the position switch mode defined above where equal times on the source and the reference position were assumed. It can be implemented as the ESA position switch mode with two different observing times or as a composition of two staring modes. As this is makes no difference for the actual observation and the reference mode is load chop in both cases, it results in one high−level observing mode:

- *Staring observation with load chop calibration*

  Preliminary priority: 1

4.2.4 Frequency surveys

As the frequency change is not part of a basic observation mode, frequency surveys consist of a series of observations separated by frequency changes. The LO tuning will be changed monotonically within one LO band. For a reliable sideband deconvolution in the reduction of the frequency surveys the spacings in frequency should be irregular to suppress possible ambiguities at harmonics of the frequency spacings.

The reliability of the reduction of the frequency surveys grows monotonically with the number of frequency settings within the spectrometer bands used in the same integration time. Without dead times for the frequency changes a very large number of frequency settings would be used. The dead times results in an optimisation problem which is described in detail in RD6. For a reliable deduction of the line spectrum at least 4 frequency settings per WBS band should be used in general. The frequency changes consists of a series always containing N_{fs} steps within $\Delta\nu_{recal}$ which can be carried out in the frequency switch time f_{fs} each. An additional calibration step follows after $\Delta\nu_{recal}$ which is required to determine the new calibration of the instrument and an additional step is necessary after $\Delta\nu_{retune}$ with retuning and recalibration of the mixer.

Frequency surveys will be made available only for pointed observations (staring) and the position switch mode. At the moment it is not yet clear whether total power, normal chop, nodding or frequency switch should be used as the reference frame in frequency surveys. As there is no fundamental difference between a frequency change and a frequency switch it is in principle possible to perform the whole frequency survey in total power mode on the source position when the instrumental baseline stays constant or varies only smoothly during the frequency changes. This depends on the reaction of the bandpass on frequency changes and on the standing waves. Preliminary tests have shown that the response of the instrumental bandpass on frequency changes in the order of 100 MHz is in general complex and nonlinear so that a new hot−cold calibration measurement is required even after relatively small frequency changes if the whole frequency survey is to be carried out without a reference. As these calibration measurements are relatively slow they will drastically reduce the efficiency of this approach.

Alternatively one has to use a differencing scheme. The most efficient scheme would be frequency switch but this depends critically on the standing wave problem. In case of strong standing waves each frequency change may result in a particular baseline ripple which cannot be removed in the data reduction. Dual beam switch or position switch as reference frame will result, however, in an observing efficiency typically as low as 10% due to the long dead times of the telescope slew. Dual beam switch observations are always more efficient than position switch observations whenever they can be performed. They have proven in ground−based frequency surveys to result in flat baselines but they should be used with the smallest possible slews for the nodding between the two chop positions to have an acceptable efficiency. If the difference of the baseline patterns between the two focal plane chopper positions is stable on long time scales so that it does not need to be measured for each frequency setting in the survey separately the application of a normal slow chop mode might also be an option which has a much better efficiency than dual beam switch and position switch.

Further simulations on the sensitivity of the data reduction algorithms to changes in the instrumental response and to the standing waves are required to obtain a definite conclusion on the best observing mode for the frequency surveys. Thus the different alternatives have to be foreseen here:

- *Frequency survey with position switch*
  Preliminary priority: 5
- *Frequency survey with dual beam switch*
  Preliminary priority: 8
- *Frequency survey with slow chop*
  Preliminary priority: 5
- *Frequency survey with frequency switch*
  Preliminary priority: 7
- *Frequency survey in total power with frequent hot−cold calibrations*
  Preliminary priority: 6

Frequency surveys will cover only single LO bands. Observations intended to cover more bands have to be split into several frequency survey modes.

4.2.5 Small maps with dual beam switch

As normal chop modes will be influenced by standing wave baseline ripples it is always favourable to use dual beam switch where the same source point is observed in both chop directions so that the different baselines cancel each out. There are two approaches to obtain this behaviour when mapping a source: chop within the map and chop out of the map. The first approach was discussed above in section 3.4.2. It is covered by the basic modes combining a map mode with slow−chop.

The second approach applies to small sources with some internal structure where the chop throw of 3’ always falls outside of the source. Here, mapping of the source may be combined with a dual beam switch corresponding to the ESA pointing mode of nodding where two reference positions without emission can be reached by the chopper throw when pointing the telescope either to the source position or the chopped position. The combination of mapping and nodding is not foreseen as a basic observing mode, so that is has to be defined as a high−level mode if needed.

Depending on the baseline stability this may be implemented in two different ways: If $t_{A,sw}$ is large, the observation consists of two chopped OTF maps differing in their pointing by the chopper throw, so that they can be combined in a way equivalent to dual beam switch observations of a single point. If $t_{A,sw}$ is small the mode will be implemented as a series of pointed DBS observations on a raster providing the map. As the reference mode is defined by the chopping this scheme results only in one mode:

- *Dual beam switch map*

Preliminary priority: 6

4.2.6 Template beam synthesis

The template beam synthesis is a special mapping mode proposed in RD4. It is used to combine observations at different frequencies by a synthetic beam convolution which is best done when the signal−to−noise ratio in the observations follows the spatial behaviour of the reconvolution kernel.

This can be achieved by a superposition of concentric OTF maps of different size and integration time. From the shape of the reconvolution kernel, the size and integration time of the different concentric maps can be computed. The maps should be observed in the same observational run to avoid relative pointing errors. Depending on the system stability it may be possible to use one OFF measurement for some of the OTF maps so that one can avoid a slew to a remote OFF in some maps. Thus the mode represents a superposition of normal line scans and line scans with OFF.

The mode still should be tested in ground−based observations, as as it can be applied in the same way for ground−based telescopes, to get some experience with it before launch.

Corresponding to the different reference scheme the template beam synthesis results in at least 4 different observing modes:

- *Template beam synthesis with OFF + total power*
  Preliminary priority: 5
- *Template beam synthesis without OFF + frequency switch*
  Preliminary priority: 2
- *Template beam synthesis with OFF + frequency switch*
  Preliminary priority: 3
- *Template beam synthesis with OFF + load switch*
  Preliminary priority: 2

4.2.7 Additional high−level modes

It is possible that a few important high−level modes were forgotten here. They should be introduced soon by the science community.

5 Additional remarks

In most cases the observations will have to rely on the pointing provided by the spacecraft. As the source structure is in general unknown, peaking up on the source will not be a standard option. However, it will be implemented for testing purposes and it will be regularly used to check by pointing of the telescope within the time dedicated to control and calibration measurements. Thus it might be an option in few cases for observations of known point sources like planets or evolved stars.

It is not possible to use other instruments like PACS for pointing measurements as only one instrument will be active in each 24h period. The pointing specifications are given in RD1.

Appendix

A System parameters determining the observing modes

The following system parameters determine the selection, the internal timing and the efficiency of astronomical observations using the different observing modes.

Symbol	***Description***	***Goal***	***Specified***	***Best guess***	***Ref.***
T_{sys}	Double sideband instrument noise temperature (Band 1)	82−127K			AD6
	Band 2	127−175K			AD6
	Band 3	178−227K			AD6
	Band 4	227−275K			AD6
	Band 5	275−583K			AD6
	Band 6	748−771K			AD6
t_{slew}	Time to slew the telescope between different pointings	$t_{slew} = t_{fix} + t_{acc} + t_{rate}$			AD1 (see 2.1.1)
t_{fix}	Fix dead time in slewing	5 s	10 s		AD1
t_{acc}	Acceleration time [s]	$\sqrt{\Delta\phi_{acc}}$	$\sqrt{2\Delta\phi_{acc}}$		AD1
$\Delta\phi_{acc,max}$	Maximum acceleration length	12.25°	24.5°		
t_{rate}	Time for constant slewing rate [s]		$(\Delta\phi-\Delta\phi_{acc,max})$ / 420’’		AD1
t_{turn}	Turn−around time between subsequent lines of an OTF observation			$t_{fix} + t_{accel}$	
$f_{fast-chop}$	Chop frequency for fast chop		2−5 Hz		AD5
$f_{slow-chop}$	Chop frequency for slow chop		0.5,0.25, 0.167Hz ...		AD5
		0.5, 0.25Hz	0.5, 0.33Hz		AD6
$t_{chop-dead}$	Chopper dead time			0.025 s	
f_{fs}	Frequency switch frequency	0.5, 0.25Hz	0.5, 0.33Hz		AD6

Symbol	***Description***	***Goal***	***Specified***	***Best guess***	***Ref.***
t_{fs}	Frequency switch time		≤ 0.1 s		AD6
$t_{s,WBS}$	WBS IF switch settling time			0.1 s	AD4
$t_{s,Bragg}$	Thermal settling time of the WBS−Bragg cell for a changing IF input power			15 s	
$t_{s,HRS}$	HRS IF switch settling time			0.1 s	
$\Delta\nu_{recal}$	Bandwidth of possible LO change with a change of the mixer response below the calibration uncertainty			100 MHz	
$\Delta\nu_{retune}$	Bandwidth of possible LO change without retuning			1 GHz	
t_{calib}	Hot−cold calibration time			20 s	
$t_{load-cycle}$	Gain stability time giving the cycle time beween two calibration measurements			15 min	
t_{retune}	Frequency change time for changes exceeding $\Delta\nu_{retune}$			60 s	
t_{bs}	Band switch time			15 min	
$t_{dead-wbs-fast}$	WBS readout dead time for fast chop modes		2 s		AD5
$t_{dead-wbs-slow}$	WBS readout dead time for slow chop modes		0		AD5
$t_{data-wbs-slow}$	Time between subsequent WBS readouts in slow chop		1−80 s		AD5
$t_{data-wbs-fast}$	Time between subsequent WBS readouts in fast chop		1−160 s		AD5
R_{bus}	Maximum data rate on the bus	140 kB/s	100 kB/s		AD1
$t_A\ (\Delta\nu_{res})$	Allan time at the intended resolution		≥50−70 s at 1 MHz	150 s at 1 MHz	AD6

Symbol	*Description*	*Goal*	*Specified*	*Best guess*	*Ref.*
$t_{A,sw-chop}$	Allan time of the standing wave difference between both chopper positions			600 s at 1 MHz	
$t_{A,sw-load}$	Allan time of the standing wave difference between cold load and sky			300 s at 1 MHz	
$t_{A,sw-fs}$	Allan time of the standing wave difference between the two frequencies in frequency switch			150 s at 1 MHz	

B Open questions

B.1 Questions to the HIFI science board

AI nr.	Question	Status
1.1	Which of the basic observing modes can be dropped?	open
1.2	Priorities of the different basic observing modes	under discussion
1.3	Are there additional high–level modes missing?	under discussion
1.4	Is there any need for fast chopped observations ?	open
1.5	Are there arguments for chop frequencies below 0.5 Hz ?	open
1.6	Is there any scientifically motivated need for more than 4 windows of channels in the WBS when selecting windows to reduce the data rate?	open
1.7	Can we expect any gain by implementing a symmetric dual frequency switch mode?	open
1.8	Which reference mode should be used for frequency surveys ?	open
1.9	Is there any need for the HRS in frequency surveys ?	open
1.10	Is it worth to implement the selection of the chop direction by an appropriate scheduling of the observations in the AOTs for objects where such a limited selection is possible and how accurately do we have to adjust the chop direction ?	open

1.11	Are there scientific arguments against specifying all integration times with a granularity of about 1s, i.e. working within a fixed 1s raster ?	open

B.2 Required updates in the Instrument Specification and the Instrument Interface Document

AI nr.	Question	Status
2.1	Staring or equivalently M=1 in ESA raster pointing mode is required	closed (IID−A 5.12.4)
2.2	For the staring mode maximum integration times have to exceed 30 min	closed (no limit defined)
2.3	K=1 in raster pointing with OFF is required to allow long integrations at limited stability and missing in IID−A	open
2.4	It has to be clarified that the solar system tracking mode is intended as a superposition to the other modes.	open
2.5	The granularity of the length of line scans has to be reduced to 5''.	closed (IID−A update)
2.6	Correction of the specified slewing rate to meet the 90°/15min requirement.	open
2.7	Increase the maximum chop and frequency switch period from 3s to at least 4s, better 6s.	under discussion
2.8	Reduce the minimum integration time in the pointing modes to at most 2s.	closed (not accepted)
2.9	Introduction of different integration times in position switch pointing mode	in progress

B.3 Questions regarding the telescope and instrument operation

AI nr.	Question	Status
3.1	Is compression of the HRS data by bit shifting in the ICU possible? Which algorithm may be used with which efficiency?	open
3.2	Can the peak−up mode use line−scans instead of a small raster?	in progress

3.3	Is it possible to modify the line–scan pointing mode to allow a non–monotonous sequence of the lines?	closed (not accepted)
	How flexible is the observational scheduling:	
3.4	Is it possible to optimise the sequence of observations with respect to minimum time for source change/frequency change ?	open
3.5	Is it possible to optimise the sequence of observations with respect to the data rate by combining high data rate observations with low efficiency observations which cannot provide 140kb/s?	closed (no)
3.6	Is it possible to perform retuning and calibration during telescope slews ?	open
3.7	Is it possible to optimise the global scheduling with respect to the match of the satellite coordinate direction with the preferred direction in different sources on the sky ?	open
	The following quantities are not specified:	
3.8	What is the turn–around time for line scans t_{turn}?	open
3.9	What is the chopper dead time $t_{chop-dead}$?	being measured
3.10	What is the retuning time t_{retune} ?	open
3.11	What is the maximum frequency change that can be performed without retuning $\Delta\nu_{retune}$?	
3.12	What is the band switch time t_{bs} ?	open
3.13	What is the standing wave stability time $t_{A,sw}$ restricted by mechanical vibrations/deformations ?	open

B.4 Observing modes that should be tested on ground

AI nr.	Mode	Status
4.1	Frequency switch modes with OTF	not reported
4.2	Load chop observations (needs very stable weather conditions)	not tested
4.3	Raster/OTF maps without OFF in total power	not tested
4.4	Forward chopped OTF heterodyne observations	not tested
4.5	Map chopped raster/OTF observations which a chop direction not parallel to the scan direction	not tested
4.6	Frequency surveys with frequency switch	not tested
4.7	Frequency surveys with load chop	not tested

4.8 Template beam synthesis observation planned