HIFI Observing Mode Descriptions

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Abstract

This document contains the general description of all observing modes that will be used for normal astronomical observations.

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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
AD7	HIFI Observing Modes Document: SRON-ICC/2002-001
AD8	The HIFI intensity calibration framework, ALMA-Memo 442, 01/09/2003, V. Ossenkopf
AD9	DM IF-1 Amplifier Gain Stability Summary, SRON 06/02/2003, N.C. Whyborn
AD10	Observing mode implementation document, SRON-ICC/2003-009
AD11	Observing mode calibration document, SRON-CC/2003-010
AD12	HIFI-HSPOT Interface Control Document, 03/10/2005, A. Martson

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 synthesis 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	H. Beuther, C. Kramer, B. Deiss, J. Stutzki, CO mapping and multi-line-analysis of Cepheus B, A&A 362 (2000), 1109
RD8	A unified Allan variance computation scheme, 7/31/2003, V. Ossenkopf
RD9	Optimisation of mapping modes for heterodyne instruments, 3/11/2004, V. Ossenkopf
RD10	Reconstructing reality: Strategies for sideband deconvolution, Comito, C. & Schilke, P. 2002, A&A, 395, 357

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1 Introduction

The HIFI Observing Modes Document provides a general framework for the design and planning of the observing modes in which HIFI can be used for astronomical observations listing all astrophysically reasonable modes and their constraints and limitations. This document extends the Observing Modes Document by providing a description of all observing modes including a layout of their main ingredients like the timeline of their performance, the effort needed for their calibration, and estimates of their efficiency.

The design of the observing modes is based on the following properties of the HIFI system:

a. A usable Intermediate Frequency (IF) range of 4GHz in bands 1 – 5 and 2.4 GHz in bands 6 low and 6 high for HIFI.
b. The availability of Wide Band (WBS) and High Resolution (HRS) spectrometers providing default spectral resolutions of 0.14 – 1.1 MHz.
c. Dual sideband (DSB) spectra, with superimposed portions of observed spectra that are separated by 8 – 16 GHz in sky frequency.

This documents contains the general descriptions of the modes providing guidelines for the astronomer to allow a choice between different observing modes possible for an astronomical observation. It is accompanied by the “Observing mode implementation document” (AD10) which contains the details of the timeline of each observing mode including the equations to compute the length of each step. Only from these details an accurate time estimate for each observation can be derived. Moreover, the observing mode description is accompanied by the “Observing mode calibration document” (AD11) which contains the equations and procedures required to calibrate observations performed in the different observing modes.

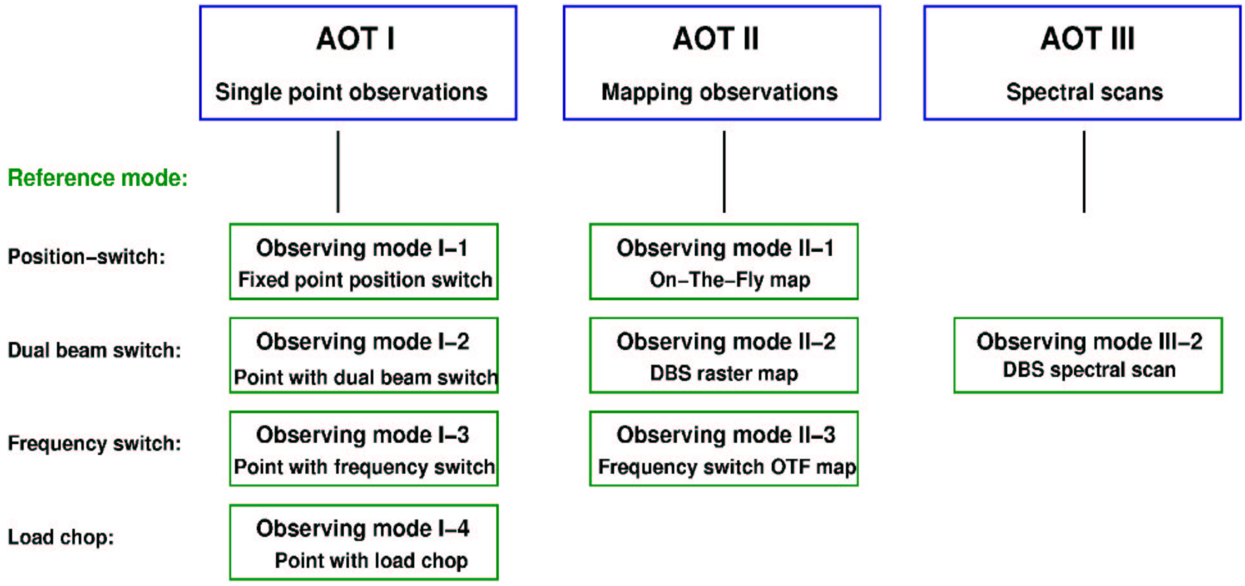
In the current draft status the document contains only descriptions of a few, more essential modes. It will be extended by adding descriptions for more modes to be implemented for HIFI observations.

2 The HIFI Astronomical Observing Modes

2.1 The HIFI AOTs

HIFI observations can use three different Astronomical Observing Templates (AOTs). These are the AOT I for single point observations, the AOT II for mapping observations, and the AOT III for frequency surveys. The AOTs I and II allow specification of only a single observing frequency in terms of the local oscillator (LO) frequency or, in the case of frequency switching, a single frequency plus offset frequency. Combinations of observations at several frequencies have to be performed as a cluster of different observations belonging to theses AOTs. In contrast AOT III is a frequency survey covering a wide frequency range continuously, by stepping through many LO settings. This AOT, however, is restricted to single pointings. No direct combination of frequency surveys with mapping observations will be provided.

Observations entered in one of the three AOTs will be performed in a number of different observing modes, which differ mainly in the selection of the reference measurements within the observation. All observations consist of source measurements, reference measurement and a set of calibration measurement that will be used to fully calibrate the spectra in both frequency and intensity. An overview on the currently designed observing modes and their relation to the AOTs is given in the following figure:



The numbering scheme of the observing modes represents an assocation between the AOT class (in Roman numerals) and four possible modes of reference treatment (Arabic numerals) that are foreseen. The dual beam switch modes (modes 2) have to be further split into two seperate modes using a slow chopper speed and a fast chopper speed, because the timing behaviour, the efficiency, and the reliability of the calibrated data will significantly differ between these two cases. Not all of the observing modes shown are implemented within the Herschel-SPOT system yet, and additional modes are planned to be provided. Eight modes will be implemented for the first science proposals. More modes are to come; ideally the full matrix of the 12 possible modes should be filled, but it is not yet clear whether manpower and scheduling constraints permit this.

Corresponding to the different reference measurements used in the observing modes, each observing mode uses a somewhat different scheme for the data analysis including the intensity and frequency calibration. Thus the noise level and the drift contribution to the total data uncertainty of the calibrated data obtained from one of the AOTs depend critically on the used reference scheme used, i.e. the observing mode. The individual observing modes will be available as options in the three main AOTs provided to the end user through ESA's Proposal Handling System (PHS), for which Herschel-SPOT will be the primary graphical interface for observation planning (AD12). Here we give a rough overview for the modes specified so far, to enable an educated selection.

2.2 Scientific Motivation for the use of different Observing Modes

2.2.1 AOT I: Single point observations

2.2.1.1. Mode I-1: Fixed-position observation with position-switch reference

Observing a fixed position and a single OFF reference position is the most simple observing mode for HIFI, and can be considered as the standard single-point and shoot mode. The only telescope motion involves the slew between source and OFF position, and additional calibration measurements can be performed during the slews. The mode is relatively insensitive to standing wave problems because only one optical path is used. However, due to the relatively slow slew of the satellite and the need for frequent slews, this mode is not very efficient for obtaining low noise in a given observing time interval.

The mode requires the existence of a nearby position which can be defined as an OFF position which is free of emission. If the closest emission-free region is too distant, then a mode with load-chop or frequency-switch may be more desirable. If baseline effects such as standing wave ripples can be ignored, fixed position staring in frequency switch will be more efficient. This is the case for observations of very narrow lines where even a distorted baseline can be approximated by a simple linear profile across the line. In contrast, if the astronomical source to be observed is smaller than 3', dual beam switch observations are to be preferred because they require only rare slews and contain and inherent baseline correction.

Normally, the subtraction of a zeroth order baseline will be necessary when using the position-switch mode. Observations aiming at a determination of the continuum level should rely on modes using the internal chopper.

2.2.1.2. Mode I-2: Fixed-position with dual beam switch reference

Dual beam switch observations will be the standard mode for pointed observations of objects which have a spatial extent well below 3'. Here, the capability of the internal chopper to switch quickly between two positions on the sky will be exploited. By moving the telescope in such a way that the source appears in both chop positions, the impact of standing wave differences on the spectral baseline of the calibrated data is expected to be completely eliminated.

Due to the low dead time for the chopper motion and a baseline calibration including source measurements, the mode is the most efficient observing mode for single points, but it is restricted to small astronomical objects. Unfortunately, the direction of the chopper motion on the sky depends on the orientation of the spacecraft which changes during the orbit. Thus the chopper motion is only predictable when fixing the data and time of an observation. Only observations with a restricted time frame for their scheduling may base their planning on the assumption of a particular chop angle. Such scheduling constraints should be avoided whenever possible so that the mode should be restricted in general to objects with a size below 3' in all directions. Otherwise the observations should use position switch, frequency switch or load chop modes.

The mode is limited to chop frequencies below 0.5 Hz, which is sufficient for the spectroscopic observation of lines with a goal frequency resolution of up to a few ten MHz. At lower frequency resolutions or for observations of the continuum level, however, the instrumental drift would exceed the radiometric noise, so that the calibrated spectra may be drift dominated resulting in baseline distortions and increased uncertainties. In these cases, it is more efficient (with respect to the minimum total uncertainty which can be obtained in a given observing time) to use the dual beam switch mode with fast-chop (mode I-2a) .

The dual beam switch mode has been extensively tested at ground-based telescopes, where it is frequently used. Thus no major uncertainties in the implementation and calibration are to be expected even though it cannot be tested for HIFI on ground in AIV tests.

2.2.1.3. Mode I-2a: Fixed-position with dual beam switch reference in fast-chop mode

This mode represents a special case of the dual beam switch mode introduced because of instrumental limitations. The combination of telescope and chopper motions follows the same scheme as in mode I-2, so that the basic advantages and disadvantages of the mode with respect to the baseline calibration and the object size remain the same here.

The difference with respect to the normal dual beam switch mode is the use of chop frequencies up to 4 Hz. However, larger dead times exist due to a different readout cycle of the wide band spectrometer required in this case. Fast-chop observations will be required in all cases where the Allan time at the goal resolution, characterizing the ratio between drift noise and radiometric noise, is smaller than one second. This will be the case for most observations aiming at an accurate determination of the continuum level and for observations of very broad lines where it is planned to bin several ten to hundred WBS channels to reduce the radiometric noise.

The mode is always less efficient than the normal dual beam switch mode I-2 due to the relatively larger overhead of the chopper motions and the additional readout dead time and it is potentially less accurate in the calibration of the WBS readouts due to the more critical timing. As a dual beam switch mode it is also only applicable for small astronomical sources. Observers planning to use this mode because of a desired low spectral resolution or an accurate continuum level determination should also consider using the spectroscopic modes of SPIRE or PACS instead of HIFI.

2.2.1.4. Mode I-3: Single point in frequency switch mode

The observing mode of a single point in frequency switch mode with OFF calibration will be used for the observation of points in sources with few narrow lines where no emission-free reference can be found in close proximity to the source position. Here, a measurement at a second, slightly shifted frequency will be used as reference, to compensate for instrumental drifts. The mode is typically more efficient by at least a factor two than load-chop observations with OFF calibration (mode I-4), but it is restricted to sources with a simple spectral behaviour. It cannot be used for sources with rich spectra or with very broad lines. Here it would be impossible to deconvolve the contribution of both phases from the difference spectrum, preventing any reliable data reduction.

This mode is the most efficient for the observation of points in very extended emission regions, where slews to an emission-free position take so much time that they should be performed as rarely as possible. Even in sources that are less extended, frequency switch observations are more efficient than normal position-switch observations, because the absolute noise in the calibrated data per integration time is the same, but the slews to the OFF position can be performed less frequently. If the baseline calibration requires a lower frequency resolution, the advantage of the frequency switch becomes even clearer. As a drawback it has to be acknowledged that the frequency switch mode is still in a relatively experimental state. It has not been demonstrated yet, that it is able to provide clean baselines with the HIFI instrument. This depends on the change of the system response between the two frequency settings used. Moreover, the limitation to sources with simple spectra with narrow lines will provide a major criterion excluding this mode for several observations.

The mode can be tested in detail on ground during the AIV period as soon as a representative combination of the full LO and mixer system becomes available. The slews to the OFF position have to be replaced here by the introduction or removal of a proper absorber in the signal path.

2.2.1.5. Mode I-4: Fixed-position in load chop

The observing mode of a single point in load chop with OFF calibration will be used for the observation of points in sources where no emission-free reference can be found in close proximity to the source position, where baseline distortions due to the different instrumental responses on the sky and on the cold load cannot be accepted, and where frequency switch modes cannot be used due to the frequency structures of the observed lines. It is one of the most efficient modes for the observation of sources in very extended emission regions where slews to an emission-free position take so much time that they should be performed as rarely as possible, excluding normal position-switch observations. In other words, this mode can be used as a fallback for observations which would normally use a position-switch mode, but where the overhead from the slew to the OFF position is comparable to the integration time. In principle all observations could use this mode, but at the cost of low efficiency.

AIV tests can use an equivalent observing mode where only the slews to the OFF position are replaced by the introduction or removal of a proper absorber in the signal path. Thus the mode can be tested and verified on ground and can be used to characterise the properties of the instrument during the AIV phase.

2.2.2 AOT II: Mapping observations

2.2.2.1. Mode II-1: On-the-fly maps with position-switch reference

The observing mode of OTF-maps with position-switch reference is in many cases the most efficient observing mode for mapping observations with HIFI. Because one reference measurement can be used for several source measurements and little time is lost to telescope motions without data integrations, it can in principle approach an observing efficiency of 100%. The mode is relatively insensitive to standing wave problems because only one optical path is used.

It should be considered the standard mode for astronomical mapping with HIFI. Its use is, however, problematic if no nearby position can be defined as OFF position which is free of emission. Then it is often still possible and efficient to use an auxiliary nearby OFF position the emission of which is determined in a separate position-switch observation. However, if the closest emission-free region is too distant from the area to be mapped, OTF modes with load-chop or frequency switch can be more efficient. The same holds in all cases where the scientific aim of the observation does not require an accurate treatment of baseline effects, ignoring standing wave ripples or other baseline distortions. This will be the case for observations of very narrow lines where even a distorted baseline can be approximated by a simple linear profile across the line. Then OTF maps in frequency switch can be more efficient.

Because of instrumental limitations with respect to data rates, the speed of the telescope motion, and the gain instabilities it will not be possible to obtain an accurate determination of the continuum level from observations in OTF-maps with position-switch reference. The subtraction of a zeroth order baseline should always be expected. Observations aiming at a determination of the continuum level have to rely on modes using the internal chopper.

2.2.3 AOT III: Spectral scans

2.2.3.1. Mode III-2: Spectral scans in dual beam switch

The spectral scan mode may be considered to be successive staring observations of the same astronomical source at a series of LO frequencies using the WBS. The total frequency coverage of a spectral scan is typically much larger than the instantaneous 4 GHz IF bandwidth, but it is restricted to one LO band due to the long stabilisation times required to switch bands. It is not clear yet whether every frequency step needs a new internal hot/cold load calibration measurement or a number of steps can be calibrated with the same measurement.

A special concern for spectral scans is the overlap between the two sidebands, especially in regions that are rich of molecular lines. HIFI data is acquired in double sideband (DSB) mode so that lines from both sidebands appear at the same IF frequency. Spectral scans will thus consist of several readjustments of the LO frequency in steps smaller than the IF bandwidth, so that the lines from both sidebands move relative to each other in the IF and a deconvolution of the sidebands by means of iterative techniques will be possible in IA software, using a Maximum Entropy Method (MEM) method as described in RD10. The redundancy of a spectral scan, giving of the number and separation of independent LO settings per IF bandwidth, determines the effectiveness of the sideband deconvolution. To deconvolve crowded spectra requires a higher degree of redundancy (smaller frequency spacing between scans).

The quality of single sideband reconstruction will also be affected by drifts of the receiver gain and by pointing errors (particulary for sources that are structured on scales comparable to the HIFI beam size). These detrimental effects can be countered with increased redundancy, but again at the price of frequent retuning. Standing waves will also be present but can be compensated for with by the use of dual beam switching. This is a reliable mode for sources spatially confined to less than the 3' chop angle. Because dual beam switch is used as the reference frame here, the same advantages and limitations described for the single point with dual beam switch (mode I-2) apply here as well. LO frequency retuning and sky chopping are likely to keep the efficiency of this mode to as low as ~10%.

It is important to note that the optimum strategy and implementation of this AOT are being devised in parallel with the development of the deconvolution methods, which are heavily dependent on realistic simulations for HIFI.

2.2.3.2. Mode III-2a: Spectral scans with dual beam switch reference in fast chop

This mode represents a special case of the dual beam switch mode for providing maximum baseline calibration accuracy in spectral scans of the most spectrally complicated sources involving both emission and absorption features over the desired range of frequencies. The sideband deconvolution needs an accurate determination of the continuum baseline, but normal slow-chop observations permit no reliable determination of the continuum level due to short total power Allan times. This may be mitigated by the use of a fast chop cycle of up to 4 Hz. The fast-chop mode for spectral scans is thus to be used in observations of sources with an unknown continuum level which needs to be measured accurately simultaneous with the lines to be determined in the spectral scan. In contrast the corresponding normal dual beam switch mode (III-2) can be used only for sources with a negligible or well known continuum level.

The scheme for telescope and chopper motions is similar to that used in mode III-2, so that the basic advantages and disadvantages with respect to data calibration and object size are the same. As a dual beam switch mode it is only applicable for small astronomical sources. However, larger dead times exist in the fast-chop mode due to a different readout cycle of the wide band spectrometer required in this case. The mode is always less efficient than the normal dual beam switch mode due to the relatively larger overhead of the chopper motions and the additional readout dead times, bearing in mind that observing efficiency of spectral scans in normal dual beam switch mode is already expected to be no more than ~10%.

3 Considerations applying to all observing modes

3.1 Prerequisites for the observing modes

The definition of all observing modes assumes an independent operation of the Herschel telescope and the HIFI instrument. HIFI provides certain indicators of its health and safety to the spacecraft's central computer, but synchronisation between instrument and spacecraft operations is performed exclusively on the basis of time tags. All time intervals are predefined by deterministic resource estimates of instrument operation and spacecraft pointing commands. The detailed computations on the observing mode efficiencies performed in AD10 use the assumption of predefined but configurable time intervals for all spacecraft operations. The independent operation also means that telescope slews can be used for a retuning of the instrument and internal calibration measurements.

A current prerequisite for the interdependency of subsequent observations is that **all observations during an operational day are to be performed using the same HIFI band.** The procedure for switching between different HIFI bands requires considerable stabilisation times. This is not considered to be part of any observing mode as it is not expected to occur during a normal operational day.

Several observations within one observing request can be declared to be a cluster of observations. In this case, they will be performed as a sequence and they can share some calibration measurements increasing the overall efficiency. Moreover, the initialization time for the observations within a cluster can be drastically reduced. Whereas a single observation and the first observation of a cluster of observations typically face an overhead from the initialization of about 3 minutes, the initialization for all other members of the cluster is reduced to less than one minute. A prerequisite for a clustering of observations is the agreement of their spatial positions within 4 degrees (TBC). A clustering can be performed for observations with the same frequency settings for different sources within this region or it can be performed for observations of the same source at different frequencies within the same HIFI band.

3.2 The general timeline

All observations consist of a sequence of source, reference and calibration measurement loops. These loops are set up to correct for the different kinds of instabilities that will occur in the instrument, leading to different types of calibration errors. The period of the loops is adapted to the stability times of the different drift effects. The drift of the overall system response leads to a source-reference loop which is performed on the shortest time scale. Drifts in the difference of the instrumental response between source and reference lead to a baseline calibration loop which is much longer than the source-reference loop. Drifts in the gain of the instrument, visible as a variation of the difference between the output signals on the two thermal calibration sources, are taken into account by a load-calibration loop, the period of which should be comparable to the baseline calibration loop.

In the load-calibration loop the instrumental sensitivity is measured using the known difference of the radiation field between the hot and the cold internal loads. The frequency calibration of the WBS can be established by measuring a known comb spectrum. This load calibration has to be repeated periodically, as both load and comb spectrum characteristics may change over time The overall load calibration measurements consist of a measurement of the zero level and a frequency calibration measurement (for the WBS) and integrations on the hot and the cold thermal loads. To guarantee a sufficient thermal stability during the measurement, a dead time of about ten seconds before and after switching to the hot thermal load is required. For measurements with the HRS only, no initial frequency calibration is performed and the dead time before and after switching to the hot thermal load is shorter than when using the WBS. The load calibration measurements, typically taking a total of 20-60 seconds, can be performed during telescope slews.

3.3 Constraints on the length of each element

The actual length of all loops is computed from an optimisation strategy aiming at a minimum total error of the calibrated data. The principle error components are radiometric noise and drifts internal to the instrument and potential external (telescope) related effects.. The reduction of drift errors via shorter and more frequent calibration loops is traded off by an increase in radiometric noise because of the dead time overheads involved in the loops. The exact relations used to optimise this balance are given in AD10. The actual length of the loops in an observation may, however, deviate from these optimum values either because the total time of an observation is actually shorter than the optimum loop length, so that the latter has to be reduced, or because a certain type of calibration loop is not needed in a particular observation. For example, the same calibration may have been performed in a preceding observation, shortly before the source measurement, or because no instability of a kind specific to the calibration loop is expected. It still has to be decided which calibration loops may be shared between different observations,which loops have to be performed in each observation, and on what frequencies they should be performed Sharing calibration loops between separate observations can drastically increase observing efficiency, but creates an interdependency which would in turn significantly raise the risk of calibration errors in the event of a failed previous measurement.

The stability of the instrument determines how the calibration loops are implemented, and is measured in terms of the Allan time (RD1 and RD8). There are, however, two different Allan time definitions. Both are potentially relevant. The time obtained from the spectroscopic Allan variance may be used when the continuum level of the observations is not needed. Then drifts in the continuum level are neglected so that all spectra may need correction by a zeroth order baseline subtraction. It is not possible to obtain a reliable continuum level from these measurements under this definition of the Allan variance. When the total-power Allan variance is used, the continuum level is obtained with the same accuracy as the line strength within each spectrometer channel, but all loops have to be considerably faster. The difference between the two Allan time definitions is expected to amount to a factor 3 to 10. Thus the use of the total power Allan variance results in a drastically reduced overall observing efficiency.

The period after which a new load calibration measurement has to be taken is determined by the requirement that the calibration error due to drifts in the system sensitivity may not exceed 1%. This translates into a relation between the Allan time and the spectral index for the drift of the load-difference measurement and the resulting load-calibration period. Depending on the instrument stability this will result in periods between about 20 minutes and up to two hours. The length of the integration on each of the thermal loads is determined as well by the requirement that the radiometric noise from the load measurement may not contribute by more than 1% to the total calibration error of the observations. For most observations this results in integration times of a few seconds, but for observations at the maximum frequency resolution of the HRS at the highest frequencies integration times up to 30s are needed.

It is important to stress that all timing parameters not only depend on the intended total observing time and the stability of the instrument but also on the desired frequency resolution of the observations.

3.4 Interdependency of observations

The implementation of all observing modes asks for a compromise between complexity and efficiency. As more information about the state of the instrument and in particular about the history of the observations, i.e. previously done calibration measurements, can be used in planning an observation the efficiency of each observation is increased. This requires, however, that information about the state of the instrument is transferred between successive observations. Then the internal sequence of operations within an observation can be adapted to the information available from previous measurements. In practice, this means that retuning procedures can be omitted and several calibration measurements can be omitted in one observation when these measurements have already been performed in a prior observation. This increases the efficiency of the observations but it also results in different timelines for the same observing mode.

Compared to the optimum use of calibration information, neglecting all information from previous observations reduces the efficiency of an observation by up to 50% in extreme cases. On the other hand, a complete use of all information about the instrumental state would create a strong interdependency of different observations, leading to a difficult mission-planning, and it would result in several different sequences how an observation is actually executed, depending on the previous observations. Thus some compromise has to be found. Thus we foresee currently only two scenarios: in case of a single observation, all information from previous observations is neglected resulting in a potentially low efficiency. In case of clustered observations at the same frequency, the initial tuning will be dropped for all but the first observation and baseline calibration measurements can be completely omitted when the stability time of the standing wave pattern exceeds the total observing time of the observation. More complex scenarios might be discussed in the future if it turns out that a more flexible share of calibration information betweenseveral observations becomes possible in the mission planning .

Currently it is impossible to determine the actual beginning of an observation.The initial slew from the satellite pointing of a previous observation to the new position does not allow computation of the total time of the mode. The length of this slew is only known when the sequence of the observations is known. However, this slew is part of the observation because it is used for the tuning of the instrument and the load calibration measurement. The current compromise foresees, to assign a general dead time of 3min to each new observation which includes the instrument tuning and load calibration, and is independent from the actual start of the slew to the initial position of the observation.

3.5 Open questions

It is planned that each observation starts with a load calibration measurement. In clustered observations at the same frequency it would be possible, however, to reuse the calibration measurement from a previous observation. This assumption has only practical implications for the observing efficiency if the time needed for the load calibration exceeds the slewing time. Even in cases with a retuning it might be feasible to delay the required load measurement until the next telescope slew. The exclusion of such a postponed load measurement was chosen here to guarantee that each observed spectrum can, in principle, be calibrated even if some instrumental error occurs later in the observation. This choice remains open for debate.

It is currently not clear whether every observation (which is not part of a cluster) has to include an initial retuning, even if the same instrumental parameters were used before.

Finally, the applicability and feasibility of peaking up, as part of an observing sequence, remains to be resolved. At least for bands 5 and 6 such a peak-up capability would be highly desirable, to compensate for blind pointing inaccuracies which will depend on the utilization and calibration strategy of the Herschel telescope's pointing system. Many factors such as the balancing of spacecraft attitude control between the star tracker and inertial reference units, the number and angular distance of offset positions in a request, and the identification and verification of peak up calibrators are still to be resolved. Currently, peaking up on the primary science target or on a nearby offset star chosen by the observer is not foreseen to be an option available within an observing request. Pointing accuracies required for HIFI's needs may instead be tuned up periodically between science observing requests, with special observing sequences designed specifically for this task. All high-frequency observations using single point observing modes should, however, take into account that an additional overhead, either from an initial or periodic peak-up procedure or from performing a micro-map within the observation, might ultimately be needed for sources with a sharp spatial structure.

3.6 Calibration of the resulting data

The general principles of the calibration of the data obtained in every observing mode are described in the “End User Requirements for HIFI Interactive Analysis” (AD3). The mathematical description of the calibration of the measured data is contained in the “HIFI intensity calibration framework” (AD8). In principle, the data calibration consists of several steps for the intensity calibration resulting in the desired intensity scale for the data, several steps for the frequency calibration for the transformation of the spectrometer channel scale into the desired frequency or velocity scale, and the combination of data from different measurements into one data product. This combination is already necessary to perform the intensity calibration because a number of measured spectra have to be added, subtracted, and divided here to correct for all drift effects.

Unfortunately, the sequencing of the different intensity and frequency calibration steps is not commutative so that a sophisticated procedure for the combination of scans taken at different times is required. In general there are two strategies to be foreseen: on time scales below the frequency stability of the instrument all scans have to be combined on a fixed channel scale. On time scales above the frequency stability time the pre-integrated data have to be re-sampled onto the common linear frequency scale and combined later for the intensity calibration and when coadding many observations. For HRS data, this corresponds to an intensity calibration performed, in large part, in the time domain instead of the frequency spectrum.

A robust intensity calibration is only possible if load calibration measurements and baseline calibration measurements are available within the corresponding stability period for the instrumental settings used in the astronomical observations. In principle it is possible to avoid part of these calibration measurements, e.g. the load calibration measurements for all frequency settings in a spectral scan or the baseline calibration measurements in sky-chopped observations but in all these cases small intensity calibration errors will show up as baseline distortions. It is nevertheless acceptable for a number of observations to ignore these baseline distortions in favour of a higher observing efficiency by omitting the calibration measurements.

All observations performed in the single-point and mapping modes will provide only double-sideband (DSB) spectra, where the astronomer has to assign the different contained lines to the two sidebands using available background knowledge on the positions and strengths of the lines. In line-poor sources, this will be easy in general, but in line-rich sources it may be non-trivial. The user is advised here, to split the observation into two or three observations with slightly changed LO frequencies, so that the assignment to the two sidebands can be performed on the base of the relative shift of the lines with the LO frequency in the measured spectra. Since the decision on such a split can only be made by the astronomer, our observing mode definitions do not foresee any automatic LO frequency changes.

4 Mode I-1: Fixed-position with position-switch reference

4.1 General properties of the mode

The fixed or single-point mode with position-switch reference will be used to observe a specific position on the sky, suited to single points in objects which are extended by more than 3', so that the internal HIFI chopper can not be used to measure a suitable reference. This could include cores of extendedgalaxies or comets, for example. The system instability and resulting variance of the standing wave pattern is corrected for by the repeated observation of an OFF position which is either free of emission or has a well known emission profile.

The mode can be broken down into two basic sequences:

1. The instrument integrates at one position for a specified time, continuously dumping data to the satellite. After a period determined by the system stability time, source integrations are interrupted for the reference measurement on the OFF position.
2. Changes in the instrumental sensitivity are measured in the frame of a second loop using the known difference of the radiation field between the hot and the cold internal loads. This load calibration can be performed during slews to the OFF position.

Chopping to the cold and hot internal sources can be performed during initial slew to the target, following retuning of the instrument, and during slewsbetween the source and OFF position. The timing and placement of the load measurements will be determined automatically from efficiency and stability requirements

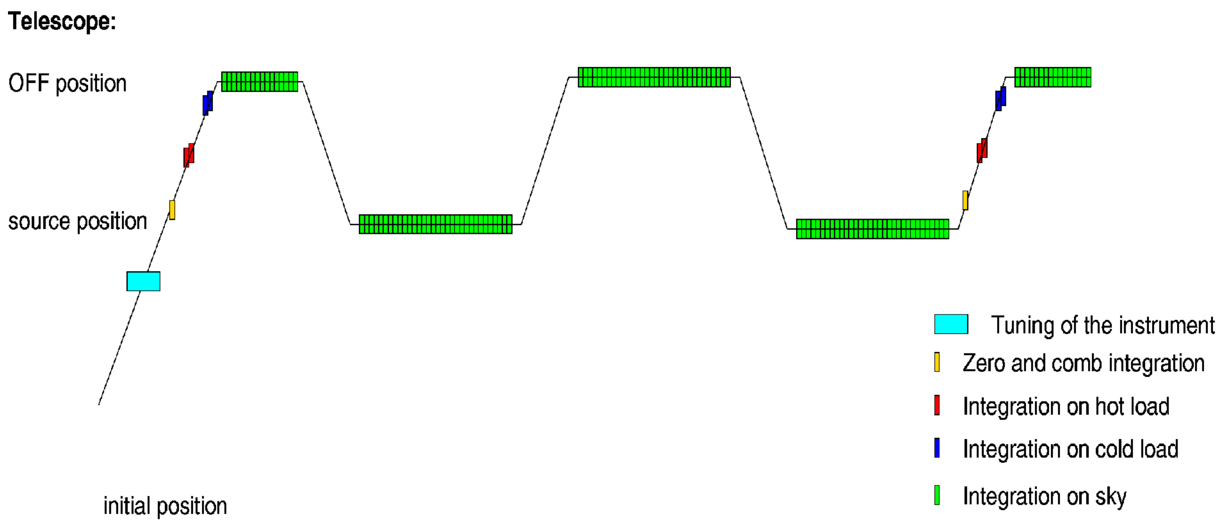
Note also that since the same optical path is used here for the source and the reference observation, no baseline calibration is required, unless the OFF position is not free of emission. In this case the emission from the OFF position has to be calibrated using another OFF position, measured in the frame of a separate observation.

4.2 The timeline of the mode

4.2.1 The general sequence of operations

The timeline of the observation consists of telescope motion to an OFF position (designated by the user), integrations at the OFF position, telescope motion to the science target, and integrations on this fixed-position. In either position, multiple readouts occur for the same pointing. The length of the integrations on both positions agrees and the sequence of pointings follows an OFF-ON-ON-OFF scheme. During slews between source and OFF positions, load calibration measurements may be interleaved. OFF position measurements are generally the first pointed observation in an observing request, and may occur more than once, depending on the length of the observation and stability requirements.

To illustrate the timeline we can translate this figure from a spatial representation into a temporal sketch:



In case of different instrumental settings compared to the prior measurement a retuning of the instrument has to be performed as an initial step. This will generally occur during the initial slew to the requested OFF position, and starts with a load calibration measurement that consists of a measurement of the zero level and a frequency calibration measurement (for the WBS, yellow) and integrations on the hot (red) and the cold thermal loads (blue). Further load calibration measurements can be performed during slews between the astronomical source and OFF position, but it is not necessary to perform a load calibration during each telescope slew.

4.2.2 Parameterizations

1. User Inputs

   1. Observation goal parameters:

      - Total observing time estimate [s]
      - Noise limit at lowest goal resolution [K]

      (The user may specify either a total observing time, or a noise limit.)

   2. Observation setup parameters:
      - Source position [x,y in the specified coordinate system]
      - OFF position [x,y in the specified coordinate system]
      - HIFI band
      - LO frequency [MHz]
      - Minimum and maximum goal frequency resolution of calibrated data [MHz]
      - HRS and WBS resolution and frequency settings

2. Sequence Parameters

   - Data dump time interval [s]
   - Number of data dumps per phase
   - Number of half OFF-ON-ON-OFF cycles
   - Internal load period [s]

4.2.3 Constraints on the length of each element

4.2.3.1. ON and OFF integrations

The time spent on ON and OFF positions will be identical . The mode is fully symmetric with respect to these phases. The maximum length of an OFF-ON cycle is determined by the stability time of the instrument with respect to baseline variations at the frequency resolution of the observations. The stability is measured by means of the Allan time at the nominal resolution of the backends and translated to the stability time at the desired frequency resolution by the spectral index of the standing wave drift. The total number of half OFF-ON-ON-OFF cycles is then given by the ratio between this maximum OFF-ON cycle length and the total time of the observation.

4.2.3.2 Load calibrations

Load calibration measurements can be performed during telescope slews. Because the stability time with respect to changes in the load difference is much longer than the overall system stability time, not every telescope slew needs to be used for a load calibration, but they should be repeated typically every half an hour.This is independent of the observing mode, as discussed in Sect. 3.2. Explicit equations for all quantities are provided in AD10.

4.3 Calibration of the resulting data

The data from on-source and position-switch reference integrations are straightforward to calibrate because no explicit standing wave correction is needed (a standing wave correction is only to be applied to the gain factor). The simple difference of the count rates between ON and OFF integration can be calibrated. The transformation into a brightness temperature scale is performed by dividing the difference measurement by the results from the load calibration measurements and multiplying by the corresponding temperatures. The final translation into a beam temperature relies on the beam efficiency, as measured at the primary calibration sources.

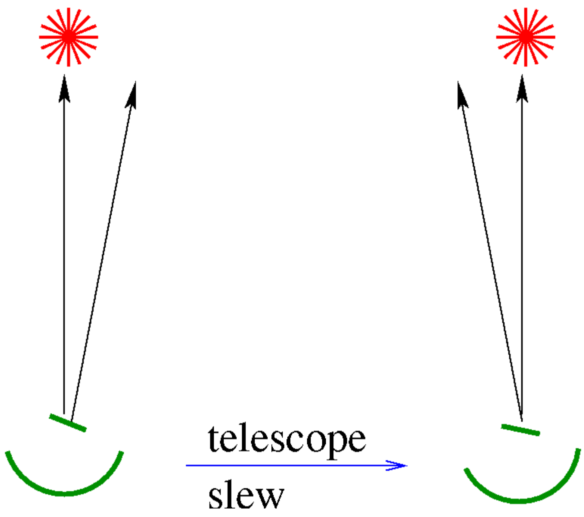
The mode is sensitive to all instrumental drifts in the system response. They limit the length of the integrations on both positions. From the stability parameters of the instrument measured in terms of an Allan variance spectrum the total noise in the resulting data composed of drift and radiometric contributions can be computed following the formalism given in RD 8. If the timing constraints from the system stability are not met it is easily possible to arrive at an uncertainty of the calibrated data that is dominated by the drift noise instead of the radiometric noise. In general the resulting timing constraints do not allow to derive accurate continuum levels. Observations requiring accurate continuum levels should be acquired with modes making optimum use of the internal chopper (e.g., mode 2 or 2a).

5 Mode I-2: Slow-chop dual beam switch

5.1 General properties of the mode

In dual beam switch observations the capability of the internal chopper to switch quickly between the source and the reference position on the sky will be exploited. Source and reference measurements can be performed in a short cycle without large overheads allowing to minimize the influence of drift effects on the spectra. Thus the mode is reliable in determining the shape of broad lines at a low velocity resolution, where the system Allan time is relatively short. However, the different optical path for the two chopper positions results in a change of the standing wave pattern between the two phases, so that the spectral response to the overall system noise is changed. Subtracting the spectra from the two phases then results in strong baseline ripples created by the residuals of the standing wave amplification of the system noise. To compensate for this effect the source is observed in the same way with the opposite chopper configuration, where the source appears at that chopper position which was used in the other part of the observation for the reference measurements.

Consequently, the new reference position falls then at the opposite side of the astronomical source. This scheme is illustrated in the following figure:



The black arrows indicate the directions of the chopped observations. The telescope slew changes these directions in such a way that one of them always points towards the source. Thus the satellite has to be moved exactly by the chop throw distance between the two parts of the observation. These position switch cycles can be performed on a much longer timescale than the chopper cycles. When the observations in both positions are taken with the same integration time, the impact of standing wave differences on the spectral baseline of the calibrated data can be completely eliminated in the sum spectra.

Because the mode uses points on both sides of the source as reference, the application of the mode is restricted to small astronomical objects where both reference positions are free of emission. The orientation of the chopper rotates on the sky depending on the date and time of the observation. The range of possible chopping angles increases with ecliptic latitude. In general one should consider the size limit in all directions, except for observations that are fixed to a particular time or which are close to the ecliptic plane. The maximum chop throw of the HIFI instrument is 3', providing the actual limit to the source size. Since the performance of the mode mode is not expected to depend on the actual chop throw, it is planned to use this maximum chop throw for all dual beam switch observations.

5.2 The timeline of the mode

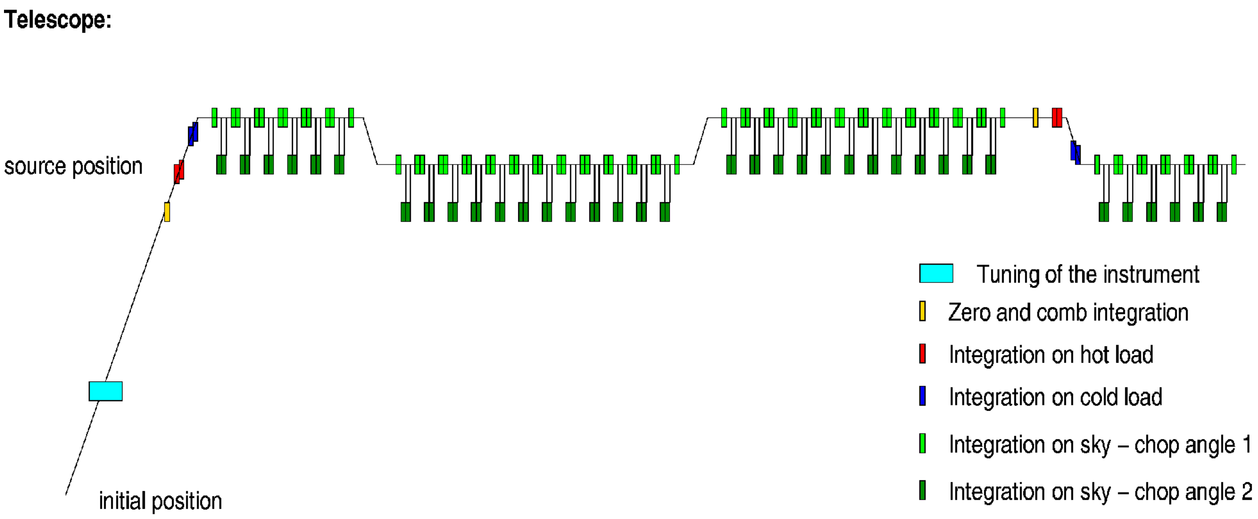
5.2.1 The general sequence of operations

This mode consists of three loops.:

1. With a period of a few seconds, the internal chopper changes the sky path to point towards the astronomical source and to a position 3' apart from the source.

2. Differences in standing wave pattern between the two paths are corrected by a periodic move of the telescope in such a way that the astronomical source appears in the opposite chop phase. The period of this position switch is determined by the time over which the standing wave difference is stable relative to the accuracy determined by the radiometric noise at the selected resolution. This leads to periods of some ten minutes.
3. The instrumental sensitivity is measured using the known difference of the radiation field between the hot and the cold internal loads. This load calibration also has to be repeated in a loop with a duration of typically less than one hour.

The mode is fully symmetric with respect to all four involved integration times, i.e. the integration times of both chop phases have to agree as well as the time spent in each telescope pointing. The whole timeline can be illustrated by the following schematic picture:



The measurements indicated by the two shades of green represent the sky integrations at the two chop angles. The displacement of the dark green read outs is supposed to indicate the different position on the sky at the fixed telescope position. During each chop phase multiple readouts can occur.

The load calibration measurements consist of a measurement of the zero level and a frequency calibration measurement (for the WBS, yellow) and integrations on the hot (red) and the cold thermal loads (blue). Load calibration measurements can be performed during telescope slews, but for dual beam switch measurements it is expected that the load calibration time exceeds the slew time in most cases, so that the spacecraft has to wait until the measurement is finished.

5.2.2 Parameterizations

1. User Inputs

1. Observation goal parameters:

   - Total observing time estimate [s]
   - Noise limit at lowest goal resolution [K]

   (The user may specify either a total observing time, or a noise limit.)

2. Observation setup parameters:
   - Source position [x,y in the specified coordinate system]
   - HIFI band
   - LO frequency [MHz]
   - Minimum and maximum goal frequency resolution of calibrated data [MHz]
   - HRS and WBS resolution and frequency settings

2. Sequence Parameters

   - Data dump time interval [s]
   - Number of data dumps per per chop phase
   - Number of half θ_1-θ_2-θ_2-θ_1 chop cycles per telescope pointing
   - Number of half OFF-ON-ON-OFF pointing cycles
   - Internal load period [s]

5.2.3 Constraints on the length of each element

The length of the chop cycles is determined by the total system stability time at the goal frequency resolution of the observation. The spectral index of the system drift translates the Allan time at the nominal resolution of the backends into the system stability time at the desired resolution. The length of the chop cycles will fall between 2s and some ten seconds depending on the required frequency resolution and the stability of the instrument. During each chop phase several data readouts can occur. The length of such a readout step is limited by the data rate that can be stored. If all channels from both spectrometers are to be stored one readout may be taken only every 3s. In case of smaller amounts of backend data, a readout can be performed down to once a second. Practically, the maximum number of integer seconds below or equal to 5s and below the chop phase length is to be used.

The maximum length of the telescope position-switch cycle is determined by the stability of the instrument with respect to baseline variations at the frequency resolution of the observations. The total number of ON-OFF cycles is then given by the ratio between this maximum OFF-ON cycle length and the total time of the observation. Baseline stability times are expected to be typically some ten minutes.

The period after which a new load calibration measurement has to be taken is independent from the observing mode and was discussed in Sect. 2.2. Explicit equations for all quantities are provided in AD10.

5.3 Calibration of the resulting data

For the standard data reduction of dual beam switch observations the double difference has to be computed between the counts in the two chop phases at one telescope position and the corresponding difference for the second position. As two of the phases contain signal from the source, the total radiometric signal to noise ratio of the calibrated data corresponds exactly to the value from one phase. The mode thus has a maximum efficiency of ¼ in case of no dead times. The double difference completely cancels out all standing wave contributions from the receiver noise and from warm telescope components promising a perfect calibration of the underlying continuum or a perfect zero-level baseline in case of sources with no continuum contribution. It also guarantees a cancellation of all intensity drift effects that are purely linear within the corresponding cycle time. An estimate of the total drift noise contribution can be obtained from the stability parameters of the instrument measured in terms of an Allan variance spectrum (see RD8). When all cycles are performed with a sufficiently small period, it is guaranteed, that the drift noise is small compared to the radiometric noise of calibrated data. The translation into brightness temperatures is performed on the basis of the counts from the thermal load measurements.

6 Mode I-2a: Fast-chop dual beam switch

6.1 General properties of the mode

This mode represents a special case of the dual beam switch mode as described above for the slow-chop dual beam switch mode. The combination of telescope and chopper motions follows the same scheme and the mode has the same advantages with respect to the baseline calibration and the same restrictions with respect to the source size. Here, only the main differences to the slow-chop mode are described.

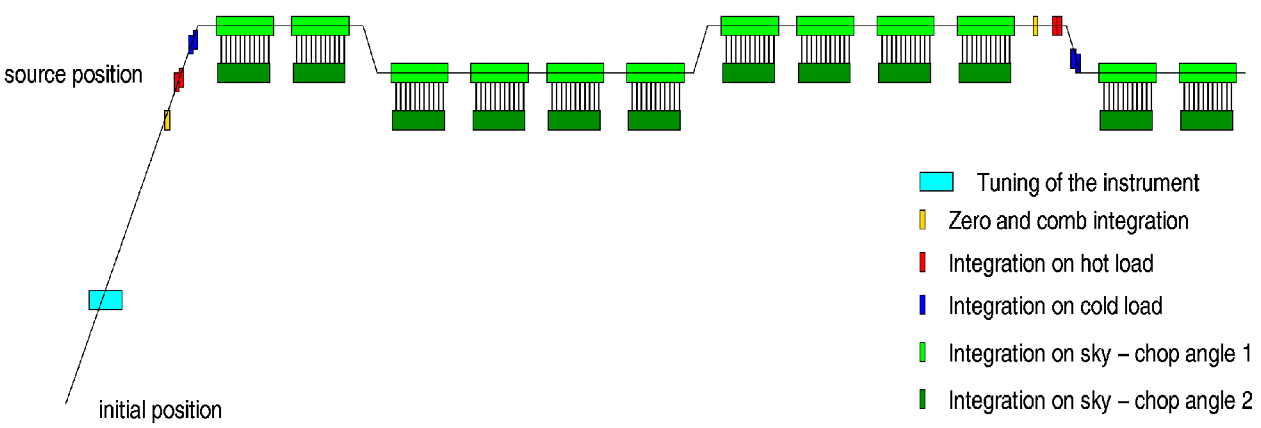
The main difference is another instrumental timing where chop frequencies up to 4 Hz are possible, but larger dead times have to be taken into account for the readout of the WBS. Fast-chop observations are required in all cases where the Allan time at the goal resolution is smaller than one second. The mode is always less efficient than the slow-chop dual beam switch mode due to the relatively larger overhead of the chopper motions and the additional readout dead time.

6.2 The timeline of the mode

6.2.1 The general sequence of operations

In the fast chop mode, the focal plane chopper switches between the two sky positions at a rate faster than 0.5 Hz. Practically only discrete frequencies of 1, 2, and 4 Hz will be used. Here, it is not possible to store the readouts from every chop phase. Instead a pre-integration of the counts from all negative and positive phases is performed in the ICU (for HRS data) and in the WBS (for WBS data). After a number of chop cycles, integration will stop and the data are transferred from the WBS to the ICU and from the ICU to the satellite. As the readout does not occur in parallel with the integration, a dead time is involved. The whole timeline can be illustrated by the following schematic picture:

Telescope:



The measurements indicated by the two shades of green represent the sky integrations at the two chop angles. Although the corresponding bars appear continuous in the drawing the integrations are actually quickly switching between the two chop phases. The data readout and transmission to the satellite occurs only at the end of the chop measurement blocks. Several readout blocks can be combined during one position-switch phase of the telescope. As for the slow chop dual beam switch mode, the fast chop mode is fully symmetric with respect to all four involved integration times, i.e. integration times of both chop phases agree as well as the time spent in each telescope pointing.

6.2.2 Parameterizations

1. User Inputs

   1. Observation goal parameters:

      • Total observing time estimate [s]

- Noise limit at lowest goal resolution [K]
  (The user may specify either a total observing time, or a noise limit.)

2. Observation setup parameters:
   - Source position [x,y in the specified coordinate system]
   - HIFI band
   - LO frequency [MHz]
   - Minimum and maximum goal frequency resolution of calibrated data [MHz]
   - HRS and WBS resolution and frequency settings

2. Sequence Parameters

   - Chop frequency [Hz]
   - Number of chop cycles per readout cycle
   - Number of data dumps per telescope pointing
   - Number of half OFF-ON-ON-OFF pointing cycles
   - Internal load period [s]

6.2.3 Constraints on the length of each element

The chop frequency is determined by the total system stability time at the goal frequency resolution of the observation. The spectral index of the system drift translates the Allan time at the nominal resolution of the backends into the system stability time at the desired resolution. The fast chop mode is to be used only for spectral observations with low goal resolutions of typically several ten to hundred MHz or in observations aiming at an accurate determination of the continuum level where the system Allan time is shorter than 2 seconds. For some observational goals, in particular measurements of the continuum level at a low spectral resolution, the capabilities of the instrument will not be sufficient to allow a chop cycle which is small compared to the system Allan time. In this case, the measured data will be dominated by drift noise.

At low resolutions it is also expected that all other Allan times determining the internal timing of the mode are shorter than at higher resolutions. Thus both the length of the position switch cycle and the length of the thermal load calibration cycle will be shorter than in slow-chop dual beam switch observations, but the general sequence of the operations in the observing mode with respect to telescope motions and calibration measurements is maintained and the same equations for the determination of the length of the elements can be applied.

6.3 Open questions

When using only the HRS in fast chop, the readout dead time can be reduced, but the HRS is clearly less suited to observe very broad lines. Thus it is not clear whether a timing optimized for the use of the HRS should be developed here.

According to the design of the WBS, the internal integration of the two chop phases leads to very strict timing requirements and is a potential cause of stronger platforming effects. This might reduce the accuracy of the observations and may ask for additional correction steps. This has to be tested first on the ground before the quantitative effect can be judged.

It is not clear whether HIFI should be offered at all to the general user as an instrument to measure the continuum level in astronomical sources. For this purpose PACS and SPIRE are clearly better suited. Currently it is not known whether observations with both types of instruments can be combined in all cases with a sufficient accuracy to make HIFI continuum observations superfluous.

6.4 Calibration of the resulting data

The calibration of fast-chop dual beam switch observations follows the same scheme as discussed above for the slow-chop dual beam switch observations. The double differences should completely eliminate any standing wave contributions and linear intensity drifts.

One major change results from the pre-integration of the data in the WBS or the ICU. Here, simple spectrometer counts are added. In contrast the combination of spectra which are downlinked to the ground can be performed in an arbitrary way, in particular it is possible to correct drifts both of the intensity and the frequency scale before adding spectra here. If the system performs within the current specifications now such correction will be necessary, so that no information is lost in the fast chop mode, however, in case of strong instabilities, there is no way to correct them on the ground in this mode.

In the computation of the total data uncertainty, the additional readout dead times do not change the estimates for the drift contributions in the chop cycle; for the drift contribution in the position-switch cycle they can be simply added to the overall dead time. Then all equations from RD8 are applicable as well. In case of observations corresponding to Allan times below 0.125s the drift contribution will exceed the radiometric noise. Depending on the spectral behaviour of the instrumental fluctuations, the decay of the total noise in the calibrated data as a function of the total observing time may turn out to be much shallower than the radiometric $1/\sqrt{t}$ behaviour.

7 Mode I-3: Frequency Switch

7.1 General properties of the mode

The general setup of the mode is very similar to the load-chop observing mode (mode 6), so that most details from the description and most conclusions on this mode are applicable here in the same way. Thus we repeat only those parts of the description where differences occur.

Whereas the reference measurement in the load chop observation is performed with the instrument looking at the internal cold load of the instrument, the reference in frequency switch is given by a measurement at a slightly changed LO frequency. The frequency step has to be small enough, so that the system response does not change between the two settings. Typical frequency switch lengths will vary between 20 and 200 MHz.

The main reference loop consists of switching between the two frequencies which is expected to be somewhat faster than a chopper scan to the cold load. Normal frequency switch cycles will take a few seconds up to a few ten seconds. This loop is again embedded in two slower loops, the baseline calibration loop using a periodic OFF observation and a load calibration loop to trace the drift of the system response.

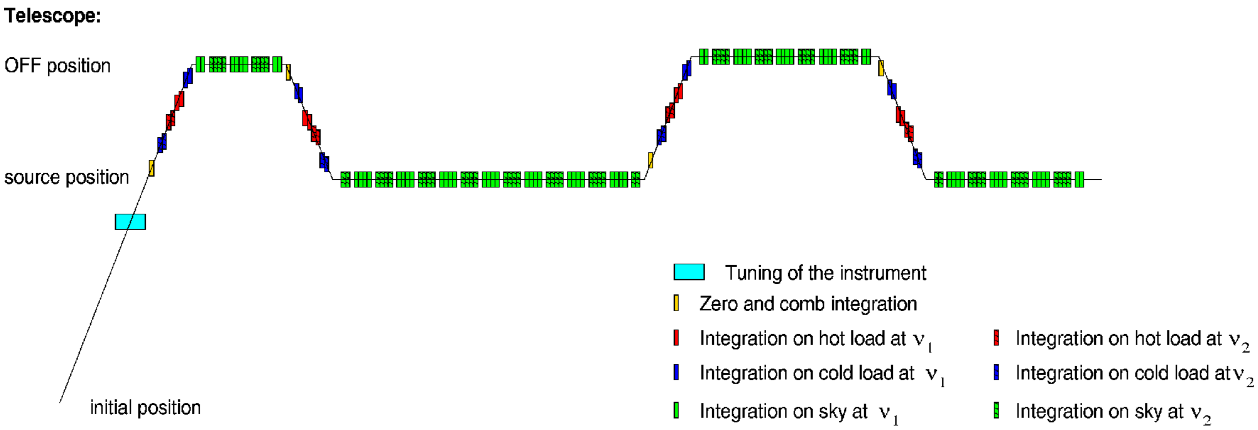
There are four major differences determining the general behaviour of the frequency switch mode relative to the load-chop observing mode:

1. Both phases of the source-reference cycle are spent on the source position, thus containing signal from the source. If their contribution can be deconvolved from the difference spectrum, we obtain twice the signal per observing time interval compared to load-chop observations. Thus the mode is potentially at least twice as efficient as the load-chop mode.
2. The signal level difference between the two phases is much lower than the typical level difference between the source and the internal cold load for load-chop observations. Thus the stability of this difference is expected to be better than the difference stability in load-chop observations. Consequently, baseline calibrations using an OFF measurement can be performed less frequently.
3. In the difference spectrum each signal appears twice – with different signs, separated by the frequency switch length. For the observation of few narrow lines, special care has to be taken when choosing the LO frequency and the frequency switch length to avoid blending. For sources with rich spectra or with very broad lines, blending of the different contributions cannot be avoided. Here it will be impossible to deconvolve the contribution of both phases from the difference spectrum, preventing any reliable data reduction. For these sources frequency switch should not be used.
4. The system response will always differ slightly between the two frequency settings. For a reliable data calibration, measurements of the response using the internal thermal loads should be performed at both frequencies, so that all load calibration measurements in load-chop observations are to be replaced by two measurements at both frequency settings here.

7.2 The time line of the mode

7.2.1 The general sequence of operations

The time line of the observation consists of switching the LO frequency of the instrument periodically between the standard LO frequency and a frequency which differs by the frequency switch length. Superimposed on this are motions of the telescope between the source and the OFF position, to get a baseline calibration, and interleaving load calibration measurements. All sequences follow a symmetric scheme like OFF-ON-ON-OFF-OFF-ON-ON-OFF and so on, where the number of half cycles OFF-ON or ON-OFF is not necessarily even. The general timeline is illustrated by the following schematic picture:



Different colours represent here different operations or different positions of the internal chopping mirror, overlayed gray patterns indicate the LO frequency shifted by the frequency switch length. The main cycle of frequency switches is represented by the green areas with alternating gray overlays. During each frequency phase multiple readouts can occur. Between the two phases a dead time for the LO change has to be taken into account. The measurements on the telescope OFF position follow the same general sequence but may deviate from the integration on the source position in the exact timing because the integration times on both positions do not necessarily agree.

The load calibration measurements consist here of a measurement of the zero level and a frequency calibration measurement (for the WBS, yellow) and a pair of integrations on the hot (red) and the cold thermal loads (blue) for the two frequencies. The frequency switch occurs between the two integrations on the hot load minimizing the total dead time for the WBS stabilization. Only one frequency switch is required during a load calibration, the consequent measurement will therefore start with the frequency setting of the last load measurement. Load calibration measurements can be performed during telescope slews, but they may exceed the slew time.

The frequency switch stability time for the selected frequency switch length determines the phase length of the ON-OFF cycle, and the load-difference stability time determines the time between two load calibration measurements.

7.2.2 Parameterizations

1. User Inputs

   1. Observation goal parameters:

      - Total observing time estimate [s]
      - Noise limit at lowest goal resolution [K]

      (The user may specify either a total observing time, or a noise limit.)

   2. Observation setup parameters:
      - Source position [x,y in the specified coordinate system]
      - OFF position [x,y in the specified coordinate system]
      - HIFI band
      - LO frequency [MHz]
      - Frequency switch length [MHz]
      - Minimum and maximum goal frequency resolution of calibrated data [MHz]
      - HRS and WBS resolution and frequency settings

2. Sequence Parameters

   - Data dump time interval [s]
   - Number of data dumps per frequency switch phase on ON
   - Number of data dumps for integration per frequency switch phase on OFF
   - Number of half ν_1-ν_2-ν_2-ν_1 cycles on ON
   - Number of half ν_1-ν_2-ν_2-ν_1 cycles on OFF
   - Number of half OFF-ON-ON-OFF calibration cycles
   - Internal load period [s]

7.2.3 Constraints on the length of each element

The approach to compute the lengths of the individual elements of the sequence is equivalent to the approach described in detail for the load-chop mode. The only difference is that the frequency switch stability time is to be used here to compute the frequency of the baseline calibration measurements instead of the load-chop stability time and that the thermal load calibration measurements take somewhat longer.

The total time spent on the OFF position relative to the total time spent on the source position depends on the ratio of the frequency resolutions needed in both phases. The OFF measurement is only needed for a baseline calibration. Thus the data from the OFF position can be smoothed to the frequency spacing needed to resolve the standing waves in the baseline. The ratio of the observing times on OFF and ON follows the inverse square root of the ratio between the two resolution bandwidths. The maximum length of an OFF-ON cycle is determined by the stability time of the instrument with respect to baseline variations at the frequency resolution of the observations. A large part of the observations will consist of a single OFF-ON cycle, because the stability time exceeds the observing time.

The length of the frequency switch cycles is determined by the total system stability time at the corresponding frequency resolution. Due to the different requirements on the spectral resolution for the source observation and the baseline calibration, the length of the chop cycles in the ON-phase and the OFF-phase do in general not agree. During each chop phase several data readouts can occur. The length of such a readout step is limited by the data rate that can be stored.

The period after which a new load calibration measurement has to be taken is independent from the observing mode and was discussed in Sect. 2.2. Explicit equations for all quantities are provided in AD10.

7.3 Initial steps

Equivalent to the load chop mode, we foresee two scenarios with respect to the initial steps in the frequency switch observations.

a) Standard initial steps:

The observation starts with a retuning, a load-calibration measurement and an OFF measurement for the baseline calibration.

b) no initial OFF measurement:

The baseline calibration data from a previous measurement are used for the initial ON pointing of the current observation so that no new OFF measurement is needed. The observation starts with a load-calibration and directly with the source integration. In case of observations consisting only of one OFF-ON cycle, the OFF observation is completely dropped. Moreover, no initial tuning is required here, because the same instrumental settings have to be used. This scenario will occur if different astronomical sources are observed in a cluster of observations at the same frequency, i.e. in the same line transition.

As discussed for the load-chop mode, there are still several open questions with respect to the implementation of these scenarios:

1. The reuse of an OFF calibration for several observations requires that either the observation of different sources with the same instrument settings will use the same integration times or the OFF calibration is included in the measurement with the longest integration time and the chop-difference stability times is sufficiently long to cover also all other measurements to be calibrated from this measurement.
2. It is not yet clear whether observations without a baseline calibration are to be implemented as a special case of scenario *b).*
3. The current definition always starts with a load calibration. It might be discussed whether this can be omitted in case *b)*.
4. It is not yet clear whether for observations where an initial OFF calibration is to be performed, but where the frequency setting agrees with the preceding observation an initial retuning of the instrument can be avoided.

7.4 Calibration of the resulting data

For frequency switch observations, the user has to be aware, that the data reduction consists of two steps: the normal calibration of the data resulting in a calibrated difference spectrum, and the deconvolution of the contributions from both phases. For this second step, several common tools will be available to the user, but their result has to be interpreted with care by the user based on available knowledge on the expected source spectrum. It is in general not possible to generate a “normal” spectrum representing only one frequency phase from the difference spectrum. In the simplest approach – shift-and-subtract – the difference spectrum is shifted relative to itself by the frequency switch step and subtracted, resulting in calibrated lines with the best possible signal to noise ratio, but where each line is accompanied by “ghost” lines with the opposite sign which cannot be easily removed. None of the more sophisticated methods can completely eliminate this problem.

For the pure calibration of the difference spectrum, the difference of the measurement between the two phases on the OFF position is subtracted from the difference on the source, but in contrast to the load-chop mode, this double-difference is not taken from the pure spectrometer counts, but each measurement is translated individually into a temperature scale by applying the load-calibration for the corresponding frequency setting. Their mutual difference is computed only in the second step. The double difference potentially cancels out all standing wave differences between the two phases, but a perfect zero-level baseline is only obtained if the system response, as measured with the load calibration measurements, agrees relatively well between the two frequency switch phases. The double difference also guarantees a cancellation of all intensity drift effects that are purely linear within the corresponding cycle time. This robustness is, however, obtained on the costs of an increased spectral noise produced by the double-difference. Additional time has to be spent for the baseline calibration measurement and the noise from this measurement is added to the calibrated data. This may represent a considerable overhead if the goal frequency resolution of the observation is not much smaller than the resolution needed to determine the standing wave ripple.

8 Mode I-4: Single point in load chop with position switch reference

8.1 General properties of the mode

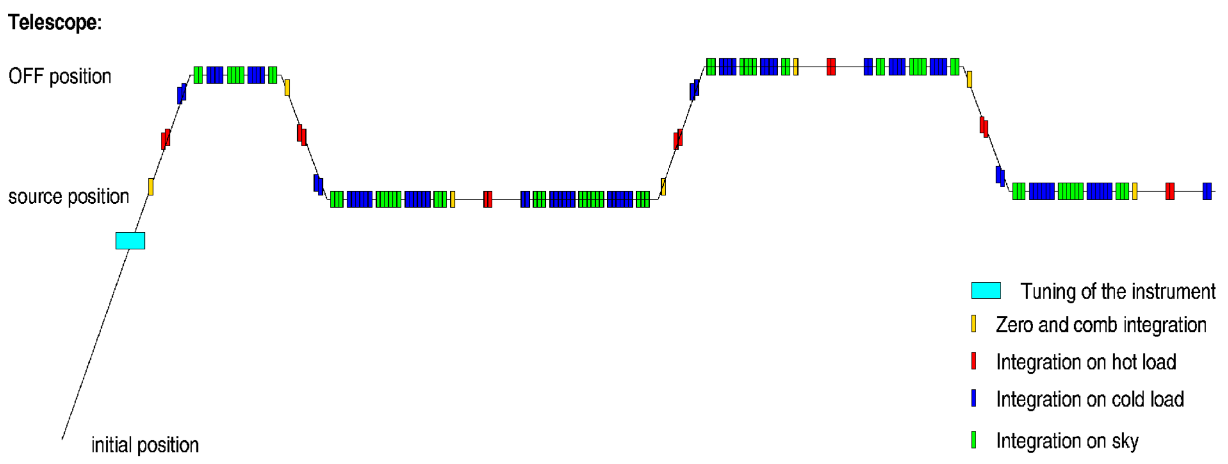
This mode consists of three loops.

1. Observations of a fixed celestial position, with alternating measurements of the internal cold load. The cold load is located in the focal plane unit, and provides a reference for correcting short term changes in instrument behaviour. Switching between the astronomical source and the cold load is done by an internal chopping mirror M6 with a typical period of a few seconds.
2. Differences in instrumental response between the cold load and towards the sky, due to optical path differences, are corrected for by measurements of an OFF (blank sky) position. The OFF position is selected by the user. Thus the telescope has to be pointed towards an emission-free region once in the time over which this difference is stable.This leads to a baseline correction loop with a period of some ten minutes up to several hours. The total time spent on the OFF position depends on the frequency resolution needed to describe the baseline ripple. It may be considerably smaller than the integration time spent on the source.
3. The instrumental sensitivity is measured using the known difference of the radiation field between the hot and the cold internal loads. This load calibration also has to be repeated in a loop with a duration of typically less than one hour.

8.2 The time line of the mode

8.2.1 The general sequence of operations

The time line of the observation consists of motions of the telescope between the source and the OFF position, motions of the focal plane mirror between the sky and the cold load, and interleaving load calibration measurements. The telescope motions between the source position and the OFF position follow a sequence OFF-ON-ON-OFF-OFF-ON-ON-OFF and so on. The HIFI chopper motions between the sky and the cold thermal load follow a comparable series of sky-cold-cold-sky-sky-cold-cold -sky and so on. The general timeline is illustrated by the following schematic picture:



The actual observations always consist of a sequence of integrations on the sky (green) and on the cold load (blue) with the telescope pointing towards the astronomical source. During each chop phase multiple readouts can occur. Between the two chop phases a dead time for the chopper motion has to be taken into account. The measurements on the telescope OFF position follow the same general sequence but may deviate from the integration on the source position in the exact timing because the integration times on both positions do not necessarily agree. Because the results from the OFF measurement can be smoothed to the frequency resolution of the standing waves, the two integration times are related to each other by the ratio between the expected standing wave frequency and the frequency resolution of the observations.

The load calibration measurements consist of a measurement of the zero level and a frequency calibration measurement (for the WBS, yellow) and integrations on the hot (red) and the cold thermal loads (blue). Load calibration measurements can be performed during telescope slews. It is, however, not guaranteed that the slewing time exceeds the load calibration time. If the slew time is shorter we have to wait for the calibration to finish before the next observation starts. To minimize the corresponding dead time it is not planned to perform a load calibration during each telescope slew but only as often as necessary.

The chop-difference stability time, determining the phase length of the ON-OFF cycle, and the load-difference stability time, determining the time between two load calibration measurements, are expected to be in the same order of magnitude. Thus it depends on the detailed parameters of the observation whether it is necessary to perform several load calibration measurements during one cycle of ON-OFF measurements or whether several ON-OFF cycles can be performed between two load measurements.

8.2.2 Parameterizations

1. User Inputs

   1. Observation goal parameters:

- Total observing time estimate [s]
- Noise limit at lowest goal resolution [K]

  (The user may specify either a total observing time, or a noise limit.)

2. Observation setup parameters:
   - Source position [x,y in the specified coordinate system]
   - OFF position [x,y in the specified coordinate system]
   - HIFI band
   - LO frequency [MHz]
   - Minimum and maximum goal frequency resolution of calibrated data [MHz]
   - HRS and WBS resolution and frequency settings

2. Sequence Parameters

- Data dump time interval [s]
- Number of data dumps per per chop phase on ON
- Number of data dumps for integration per chop phase on OFF
- Number of half load-sky-sky-load cycles on ON
- Number of half load-sky-sky-load cycles on OFF
- Number of half OFF-ON-ON-OFF calibration cycles
- Internal load period [s]

8.2.3 Constraints on the length of each element

The total time spent on the OFF position relative to the total time spent on the source position depends on the ratio of the frequency resolutions needed in both phases. Because the OFF position is only needed for a baseline calibration, mainly with respect to the influence of standing waves, it is sufficient to smooth the data from the OFF position to the frequency spacing needed to resolve the standing waves. This is in general a lower resolution than the resolution bandwidth required for the source observation itself. As both contributions are added up in the calibration of the mode, the observing time on the OFF position can be optimised with respect to a minimum total noise in the calibrated data. This results in a ratio of the observing times following the inverse square root of the ratio between the two resolution bandwidths. An assumed standing wave resolution bandwidth of 15 MHz and a desired frequency resolution of the observation of 3 MHz implies that 30% of the observing time is needed for the baseline calibration. In contrast, 50% of the observing time is spent for the baseline calibration if the desired frequency resolution bandwidth exceeds the standing wave resolution.

The maximum length of an OFF-ON cycle is determined by the stability time of the instrument with respect to baseline variations at the frequency resolution of the observations. The stability is measured by means of the Allan time at the nominal resolution of the backends and translated to the stability time at the desired frequency resolution by the spectra index of the standing wave drift. The total number of ON-OFF cycles is then given by the ratio between this maximum OFF-ON cycle length and the total time of the observation. A large part of the observations will consist of a single OFF-ON cycle, because the stability time exceeds the observing time. Baseline stability times are expected to fall between some ten minutes and few hours depending on the thermal stability of the satellite and the frequency resolution of the observations. The timeline of the observing mode should include as few slews between ON and OFF as possible, since this produces a relatively large overhead of dead-times. For many observations the total slewing time will depend only weakly on the slewing distance because it includes a constant dead time and the time for the actual motion grows only as the square root of the distance.

The length of the chop cycles is determined by the total system stability time at the corresponding frequency resolution. The spectral index of the system drift translates the Allan time at the nominal resolution of the backends into the system stability time at the desired resolution. Due to the different requirements on the spectral resolution for the source observation and the baseline calibration, the length of the chop cycles in the ON-phase and the OFF-phase do in general not agree. The length of the chop cycles will fall between 2s and some ten seconds depending on the required frequency resolution and the stability of the instrument. During each chop phase several data readouts can occur. The length of such a readout step is limited by the data rate which can be stored. If all channels from both spectrometers are to be stored one readout may be taken only after 3s. In case of smaller amounts of backend data, a readout can be performed down to every second. A simplified handling of the data from the WBS is possible if the readout cycle time does not exceed 5s. Thus the maximum number of integer seconds below or equal to the 5s and below the chop phase length is to be used.

The period after which a new load calibration measurement has to be taken is independent from the observing mode and was discussed in Sect. 2.2. Explicit equations for all quantities are provided in AD10.

8.3 Initial steps

8.3.1 Proposed scenario

The timeline discussed above always starts with a load calibration and the measurement on the OFF position. For the sake of efficiency it is, however, possible to reuse calibration information from a previous measurement if this was carried out at the same frequency. This leads to an interdependency of subsequent measurement but may result in a considerable efficiency gain. Instead of reusing all possible calibration information from a previous observation we propose here only one modification of the standard scenario for clustered observations: the omission of the initial OFF measurement. The overhead for the baseline calibration by an OFF measurement amounts to up to half the observing time in extreme cases.

Thus we can distinguish two situations:
a) Standard initial steps

Have to be performed when the new observation uses different instrument settings than the previous observation or when at identical instrument settings no sufficiently long OFF integration was previously performed within the current baseline stability time.

This case will occur in the case of a sequence of non-related observations of different astronomical sources or for several close sources with the same OFF position observed at different frequency settings, i.e. in different molecular lines within the same HIFI band.

b) no initial OFF measurement needed:

The observing time of the initial OFF measurement can be saved when the new observation uses identical instrument settings to the previous mode and an OFF integration with the required OFF integration time of one cycle was performed already within the baseline stability time.

Here, the baseline calibration data from a previous measurement are still valid for the initial ON pointing of the current observation so that no new OFF measurement is needed. The observation starts directly with the source integration. In case of observations consisting only of one OFF-ON cycle, the OFF observation is completely dropped and the observing efficiency is increased by up to a factor two. Moreover, no initial tuning is required here, because the same instrumental settings have to be used.

This scenario will occur if different astronomical sources are observed in a cluster of observations at the same frequency, i.e. in the same line transition. In such a case it may also be appropriate to consider the baseline calibration measurement not to be part of the astronomical observing mode, but as a separate calibration measurement which is performed from time to time between the astronomical observations, provided that the chop-difference stability time is long enough.

8.4 Open questions

The reuse of an OFF calibration for several observations requires that either the observation of different sources with the same instrument settings will use the same integration times and the chop-difference stability times is sufficiently long or that there is a dedicated baseline measurement sufficiently long for all measurements outside of the pure astronomical observations. This can be obtained by defining the OFF calibration measurement as a separate calibration measurement which is performed from time to time between the astronomical observations. Here, a number of observations have to be clustered to build a block of observations at the same frequencies and approximately in the same area of the sky sharing one OFF calibration measurement, provided that the chop-difference stability time is long enough to cover several observations. The details for the creation of such clusters still have to be worked out.

The astronomer may chose for some observations, that no baseline calibration is required at all, because the line width is considerably narrower than all possible standing wave ripples in the system. The corresponding load-chop observations without an OFF calibration may be regarded as a separate observing mode or as a special case of this mode without initial OFF measurement where the period of the baseline calibration is longer than the total observation. In this case the more general implementation of this mode could be reused, but the calibration will slightly differ. At the moment it is not clear whether the representation of the load-chop mode without OFF calibration as a special case of this mode is the most appropriate approach.

It is not clear yet whether for observations where an initial OFF calibration is to be performed, but where the frequency setting agrees with the preceding observation an initial retuning of the instrument can be avoided.

8.5 Calibration of the resulting data

The observing mode of load-chop observations with an OFF calibration is extremely robust with respect to calibration uncertainties, because it uses a double difference to determine the flux from the astronomical source relative to the flux from the sky on the OFF position. The double difference completely cancels out all uncertainties in standing wave contributions from the receiver noise and from warm telescope components promising a perfect calibration of the underlying continuum or a perfect zero-level baseline in case of sources with no continuum contribution. It also guarantees a cancellation of all intensity drift effects that are purely linear within the corresponding cycle time. This robustness is, however, obtained at the cost of an increased spectral noise produced by the double-difference. If the period of standing waves in the system is equal or less than the desired frequency resolution of the observations, the observing time has to be doubled to obtain the same signal-to-noise ratio like in observations without baseline calibration. Many observations will, however, require a frequency resolution that is finer than the standing wave ripple so that the overhead from the baseline calibration is smaller.

From the stability parameters of the instrument measured in terms of an Allan variance spectrum, an accurate estimate of the uncertainty of the intensity calibration of the resulting data is possible for this mode. The computational details are given in RD 8.

9 Mode II-2: OTF-maps with position-switch reference

9.1 General properties of the mode

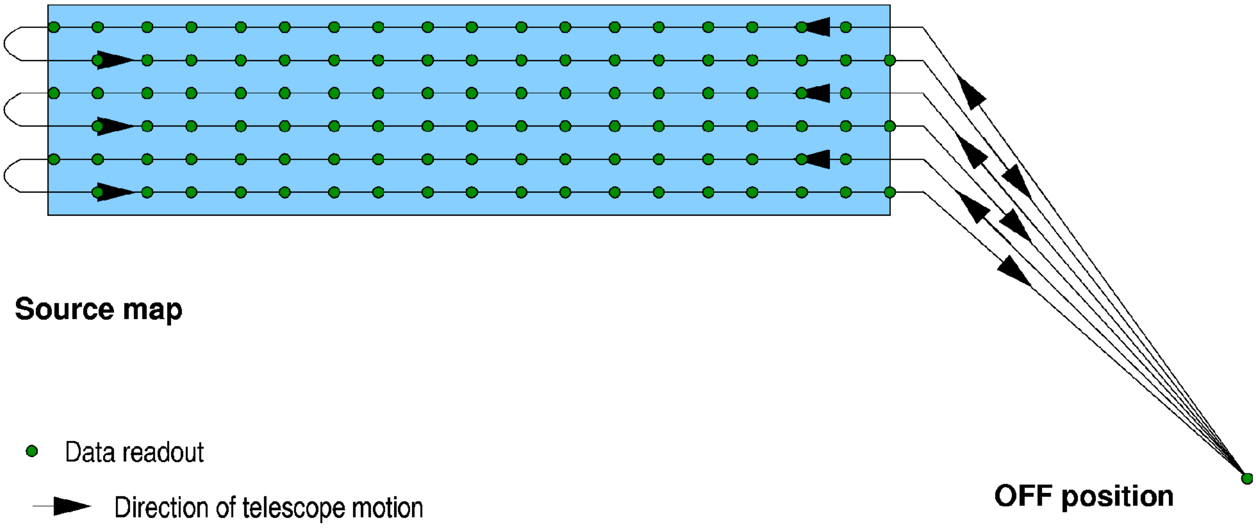
The On-The-Fly (OTF) mode with position-switch reference will be used to map various areas on the sky. The system instability is taken into account here by the repeated observation of an OFF position which is either free of emission or has a well known emission profile. The mode can be considered to be composed of four sequences. While the telescope scans any particular row of the map permanent data dumps are taken in regular intervals. The source integration is performed during the whole scan except for very small breaks for the data readout. After each row, the telescope motion changes its orientation so that the next row will be scanned. The integration of instrument data is stopped during these turns (taking serendipity data might be possible, but this must not interfere with the optimum start and stop times for the integration within each row). After a period determined by the system stability time, the scanning of the map has to be interrupted for the reference measurement on the OFF position. Changes in the instrumental sensitivity are measured in the frame of a fourth loop using the known difference of the radiation field between the hot and the cold internal loads. This load calibration can be performed during slews to the OFF position. Because the efficiency of the mode profits from high scan velocities, the map will be typically observed in a series of multiple coverages adding up to the required total integration time per source position.

Because the same optical path is used here for the source and the reference observation, no baseline calibration is required. A procedure comparable to the baseline calibration is required only if the OFF position is not free of emission. In this case the emission from the OFF position has to be calibrated using another OFF position, but this calibration measurement does not need to be included in the OTF observing mode so that it can be treated as a separate observation.

9.2 The timeline of the mode

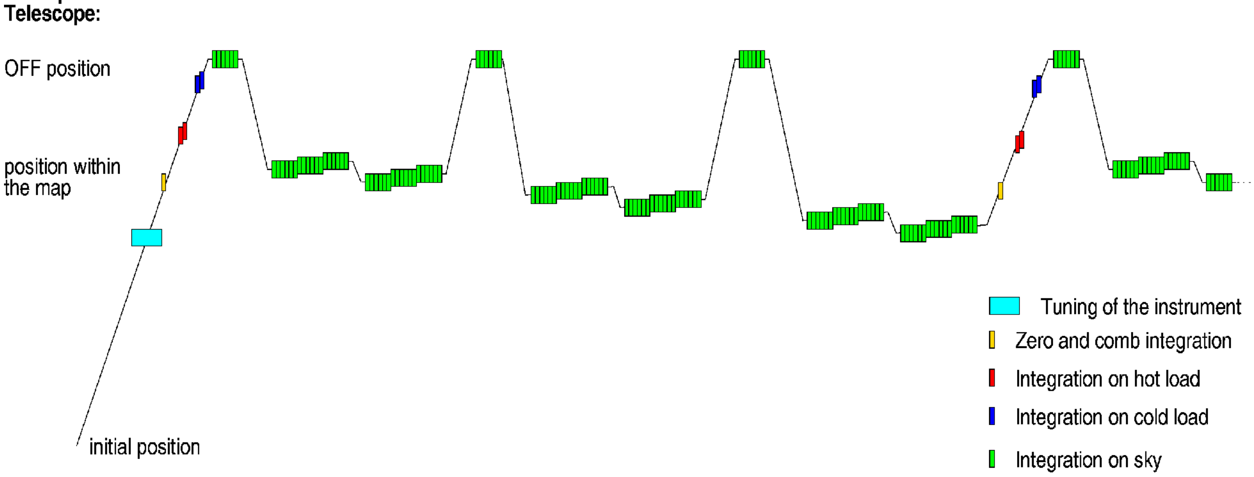
9.2.1 The general sequence of operations

The time line of the observation consists of motions of the telescope across the map and between the map and the OFF position, integrations of the instrumental output during the different phases and interleaving load calibration measurements. The telescope motion can be illustrated as:



In this example, the OFF position is visited three times within one coverage of the whole map – after every two scanned lines. It is planned to always complete full scan lines before an OFF observation. A series of subsequent coverages will be performed with one extra OFF measurement at the end of the observation guaranteeing a complete enclosing of the source observations by OFF observations. The green dots symbolise the points where the backends are read out. The integration starts as soon as the telescope enters the blue area of the map. Please, note the change of the scanning direction after each row.

To illustrate the timeline we can translate this figure from a spatial representation into a temporal sketch:



In case of different instrumental settings compared to the previous measurement a retuning of the instrument has to be performed as an initial step. The actual observation always starts with a load calibration measurement, the main part of which can be performed during the initial slew to the OFF position. The load calibration measurement consists of a measurement of the zero level and a frequency calibration measurement (for the WBS, yellow) and integrations on the hot (red) and the cold thermal loads (blue).

Further load calibration measurements can be performed during other telescope slews in the course of the observation. It is, however, not necessary to perform a load calibration during each telescope slew. On contrary, a single sequence consisting of an OFF measurement and the corresponding number of points within the map should not be interrupted by a load calibration measurement.

The actual observations always consist of a sequence of integrations on the OFF position and always using the same position of the internal chopper while scanning the map. In the timeline figure, the motion within the map is only symbolised by the step-like structure. On the OFF position multiple readouts (green points) occur for the same pointing. The velocity for scanning the map has to be adjusted in such a way that the telescope motion during a single integration between two data readouts covers exactly half the beam resolution. In this way only 4% of the theoretical resolution of the telescope are lost through dynamical blurring in the direction of the telescope motion (RD7). There is no a-priori correlation between the length of the lines used in scanning the map and the number of points observed between two observations of the OFF position.

9.2.2 Parameterizations

1. User Inputs

   1. Observation goal parameters:

      - Total observing time estimate [s]
      - Noise limit at lowest goal resolution [K]

      (The user may specify either a total observing time, or a noise limit.)

   3. Observation setup parameters:
      - Map start position [x,y in the specified coordinate system]
      - Distance between subsequent OTF lines [arcsec]
      - Distance between subsequent points in the OTF line [arcsec]
      - Number of lines in the map
      - Number of data dumps per OTF line
      - OFF position [x,y in the specified coordinate system]
      - HIFI band
      - LO frequency [MHz]
      - Minimum and maximum goal frequency resolution of calibrated data [MHz]
      - HRS and WBS resolution and frequency settings

2. Sequence Parameters

   - Data dump time interval [s]
   - Number of points between two OFFs
   - Total number of OFF-scan-OFF cycles
   - Internal load period [s]

9.2.3 Constraints on the length of each element

A detailed discussion of the general properties of the OTF mode with position-switch reference was given by Beuther et al. (2000, RD7). An generalization of this work including corresponding detailed computations adapted to HIFI observations are given in RD9.

The optimum value for the total time of the integration on the OFF position is given approximately by the time of the single source integrations times the square root of the number of source integrations between two OFF integrations.

$$t_{int}^{OFF} = q \times \sqrt{N}\, t_{int}^{on}$$

The factor q is specific to the calibration scheme to be applied when reducing the data. For the most efficient setup using an interpolation between two OFF measurements for calibration a value q=2/3 can be used. This approach minimises the total noise in the calibrated data obtained from the difference between the source integrations and the OFF integration with respect to the total observing time.

During the OFF integration phase several data readouts can occur. The length of such a readout step is limited by the data rate that can be stored. If all channels from both spectrometers are to be stored, then a readout may be done only every 3s. In the case of smaller amounts of backend data, a readout can be performed as often as every second. Depending on the number of stored spectrometer channels reasonable values for the readout rate will be integer seconds between 1 and 5.

Due to the square root relation given above, the relative overhead from the OFF measurements can be minimised by maximising the number of source points per OFF measurement. It is thus clear that an efficient use of the observing mode calls for a fast scanning where the largest possible number of source integrations is performed between two OFF integrations. The maximum time between two OFF integrations is limited by the system stability, but the minimum integration time per source point is limited by the data rate that can be stored. If less data are needed more source points can be observed within the system stability time allowing a more efficient observation. However, it may turn out that a fast scanning of several lines per OFF integration is less efficient than a slower scanning of fewer lines if the relative overhead from the dead time for the turn of the telescope motion is too large. Here, for each actual observation a complex optimisation is required. It can be performed using the relations given in RD 9. In case of very small maps this may result in single point integration times exceeding the upper limit for the readout time. Then the data from several readouts spatially shifted by less than half a beam width have to be combined into a single point in the calibration.

The total length of the reference cycle consisting of integrations on the astronomical source and one integration on the OFF position is determined by the total system stability time at the corresponding frequency resolution and the number of map points which are to be observed within one cycle. The spectral index of the system drift translates the Allan time at the nominal resolution of the backends into the system stability time at the desired resolution. The cycle length is not strictly limited by the stability time but it turns out that in case of many source observations per cycle, the calibration error from instrumental drifts remains small even if the cycle length exceeds the stability time by a factor of a few. We obtain a nonlinear function of the stability time, the dead time during one cycle and the number of points per reference cycle giving the optimum cycle length guaranteeing a control of the overall calibration error (RD1).

Because the time needed for slews to the OFF position, determining the total dead time in the cycle, depends on the maximum distance between ending and starting positions within the OTF-map and the OFF position, the most efficient solution will often use an even number of full scans between two OFF measurements so that all slews start and end on that side of the map which is closest to the OFF position, thus minimising the slew time to the OFF position per cycle.

The whole observation will in general consist of multiple coverages of the whole map each taken with a short integration time per source point. Altogether we arrive at a nontrivial two-dimensional optimisation problem to be solved for the most efficient implementation of the observation (see RD9). The two dimensions are given by the integration time per source point (corresponding to the scan velocity) and the number of source points per reference cycle. A lower limit to the integration time is set by data rate limitation and an upper limit is set by the system stability time or by half the total observing time. Typical reference cycle lengths will fall between about a minute for small maps and up to ten minutes for large maps.

Load calibration measurements can be performed during telescope slews. Because the stability time with respect to changes in the load-difference is much longer than the overall system stability time not every telescope slew has to be used for a load calibration but they have to be repeated only after typically half an hour.

9.3 Open questions

The choice of the optimum values for the integration time per source point and the number of source points per OFF integration requires a complex numerical procedure the outcome of which is not obvious to the observer. The astronomer can only check the result but cannot control the optimisation. This may lead to acceptance problems. It should be discussed under which circumstances and by which mechanism the observer should be enabled to overrule the computation of the optimum values using different parameters which are less efficient but might be preferable for a particular astronomical question.

Unfortunately, the discrete integration times together with a discrete number of map points and a discrete number of coverages of the whole map will always result in a relatively rough granularity of the reasonable total observing times. Remaining parts of the observing time which do not allow a full coverage could only be used to scan a part of the map in an additional coverage resulting in a slightly variable noise across the map and remaining parts which are smaller than the stability time are even completely lost. It has to be discussed how the granularity is to be handled in the planning of the observations.

9.4 Calibration of the resulting data

The data from the observing mode of OTF-maps with position-switch reference are straight forward to calibrate because no explicit standing wave correction is needed (a standing wave correction is only to be applied to the gain factor). The simple difference of the count rates between source and OFF integration can be calibrated. The total noise of the calibrated data is dominated by the noise from the source position because the noise from the OFF position is lower by $N^{-1/4}$, where N is the number of source points measured per OFF integration. In the limit of very long scans between two OFF measurements this means that the noise is only determined by the integration time on the source positions, enabling an observing efficiency close to one.

The mode is, however, sensitive to all instrumental drifts in the system response. The resulting timing constraints forbid its use in continuum observations and they are also difficult to fulfill in spectroscopic measurements. In fact, instrumental drifts put in fact a severe limit on the length of scans that can be observed between two OFF measurements. If the timing constraints from the system stability are not accurately met it is easily possible to arrive at an uncertainty of the calibrated data which is dominated by the drift noise instead of the radiometric noise. From the stability parameters of the instrument measured in terms of an Allan variance spectrum the total noise in the resulting data composed of drift and radiometric contributions can be computed following the formalism given in AD11.

10 Mode III-2: Spectral scan with dual beam switch reference

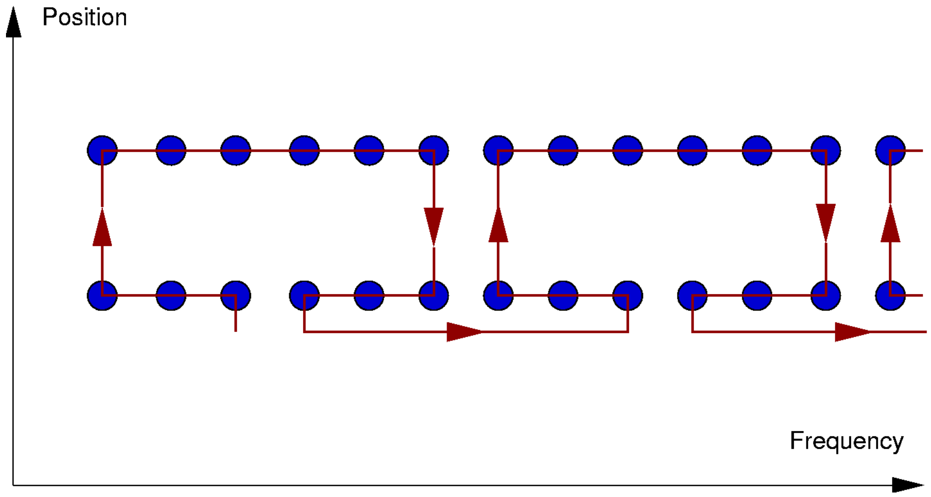
10.1 General properties of the mode

Spectral scans still have to be considered as experimental modes because they are not yet standard observations at ground-based telescopes and the limitations given by the spacecraft and instrument and the much larger covered frequency range of HIFI exclude a one-to-one application of the experience gained on ground. Active experimentation is going on with simulated data and actual HIFI lab data to refine the properties of this mode. Thus several details of the implementation of this mode are likely to change, and we describe only the current knowledge here.

Spectral scans consist of a series of observations of a fixed single target at several frequencies using the WBS as main backend. After data processing, the result of such an observation will be a continuous single-sideband spectrum for the selected position covering the selected frequency range. The LO tuning will be advanced in small steps across a single LO band. From a data analysis standpoint (AD3, RD10), the reduction to a SSB spectrum is most reliable when the number of frequency settings within the instantaneous bandwidth of the instrument is high, i.e. the frequency coverage is redundant. This must be balanced with the loss of observing efficiency imposed by the dead times associated with retuning to each new LO frequency. For most sources, a reliable reduction of the line spectrum requires at least 5 frequency settings within the IF bandwidth, i.e. a redundancy of 4. The spacings between the different LO frequencies have to contain a small random component to prevent harmonics which could occur in the reduction of the multiple double-sideband measurements to a single sideband (SSB) spectrum in a deconvolution process.

This mode uses the dual beam switch reference frame to compensate for instrumental drifts and to correct for standing wave variations between the chop phases. It thus inherits all advantages and restrictions from the single point dual beam switch observing mode (mode 3). The combination of telescope and chopper motions follows the same scheme and the timing constraints of mode 3. This implies also that this spectral scan mode can only be applied to astronomical sources that are smaller than the chop angle of 3'. Spectral scan observing modes for extended sources are not yet defined.

In contrast to a series of separate observations at different frequencies, it is expected that a group of frequency steps in a spectral scan can be calibrated from one thermal-load calibration measurement. This enhances the observing efficiency, but it is not yet known how many frequency settings can be combined in such a way. As the time needed for a load calibration agrees roughly with the slew time between the two pointing positions of the telescope used in the dual beam switch scheme, all the frequency steps that can be calibrated from the same load measurement will be performed first in one pointing and then repeated in the second pointing with the corresponding load calibration performed during the slew between the two positions. A possible implementation of the scheme is illustrated in this figure:



The figure covers the position-frequency space, the brown line indicates the temporal sequence of the observation, but does not reflect any actual step duration. The slightly irregular spacing of the frequency steps in the spectral scan is not visible here. In the plotted example it is assumed that three frequency points can be calibrated from the same load measurement (as a group), so that they are always combined in one pointing phase. Thus a monotonic frequency scale is not scanned monotonically but two steps of the group size are combined in one full pointing cycle of the dual beam switch mode. During each slew to another position a load calibration measurement is performed. Within each pointing and frequency setting, several chop cycles are possible. Currently, we cannot yet exclude the worst case possibility that all frequency steps need a separate load calibration. In this case the scheme is reduced to a group size of one.

10.2 The timeline of the mode

10.2.1 The general sequence of operations

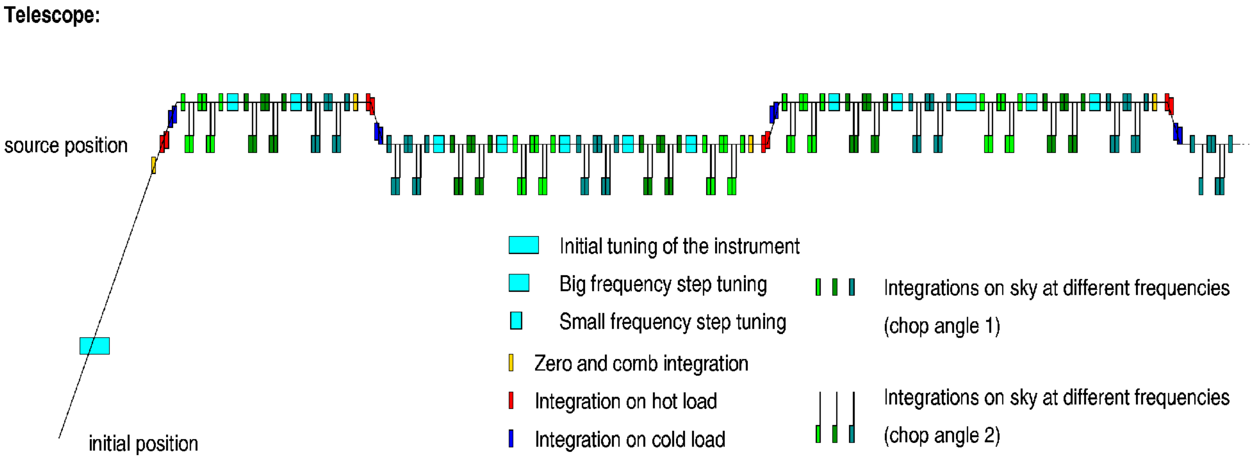
The timeline of a spectral scan consists of the following steps and loops:

1. Like all observing modes the observation starts with a slew to the fixed source, a retuning to the initial frequency of the scan and load-calibration measurement to characterize the instrument. The initial LO frequency is determined in the logic and will be chosen in such a way that the boundary of the frequency range is well covered, in order to reconstruct all lines up to the edges of the requested frequency range.
2. In a fast loop the orientation of the internal chopper is changed so that the sky path points towards the astronomical source and to a position 3' apart from the source. In this way we obtain the primary reference measurement that is used to correct for general gain drifts of the instrument. The length of the chop phases will be typically a few seconds.
3. In a second loop the LO frequency of the instrument is changed within the frequency range Δ_{recal} that can be calibrated with a common load-measurement. Each frequency setting has to be optimized for the scan. They will differ by a variable frequency step size determined either in the AOT logic algorithmically or from calibration lookup tables, according to the requested boundary of the spectral scan and the selected redundancy of the observation. The retuning time for these frequency steps of some hundred MHz should be about 10s.
4. Differences in standing wave pattern between the two optical paths used in the two chop phases are corrected by a periodic move of the telescope in such a way that the astronomical source appears in the opposite chop phase. In this way we guarantee a cancellation of baseline ripples produced in the two pointing phases.

   During each of the slews between the two pointings a load-calibration measurement is performed. This load calibration measurement is used to obtain the intensity scale for all measurements in the group of frequencies Δ_{recal} measured in the second loop. At the second pointing all frequency steps are repeated in the opposite order so that at each frequency and in each pointing position the same chop cycles are measured.

The period of this third loop of switching between the two pointing phases is in principle determined by the stability time of the standing wave difference between the two chopper positions. However, as the design of the observing mode couples the slews to the second position with the load calibration measurement, the length of the pointing periods will be determined in most cases by the number of frequency steps and their duration within a group that can be calibrated from the same load measurement.

The general timeline is illustrated by the following schematic picture:



As demonstrated in the above figure, the frequency space coverage assumes the use of three frequency steps that are combined into one calibration group. Both figures should be combined to understand the sequence in time, position and frequency. For each frequency and pointing phase two ON-OFF-OFF-ON chop cycles are shown. Due to the lack of a large number of well distinguishable colours only three shades of green were used here to represent the different LO frequency settings. They have to be interpreted in the sense of the figure given above, i.e. every frequency setting occurs once in each pointing phase, but after a group of three frequencies has been observed a new group with three different frequencies is started. It is not yet clear whether the LO tuning time is the same for each frequency step. To represent the general case we have indicated three different times for small frequency steps, big steps and the initial tuning.

The load calibration measurements consist of a measurement of the zero level and a frequency calibration measurement (yellow) and integrations on the hot (red) and the cold thermal loads (blue). Load calibration measurements can be performed during telescope slews, but for dual beam switch measurements it is possible that the load calibration time exceeds the slew time slightly, so that the spacecraft has to wait until load measurements are finished. The initial load calibration measurement does not fit into the regular raster of frequency and load calibration steps but is rather intended as a check of the instrumental performance. It does not take any extra time because it is contained in the initial slew.

10.2.2 Parameterizations

1. User Inputs

   1. Observation goal parameters:

      - Total observing time estimate [s]
      - Noise limit at lowest goal resolution [K]

      (The user may specify either a total observing time, or a noise limit.)

   2. Observation setup parameters:

      - Source position [x,y in the specified coordinate system]
      - HIFI band
      - Lower frequency limit [MHz]
      - Upper frequency limit [MHz]
      - Redundancy (default = 4)
      - WBS selection (The user may chose to use only one WBS to reduce the total data rate in favour of a faster observation in case of very bright objects.)

2. Sequence Parameters

   - Data dump time interval [s]
   - Number of data dumps per per chop phase
   - Number of half θ_1-θ_2-θ_2-θ_1 chop cycles per telescope pointing
   - Number of frequency steps before pointing to the second position
   - Number of half OFF-ON-ON-OFF pointing cycles between load calibrations
   - Total number of half OFF-ON-ON-OFF pointing cycles

10.2.3 Constraints on the length of each element

The length of the chop cycles is determined by the total system stability time during the scan. The spectral index of the system drift translates the Allan time at the nominal resolution of the backends into the system stability time at the desired resolution. The length of the chop cycles will fall between 2s and some ten seconds depending on the frequency spacing and the stability of the instrument. During each chop phase several data readouts can occur. The length of such a readout step is limited by the data rate that can be stored. Since the observations can be performed using the WBS only, a readout can be performed every two seconds. If only a part of the WBS's is used in band 6, this can be reduced down to one second.

The length of the frequency steps in each pointing phase will be determined in most cases by the total integration time per frequency setting. Because spectral scans usually cover a large frequency range with a high redundancy the total time spent at each frequency setting is relatively short. Only if the baseline stability time is shorter than the integration time per frequency setting, additional position switch cycles have to be included.

The period of this position switch is determined by the time over which the standing wave difference is stable or by the stability time of the instrument gain or by the maximum number of frequency steps which can be performed without a load calibration. In most cases, the group size will determine the position switch period. If the baseline stability requires a more frequent position switch additional slews without load calibration can be included.

10.3 Open questions

The main uncertainty with respect to the implementation of the proposed efficient scheme of the observing mode based on groups of frequency settings is the implicit assumption of a reproducibility of the standing wave pattern when retuning to the same LO frequency. The validity of this assumption has to be confirmed first in ILT tests. If the assumption is not met a reduction of the proposed scheme to a group size of one is still possible, but further thinking should be invested in this case to find possible other ways to increase the efficiency of the mode again.

In order to avoid periodicity in the data artificially created by the deconvolution routine through the use of a regular frequency step size, frequency stepping must be done over irregular frequency intervals. A type of monotonic but random grid must be established for each LO band with all degrees of redundancy that are practical for the spectral scan mode. Random number generators with the desired density of frequency settings are not permissible in the AOT logic, and would anyway raise serious concerns for repeatability, even for the same source with the same input parameters. The problem may be solved with static uplink tables of frequency settings, randomly generated for each receiver band at all selectable redundancies. This has the advantage that certain LO settings can be avoided where problems become known, and are relatively easy to modify without code change. It also has the advantage that a set of well understood frequency settings is created in this way due to repeated usage of particular LO settings which will potentially improve the general data calibration. Maintenance issues, on the other hand, may restrict users to only a few selectable degrees of redundancy in this case.

It is not yet clear whether an overall monotonic frequency stepping strategy minimizes the errors in the deconvolution process. There are indications that a stepping in which the lines are first observed in both sidebands is less sensitive to drift effects. It is also not clear whether a monotonic stepping within a frequency group is required to guarantee the reproducibility of the frequency setting. If a nonmonotonic stepping is possible, this may help to place the load measurements more equidistant in frequency space. This requires, however, a more sophisticated approach to chose the optimum step sequence as a function of the group size. Further studies are necessary to find the optimum strategy.

The lower coverage of the frequencies at the edges of the selected frequency range should be compensated by denser frequency steps towards the edges to guarantee a constant data reliability across the selected spectral range. The required change of the spacing depending on the redundancy of the observation has not yet been determined. With such a change of the average frequency step size towards the edges of the band, the number of frequency settings that can be calibrated with the same load calibration, i.e. all frequency settings fitting into Δ_{recal} may no longer be constant over the full frequency range resulting in a variable group size. It is not clear yet whether just the minimum group size should be used throughout the full spectral scan or a variable group size should be permitted leading to a variable pointing cycle length.

If both the system stability and the integration time per setting do not ask for readout times shorter than 4 seconds the HRS can be used in parallel to the WBS as serendipity backend with higher resolution. No logic has been considered yet to select the resolution and the optimum IF setting of the HRS subbands yet.

10.4 Calibration of the resulting data

Data reduction consists of two parts: the calibration of the double sideband spectrum and the deconvolution into a single sideband spectrum. The calibration of the double sideband spectrum is identical to the calibration in the single point with dual beam switch (mode 3). The only practical exception is given by the fact that the load measurement for the bandpass calibration is not necessarily taken exactly the same LO frequency, but the the load measurement from the same group of frequency steps is to be applied.

The sideband deconvolution is the detailed subject of AD3, with references to RD10.

11. Mode III-2a: Spectral scan with fast chop dual beam switch reference

11.1 General Properties of the Mode

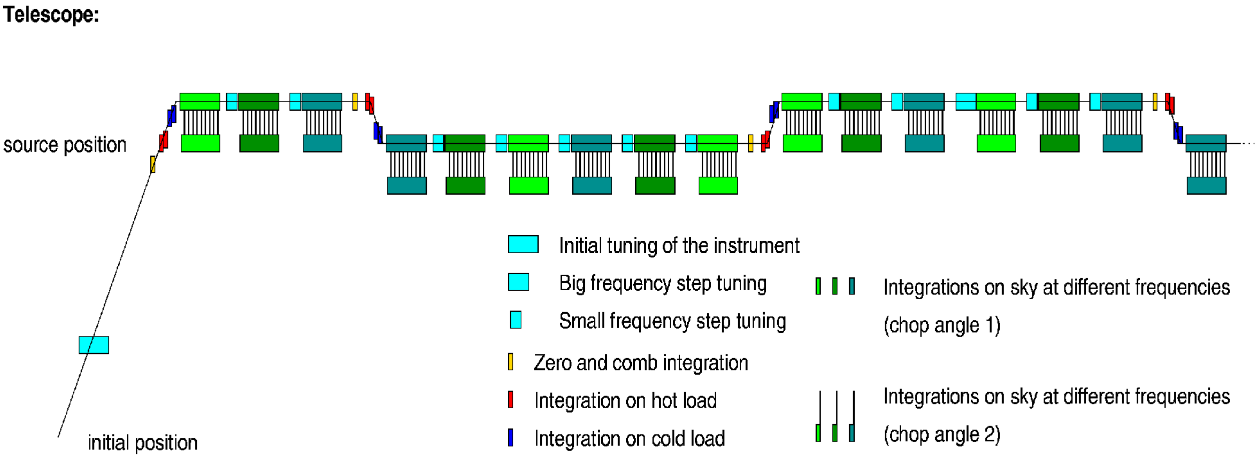
This mode represents a special case of the mode described above for a spectral scan with a DBS reference calibration (mode III-2), but instead uses the same telescope and chopper motions as described for the fast-chop DBS reference when observing a fixed point (mode I-2a). Therefore the same advantages to the baseline calibration and the same restrictions with respect to the source size apply here. Chop frequencies up to 4 Hz are possible, and larger dead times must be taken into account for the readout of the WBS at each frequency setting of the spectral scan. The overheads associated with the chopper motions and additional readout dead time reduce the observing efficiency of this mode, probably to less than 10%. Due to the low overall efficiency data rate constraints provide no limitations for this mode so that the WBS's for both polarizations will be used. Fast-chop observations are required in cases where the Allan time at the goal resolution is smaller than two seconds. This applies in particular for observations aiming at an accurate determination of the continuum level where the total-power Allan times have to be considered instead of spectroscopic Allan times.

11.2 The timeline of the mode

11.2.1 The general sequence of operations

The timeline for this mode is a combination of the timeline described and illustrated for mode III-2 on the scale of several seconds with the timeline of the fast chop described for mode I-2a on shorter time scales. Load-calibration measurements necessary to characterize the state of the instrument and assign the intensity scale are acquired during initial slew to target, the LO is retuned to an optimum beginning frequency in the desired frequency range, and the telescope initially points to a position 3' apart from the source. The actual chopper motion to obtain the reference measurements to compensate for system drifts occurs now with a fast cycle of a few Hz where the WBS internally integrates the counts from both chop phases. After a sequence of some ten chop cycles lasting a few seconds in total, the WBS is read out and the LO frequency is changed to the next setting. Retuning over steps of some 100 MHz will typically require some 10s. After a series of loops of fast-chop measurements and LO changes within a range that can be recalibrated with a common load measurement the telescope is pointed to the sky position corresponding to the second chop position. During each slew between the two sky positions a load calibration measurement is performed. At the second pointing all frequency steps are repeated in the opposite order so that at each frequency and in each pointing position the same chop cycles are measured symmetrically.

The periodic switch of the telescope orientation between two positions so that the science target appears in opposite chop phase leads to a cancellation of standing wave pattern differences occuring between the two chop phases (see mode I-2). In the fast chop mode, it is not possible to store the readouts from every chop phase. Instead a pre-integration of the counts from all negative and positive phases is performed in the ICU and in the WBS. After a number of chop cycles, integration will stop and the data are transferred from the WBS to the ICU and from the ICU to the satellite. As the readout does not occur in parallel with the integration, a dead time is involved. The whole timeline can be illustrated by the following schematic picture:



They above figure must be interpreted in the same way as that shown for the timeline of the slow chop spectral scan mode (Mode III-2). In particular, every frequency setting occurs once in each pointing phase, but after a group of three frequencies has been observed a new group with three different frequencies is started. It is not yet clear whether the LO tuning time is the same for each frequency step. To represent the general case we have indicated three different times for small frequency steps, big steps and the initial tuning.

The load calibration measurements consist of a measurement of the zero level and a frequency calibration measurement (yellow) and integrations on the hot (red) and the cold thermal loads (blue). Load calibration measurements can be performed during telescope slews, but for fast chop DBS measurements it is expected that the load calibration time exceeds the slew time, so that the spacecraft has to wait until load measurements are finished.

Fast-chop measurements will be needed only when the system Allan time for the goal resolution of the observations is shorter than two seconds. It is expected that in these cases, also the corresponding differential Allan time characterizing the stability of the standing wave baseline difference between the two chop phases is relatively short. Thus it may be necessary to reduce the number of frequency settings in one group observed in a single telescope pointing phase relative to the group size determined by the number of frequencies which can be calibrated with a common load calibration (and which would be used in slow-chop spectral scans) to guarantee a pointing cycle which is shorter than the differential Allan time.

11.2.2 Parameterizations

1. User Inputs

   1. Observation goal parameters:

- Total observing time estimate [s]
- Noise limit at lowest goal resolution [K]

(The user may specify either a total observing time, or a noise limit.)

2. Observation setup parameters:

- Source position [x,y in the specified coordinate system]
- HIFI band
- Lower frequency limit [MHz]
- Upper frequency limit [MHz]
- Redundancy (default = 4)

2. Sequence Parameters

- Data dump time interval [s]
- Number of data dumps per per chop phase
- Number of half θ_1-θ_2-θ_2-θ_1 chop cycles per telescope pointing
- Number of frequency steps before pointing to the second position
- Number of half OFF-ON-ON-OFF pointing cycles between load calibrations
- Total number of half OFF-ON-ON-OFF pointing cycles

11.2.3. Constraints on the length of each element

The chop frequency is determined by the total system stability time at the goal frequency resolution of the observation. The spectral index of the system drift translates the Allan time at the nominal resolution of the backends into the system stability time at the desired resolution. In case of a very low total power system stability it is possible that the hardware limitations of the chopper no not allow a chop cycle which is small compared to the system Allan time. In this case, the measured data will be dominated by drift noise.

The total length of chop observations at one telescope position and LO frequency is typically determined by the total integration time requested for these settings. It is limited to 160s by the internal buffer of the WBS. It is not foreseen to allow longer phases of chop observations in this mode. If observations actually need longer integration times they should instead increase the redundancy which improves simultaneously the quality of the sideband deconvolution. The minimum length of such a chop cycle is 4s. If the baseline stability time is shorter than the integration time per frequency setting, additional position switch cycles have to be included. Data rate limitations provide no problem in this observing mode due to its low overall efficiency.

The length of the position switch cycle will be shorter than in slow-chop DBS observations, but the general sequence of the operations in the observing mode with respect to telescope motions and calibration measurements is maintained and the same equations for the determination of the length of the elements can be applied. Three conditions may actually constrain the length of the position switch cycle: the time over which the standing wave difference is stable,the stability time of the instrument gain, and the maximum number of frequency steps which can be performed without a load calibration. In most cases, the group size will determine the position switch period. If the baseline stability requires a more frequent position switch additional slews without load calibration can be included.

11.3.Open questions

The main uncertainties with the fast-chop DBS mode of spectral scan observation are generally the same as those pertaining to the slow-chop mode, namely in the assumption of stable standing waves over more than one LO frequency that allows retuning to the same frequency or set of frequencies thereby allowing these settings to be grouped together for intensity calibration with a single load measurement. If this assumption turns out to be incorrect (such that a reduction to a freqeuency group size of one is necessary), the impact on observing efficiency can be expected to be higher on the fast-chop mode due to the additional overheads involved. Other conerns that similarlly apply are the frequency stepping strategy, and the density of steps near the edges of the desired frequency range (limited by each LO's total available range and avoidance of any unstable or otherwise undesirable frequency settings near the edges). Some investigation into the optimum step sequence as a function of group size and redundancy is necessary.

Like in mode III-2, the HRS could be used as serendipity backend with higher resolution but no logic has been developed yet to select the optimum IF setting of the HRS subbands.

11.4. Calibration of the resulting data

Data reduction consists of two parts: the calibration of the double sideband spectrum and the deconvolution into a single sideband spectrum. The calibration of the double sideband spectrum is identical to the calibration in the single point with dual beam switch (mode I-2a). The only practical exception is given by the fact that the load measurement for the bandpass calibration is not necessarily taken exactly the same LO frequency, but the the load measurement from the same group of frequency steps is to be applied.

The sideband deconvolution is the detailed subject of AD3, with references to RD10.