HIFI Observing Modes Implementation Document

Version DRAFT 0.2 of 11/05/04, by V. Ossenkopf

Abstract

This document contains the equations and algorithms needed to compute the exact time sequence of the different observing modes that will be used for normal astronomical observations with HIFI.

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		Added sections visualising the timing interrelations	2.2.2, 3.2.4	

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 modes description document, SRON-ICC/2003-008
AD11	Observing modes calibration document, SRON-ICC/2003-010
AD12	The HIFI frequency calibration framework document, L3AB/HIFI/CAL/2003-02, F. Herpin et al.

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	A unified Allan variance computation scheme, 06/17/2003, V.Ossenkopf

Contents

1 Introduction

1.1 Scope of this document

This document is the third out of a series of four interrelated documents on HIFI observing modes. The “HIFI Observing Modes Document” (AD7) provides the general framework for the design and planning of the observing modes in which HIFI can be used for astronomical observations. It contains a summary of all constraints and limitations for the modes. The “HIFI Observing Modes Description Document” (AD10) provides the general descriptions of the modes intended as a guideline for the astronomer to allow a choice between different observing modes possible for an astronomical observation. The “Observing mode calibration document” (AD11) contains the equations and procedures required to calibrate observations performed in the different observing modes.

This document complements the observing mode descriptions by a comprehensive and detailed description of the timeline of the different observing modes outlining all computations required to derive the length and sequence of the different steps from the properties of the instrument and the target of the observation. Following these computations it is possible to compute the overall efficiency of an observing mode, to implement a time estimator and to plan the actual observations.

In the current draft status the document contains only descriptions of few, most essential modes. It is continuously extended by adding implementation details for more modes to be used for HIFI observations.

1.2 Prerequisites

In the parametric description of the observing modes it is presumed that the observing parameters are translated already from an astronomical notation into an instrumental notation. This refers in particular to the transformation between a chosen astronomical coordinate system and the instrumental standard coordinate system and to the selection of the LO frequency from the desired rest frequency of the observed transition, the sideband, and the relative line-of-sight velocity. These translations are discussed already in the observing modes document and will not be repeated here, where we use instrumental parameters.

Moreover, the document does not cover any details on the timing and implementation of the communication between the ICU and the backends or the other parts of the instrument. Constraints set by the hardware in this communication as specified in AD4 and AD5 are taken into account but the actual process is not considered here, although it also differs in the frame of different observing modes. All references to data taking start on the interface between the ICU and the satellite, thus covering only data which are actually transmitted to the ground.

2 Computations applying to all observing modes

2.1 Parametric description of the instrument

2.1.1 Instrument parameters

A complete list of all parameters determining the instrumental properties is given in Appendix A. Here, only those parameters are explicitly repeated which determine the timeline of all observing modes.

Instrumental sensitivity:	double sideband system radiative temperature $\mathbf{J_{sys}}$
Telescope slew parameters:	constant dead time in slews $\mathbf{t_{fix}}$ slewing acceleration $\mathbf{r_{acc}}$
Tuning+calibration overhead:	time for tuning the receiver to ν_{LO} $\mathbf{t_{tune}}$ overhead in a load calibration $\mathbf{t_{load\text{-}dead}}$
Instrumental stability:	System stability Allan time at $\Delta\nu$=1MHz $\mathbf{t_A}$ Spectral index (absolute value of the exponent of the power spectrum) of the system drift α Load-difference Allan time at $\Delta\nu$=1MHz $\mathbf{t_{A,load}}$ Spectral index of load-difference drift $\alpha_{\mathbf{load}}$
Thermal load temperatures:	Hot load temperature $\mathbf{T_{hot}}$ Cold load temperature $\mathbf{T_{cold}}$
Data rate:	Maximum data rate which can be stored $\mathbf{R_{data}}$

2.1.2 Instrumental state

Beside the permanent parameters of the instrument its current state can be important as well, because its knowledge allows to optimise the observations by exploiting information previously obtained:

Initial satellite pointing:	at source | at OFF | at other coordinates initial slewing time to the source position $\boldsymbol{t_{init\text{-}slew,on}}$

initial slewing time to the OFF position $t_{init\text{-}slew,OFF}$

Initial instrument tuning: same HIFI band, LO frequency, backend parameters | different instrument settings

Calibration history: time since the last OFF calibration Δt_{OFF}
integration time of the last OFF calibration $t_{last\text{-}OFF}$
time since the last load calibration Δt_{load}

2.2 Timing parameters applying to all modes

2.2.1 Computation of the timing parameters

- *Slewing time* t_{slew}*:*

The time for a telescope slew between two positions characterised by the coordinates l_1,b_1 and l_2,b_2 can be computed from their angular distance

$$\Delta\phi = \mathrm{acos}[\cos(l_1)\cos(b_1)\cos(l_2)\cos(b_2) + \sin(l_1)\cos(b_1)\sin(l_2)\cos(b_2) + \sin(b_1)\sin(b_2)] \quad (1)$$

and the instrumental slewing parameters by

$$t_{slew} = t_{fix} + \sqrt{\frac{\Delta\phi}{r_{acc}}} \quad (2)$$

This equation holds for all slews permitted within an observing mode, i.e. slews up to 2° (AD1).

- *System Allan time at the resolution of the observation* $t_{A,\Delta\nu}$*:*

The instrumental stability time at the effective resolution bandwidth $\Delta\nu_{res}$ of the observation is approximated from the Allan time at 1MHz by

$$t_{A,\Delta\nu} = t_A\ (\Delta\nu_{res} / 1\mathrm{MHz})^{(-1/\alpha)}$$

It this thus determined by the desired goal resolution of the calibrated data.

- *System Allan time at the resolution needed for the baseline structure* $t_{A,\Delta\nu-sw}$*:*

The frequency resolution needed to resolve all relevant baseline structure is given by the maximum of the resolution of the observation $\Delta\nu_{res}$ and the resolution used to resolve standing waves $\Delta\nu_{sw}$.

$$t_{A,\Delta\nu-sw} = t_A\ (\max(\Delta\nu_{res}, \Delta\nu_{sw})/ 1\mathrm{MHz})^{(-1/\alpha)} \quad (3)$$

- *Minimum readout length* $t_{data,min}$*:*

During each integration the spectrometer data can be stored multiple times. A lower limit to the readout cycle is set by the maximum amount of data which can be stored per second. The number of HRS channels which are to be stored is given by

$$n_{\text{HRS-pixels}} = \begin{Bmatrix} 4096\, n_{\text{HRS-bands}} \text{ in hires mode} \\ 2056\, n_{\text{HRS-bands}} \text{ in normal mode} \\ 1036\, n_{\text{HRS-bands}} \text{ in lowres mode} \end{Bmatrix} \tag{4}$$

For the WBS it is possible to select in each subband a range of channels to be stored. The total number of WBS channels to be stored is then computed from

$$n_{\text{WBS-pixels}} = \sum_{\text{WBS-subband}=0}^{3} n_{\text{selected-channels}} \tag{5}$$

Combining both backends into one equation where $n_{\text{HRS-pixels}}$ or $n_{\text{WBS-pixels}}$ might actually be zero leads to minimum data dump period given by the maximum data rate which can be stored:

$$t_{\text{data,min}} = (16\text{bit} \times n_{\text{WBS-pixels}} + 24\text{bit} \times n_{\text{HRS-pixels}})/R_{\text{data}} \tag{6}$$

This assumes that the dead time for reading out the spectrometers is negligible, i.e. less than 10ms. With the specified data rate R_{data} the minimum readout length will be at most 3s. In case of fast-chop-observations where the readout dead time is longer, the minimum readout length is not relevant.

- *Load integration time during the load measurement* t_{load}:

The noise during the load calibration depends on the radiation temperatures from the thermal loads which can be approximated here as

$$J_{\text{hot}} = T_{\text{hot}} - 0.0240\, \nu_{LO} \text{ [GHz]}$$
$$J_{\text{cold}} = T_{\text{cold}} - 0.0240\, \nu_{LO} \text{ [GHz]} \tag{7}$$

Allowing a 1% maximum calibration error from the noise in the load calibration then leads to a minimum integration time on each of the the thermal loads (AD8):

$$t_{\text{load}} = \frac{10^4}{\Delta\nu_{\text{res}}} \frac{(J_{\text{hot}} + J_{\text{rec}})^2 + (J_{\text{cold}} + J_{\text{rec}})^2}{(J_{\text{hot}} - J_{\text{cold}})^2} \tag{8}$$

- *Actual readout length during load measurements* $t_{\text{data,load}}$:

The actual length of a readout cycle during a load measurement is constrained by the minimum data readout length, and the design of the communication between the backends and the ICU allowing only integer seconds. In general, the accuracy of the measurement profits from a longer cycle due to the lower impact of timing jitter. An upper limit is, however, set by the load integration time and the fact that integrations longer than 5s need a 24 bit communication between the WBS and the ICU whereas for shorter integrations the communication can be simplified to use always only 16 bit. This can be summarised as

$$t_{data,load} = \max\left(\overline{t_{data,min}}, \min\left(\overline{t_{load}}, 5\right)\right) \quad [s] \qquad (9)$$

where $\overline{x}$ stands for the next integer ≥x. The function max(a,b,c) denotes the maximum of its arguments a,b, or c. The function min(a,b,c) is equivalent for the minimum.
Eq. (11) means that only readout lengths of 1, 2, 3, 4 or 5s occur.

- *Actual length of the integration on the thermal loads* $\boldsymbol{t_{phase,load}}$ *:*

In a similar way the actual time spent on the thermal loads is determined. Here, however, the time has to be rounded up to guarantee the intended calibration accuracy

$$n_{readout,load} = \overline{t_{load} / t_{data,load}} \qquad (10)$$

$$t_{phase,load} = n_{readout,load} \times t_{data,load} \qquad (11)$$

- *Total time for load measurements spent in each load calibration* $\boldsymbol{t_{load,tot}}$ *:*

The total time for a load measurement consists of the phases spent on each thermal load and additional fixed times for frequency calibration, system stabilisation and the motion of the mirror

$$t_{load,tot} = 2 \times t_{phase,load} + t_{load\text{-}dead} \qquad (12)$$

- *Load calibration period* $\boldsymbol{t_{cal,load}}$*:*

The period after which a new load calibration measurement has to be taken is limited the allowed maximum absolute drift of the calibration factor. Here, we allow a maximum change of the calibration factor of 1% due to a drift of the load calibration. We can compute the time after which this 1% error has accumulated from the load difference Allan time at which the calibration error is equal to the radiometric noise. Resolving for this time we find that a new load calibration has to be performed after

$$t_{cal,load} = t_{A,load}\left(0.01^2 \times \sqrt{1\,\mathrm{MHz} \times t_{A,load}}\right)^{1/H}$$

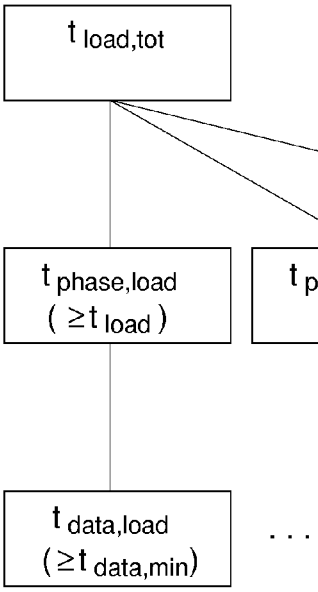
$$= t_{A,load}\,(10 \times \sqrt{t_{A,load}[s]}\,)^{1/H} \qquad (13)$$

where H denotes the drift index (Hurst exponent) of the fluctuations of the load measurement. The drift index is related to the spectral index by $H=(\alpha_{load}-1)/2$ for spectral indices $\alpha_{load}>1$. It cannot drop below 0, but further studies on optimum assumptions for H are required if it turns out that the load drift noise should be shallower than 1/f.

If all observations are enclosed by pairs of load calibration measurements the maximum temporal distance between an observation and the closest load calibration is half the period between two load measurements. In these cases the 1% calibration accuracy can be guaranteed even from a load calibration period which is twice the value of $t_{cal,load}$ given above.

2.2.2 Relations between the timing parameters

The mutual relation between the different timing parameters describing a full load measurement can be visualised as:



The load observation consists of two phases with equal length and a dead time. Each phase may contain several data readout intervals. Periods which may occur multiple times, but where the number of repetitions depends on the details of the observation are visualised by three dots here. The number of $t_{data,load}$ intervals within $t_{phase,load}$ is given by $n_{readout,load}$ which is at least 1 and in most cases will be just 1.

2.3 Sequences applying to all observing modes

The temporal sequence of a load measurement is independent from the observing mode always following:

M6 chopper	***Duration***	***Backend***	***Duration***	***Repetition***
move to the hot load	$t_{chop-hot}$	zero integration with full backend	3s	1
		comb integration with full backend	3s	
		zero integration with the selected backend settings	t_{data}	

M6 chopper	*Duration*	*Backend*	*Duration*	*Repetition*
hot load		possibly WBS Bragg cell relaxation	$t_{s,Bragg}$	1
		integration on the hot load with the selected backend settings	t_{data}	$n_{readout,load}$
move to the cold load	$t_{chop\text{-}hot}$	possibly WBS Bragg cell relaxation	$t_{s,Bragg}$	1
cold load		integration on the cold load with the selected backend settings	t_{data}	$n_{readout,load}$
move to the sky	$t_{lchop\text{-}dead}$			1

After each step marked as integration for the backends, a readout is performed. The duration of the readout is neglected here, so that the readout phases are not explicitly marked in the time line.

The first two steps, i.e. the first zero and the comb measurement, represent the internal frequency calibration of the WBS. All other steps are needed for the intensity calibration. When only the HRS is used as backend the frequency calibration steps can be omitted.

The sequence for the hot and cold measurement is in principle arbitrary. The choice of a hot-cold sequence has the advantage that the actual measurement is less influenced by any possible thermal effects originating from the hot load measurement and that a switch time can be saved in case of following load-chop observations. At the moment it is not yet known how much time will be needed for the thermal stabilisation of the backends when switching from or to the hot thermal load and how fast the switch can be done mechanically. Thus, the total length of the dead times is not yet specified. Here, we sum up the fixed times for the zero and comb measurements, the stabilisation times and the chopper motion dead times which do not depend on the details of the observing mode as load calibration overhead $t_{load\text{-}dead}$.

Individual observing modes

3 Single point in load chop with OFF calibration

3.1 Observing mode parameters

The following parameters determine the timeline of the actual observation:

3.1.1 Astronomical parameters

Pointing parameters: source coordinates **l,b**
OFF coordinates $\mathbf{l_{OFF}, b_{OFF}}$

Timing parameters: total observing time $\mathbf{t_{tot}}$

Receiver parameters: HIFI band
LO frequency ν_{LO}

Backend parameters: backend to use: HRS, WBS, both
max. desired resolution bandwidth of calibrated data $\Delta\nu_{res}$

HRS: resolution mode: hires/normal/lowres
number of subbands to be read $\mathbf{n_{HRS-bands}}$
IF setting of subbands

WBS: first and last channel of the up to four frequency windows $\mathbf{l_{1,i}, l_{2,i}}$

3.1.2 Instrumental parameters

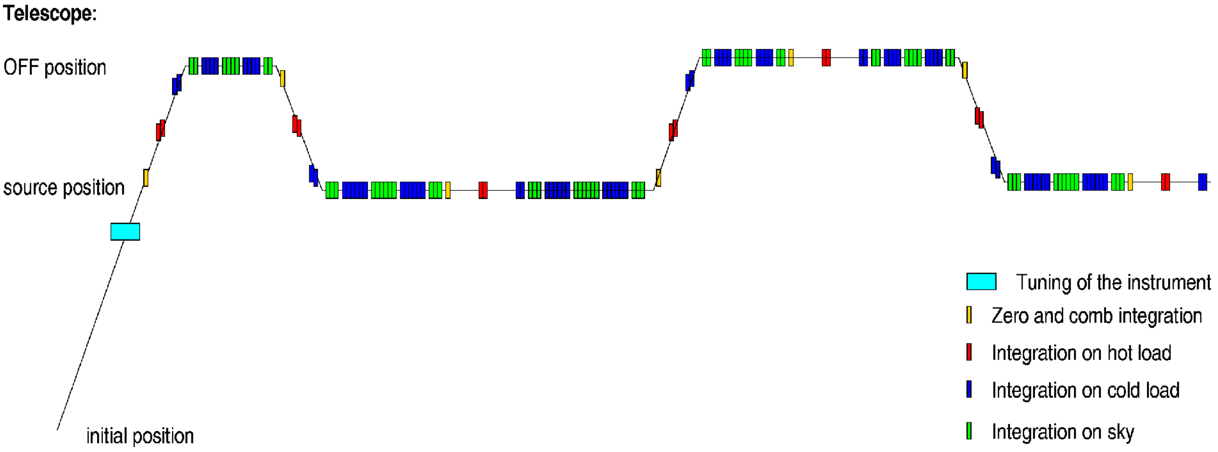
Here, only those instrumental parameters are given which actually apply to the load-chop mode and which are not yet mentioned in the general section above:

Chop parameters: dead time for switching to the cold load $\mathbf{t_{lchop-dead}}$

Instrumental stability: System stability Allan time at $\Delta\nu$=1MHz $\mathbf{t_A}$
Spectral index of system drift α
Chop-difference Allan time at $\Delta\nu$=1MHz $\mathbf{t_{A,sw-lchop}}$
Spectral index of chop-difference drift $\alpha_{sw-lchop}$
Resolution for resolving standing waves $\Delta\nu_{sw}$

3.2 The time line of the mode

The time line of the observation consists of infrequent motions of the telescope between the source and the OFF position, frequent motions of the focal plane mirror between the sky and the cold load and load calibration measurements which can be more or less frequent than the telescope motions. 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 as well a series sky-cold-cold-sky-sky-cold-cold -sky and so on. 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. Load calibration measurements are partially performed during telescope slews but not necessarily during each telescope slew. The general timeline is illustrated in the following figure:



As discussed in AD10 it is possible to save a large amount of observing time by an adapted sequence of initial steps depending on the state of the instrument resulting from the previous observation. The two different initial scenarios proposed there lead to two different ways for computing the timing of the observing mode from the total observing time. In the case *a)* discussed there, no information about previous calibration measurements is used and the timeline follows basically the picture sketched above. In case *b)* no initial OFF calibration is necessary because the corresponding information from a previous measurement can be reused. Here, the measurement omits the first OFF-step, starting directly with the source integration after the load measurement. The computations thus have to distinguish between both cases.

3.2.1 Limiting timing parameters

For computing the actual length of each cycle and the number of cycles in the observing mode it is necessary to first estimate the theoretical optimum values taking either the astronomical parameters or the instrument stability parameters. In a second step they are then combined with all other instrumental limitations to provide the actual timing parameters.

From the astronomical parameters of the observations we can derive one auxiliary parameter:

- *Optimum ratio between OFF and source integration time* t_{OFF}/t_{on}:

The optimum ratio between the time spent on the OFF position and the time spent on the source is determined by the ratio between the frequency resolution needed for the baseline calibration $\Delta\nu_{SW}$ and the frequency resolution of the astronomical observations $\Delta\nu_{res}$. Here, it is assumed that the baseline calibration data are smoothed to $\Delta\nu_{SW}$ so that their noise contribution is reduced. If the observations ask for a lower resolution than the standing waves, the baseline calibration data are smoothed as well to the $\Delta\nu_{res}$ resolution. The minimum total noise per observing time is obtained if the ratio of the two integration times follows

$$t_{OFF}/t_{on} = \sqrt{\frac{\Delta\nu_{res}}{\max(\Delta\nu_{SW},\Delta\nu_{res})}} \quad (14)$$

From the instrument stability parameters we can derive a number of timing constraints:

- *Chop-difference Allan time at the resolution of the observation* $t_{A,sw-Ichop,\Delta\nu}$:

This is an auxiliary parameter for the stability time characterising the drift of the baseline difference between the two phases of the chop cycle compared to the noise on the relevant resolution bandwidth. It is approximated by

$$t_{A,sw-Ichop,\Delta\nu} = t_{A,sw-Ichop}\,(\max(\Delta\nu_{res},\Delta\nu_{SW}) / 1\mathrm{MHz})^{(-1/\alpha_{sw-Ichop})} \quad (15)$$

- *Maximum load chop phase length* $t_{phase,max}$:

This is the length of the phases on the sky and on the cold load within one chop cycle. Their sum forms together with the chop dead time the maximum length of a full chop cycle. It is constrained by the instrumental stability, which asks for a short cycle to minimise the distortions by instrumental drift, and the dead time of the chopper motion which asks for a long period to maximise the observational efficiency. The best compromise is described by a general relation for the optimum phase length in a symmetric observation as a function of dead time:

$$x_{opt}(\alpha,d)=root_x\{(2x+d)^{\alpha+1}(\alpha x-d)-2(x+d)^{\alpha+1}(2x+d)(\alpha x+d)+(x+d)^{\alpha+1}d - x^{\alpha+1}[\alpha(2x+d)-d]-d^{\alpha+1}(x+d)-(2^{\alpha}-2)dx\} \quad (16)$$

where α is the spectral index of the drift contribution, d is the dead time during the cycle normalised to the Allan time, and the resulting x_{opt} is the time of each phase relative to the Allan time. The function $root_x\{\}$ denotes the root of the expression with respect to the variable x. A detailed derivation of this equation is given in RD7. For phases longer than $t_{phase,max}$, the drift contribution exceeds the radiometric noise, at shorter phase lengths the relative overhead from the dead time is larger than required.

For the chop phase lengths the dead time in one chop cycle is just given by $t_{lchop\text{-}dead}$ if the backends are read out twice between two motions of the chopping mirror, i.e. the data dump sequence is COLD-SKY-SKY-COLD. Thus we arrive at a maximum chop phase length of

$$t_{phase\text{-}on,max} = t_{A,\Delta\nu}\, x_{opt}(\alpha, t_{lchop\text{-}dead}/t_{A,\Delta\nu}) \quad (17)$$

- *Maximum chop phase length on the OFF position* $t_{phase,max,OFF}$:

Because of a different stability time at the frequency resolution needed for the baseline calibration the length of the chop cycle on the OFF position may differ from the length on the source position.

$$t_{phase\text{-}OFF,max} = t_{A,\Delta\nu\text{-}sw}\, x_{opt}(\alpha, t_{lchop\text{-}dead}/t_{A,\Delta\nu\text{-}sw}) \quad (18)$$

- *Baseline calibration source phase length* $t_{cal,on}$:

This is the length of the phase on the source position within the cycle including the source and the OFF position needed to perform the baseline calibration. The source phase length forms together with OFF phase length and the slewing time the full baseline calibration cycle. The frequency of slews to the OFF position for a chop-difference baseline calibration is determined by the stability of the chop difference and the dead time needed for the slew. It follows the same relation as the load chop phase length, but takes into account that in general different integration times on the source and on the OFF position are possible :

$$t_{cal,on}= \frac{t_{on}}{t_{on}+t_{OFF}}\; t_{A,sw\text{-}lchop,\Delta\nu}\; x_{opt}(\alpha, t_{slew}/t_{A,sw\text{-}lchop,\Delta\nu}) \quad (19)$$

where the ratio between the integration times on the source position and on the OFF position from Eq. (14) is to be used.

- *Baseline calibration OFF phase length* $t_{cal,OFF}$:

The complementary OFF phase length is given by:

$$t_{cal,OFF}= \frac{t_{OFF}}{t_{on}+t_{OFF}}\; t_{A,sw\text{-}lchop,\Delta\nu}\; x_{opt}(\alpha, t_{slew}/t_{A,sw\text{-}lchop,\Delta\nu}) \quad (20)$$

3.2.2 Actually used timing parameters

Combining the astronomical parameters for the actual observation with the instrumental parameters and the instrumental limitations provides the eventually used time steps in the observation. Here, all adjustments relative to the optimum values computed above are made into the direction of reduced calibration errors, i.e. a small part of the observing efficiency may be lost in favour of guaranteeing the theoretically predicted calibration accuracy as computed in detail in AD10.

- *Total number of pointing cycles* $\boldsymbol{n_{cycles}}$*:*

The number of pointing cycles is given by the total observing time and the maximum cycle length. The relation between the total observing time and this number differs between the two different initial scenarios. If the observation starts with an OFF calibration (scenario *a*) we obtain

$$n_{cycles} = \overline{(t_{tot} - t_{init})/(t_{cal,on} + t_{cal,OFF} + t_{slew})} \quad (21)$$

with the initial overhead

$$t_{init} = t_{tune} + t_{load,tot} \quad (22)$$

If the observation can reuse the OFF calibration data from a previous measurement at the same instrumental settings (scenario *b*) we obtain

$$n_{cycles} = \overline{(t_{tot} - t_{init} + t_{cal,OFF} + t_{slew})/(t_{cal,on} + t_{cal,OFF} + t_{slew})} \quad (23)$$

and the initial overhead

$$t_{init} = t_{load,tot} \quad (24)$$

- *Maximum length of a single pointing to the source position* $\boldsymbol{t_{point\text{-}on,max}}$*:*

From this integer number of cycles the maximum actual length of the time spent in each baseline calibration cycle on the source position can be computed for both scenarios. For initial scenario *a)* we obtain:

$$t_{point\text{-}on,max} = \frac{(t_{tot} - t_{init})/n_{cycles} - t_{slew}}{1 + t_{OFF}/t_{on}} \quad (25)$$

For initial scenario b) the corresponding equation reads:

$$t_{point\text{-}on,max} = \frac{t_{tot} - t_{init} - (n_{cycles} - 1)\, t_{slew}}{n_{cycles} + (n_{cycles} - 1)\, t_{OFF}/t_{on}} \quad (26)$$

where the two different initial overhead times were given above. The actual source pointing phase length is further constrained by the granularity of the data readout and the load chop as computed below.

For many observations, the number of baseline calibration cycles n_{cycles} will be one. In case of a reuse of a previous OFF calibration measurement (scenario *b*), the resulting source pointing time $t_{point\text{-}on,max}$ is then identical to the total observing time diminished by the initial overhead.

- *Readout length* $\boldsymbol{t_{data}}$:

The readout length determines the integration time after which the accumulated data are transmitted from the ICU to the satellite to be stored. The actual length of a readout cycle is constrained by the minimum data readout length, and the request for integer seconds in the slow-chop mode. Longer cycles are favourable but an upper limit is set by the maximum phase length and the fact that integrations longer than 5~s need a 24 bit communication between the WBS and the ICU whereas for shorter integrations the communication can be simplified to use always only 16 bit. This can be summarised as

$$t_{data} = \max\left(\overline{t_{data,min}}, \min\left(\underline{t_{phase,max}}, \underline{t_{phase,max,OFF}}, 5\right)\right) \quad [s] \qquad (27)$$

where $\overline{x}$ stands for the next integer $\geq x$ and $\underline{x}$ stands for the next integer $\leq x$. This means that only readout lengths of 1, 2, 3, 4 or 5s occur.

Here, it is assumed that the dead time for reading out the spectrometers is negligible.

- *Actual chop phase length* $\boldsymbol{t_{phase,on}}$:

The actual length of a single integration on the source or on the cold load within a load chop cycle is constrained by the maximum load chop phase length and the actual data readout length. In case of very short integrations the upper limit may be given as well by the total time in the source pointing phase.
The number of readout cycles during one source integration chunk is

$$n_{readout,on} = \underline{\min\left(t_{point-on,max}, t_{phase-on,max}\right)/t_{data}} \qquad (28)$$

leading to the chunk length of

$$t_{phase,on} = n_{readout,on} \times t_{data} \qquad (29)$$

This leads to a total chop cycle length of

$$t_{lchop,on} = 2\, t_{phase,on} + t_{lchop\text{-}dead} \qquad (30)$$

- *Number of load calibration intervals on the source* $\boldsymbol{n_{load,on}}$:

If the maximum load calibration period $t_{cal,load}$ is smaller than the maximum baseline calibration phase length $t_{point\text{-}on,max}$ then each source pointing has to be intermitted by load calibration measurements. The number of load calibration intervals during one source pointing is given by the two periods as

$$n_{load,on} = \overline{\frac{\underline{t_{point-on,max}/t_{lchop,on}} \times t_{lchop,on} + t_{load,tot}}{t_{cal,load}} - 1} \qquad (31)$$

If $t_{point\_on,max}+t_{load,tot}$ is smaller than the load calibration period $t_{cal,load}$ not additional load calibration measurements are required during one source pointing, i.e. $n_{load,on}=0$.

- *Number of chop cycles between calibration steps on the source* $\boldsymbol{n_{lchop\text{-}on,series}}$:

The number of subsequent chop cycles on the source position is limited by the maximum length of the source phase of the baseline calibration cycle $t_{point\text{-}on,max}$, and the number of interleaving load calibration measurements

$$n_{lchop\text{-}on,series} = \left[\frac{t_{point-on,max} - n_{load,on}\, t_{load,tot}}{(n_{load,on}+1)\, t_{lchop,on}}\right] \qquad (32)$$

- *Actual length of a single pointing to the source position* $\boldsymbol{t_{point\text{-}on}}$:

The actual length of a single pointing towards the source position is then composed of the chop cycles and the load measurements on the source:

$$t_{point\text{-}on} = (n_{load,on}+1)\, n_{lchop-on,series}\, t_{lchop,on} + n_{load,on}\, t_{load,tot} \qquad (33)$$

- *Maximum length of a single pointing to the OFF position* $\boldsymbol{t_{point\text{-}OFF,max}}$:

The maximum length of the pointings to the OFF position is given by the remaining time in each baseline calibration cycle. We obtain again two different equations for the two possible initial scenarios. For scenario *a)* :

$$t_{point\text{-}OFF,max} = (t_{tot} - t_{init})/n_{cycles} - t_{slew} - t_{point-on} \qquad (34)$$

For initial scenario b) the corresponding equation reads:

$$t_{point\text{-}OFF,max} = (t_{tot} - t_{init} - t_{point-on})/(n_{cycles} - 1) - t_{slew} - t_{point-on} \qquad (35)$$

In case of n_{cycles}=1, i.e. only one baseline calibration cycle, there is no OFF measurement in scenario *b)* at all, so that the computations for the OFF phase can be ignored in this scenario.

- *Actual chop phase length on the OFF position* $\boldsymbol{t_{phase,OFF}}$:

For the timing parameters within the OFF calibration phase the same relations hold like for the source pointing phase but adapted to the different integration times. The number of readout cycles during a single integration on the sky or on the cold load when pointing towards the OFF position is given by

$$n_{readout,OFF} = \underline{\min(t_{point-OFF,max}, t_{phase-OFF,max})/t_{data}} \qquad (36)$$

leading to the actual length of a single integration of

$$t_{phase,OFF} = n_{readout,OFF} \times t_{data} \qquad (37)$$

and a total chop cycle length of

$$t_{lchop,OFF} = 2\, t_{phase,OFF} + t_{lchop\text{-}dead} \qquad (38)$$

- *Number of load calibration intervals on the OFF position* $\boldsymbol{n_{load,OFF}}$:

In the same way as for the source pointing the OFF position integration may be intermitted by load calibration measurements. Their number is given by

$$n_{load,OFF} = \frac{\underline{t_{point-OFF,max}/t_{lchop,OFF}} \times t_{lchop,OFF} + t_{load,tot}}{t_{cal,load}} - 1 \qquad (39)$$

- *Number of chop cycles between calibration steps on the OFF* $\boldsymbol{n_{lchop\text{-}OFF,series}}$:

The number of subsequent chop cycles is limited by the time between two load calibration measurements

$$n_{lchop\text{-}OFF,series} = \left[\frac{t_{point-OFF,max} - n_{load,OFF}\, t_{load,tot}}{(n_{load,OFF}+1)\, t_{lchop,OFF}}\right] \quad (40)$$

- *Length of a single pointing to the OFF position* $t_{point\text{-}OFF}$*:*

Equivalent to the situation for the source pointing length we obtain the resulting length of a single pointing to the OFF position

$$t_{point\text{-}OFF} = (n_{load,OFF}+1)\, n_{lchop-OFF,series}\, t_{lchop,OFF} + n_{load,OFF}\, t_{load,tot} \quad (41)$$

- *Number of baseline calibration intervals per load calibration* $n_{sw\text{-}load}$ *:*

When the load calibration period $t_{cal,load}$ is longer than the baseline calibration cycle it is not necessary to perform a new load calibration after each pointing phase. Instead a single load calibration measurement can be use to calibrate multiple ON-OFF or OFF-ON calibration cycles. The number of baseline calibration intervals per load calibration is

$$n_{sw\text{-}load} = \left\lfloor t_{cal,load}/(t_{point-on}+t_{point-OFF}+t_{slew}) \right\rfloor \quad (42)$$

If $n_{sw\text{-}load}$ is zero a load calibration has to be performed after each pointing unit $t_{point\text{-}on}$ and $t_{point\text{-}OFF}$.

3.2.3 Resulting integration time

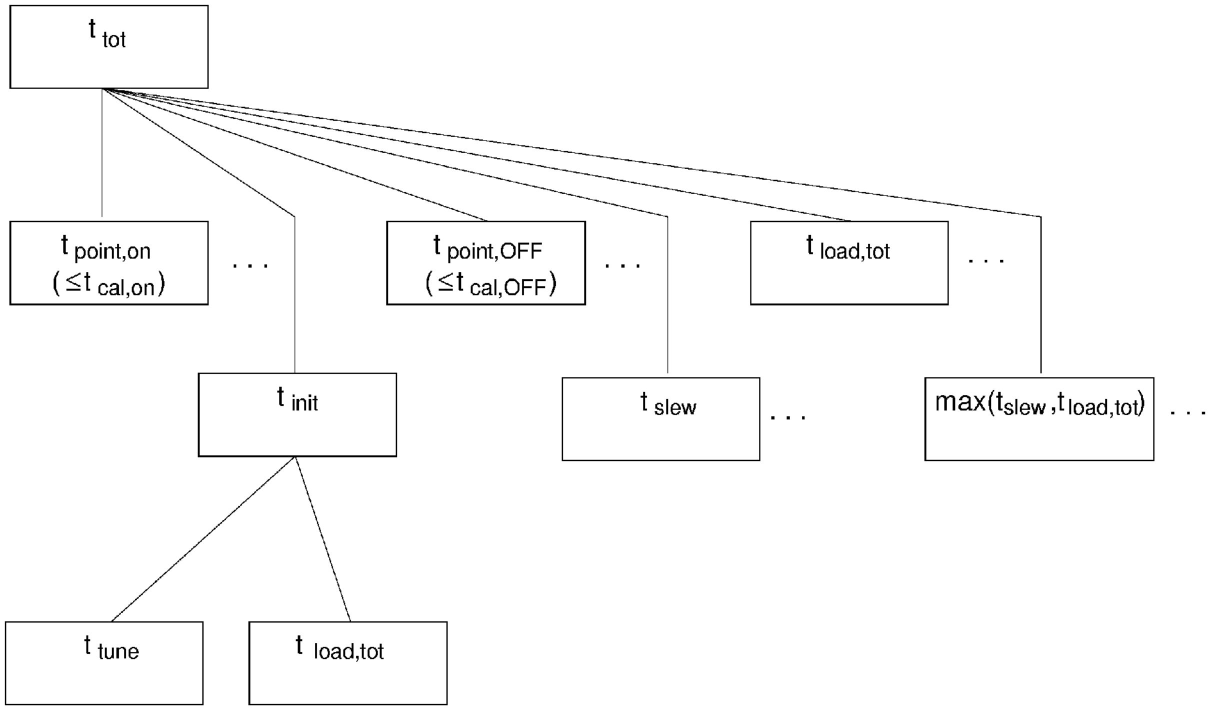
- *Total integration time on the source* t_{on}*:*

A number which is not actually important for the implementation of the observing mode but which is interesting for the astronomer to judge the efficiency of the mode is the actual total time spent pointing towards the source and integrating on the sky. It can be computed as

$$t_{on} = (n_{load,on}+1)\, n_{lchop-on,series}\, t_{phase,on} \quad (43)$$

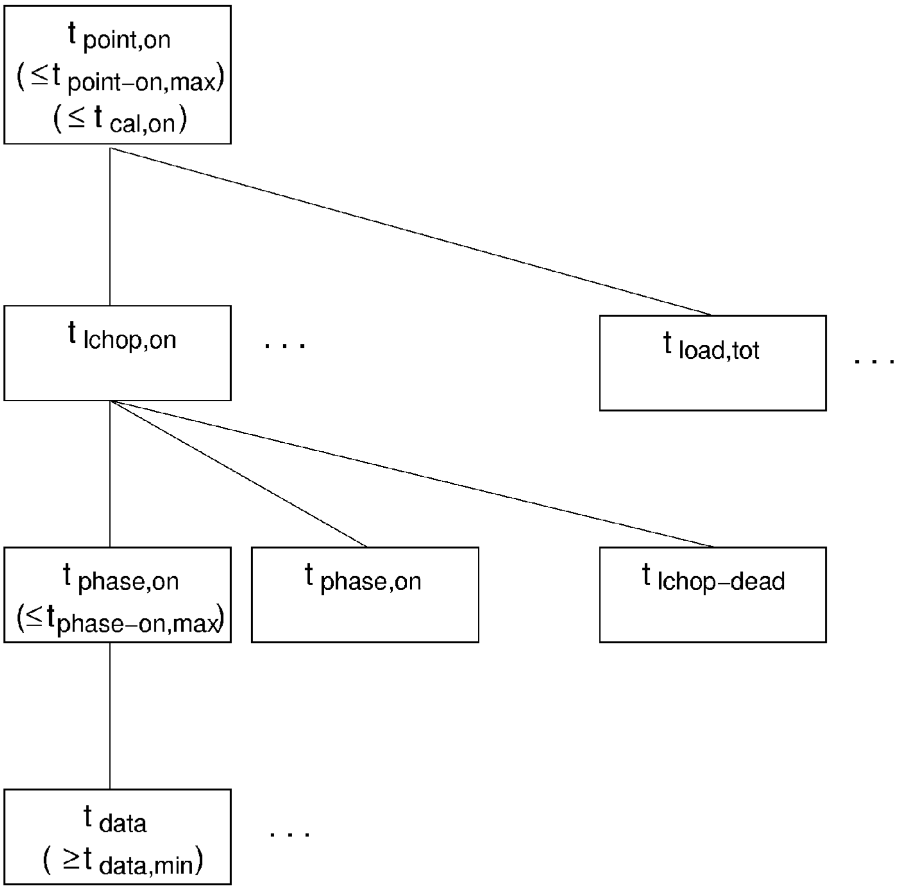
3.2.4 Relations between the timing parameters

The total observing time is split between the two pointing phases and possible dead times. The different components can be listed as:



The number of $t_{point,on}$ intervals within t_{tot} is given by n_{cycles} which is ≥ 1. The number of $t_{point,OFF}$ intervals is n_{cycles} for initial scenario *a* and n_{cycles}-1 for scenario *b*, i.e. they may be completely dropped in some cases. The intervals with a length of max(t_{slew}, $t_{load,tot}$) characterise slews with simultaneous load measurements. In initial scenario *a* their number is given by $\overline{n_{cycles}/n_{sw-load}}$, in initial scenario *b* their number is $\overline{(n_{cycles}-1)/n_{sw-load}}$. The rest of the n_{cycles} (case *a*) or n_{cycles}-1 (case *b*) slews within the observation contribute by t_{slew} intervals. If $n_{sw\text{-}load}$ =0, load calibration measurements are performed during all slews, so that all slews contribute by max(t_{slew}, $t_{load,tot}$) and none by t_{slew} , but then -and only then- n_{cycles} additional $t_{load,tot}$ intervals have to be added.

The internal timing parameters describing the source pointing phase used above can be visualised by the following scheme:



The number of t_{data} intervals within $t_{phase,on}$ is given by $n_{readout,on}$ which is ≥ 1. The number of $t_{lchop,on}$ intervals within $t_{point,on}$ is given by $(n_{load,on}+1)n_{lchop\text{-}on,series}$ and the number of $t_{load,tot}$ intervals within $t_{point,on}$ by $n_{load,on}$ where $n_{lchop\text{-}on,series} \geq 1$ and $n_{load,on} \geq 0$.

The corresponding scheme for the OFF pointing phase follows the same hierarchy and relations where only the indices of the different quantities have to be changed from "on" to "OFF".

3.2.5 The basic integration unit

After computing the length of each step by splitting the total observing time into appropriate chunks the sequence of the different steps has to be specified. The sequence is described in terms of algorithmic loops where counters are incremented and the value of the counter is used to check the end of the different loops.

Here, we start with the most simple building blocks. The sequence of integrations and data readout on the source position and on the OFF position follow the same general schemes. The pure load-chop cycle series on the source position can described by a simple algorithm:

The loop counter is initialised as i_{lchop}=0 and the following loop is executed until the condition for the end of the chop series in the first or fifth line is fulfilled.

M6 chopper	***Duration***	***Backend***	***Duration***
if $i_{lchop}=n_{lchop-on,series}$: end of the series else: $i_{lchop}=i_{lchop}+1$			0
cold load		cold load integration	$n_{readout,on} \times t_{data}$
move to the sky	$t_{lchop-dead}$		
sky		sky integration	$n_{readout,on} \times t_{data}$
if $i_{lchop}=n_{lchop-on,series}$: end of the series else: $i_{lchop}=i_{lchop}+1$			0
sky		sky integration	$n_{readout,on} \times t_{data}$
move to the cold load	$t_{lchop-dead}$		
cold load		cold load integration	$n_{readout,on} \times t_{data}$

This building block of the load chop series is part of the total integration in the source pointing phase which may additionally contain load measurements. The whole source pointing phase is initialised by i_{load}=0 and performs the loop:

M6 chopper and backend processing	***Duration***
load chop series from table above	$n_{lchop-on,series} \times t_{lchop-on}$
if $i_{load}=n_{load,on}$: end of the source pointing else: $i_{load}=i_{load}+1$	0
load measurement (see 2.3)	$t_{load,tot}$

The loop stops when the condition in the second line is fulfilled.

For the integration during the OFF position phase, the same scheme can be used when the quantities $n_{lchop-on,series}$, $n_{load,on}$, $n_{readout,on}$, and $t_{lchop-on}$ are substituted by $n_{lchop-OFF,series}$, $n_{load,OFF}$, $n_{readout,OFF}$, and $t_{lchop-OFF}$.

3.2.6 Initial steps

As discussed in AD10 there are two different initial sequences foreseen to save observing time depending on the state of the instrument resulting from the previous observation.

a) different instrument settings or identical instrument settings but no sufficiently long OFF integration within the current baseline stability time:

Satellite	Duration	Instrument	Duration
slew to l_{OFF}, b_{OFF}	$t_{init\text{-}slew,OFF}$	simultaneous tuning of the instrument to the new settings (ν_{LO}, backend settings)	t_{tune}
		simultaneous load calibration measurement	$t_{load,tot}$
stable pointing at l_{OFF}, b_{OFF}		integration on the OFF position	$t_{point\text{-}OFF}$
slew to l,b	t_{slew}	load calibration measurement	$t_{load,tot}$
stable pointing at l,b		integration on the source position	$t_{point\text{-}on}$
		if $n_{sw\text{-}load}=0$: load calibration measurement	$(0 \mid t_{load,tot})$

b) identical instrument settings; OFF integration with the required OFF integration time $t_{point\text{-}OFF}$ of one cycle already performed within the current baseline stability time $t_{cal,OFF}-t_{init\text{-}slew,on}$:

Satellite	Duration	Instrument	Duration
slew to l,b	$t_{init\text{-}slew,on}$	load calibration measurement	$t_{load,tot}$
stable pointing at l,b		integration on the source position	$t_{point\text{-}on}$
		if $n_{sw\text{-}load}=0$: load calibration measurement	$(0 \mid t_{load,tot})$

Only that part of the initial slew time $t_{init\text{-}slew,on}$ which is covered by the initial tuning and the initial load measurement is considered here as part of the observing time.

3.2.7 The main loop

After the initial step including either an OFF-ON cycle, or a pure ON integration when the OFF calibration was already previously performed, the cycle counter i_{cycle} will be set to 1.

The following observation consists of more ON-OFF-OFF-ON cycles, where each OFF-ON pair represents one baseline calibration cycle as counted by n_{cycles}. In all cases where an observation consists only of one cycle, i.e. n_{cycles}=1 this cycle was already performed in the initial steps so that the main loop is empty. The main loop can be described as

Satellite	***Duration***	***Instrument***	***Duration***
if $i_{cycles}=n_{cycles}$: end of the observation else: $i_{cycles}=i_{cycles}+1$			0
stable pointing at l,b		integration on the source position	if $i_{cycles}=n_{cycles}$: $t_{point-on,end}$ else $t_{point-on}$
slew to l_{OFF},b_{OFF}	t_{slew}	if (i_{cycles} mod $n_{sw-load}$)=0: load calibration measurement	$(0 \mid t_{load,tot})$
stable pointing at l_{OFF},b_{OFF}		integration on the OFF position	if $i_{cycles}=n_{cycles}$: $t_{point-OFF,end}$ else $t_{point-OFF}$
		if $n_{sw-load}$=0 : load calibration measurement	$(0 \mid t_{load,tot})$
if $i_{cycles}=n_{cycles}$: end of the observation else: $i_{cycles}=i_{cycles}+1$			0
stable pointing at l_{OFF},b_{OFF}		integration on the OFF position	if $i_{cycles}=n_{cycles}$: $t_{point-OFF,end}$ else $t_{point-OFF}$
slew to l,b	tslew	if (i_{cycles} mod $n_{sw-load}$)=0: load calibration measurement	$(0 \mid t_{load,tot})$

Satellite	Duration	Instrument	Duration
stable pointing at l,b		integration on the source position	if $i_{cycles}=n_{cycles}$: $t_{point-on,end}$ else $t_{point-on}$
		if $n_{sw-load}=0$: load calibration measurement	$(0 \mid t_{load,tot})$

This loop is executed until the condition for the end of the observation in the first or fifth line is fulfilled. The internal timing of the integration steps and the load steps were laid out above.

3.3 Consistency checks

- *The instrument stability has to exceed the load chop dead time:* $\boldsymbol{t_{lchop,dead} < t_{A,\Delta\nu}}$

If this condition is not fulfilled, the drift contributions in the observation will exceed the radiometric noise. This will lead to noticeable baseline distortions. The actual per-channel uncertainty of the observation will be higher than the theoretical limit discussed below. The mode is not exactly calibratable.

- *The instrument stability on the standing wave resolution has to exceed the load chop dead time:* $\boldsymbol{t_{lchop,dead} < t_{A,\Delta\nu-sw}}$

If this condition is not fulfilled the determination of the influence of standing waves on the baseline calibration from a smoothed OFF measurement is not possible. The resolution bandwidth for the determination of standing waves $\Delta\nu_{sw}$ has to be reduced until the condition is fulfilled, at most down to $\Delta\nu_{res}$.

- *The standing wave stability has to exceed the slewing time:* $\boldsymbol{t_{slew} < t_{A,sw-lchop,\Delta\nu}}$

If this condition is not fulfilled no correction of the baseline distortions by the standing wave difference between the sky position and the cold load position is possible. In this case, the observing mode should not be used.

- *The standing wave stability has to be large compared to the total instrument stability:* $\boldsymbol{t_{A,sw-lchop,\Delta\nu} \geq 4\, t_{A,\Delta\nu}}$ and $\boldsymbol{t_{A,sw-lchop,\Delta\nu} \geq 4\, t_{A,\Delta\nu-sw}}$

If this condition is not fulfilled the observing mode is highly inefficient and even might not be calibratable to the foreseen accuracy. In this case the ordinary position-switch mode should be chosen instead.

- *The load calibration stability has to be large compared to the total instrument stability:* $\boldsymbol{t_{cal,load} \geq 4\,(t_{phase,max} + t_{phase,max,OFF} + t_{A,lchop-dead})}$

If this condition is not fulfilled the observing mode cannot be calibrated to the foreseen accuracy at the desired frequency resolution.

- *Readout possible in the instrumental stability time:* $t_{data,min} \leq t_{phase,max}$ and $t_{data,min} \leq t_{phase,max,OFF}$

Otherwise, the number of spectrometer channels has to be reduced to lower $t_{data,min}$ until these conditions are fulfilled. If such a reduction is not possible, the maximum readout length must be increase, but then the instrumental drift will lead to noticeable baseline distortions above the radiometric noise level.

- *Integration time longer than maximum readout length:* $t_{on} \geq 5$ **s**

To simplify the observing mode only integrations of at least 5s are foreseen.

4 OTF-maps with position-switch reference

4.1 Observing mode parameters

The following parameters determine the timeline of the actual observation:

4.1.1 Astronomical parameters

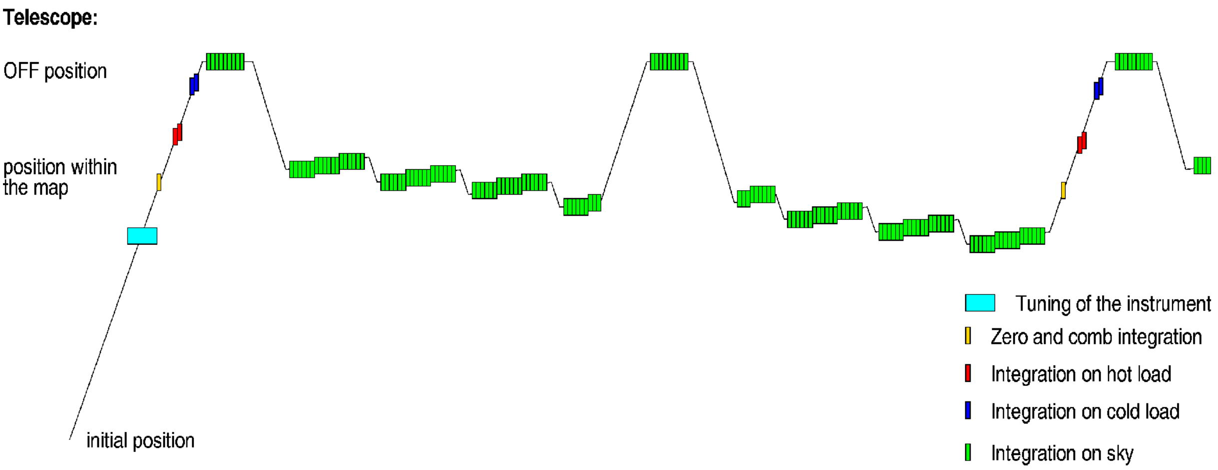
Pointing parameters:	coordinates of the corner of the map to start with l_1,b_1 distance between subsequent OTF lines $\Delta l_r,\Delta b_r$ number of OTF lines in the map n_r distance between subsequent points in a line $\Delta l_l,\Delta b_l$ number of points per OTF line n_l OFF coordinates l_{OFF},b_{OFF}
Timing parameters:	total observing time t_{tot}
Receiver parameters:	HIFI band LO frequency ν_{LO}
Backend parameters:	backend to use: HRS, WBS, both max. desired resolution bandwidth of calibrated data $\Delta\nu_{res}$ HRS: resolution mode: hires/normal/lowres number of subbands to be read $n_{HRS\text{-}bands}$ IF setting of subbands WBS: first and last channel of the up to four frequency windows $l_{1,i}$, $l_{2,i}$

4.1.2 Instrumental parameters

All instrument parameters that determine the timing of the OTF mode are mentioned already in the general section. There are no no special parameters here which do not apply as well to all other observing modes.

4.2 The time line of the mode

The time line of the observation consists of continuous scans of lines across the map, turns of the telescope between subsequent OTF lines, interleaved observations of an OFF position as reference, and load measurements performed during some of the slews to the OFF position to calibrate the system response. This scheme is illustrated in the sketch below:



In case of different instrumental settings compared to the previous measurement a retuning of the instrument has to be performed as initial step. The actual observation always starts with a load calibration measurement (see Sect. 2.3), the main part of which can be performed during the initial slew to the OFF position. The OFF integration consists of a number of separate data dumps at the same position.

The OTF lines are a sequence of short data integrations while the telescope is slewing across the line. All observations on the sky use the same position of the internal chopper. 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 the desired step length. If this step length is chosen to be larger than half the beam width the integration results in an additional artificial reduction of the spatial resolution of the observation.

In general a series of coverages of the map will be performed with one extra OFF measurement at the end of the observation.

4.2.1 Rough timing parameters

The implementation of the OTF observing mode with position switch reference requires a two step approach because of the large number of possible parameters. It is not known in advance from which positions within the OTF map it will be necessary to slew to the OFF position for the reference measurement, but the slew times between map and OFF position depend on the coordinates of these positions. Thus, we will use an average slew time in the first step to compute the general design of the observations and optimize it with respect to the cycle length between two OFF measurements. Moreover, the possible overhead from load calibrations performed during some of the slews is ignored in this step. In a second step we can compute the exact timeline where we use the actual slew times for the map positions computed in the first step and include the load calibrations. The resulting total observing time can slightly deviate from the time obtained in the first step.

Future improvements might include an additional optimization step by testing in addition to a timeline based on an average slew also configurations where the optimization uses the additional constraint that all slews start from the edge of the map which is closest to the OFF position and the smaller slew times from and to this edge.

From the astronomical parameters of the observations we can derive one auxiliary parameter:

- *Number of source points observed between two OFF measurements* $\boldsymbol{n_{scan}}$ *and integration time on each source point during one scan* $\boldsymbol{t_{point,on}}$*:*

There is no analytic expression for these two parameters, but they can be determined from numerically minimizing the expression for the total data uncertainty:

with the constraint that $t_{point,on} > t_{data,min}$.

This is the length of the phases on the sky and on the cold load within one chop cycle. Their sum forms together with the chop dead time the maximum length of a full chop cycle. It is constrained by the instrumental stability, which asks for a short cycle to minimise the distortions by instrumental drift, and the dead time of the chopper motion which asks for a long period to maximise the observational efficiency. The best compromise is described by a general relation for the optimum phase length in a symmetric observation as a function of dead time:

$$x_{opt}(\alpha, d) = \mathrm{root}_x\{(2x+d)^{\alpha+1}(\alpha x - d) - 2(x+d)^{\alpha+1}(2x+d)(\alpha x + d) + (x+d)^{\alpha+1} d \\ - x^{\alpha+1}[\alpha(2x+d) - d] - d^{\alpha+1}(x+d) - (2^{\alpha} - 2)dx\}$$

where α is the spectral index of the drift contribution, d is the dead time during the cycle normalised to the Allan time, and the resulting x_{opt} is the time of each phase relative to the Allan time. The function $\mathrm{root}_x\{\}$ denotes the root of the expression with respect to the variable x. A detailed derivation of this equation is given in RD7. For phases longer than $t_{phase,max}$, the drift contribution exceeds the radiometric noise, at shorter phase lengths the relative overhead from the dead time is larger than required.

For the chop phase lengths the dead time in one chop cycle is just given by $t_{lchop\text{-}dead}$ if the backends are read out twice between two motions of the chopping mirror, i.e. the data dump sequence is COLD-SKY-SKY-COLD. Thus we arrive at a maximum chop phase length of

$$t_{phase\text{-}on,max} = t_{A,\Delta\nu}\, x_{opt}(\alpha, t_{lchop\text{-}dead}/t_{A,\Delta\nu}) \qquad (44)$$

- *Maximum chop phase length on the OFF position* $\boldsymbol{t_{phase,max,OFF}}$:

Because of a different stability time at the frequency resolution needed for the baseline calibration the length of the chop cycle on the OFF position may differ from the length on the source position.

$$t_{phase\text{-}OFF,max} = t_{A,\Delta\nu\text{-}sw}\, x_{opt}(\alpha, t_{lchop\text{-}dead}/t_{A,\Delta\nu\text{-}sw}) \qquad (45)$$

- *Baseline calibration source phase length* $\boldsymbol{t_{cal,on}}$:

This is the length of the phase on the source position within the cycle including the source and the OFF position needed to perform the baseline calibration. The source phase length forms together with OFF phase length and the slewing time the full baseline calibration cycle. The frequency of slews to the OFF position for a chop-difference baseline calibration is determined by the stability of the chop difference and the dead time needed for the slew. It follows the same relation as the load chop phase length, but takes into account that in general different integration times on the source and on the OFF position are possible :

$$t_{cal,on} = \frac{t_{on}}{t_{on}+t_{OFF}}\; t_{A,sw\text{-}lchop,\Delta\nu}\; x_{opt}(\alpha, t_{slew}/t_{A,sw\text{-}lchop,\Delta\nu}) \qquad (46)$$

where the ratio between the integration times on the source position and on the OFF position from Eq. () is to be used.

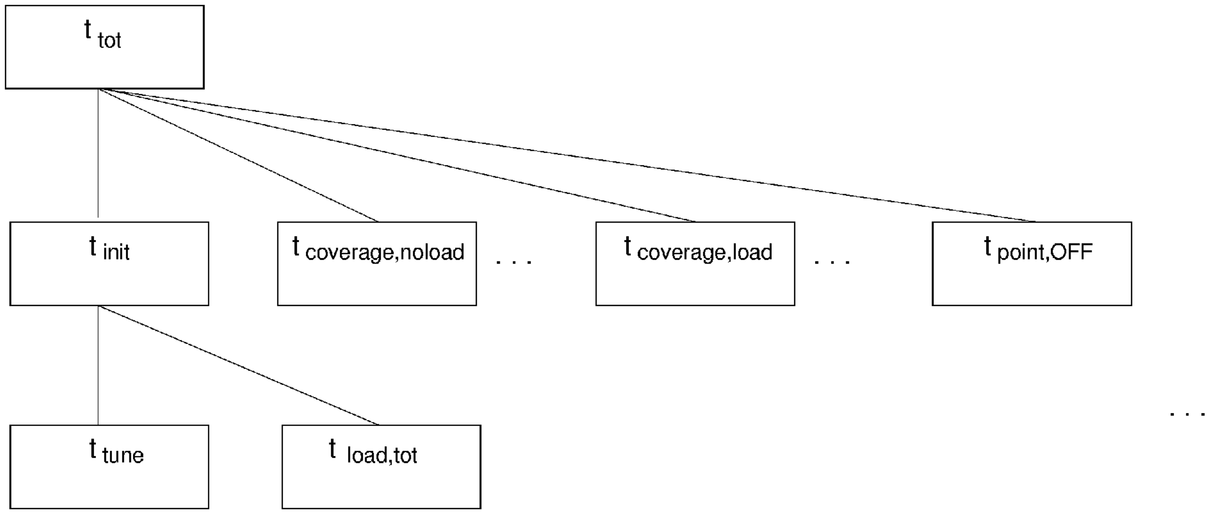
- *Baseline calibration OFF phase length* $\boldsymbol{t_{cal,OFF}}$:

The complementary OFF phase length is given by:

$$t_{cal,OFF} = \frac{t_{OFF}}{t_{on}+t_{OFF}}\; t_{A,sw\text{-}lchop,\Delta\nu}\; x_{opt}(\alpha, t_{slew}/t_{A,sw\text{-}lchop,\Delta\nu}) \qquad (47)$$

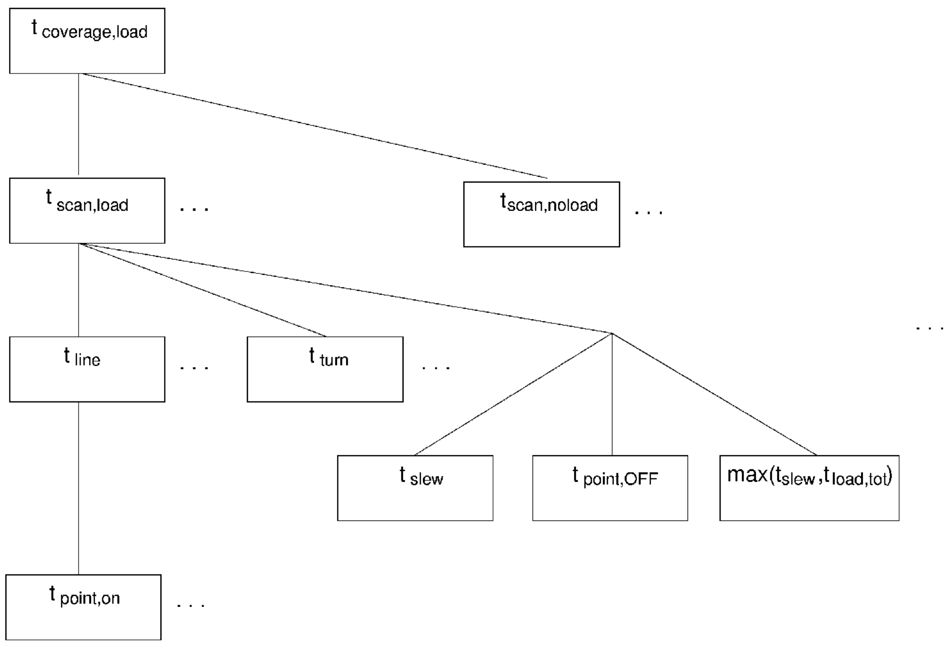
4.2.2 Relations between the timing parameters

The total observing time is split between the two pointing phases and possible dead times. The different components can be listed as:



The number of $t_{point,on}$ intervals within t_{tot} is given by n_{cycles} which is ≥ 1. The number of $t_{point,OFF}$ intervals is n_{cycles} for initial scenario *a* and n_{cycles}-1 for scenario *b*, i.e. they may be completely dropped in some cases. The intervals with a length of max(t_{slew}, $t_{load,tot}$) characterise slews with simultaneous load measurements. In initial scenario *a* their number is given by $\overline{n_{cycles}/n_{sw-load}}$, in initial scenario *b* their number is $\overline{(n_{cycles}-1)/n_{sw-load}}$. The rest of the n_{cycles} (case *a*) or n_{cycles}-1 (case *b*) slews within the observation contribute by t_{slew} intervals. If $n_{sw\text{-}load}$ =0, load calibration measurements are performed during all slews, so that all slews contribute by max(t_{slew}, $t_{load,tot}$) and none by t_{slew}, but then -and only then- n_{cycles} additional $t_{load,tot}$ intervals have to be added.

The internal timing parameters describing the source pointing phase used above can be visualised by the following scheme:



The number of t_{data} intervals within $t_{phase,on}$ is given by $n_{readout,on}$ which is ≥ 1. The number of $t_{lchop,on}$ intervals within $t_{point,on}$ is given by $(n_{load,on} + 1)n_{lchop\text{-}on,series}$ and the number of $t_{load,tot}$ intervals within $t_{point,on}$ by $n_{load,on}$ where $n_{lchop\text{-}on,series} \geq 1$ and $n_{load,on} \geq 0$.

The corresponding scheme for the OFF pointing phase follows the same hierarchy and relations where only the indices of the different quantities have to be changed from “on” to “OFF”.

4.2.3 Actually used timing parameters

Combining the astronomical parameters for the actual observation with the instrumental parameters and the instrumental limitations provides the eventually used time steps in the observation. Here, all adjustments relative to the optimum values computed above are made into the direction of reduced calibration errors, i.e. a small part of the observing efficiency may be lost in favour of guaranteeing the theoretically predicted calibration accuracy as computed in detail in AD10.

- *Total number of pointing cycles* n_{cycles}*:*

The number of pointing cycles is given by the total observing time and the maximum cycle length. The relation between the total observing time and this number differs between the two different initial scenarios. If the observation starts with an OFF

Appendix

A Instrument parameters determining the observing modes

Symbol	***Description***	***Goal***	***Specified***	***Best guess***	***Ref.***
J_{sys}	Double sideband instrument noise temperature (Band 1)	82-127K			AD6
	Band 2	127-175K			AD6
	Band 3	178-227K			AD6
	Band 4	227-275K			AD6
	Band 5	275-583K			AD6
	Band 6	748-771K			AD6
t_{fix}	Fix dead time in slewing	5 s	10 s		AD1
r_{acc}	Acceleration rate	1 "/s²	0.5 "/s²		AD1
$\Delta\phi_{acc,max}$	Maximum acceleration length	12.25°	24.5°		
t_{turn}	Turn-around time between subsequent lines of an OTF observation			10 s	
$f_{fast\text{-}chop}$	Chop frequency for fast chop		2-5 Hz		AD5
$f_{slow\text{-}chop}$	Chop frequency for slow chop		0.5,0.25, 0.167Hz ...		AD5
		0.5, 0.25Hz	0.5, 0.33Hz		AD6
$t_{chop\text{-}dead}$	Sky chop dead time			0.025 s	
$t_{lchop\text{-}dead}$	Load chop dead time			0.25 s	
f_{fs}	Frequency switch frequency	0.5, 0.25Hz	0.5, 0.33Hz		AD6
t_{fs}	Frequency switch dead time		$\leq$ 0.1 s		AD6
$t_{load\text{-}dead}$	Load calibration dead time			15-25 s	
$\Delta\nu_{recal}$	Bandwidth of possible LO change with a change of the mixer response below the calibration uncertainty			100 MHz	

Symbol	***Description***	***Goal***	***Specified***	***Best guess***	***Ref.***
$\Delta\nu_{retune}$	Bandwidth of possible LO change without retuning			1 GHz	
t_{tune}	Frequency retuning time			60 s	
$t_{dead-wbs-fast}$	WBS readout dead time for fast chop modes		2 s		AD5
$t_{data-wbs-slow}$	Time between subsequent WBS readouts in slow chop		1-80 s		AD5
$t_{data-wbs-fast}$	Time between subsequent WBS readouts in fast chop		1-160 s		AD5
R_{bus}	Maximum data rate on the bus	140 kB/s	100 kB/s	140 kB/s	AD1
t_A	System Allan time at 1 MHz resolution (total power)		≥1 s	23 s	AD6, AD9
	System Allan time at 1 MHz resolution (spectroscopic)		≥100 s	150 s	AD6
α	Spectral index of system drift (total power)			2.5	RD1
	Spectral index of system drift (spectroscopic)			0.7	AD9
$t_{A,load}$	Gain stability time at 1 MHz (total power)			500 s	
α_{load}	Spectral index of gain drift (total power)			0.7	
$t_{A,sw-chop}$	Allan time of the standing wave difference between both sky-chop positions (total power)			1200 s	
	Allan time of the standing wave difference between both sky-chop positions (spectroscopic)			1500 s	

Symbol	***Description***	***Goal***	***Specified***	***Best guess***	***Ref.***
$\alpha_{sw\text{-}chop}$	Spectral index of chop standing wave difference drift (total power)			2.5	
	Spectral index of chop standing wave difference drift (spectroscopic)			2.5	
$t_{A,sw\text{-}lchop}$	Allan time of the standing wave difference between cold load and sky (total power)			800 s	
	Allan time of the standing wave difference between cold load and sky (spectroscopic)			1000 s	
$\alpha_{sw\text{-}chop}$	Spectral index of load chop standing wave difference drift (total power)			2.5	
	Spectral index of load chop standing wave difference drift (spectroscopic)			2.5	
$t_{A,sw\text{-}fs}$	Allan time of the standing wave difference between the two frequencies in frequency switch (total power)			600 s	
	Allan time of the standing wave difference between the two frequencies in frequency switch (spectroscopic)			1200s	
$\alpha_{sw\text{-}fs}$	Spectral index of frequency switch standing wave difference drift (total power)			2.0	
	Spectral index of freq. switch standing wave difference drift (spectroscopic)			2.5	