HIFI Intensity Calibration and Observing Modes

- Basic properties of the instrument
- The advanced intensity calibration
- HIFI observing modes

Properties of the instrument

General properties:

- effective diameter 3.2 m → spatial resolution:

HIFI Band	1	2	3	4	5	6
Coverage (GHz)	480–640	640–800	800–960	960–1120	1120–1250	1410–1910
HPBW (″)	39	30	25	21	19	13

- Specified sensitivity and resulting minimum integration times (OTF mode):

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

Properties of the instrument

Advantages:

- No atmospheric emission, no atmospheric instabilities
- Relatively stable environment in L2 orbit
- Availability of two thermal loads for intensity calibration

Limitations:

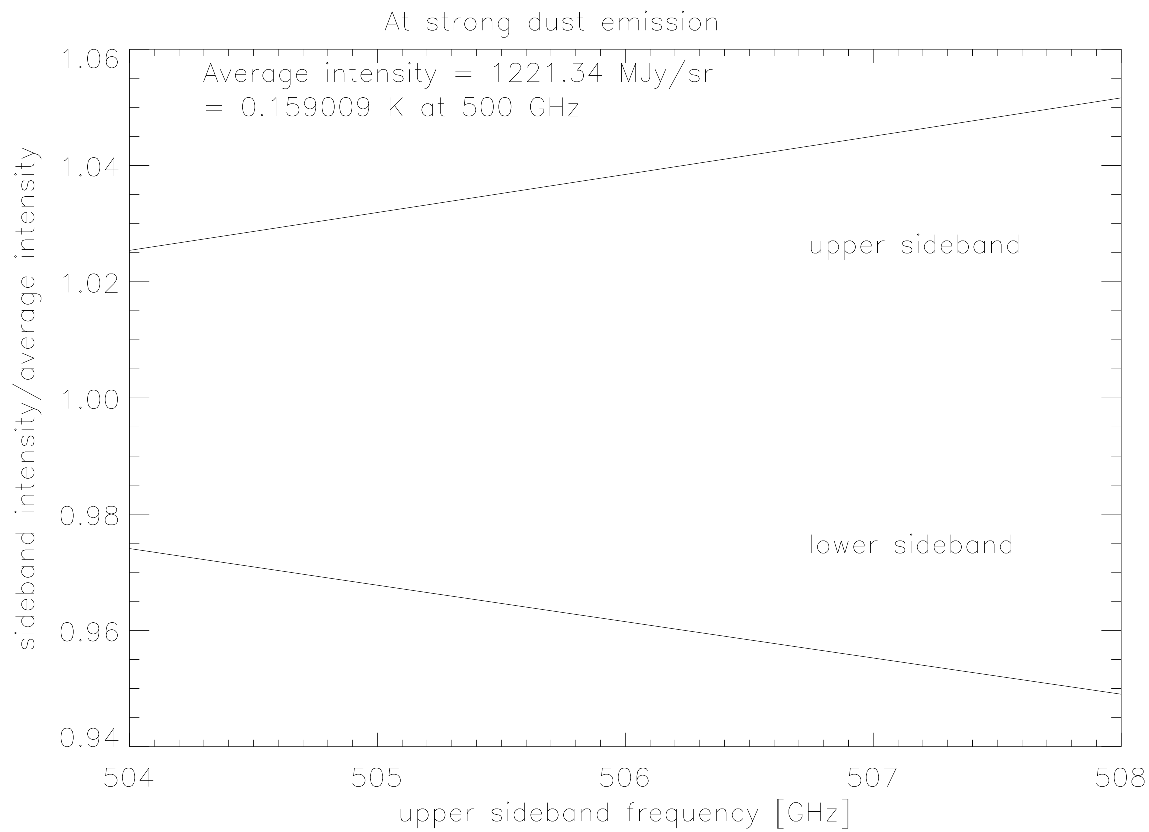
- Extremely long slew times: $\approx 10 + \sqrt{\Delta\phi['']}$ s
- Maximum OFF distance: 2°
- System stability is essentially limited by temperature drifts
- Readout frequency is limited by data rates: typically 3-4 s
- For an on-axis telescope standing wave ripples are expected, they occur also in other parts of the instrument

The intensity calibration scheme

Background

Taking the large IF of the system it is not guaranteed that any calibration quantity agrees in both sidebands.

The sideband imbalance of most continuum radiation fields is not negligible.

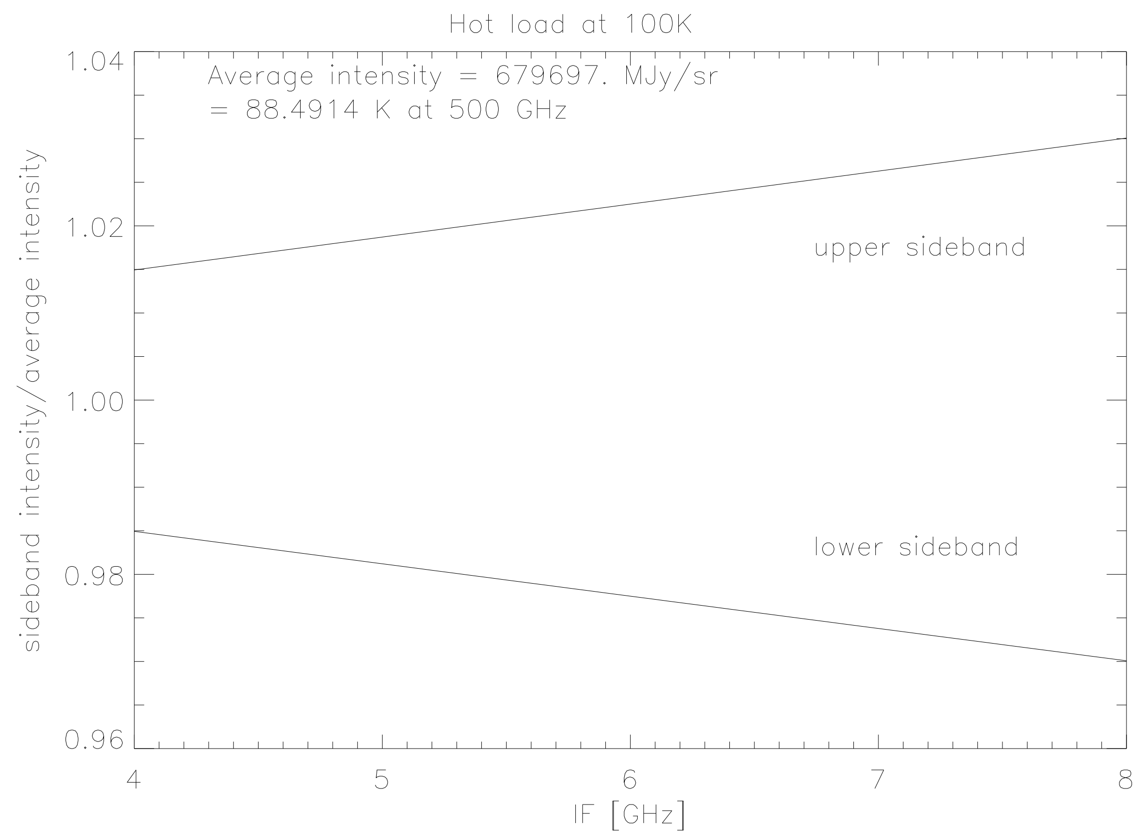


The system response in an astronomical observation

$$c = \gamma_{\rm ssb}\left\{\eta_{\rm l,ssb}\left[\eta_{\rm S,ssb}J_{\rm S,ssb} + (1-\eta_{\rm S,ssb})J_{\rm R,ssb}\right] + (1-\eta_{\rm l,ssb})J_{\rm T,ssb}\right\}$$
$$+\gamma_{\rm isb}\left\{\eta_{\rm l,isb}\left[\eta_{\rm S,isb}J_{\rm S,isb} + (1-\eta_{\rm S,ssb})J_{\rm R,isb}\right] + (1-\eta_{\rm l,isb})J_{\rm T,isb}\right\} + \gamma_{\rm rec}J_{\rm rec} + z$$

The intensity calibration scheme

Continuum treatment



The frequency dependence of all continuum signals can be described by linear expansion.

$$J_{\nu_{\mathrm{USB}}} - J_{\nu_{\mathrm{LO}}} = J_{\nu_{\mathrm{LO}}} - J_{\nu_{\mathrm{LSB}}} = b\nu_{\mathrm{IF}} \times J_{\nu_{\mathrm{LO}}}$$

In Rayleigh limit: $b = 2/\nu_{\mathrm{LO}}$

Load calibration

- Two-load chopper wheel calibration to determine intensity bandpass $\gamma_{\rm rec}$ and receiver temperature $J_{\rm rec}$.
- Both quantities are fully channel dependent.

Calibration equations

$$\begin{aligned}
\gamma^{\rm l}_{\rm rec} &= \frac{c_{\rm hot} - c_{\rm cold}}{(\eta_{\rm h} + \eta_{\rm c} - 1)(J_{\rm h,eff} - J_{\rm c,eff})} \\
J^{\rm l}_{\rm rec} &= \frac{\eta_{\rm h}(c_{\rm cold} - z) - (1 - \eta_{\rm c})(c_{\rm hot} - z)}{c_{\rm hot} - c_{\rm cold}} (J_{\rm h,eff} - J_{\rm c,eff}) - J_{\rm c,eff} \\
&= \frac{(\eta_{\rm h} + Y\eta_{\rm c} - Y)J_{\rm h,eff} - (\eta_{\rm h} + Y\eta_{\rm c} - 1)J_{\rm c,eff}}{Y - 1}
\end{aligned}$$

with

$$\begin{aligned}
Y &= \frac{c_{\rm hot} - z}{c_{\rm cold} - z} \\
J_{\rm eff} &= G_{\rm ssb} J_{\rm ssb} + (1 - G_{\rm ssb}) J_{\rm isb}
\end{aligned}$$

Load calibration

Calibration accuracy

$$\frac{\delta\gamma_{\mathrm{rec}}^{\mathrm{l}}}{\gamma_{\mathrm{rec}}^{\mathrm{l}}} = \frac{1}{\sqrt{\Delta\nu t_{\mathrm{load}}}} \begin{cases} 2.36 & \text{at } 500\,\mathrm{GHz} \\ 18.6 & \text{at } 1.9\,\mathrm{THz} \end{cases}$$

$$\frac{\delta J_{\mathrm{rec}}}{J_{\mathrm{rec}}} = \frac{1}{\sqrt{\Delta\nu t_{\mathrm{load}}}} \begin{cases} 1.94 & \text{at } 500\,\mathrm{GHz} \\ 17.9 & \text{at } 1.9\,\mathrm{THz} \end{cases}$$

Resulting integration times for each of the thermal loads:

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

OFF calibration

- Observation of the blank sky can be used to determine the telescope coupling and the standing wave pattern.
- The main impact of standing waves is not yet known. They can modify $J_{\rm rec}$, the gains $\gamma_{\rm ssb}$ and $\gamma_{\rm isb}$, or the telescope coupling.
- Minimum standing wave period in IF domain $\approx$ 21 MHz.

OFF measurement:

$$(1-\eta_{\rm l})\left[J_{\rm T,eff}+(1\pm b_{\rm T}\nu_{\rm IF})\frac{w_{\rm ssb}+w_{\rm isb}}{\gamma^{\rm l}_{\rm rec}}J_{\rm T,LO}\right]=\frac{c_{\rm OFF}-z}{\gamma^{\rm l}_{\rm rec}}-J^{\rm l}_{\rm rec}-\eta^{\rm guess}_{\rm l}J_{\rm R,eff}$$

for standing waves changing the receiver gain:

$$\begin{aligned}\gamma_{\rm ssb} &= \gamma^{\rm l}_{\rm rec}G_{\rm ssb}+w_{\rm ssb}\\ \gamma_{\rm isb} &= \gamma^{\rm l}_{\rm rec}(1-G_{\rm ssb})+w_{\rm isb}\end{aligned}$$

OFF calibration

Calibration accuracy

$$\frac{\delta J_{\rm sw}}{J_{\rm sw}} = \begin{cases} \sqrt{\dfrac{61^2}{\Delta\nu t_{\rm OFF}} + \dfrac{68^2}{\Delta\nu t_{\rm load}}} & \text{at 500 GHz} \\ \sqrt{\dfrac{960^2}{\Delta\nu t_{\rm OFF}} + \dfrac{950^2}{\Delta\nu t_{\rm load}}} & \text{at 1.9 THz} \end{cases}$$

- Standing wave have two different effects: they modulate the continuum level providing distortions to the spectral baseline of the signal and they modulate the absolute calibration of the lines.
- The standing wave ripple in the continuum baseline can always be suppressed or corrected either by total power observations or by an OFF calibration measurement.
- To correct the standing wave impact on the absolute calibration long integration times are required for the OFF measurement. Regarding the resulting timing requirements a correction of their impact to better than 10 % is not always possible.

HIFI Observing Modes

Problem:

The calibration parameters $J_{\rm rec}$, $\gamma^{l}_{\rm rec}$, η_{l}, $w_{\rm ssb}$, and $w_{\rm isb}$ are not constant in time.

$\Longrightarrow$ **need to correct for the drift of the instrumental response**

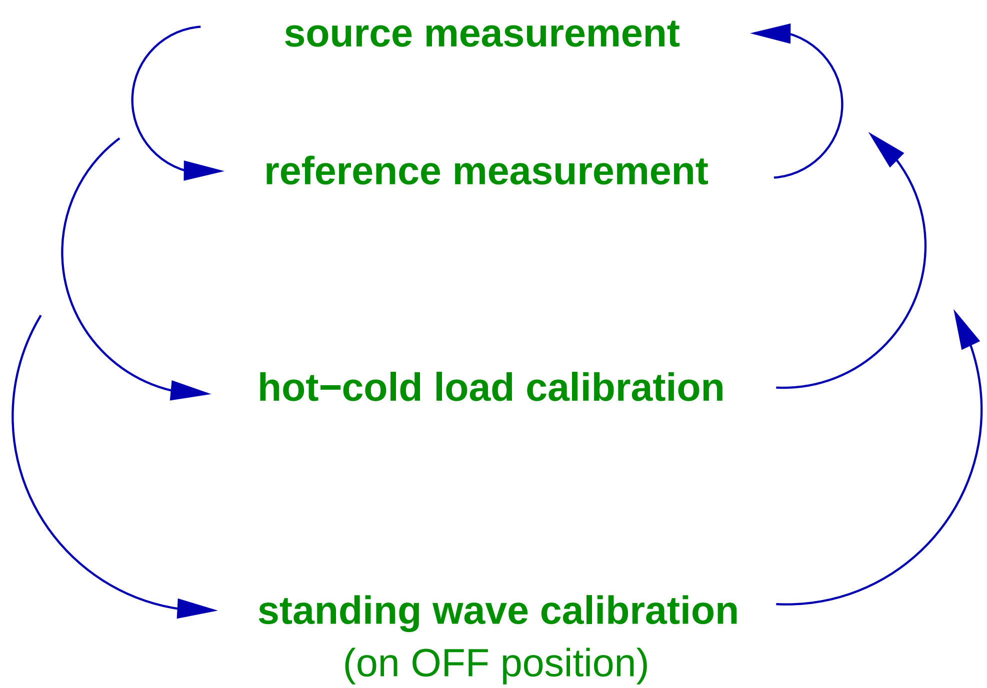
$\Longrightarrow$ **solved by the design of the observing modes:**

Hierarchical structure of reference and calibration loops:

Reference loop
length determined by total system stability time

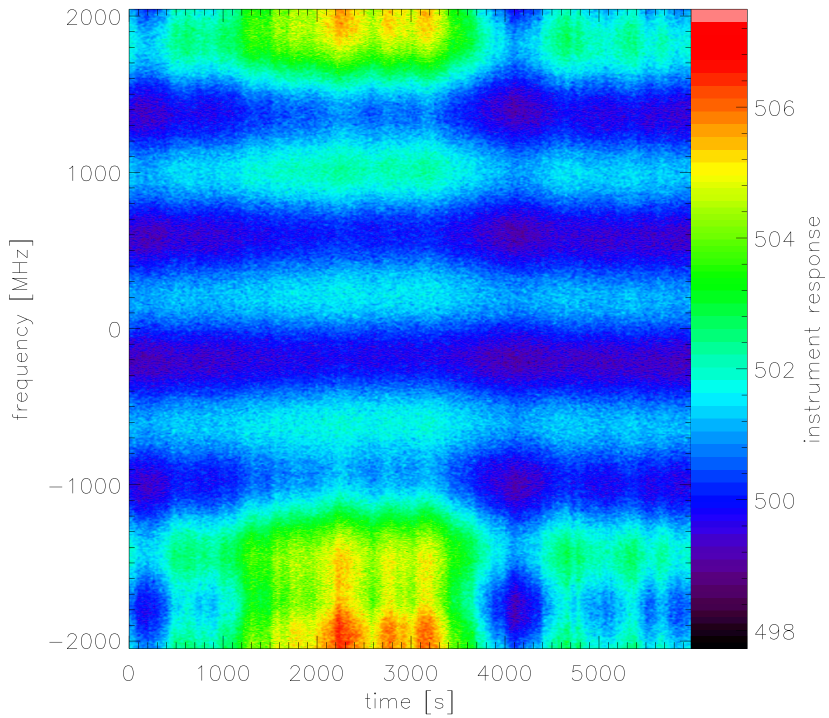
Bandpass calibration loop
length determined by bandpass stability time

Difference calibration loop
length determined by standing wave stability time

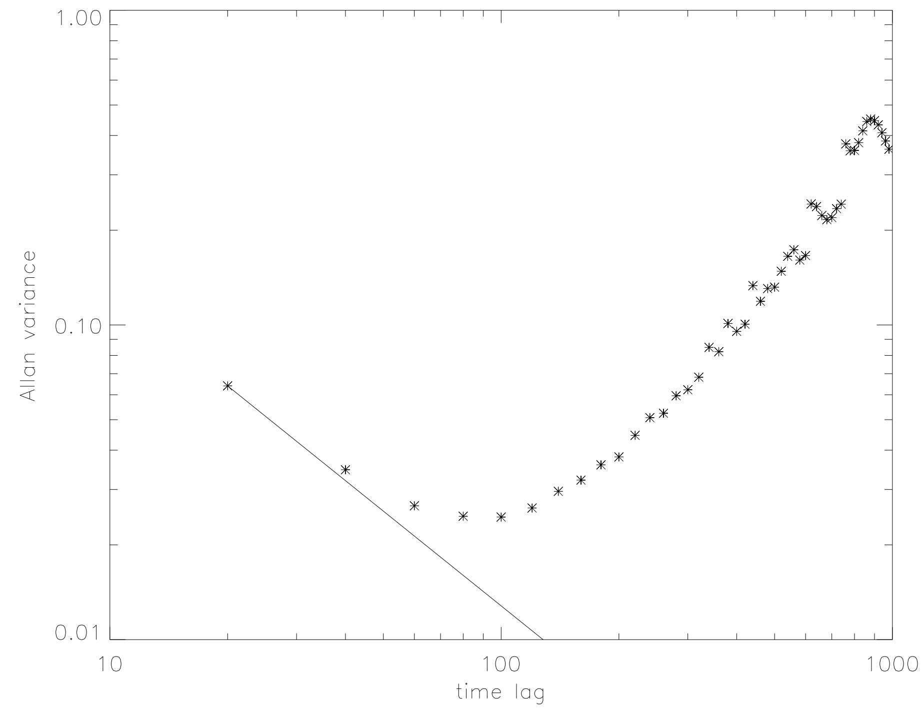


The Allan time as stability timescale

The drift timescale for the reference loop is the Allan minimum time t_A.

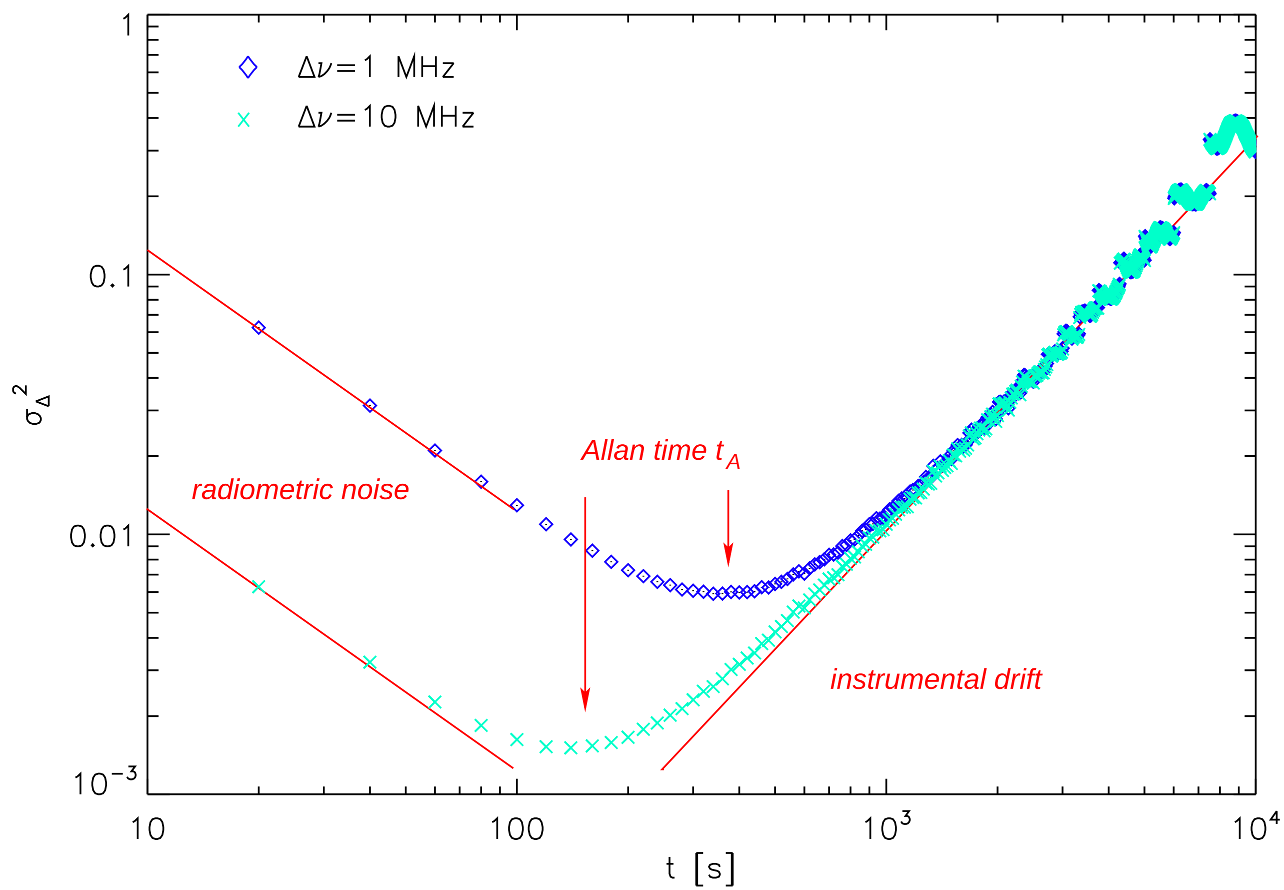


Typical instrument output (measured on a system temperature scale here) as a time sequency on the blank sky.



Allan plot measuring the variance depending on the time lag. The minimum of the Allan variance gives the Allan time. $t_A \approx 90s$ here.

The Allan time depends on the frequency resolution



- The minimum is given by the balance between radiometric noise and instrumental drift
- Radiometric noise depends on the fluctuation bandwidth
  → The loop timing depends on the desired frequency resolution of the observation

Observing mode timing

The duration and sequence of the calibration loops is determined by the mutual drift of the differences measured by the Allan minimum times:

- general system response: t_{A}
- difference between two frequency settings $t_{\mathrm{A,fs}}$
- difference between two chop positions $t_{\mathrm{A,chop}}$
- difference between load and sky $t_{\mathrm{A,load-sky}}$
- bandpass variation t_{load}

Problem: **Stability times not yet known $\Longrightarrow$ the loop hierarchy may change**

Composition of observing modes

Modular setup:

Pointing frame	Reference frame	Baseline calibration	Backend selection
single point raster map OTF map	total power sky chop load chop frequency switch	no baseline calibration OFF calibration dual beam switch	WBS HRS WBS+HRS

Reference frame problems:

- position switch is extremely slow
- frequency switch, load chop, and sky chop suffer from a possible variation of the system response between the source and the reference

Possible solutions by baseline calibration:

- OFF calibration or dual beam switch for sky chop
- double load or OFF calibration for frequency switch
- OFF calibration for load chop

Observing modes for AOTs

Basic observing modes in “HIFI Observing Modes Document”:

- based on the definition of ESA Herschel pointing modes
  - they contain already part of the reference frame
    $\Longrightarrow$ mutual exclusions with reference frames
- two different chop modes
  - the backend readout timing is different for chop frequencies above and below 0.5 Hz
- Frequency selection
- Each observing mode treated as an entity and not as composition of few building blocks

Full list of basic observing modes from the "HIFI Obsering Modes Document":

Observing options / Basic observing modes		Herschel pointing mode							Reference					Back-end		
	Preliminary Priority	Pointed observation	Position switching	Nodding (Double Beam Switch)	Raster pointing with OFF	Raster pointing without OFF	Line scanning (OTF) with OFF	Line scanning without OFF	Total power	Slow wobbler chop	Fast wobbler chop	Frequency switch	Load chop	Only HRS	Only WBS	Both backends
Staring − fast chop	1	✘								✘				?	✔	?
Staring − slow chop	5	✘									✘			✔	✔	✔
Staring − frequency switch	5	✘										✘		✔	✔	✔
Position switch	8		✘						✘					✔	✔	✔
Position switch − fast chop	1		✘							✘				✔	✔	✔
Position switch − slow chop	5		✘								✘			✔	✔	✔
Position switch − frequency switch	5		✘									✘		✔	✔	✔
Position switch − load chop	4		✘										✘	✔	✔	✔
DBS − fast chop	2			✘						✘				?	✔	?
DBS − slow chop	9			✘							✘			✔	✔	✔
Raster map with OFF	4				✘				✘					✔	✔	✔
Raster with OFF − fast chop	1				✘					✘				?	✔	?
Raster with OFF − slow chop	4				✘						✘			✔	✔	✔
Raster with OFF − frequency switch	4				✘							✘		✔	✔	✔
Raster with OFF − load chop	2				✘								✘	✔	✔	✔
Raster without OFF − fast chop	0					✘				✘				?	✔	?
Raster without OFF − slow chop	2					✘					✘			✔	✔	✔
Raster without OFF − freq. switch	2					✘						✘		✔	✔	✔
OTF map with OFF	9						✘		✘					✔	✔	✔
OTF with OFF − slow chop	5						✘				✘			✔	✔	✔
OTF with OFF − frequency switch	7						✘					✘		✔	✔	✔
OTF with OFF − load chop	5						✘						✘	✔	✔	✔

+ Additional high-level observing modes as predefined combinations of basic observing modes in a single observation.

The astronomical calibration

Different reference schemes require different astronomical calibration equations, e.g.

Total power:

$$J_{\mathrm{S,lines}} - J_{\mathrm{R,lines}} = \frac{\eta_{\mathrm{h}} + \eta_{\mathrm{c}} - 1}{\eta_{\mathrm{sf}}\eta_{\mathrm{l}}(G_{\mathrm{ssb}} + \frac{w_{\mathrm{ssb}}}{\gamma^{\mathrm{l}}_{\mathrm{rec}}})} \frac{c_{\mathrm{S}} - c_{\mathrm{R}}}{c_{\mathrm{hot}} - c_{\mathrm{cold}}} (J_{\mathrm{h,eff}} - J_{\mathrm{c,eff}}) - \frac{1 + (w_{\mathrm{ssb}} + w_{\mathrm{isb}})/\gamma^{\mathrm{l}}_{\mathrm{rec}}}{G_{\mathrm{ssb}} + w_{\mathrm{ssb}}/\gamma^{\mathrm{l}}_{\mathrm{rec}}} (J_{\mathrm{S,LO}} - J_{\mathrm{R,LO}}) \mp \frac{2G_{\mathrm{ssb}} - 1 + (w_{\mathrm{ssb}} - w_{\mathrm{isb}})/\gamma^{\mathrm{l}}_{\mathrm{rec}}}{G_{\mathrm{ssb}} + w_{\mathrm{ssb}}/\gamma^{\mathrm{l}}_{\mathrm{rec}}} (J_{\mathrm{S,LO}} b_{\mathrm{S}} - J_{\mathrm{R,LO}} b_{\mathrm{R}}) \nu_{\mathrm{IF}}$$

Load-chop:

$$J_{\mathrm{sky,lines}} = \frac{1}{(G_{\mathrm{ssb}} + \frac{w_{\mathrm{ssb}}}{\gamma^{\mathrm{l}}_{\mathrm{rec}}})} \Bigg[\frac{\eta_{\mathrm{h}} + \eta_{\mathrm{c}} - 1}{\eta_{\mathrm{l}}} \frac{(c_{\mathrm{S}} - c_{\mathrm{cold}}) - (c_{\mathrm{OFF}} - c_{\mathrm{cold}})}{c_{\mathrm{hot}} - c_{\mathrm{cold}}} (J_{\mathrm{h,eff}} - J_{\mathrm{c,eff}}) - J_{\mathrm{sky,LO}} \left(1 + \frac{w_{\mathrm{ssb}} + w_{\mathrm{isb}}}{\gamma^{\mathrm{l}}_{\mathrm{rec}}}\right) + J_{\mathrm{R,eff}} \mp \left(2G_{\mathrm{ssb}} - 1 + \frac{w_{\mathrm{ssb}} - w_{\mathrm{isb}}}{\gamma^{\mathrm{l}}_{\mathrm{rec}}}\right) \nu_{\mathrm{IF}} J_{\mathrm{sky,LO}} b_{\mathrm{sky}} \pm (2G_{\mathrm{ssb}} - 1)\nu_{\mathrm{IF}} J_{\mathrm{R,LO}} b_{\mathrm{R}} \Bigg]$$

Summary

- The calibration of all HIFI observing modes is a challenging task.
- Each observing mode includes already standard calibration measurements, i.e. the load calibration and possibly a standing wave measurement.
- The problem of standing waves between the subreflector and the receiver can be solved by means of a separate OFF calibration measurement.
- An essential input to set up the schedule for the observing modes are the different stability times. Their determination is a crucial calibration measurement for all observing modes.
- A long list of modes results from the combination with the uncertainties in the stability of the instrument and the possible compromises to obtain reliable data from an unstable instrument.
- Even within each single observing mode the exact scheduling depends critically on the desired frequency resolution.