Netherlands Institute for Space Research

HIFI Calibration Overview

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on behalf of the HIFI ICC

OSO/SRON

Herschel Calibration Workshop 25–27 March 2013

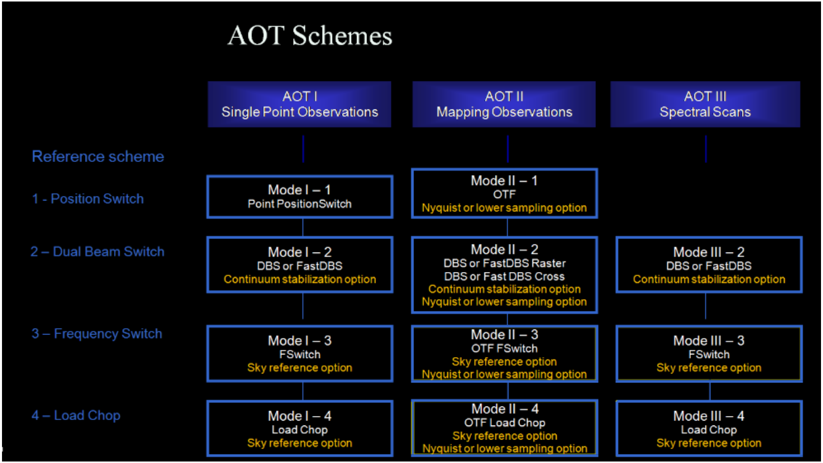
HIFI properties

- seven independent mixer bands × two polarizations
- 480–1250 and 1410–1910 GHz (625–240 and 213–157 microns)
- bands 1–5 use SIS mixers, 6 and 7 use HEB mixers
- bands 1,2 and 5 use beam splitters, bands 3,4 and 6,7 use diplexer for coupling to LO signal
- large instantaneous bandwidth of 4 GHz (2.4 GHz in HEB bands)
- 12 GHz sideband separation, DSB operation
- one WBS (acousto-optic spectrometer) and HRS (correlator) per polarization
- very high spectral resolution: 1 MHz up to 140 kHz
- two internal calibration loads
- point, mapping and frequency scan observing modes using different referencing schemes

References

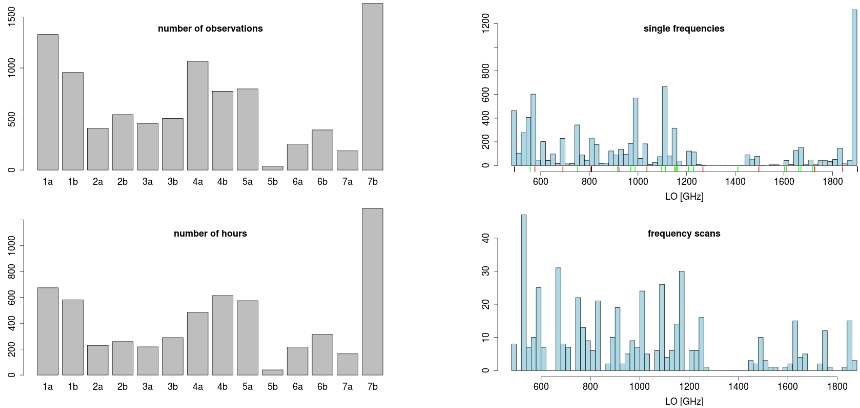
- Roelfsema et al. 2012, *In-orbit performance of Herschel-HIFI*, A&A 537, A17.
- Morris et al. 2010, *HIFI AOT Observing Mode Release and Performance Notes*
- Herschel Calibration Workshop – 18-20 January 2012
  - HIFI flux and wavelength calibration: methods (Volker Ossenkopf)
  - HIFI flux and wavelength calibration: implementation† (David Teyssier)
- Open Calibration Workshop – 25-27 March 2013
  - Sideband ratio assessment for HIFI (Higgins)
  - From the optical characteristics of HIFI to in-orbit flux calibration using Mars (Jellema)
  - Optical models for HIFI (Delforge)

† *In theory, theory and practice are the same; in practice, they are not!*



- tested for a large number of astronomical settings
- released successively
- timing optimized via HIFI sequencer
- performance in agreement with HSPOT predictions

Statistics



- Observations cluster around transitions of H_2O, CO and C.

Accuracy of frequency calibration

- 10 MHz master oscillator:
  temperature controlled to $10^{-8} \rightarrow$ 20 kHz at 2 THz; thermal control of the crystal used in the master clock is unstable, but this has no impact.
- the various LOs and clocks are locked to the 10 MHz master
- exception:
  - HEB IF up-converter free-running 10.4 GHz DRO:
    stabilized to $< 1\,\mathrm{ppm}/^\circ\mathrm{C} \rightarrow \approx 10\,\mathrm{kHz}$
  - on-board frequency uncertain to $\approx$ 30 kHz
- spectral purity
  - the LO chain multipliers can oscillate under certain circumstances and create spectral ghosts
  - can appear as more or less narrow *spur*; treated in uplink and downlink
  - can contribute as *leak* at wrong frequency

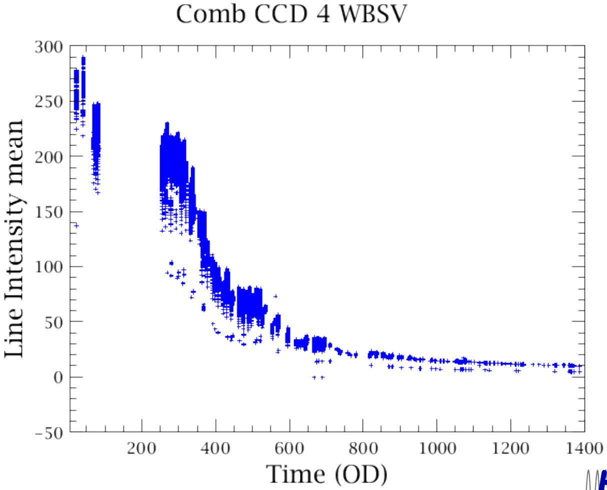
Backends

- HRS
  - frequency calibration relies on accuracy of the master oscillator
  - spectral resolution $\approx$ 125 kHz
  - relative accuracy within 50 kHz
- WBS
  - frequency calibration based on internal comb measurement, which in turn depends on master clock
  - spectral resolution $\approx$ 1.1 MHz
  - relative accuracy within 100 kHz (dominated by comb solutions)

From the AOT performance document:

The user can expect that frequencies, as presented in any of the three defined frames (LSR, SSBC, geocentric and spacecraft), are absolutely correct to the relative accuracies given above.

WBS-V shows decaying comb output power, but appears to last until end of mission; alternative scheme based on cross correlation with HRS exists.



Fundamentals of HIFI flux calibration

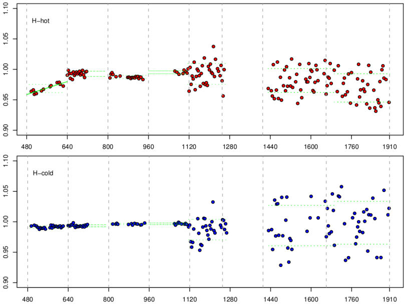
$$J_S - J_R = \frac{\eta_c + \eta_h - 1}{\eta_{sf}(\eta_l G_{ssb} + \omega_{ssb})} \cdot \frac{c_S - c_R}{c_h - c_c} \cdot (J_h - J_c)$$

- three point calibration: cold and hot load, blank sky
- HIFI is double sideband instrument, no reference line sources
- continuum: superposition of sidebands
- simplifications
  - assume linear response and linear superposition
  - split between rapidly varying bandpass and slowly varying efficiencies
  - neglect sideband imbalances for coupling factors and receiver noise

Load temperatures and coupling

$$J_S - J_R = \frac{\eta_c + \eta_h - 1}{\eta_{sf}(\eta_l G_{ssb} + \omega_{ssb})} \cdot \frac{c_S - c_R}{c_h - c_c} \cdot (J_h - J_c)$$

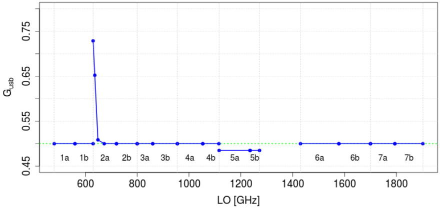
- load coupling coefficients
  - only measurable in ILT
  - measurement cycles not fast enough given continuum stability
  - large error bars in HEB bands
  - standing wave not calibrated out
- load temperatures
  - measured as HK telemetry
  - accuracy is given by sensor
  - hot load at 100 K
  - cold load at 12–13 K (FPU)



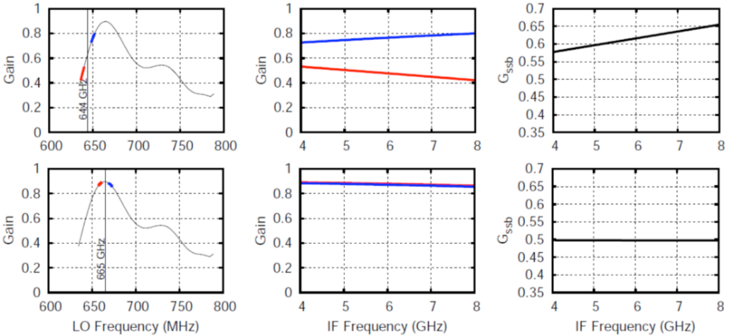
Sideband gains

$$J_S - J_R = \frac{\eta_c + \eta_h - 1}{\eta_{sf}(\eta_l G_{ssb} + \omega_{ssb})} \cdot \frac{c_S - c_R}{c_h - c_c} \cdot (J_h - J_c)$$

- relying mostly on ILT gas-cell campaign
- accuracy did not meet the 1% expectation (stability, diplexer mis-alignment, etc)
- on-going effort to revisit gas-cell output and validate SBR deviation from unity with science data (spectral scans)



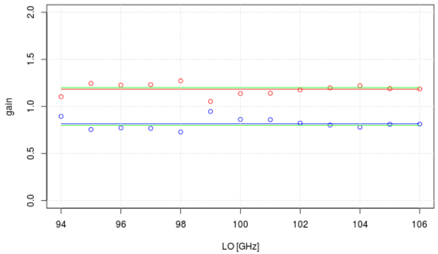
$$R = \frac{G_{usb}}{G_{lsb}} \quad \text{and} \quad G_{usb} = 1 - G_{lsb}$$



- connection between mixer response and slope over IF
- frequency-dependent transmission response of diplexers
- correction needed in areas of impure LO; documented e.g. for particular frequencies in band 5a and 3b.

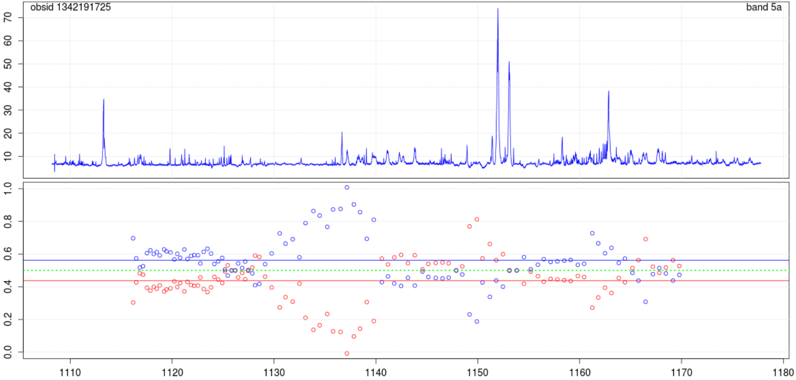
Numerical experiments

In principle, the deconvolution allows to treat the sideband gains as free parameters when retrieving the SSB spectrum.



- simulated data: constant, unequal gains
- offset appears to be retrievable

Test with real data, spectral scan of Orion KL in band 5a



Test with real data, spectral scan of Orion KL in band 5a

But naive approach doesn't work!

see presentation by Ronan Higgins

Standing waves

$$J_S - J_R = \frac{\eta_c + \eta_h - 1}{\eta_{sf}(\eta_l G_{ssb} + \omega_{ssb})} \cdot \frac{c_S - c_R}{c_h - c_c} \cdot (J_h - J_c)$$

Assumptions:

- Standing waves modulate contributions from astronomical source, telescope and receiver
- standing waves are stable
- pipeline will correct for standing waves using sky reference

Reality:

- gain standing waves (IF path, LO standing waves) unstable
- standing waves to loads, i.e. frequency dependence of $\eta_{h,c}$ large
- model for sideband separation in standing waves?
- thermalisation of LO drives stability

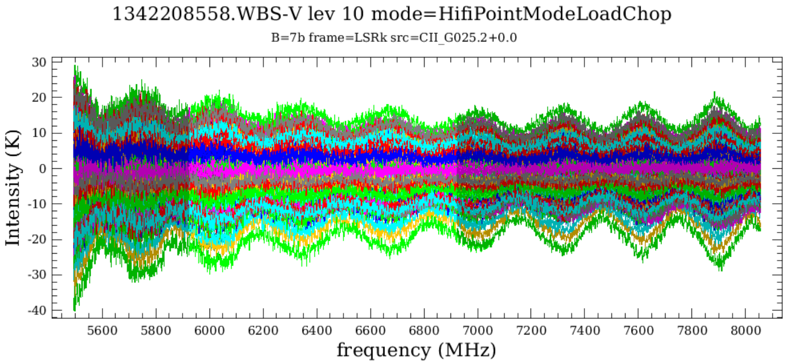
Table: Optical standing waves in HIFI

standing wave path	distance [mm]	frequency [MHz]
CBB–mixer	≈1530	98
HBB–mixer	≈1625	92
LO–mixer	≈1490	100
RTM–mixer*	≈240	620
secondary–mixer	≈4160	35

* only bands 3, 4, 6 and 7

- knowledge of periods allows smoothing of load and OFF
- HEB bands show additional standing waves in LO-mixer path
- reflections towards secondary not seen in HIFI data

Electrical standing waves in HEB bands



- strong variation seen, including drifts in baseline level
- idea:
  - build database over standing wave patterns
  - develop matching technique to remove patterns
  - see poster by Ian Avruch

Table: Optical standing waves, approximate relative error contributions

period (MHz) source band	92 & 96 CBB & HBB (%)	100 LO (%)	620 RTM (%)	overall impact (%)
band 1	3–4	< 1	–	4
band 2	3–4	< 1	–	4
band 3	1–2	2–4	1–2	4
band 4	1–2	2–4	1–2	4
band 5	1	3	–	3
band 6	< 1	3	–	$3^{\dagger}$
band 7	< 1	3	–	$3^{\dagger}$

†In HEB bands excursions up to 25% due to LO-mixer standing waves!

see presentation by Bertrand Delforge

Source coupling

$$J_S - J_R = \frac{\eta_c + \eta_h - 1}{\eta_{sf}(\eta_l G_{ssb} + \omega_{ssb})} \cdot \frac{c_S - c_R}{c_h - c_c} \cdot (J_h - J_c)$$

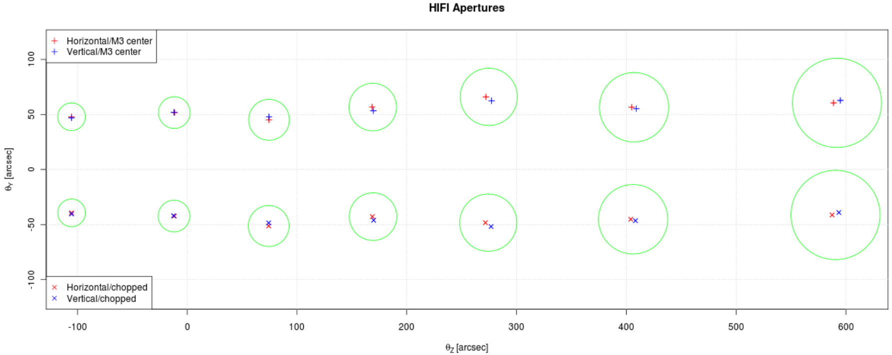
$$T_A^*(\theta, \phi) = \frac{1}{\eta_l \Omega_A} \int_S P(\theta - \theta', \phi - \phi')\, J_\nu(T_B)\, \psi(\theta', \phi')\, d\Omega'$$

Two different efficiencies relevant:

- point sources: aperture efficiency η_A
- extended sources: main beam efficiency η_{mb}
- both efficiencies represent idealized cases, there are no good calibrators to measure them directly

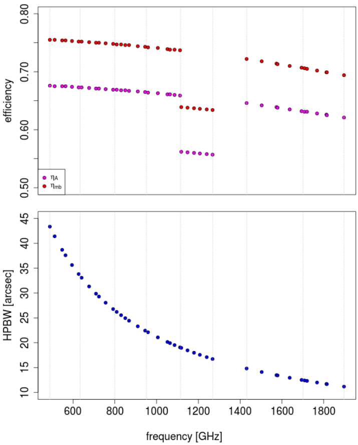
Aperture and main beam efficiency are coupled via beam size:

$$\eta_{mb} = \eta_A \frac{A_{geom}\Omega_{mb}}{\lambda^2}$$



- HIFI observations use synthesized beam (between H and V)
- coupling loss largest in band 3, very small in HEB bands

HIFI beam characterization



- using Mars as calibration source
- beamwidths in very good agreement with predictions based on telescope parameters
- aperture efficiencies agree with ILT measurements (propagated to the sky by a telescope model)
- deviations in band 5 due to "monocle"
- need to go beyond Gaussian beams, properly include truncation and blockage, address side lobes

see presentation by Willem Jellema

Standard Source Observations

- since cycle 40, standard sources are routinely observed by HIFI
  - end-to-end check of HIFI performance and calibration
  - check on flux/frequency repeatability + pointing
  - xcal with PACS+SPIRE and/or other observatories
  - 1–2 sources per cycle, taking typically 2 hr/cycle
  - lines: CO 6-5, 8-7, 10-9, 13-12, 16-5; CII (or subset thereof)
- two types of standard sources
  - point sources (mostly AGB stars), 3x3 raster maps
  - extended sources: OTF maps

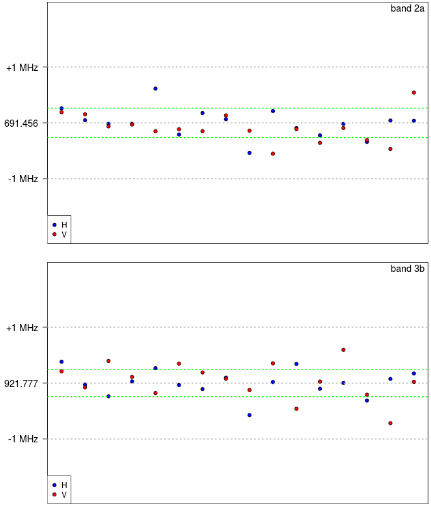
Table: 3 × 3 maps done by HIFI during routine phase

source	cycle
CRL 618	46, 62, 72, 74
CRL 2688	51, 55, 64, 80
EP Aqr	40, 53
IRC +10216	41, 51, 67, 79
NGC 6302	48, 60, 73, 75, 86
NGC 7027	43, 52, 63, 81
o Ceti (Mira)	44, 59, 69, 84
R Dor	42, 47, 53, 57, 61, 63, 65, 67, 69, 71, 73, 75, 77, 79, 81, 83, 85, 87
VY CMa	40, 49, 65, 76

Table: OTF maps done by HIFI during routine phase

source	cycle
G 34.3	50, 61, 63, 76
NGC 7023	41, 45, 50, 54, 58, 62, 66, 68, 70, 72, 74, 78, 80, 82, 84
Orion KL	60, 74, 87
S 140	45, 56, 71, 83
W 49 N	49, 64, 77

R Dor



- standard deviation of fitted line center frequency well within WBS resolution bandwidth ($\approx$ 1 MHz)

R Dor

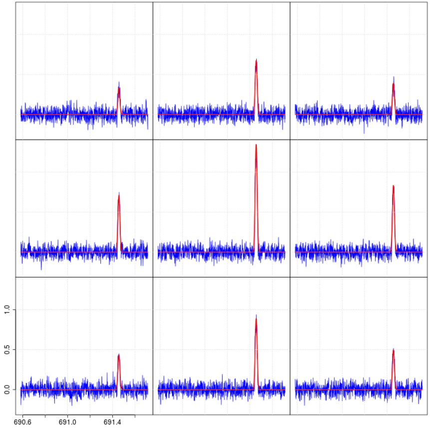
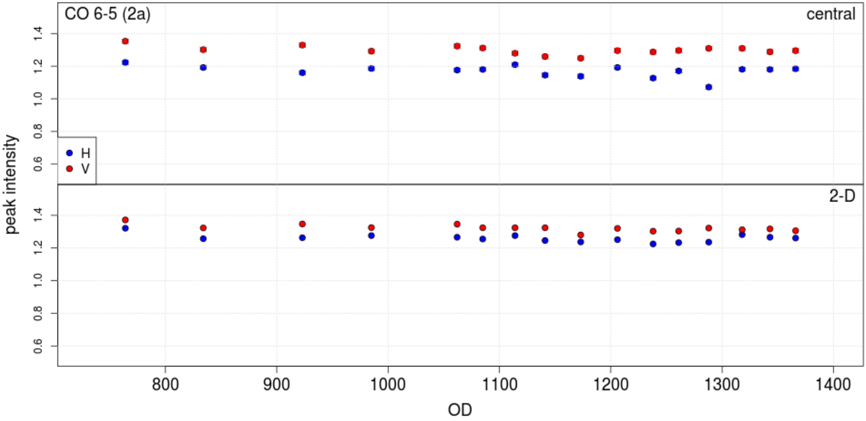


Figure: CO 6–5 map, V-polarization

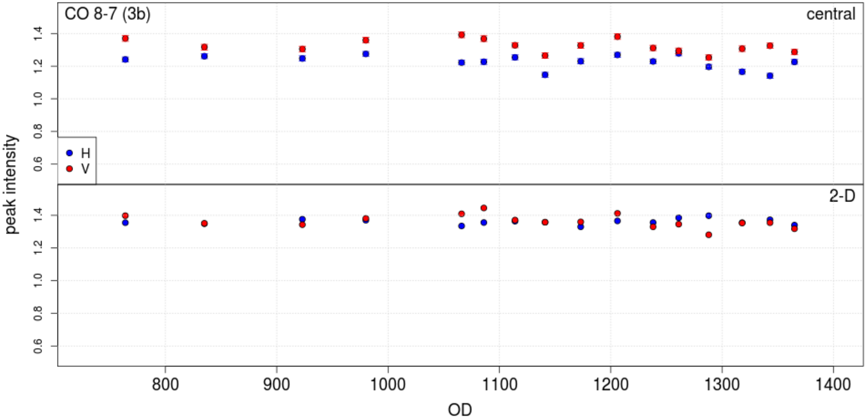
- look at central pixel
  - fit Gaussian profiles
  - get amplitude of central spectrum
- look at 2-D map
  - fit intensity distribution
  - retrieve fitted amplitude towards source

R Dor



- some H-V discrepancy remains in band 2 ...

R Dor

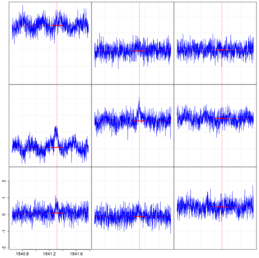


- ... but not in band 3

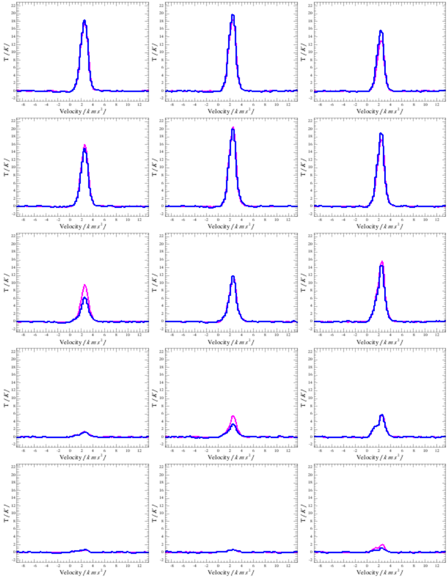
R Dor

band	mean H	mean V	stddev H	stddev V
2a	1.26	1.32	0.02	0.02
3b	1.36	1.36	0.02	0.04
5a	1.21	1.21	0.10	0.11
6a	1.23	1.30	0.08	0.14
7b	1.11	0.99	0.14	0.19

- HEB measurements harder to analyze due to standing wave effects
- example: band 7b, CO 16–15
- analysis ongoing



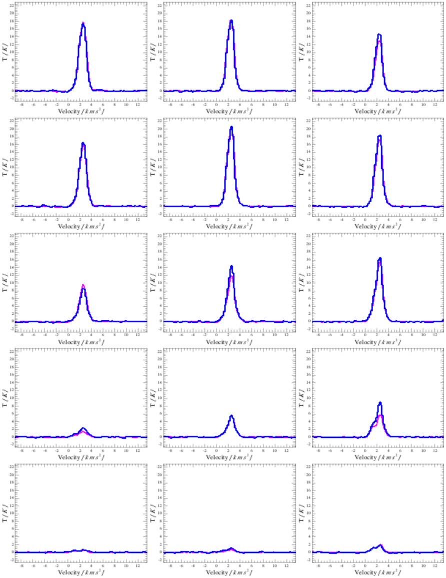
NGC 7023



- repeated OTF maps
- data regridded onto common grid
- observed in 4 CO lines (bands 2a, 3b, 5a and 6a) and in C+ (band 7b)
- here: CO 6-5 (H-polarization)
- deviations from median seen in various map positions

map 1

NGC 7023



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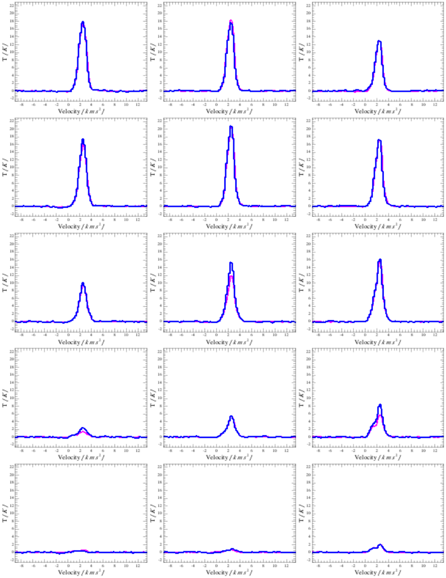
map 2

NGC 7023



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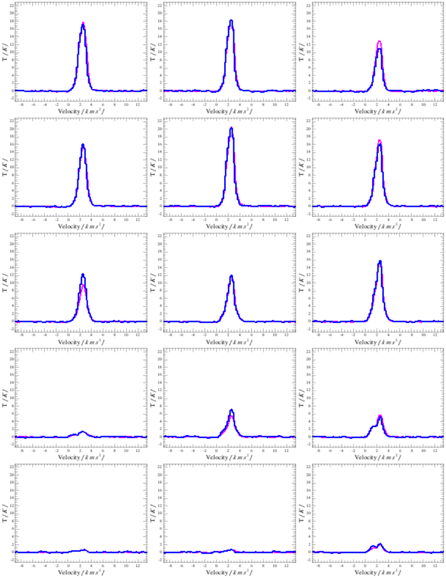
map 3

NGC 7023



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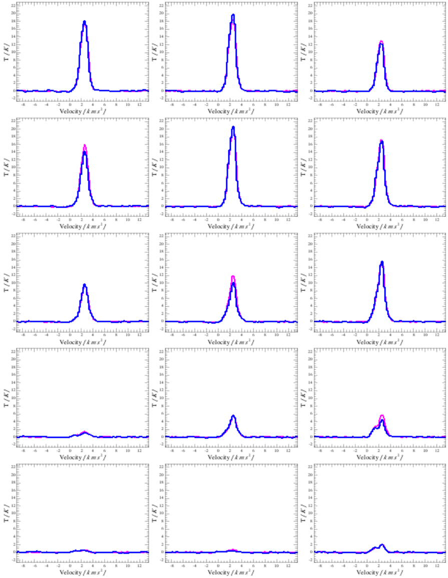
map 4

NGC 7023



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map 5

Table: Relative calibration error budget (Roelfsema et al.)

error source	HIFI mixer band			
	1 & 2	3 & 4	5	6 & 7

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error source	**1 & 2**	**3 & 4**	**5**	**6 & 7**
hot load coupling	< 1	< 1	< 2	< 3
cold load coupling	< 1	< 1	< 2	< 3
hot load temperature	< 1	< 1	< 1	< 1
cold load temperature	< 1	< 1	< 1	< 1

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cold load temperature	< 1	< 1	< 1	< 1
pointing	< 1	< 3	< 4	< 8

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planetary model	< 5	< 5	< 5	< 5

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sideband ratio	3–4	4–6	4	5–8

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pointing	< 1	< 3	< 4	< 8
planetary model	< 5	< 5	< 5	< 5
sideband ratio	3–4	4–6	4	5–8
opt.standing waves	4	4	3	3
beam efficiency	< 5	< 5	< 10	< 5

Post-operations

Table: selected HIFI Post-Op work-packages

package	description
3.1.3	optical standing wave (SW) model
3.1.4	implementation of SW mitigation
3.1.6	sideband ratio
3.1.7	beam properties
3.1.13	error computation, propagation, consistency