HIFI spectroscopic flux calibration

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Introduction

Relevant documentation:

- *HIFI Observers' Manual*, HERSCHEL-HSC-DOC-0784
- *The intensity calibration for HIFI*, V. Ossenkopf, ALMA Memo 442.1
- *HIFI Observing Modes Calibration Document*, V. Ossenkopf and A. Marston, ICC/2003-010

HIPE internal documentation:

- *The HIFI User's Manual*, C. McCoey et al, HIPE Help System
- *HIFI Pipeline Specification*, D. Kester et al, HIPE Help System

HIFI properties

- no atmosphere
- seven independent mixer bands $\times$ 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

Phases of integration

Zero dark current of CCD; WBS only

Cold Load cold calibration load at $T_C \approx 13\,\mathrm{K}$ with coupling $\eta_C \approx 1$

Hot Load hot calibration load at $T_H \approx 100\,\mathrm{K}$ with coupling $\eta_H \approx 1$

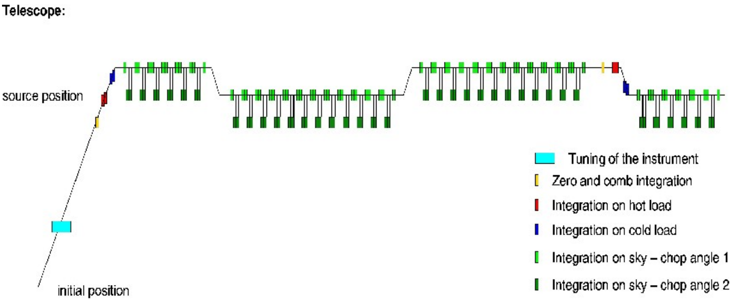
Cold Sky spectrum taken towards empty sky (*REF*)

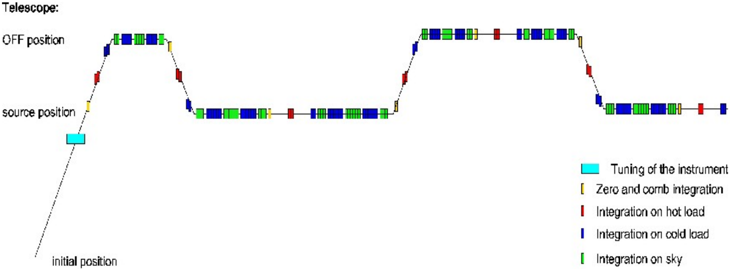
- for frequency switched data, an on-source observation at a second frequency is taken as *REF*
- for load chopped data, the cold load serves as *REF*

On Source spectrum taken towards source (*SIG*)

Off Source additional observations for baseline correction (*OFF*)

Timing


Telescope:
source position
initial position
Tuning of the instrument
Zero and comb integration
Integration on hot load
Integration on cold load
Integration on sky – chop angle 1
Integration on sky – chop angle 2


Telescope:
OFF position
source position
initial position
Tuning of the instrument
Zero and comb integration
Integration on hot load
Integration on cold load
Integration on sky

Pointing

7 mixers × 2 polarisations × 2 LO sub-bands × 2 chopper positions = 56 entries

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

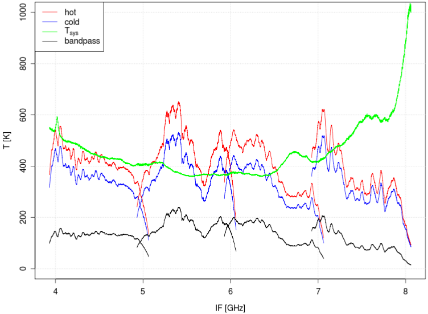
$$
J_{rec} = \frac{\left(\eta_h + Y\eta_c - Y\right)J_{h,eff} - \left(\eta_h + Y\eta_c - 1\right)J_{c,eff}}{Y-1} \approx \frac{J_{h,eff} - YJ_{c,eff}}{Y-1}
$$

$$
Y = \frac{c_{hot} - z}{c_{cold} - z} \qquad J_{eff} = G_{ssb}J_{ssb} + (1 - G_{ssb})J_{isb} \qquad G_{ssb} = \frac{\gamma_{ssb}}{\gamma_{ssb} + \gamma_{isb}}
$$

symbol	*explanation*
c	spectrometer count rate
γ	bandpass
η	efficiency
G	sideband gain
J	radiation intensity (temperature)

System temperature

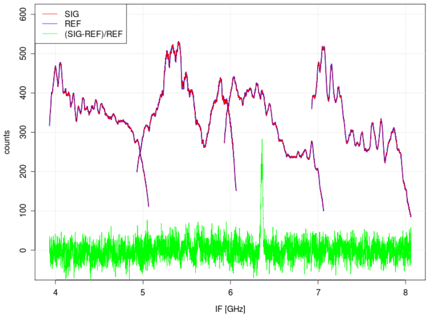
- use measurements towards hot and cold calibration loads
- calculate Y-factor: $Y = \frac{\text{hot}}{\text{cold}}$
- translate to Rayleigh-Jeans: $T_C \rightarrow J(T_C)$, $T_H \rightarrow J(T_H)$
- calculate $T_{sys} \approx \frac{J(T_H) - J(T_C)Y}{Y - 1}$
- coupling efficiencies to loads enter
- T_{sys} typically varying significantly over IF-band
- usually average T_{sys} over IF is quoted



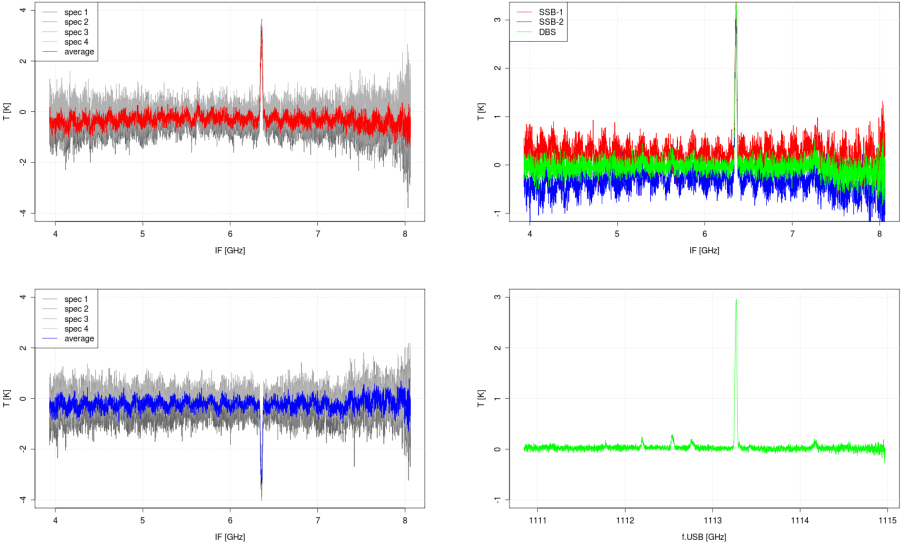
$$J(T) \equiv T_{RJ} = \frac{h\nu}{k} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

SIG-REF Switching

- line emission typically adds tiny amount to overall signal
- in case of no continuum, the contrast between *SIG* and *REF* is expected to be very small
- some modes “less symmetric”: frequency switching, load chop which may introduce baseline ripple
- double differencing techniques used to improve baseline quality, e.g. DBS switching or additional OFF measurements



Averaging



spec 1
spec 2
spec 3
spec 4
average
T [K]
IF [GHz]
SSB-1
SSB-2
DBS
spec 1
spec 2
spec 3
spec 4
average
f.USB [GHz]

Level 0 to 0.5

Level 0 pipeline

- DoHkCheck
- DoPointingTask

HRS pipeline

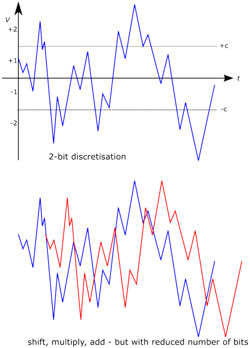
- DoHrsSubbands
- DoHrsOffsetPow
- DoHrsNorm
- DoHrsQDCFull
- DoHrsPowCorr
- DoHrsWindow
- DoHrsSymm
- DoHrsFFT
- DoHrsSmooth
- DoHrsFreq
- DoHrsCorrSP
- DoHrsCutBandEdges

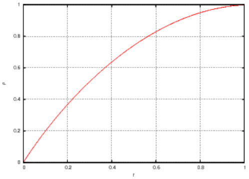
WBS pipeline

- DoWbsScanCount
- DoWbsBadPixels
- DoWbsDark
- DoWbsNonLin
- DoWbsZero
- DoWbsFreq
- DoWbsSubbands

⇒ Level 0.5:
all backend specific calibrations done

Principle of an auto-correlator





- FFT of auto-correlation function yields wanted power spectrum
- measured correlation coefficients $r(\tau)$ need to be corrected for effect of discretisation to get true coefficients $\rho(\tau)$:

$$r(\tau) = \frac{2}{\pi} \int_0^{\rho(\tau)} \frac{1}{\sqrt{1-x^2}} \exp\left(-\frac{c^2}{(1+x)}\right) dx$$

- $\rho(\tau) = Ar - \frac{(c^2-1)^2}{6}(Ar)^3$ for $|\rho| < 0.86$
- use the fact that $r(\tau) \propto \rho(\tau)$ for small $\rho(\tau)$

Level 0.5 to 1

• CheckDataStructure	
• CheckFreqGrid	
• CheckPhases	
• MkFluxHotCold	compute system temperature/bandpass
• DoChannelWeights	
• DoRefSubtract	subtract reference from signal
• MkOffSmooth	
• DoOffSubtract	subtract OFF for baseline correction
• DoFluxHotCold	transform to units of Kelvin, i.e. $\rightarrow T'_A$
• DoVelocityCorrection	
• DoRadialVelocity	

Level 1 to 2

- DoCleanUp
- DoAntennaTemp — convert $T'_A \rightarrow T^*_A$
- MkSidebandGain — calculate sideband gains…
- DoSidebandGain — …and apply
- ConvertFrequencyTask
- MkFreqGrid
- DoFreqGrid
- DoAverage — calculate weighted average
- DoFold
- DoSpurs
- DoStitch

Theoretical framework

Antenna and main beam temperature scales:

$$T_A^* = \frac{1}{\eta_l} T_A' \Rightarrow T_{mb} = \frac{\eta_l}{\eta_{mb}} T_A^* = \frac{1}{\eta_{mb}} T_A'$$

temperature and flux density from a point source:

$$T_A^* = \frac{\eta_A}{\eta_l} \frac{S_{\nu,tot} A_{geom}}{2k} K = \left(\frac{\eta_A}{\eta_l} \frac{A_{geom}}{2k} \right) (S_{\nu,tot} K) = \frac{1}{\chi_{PSS}} S_{\nu,beam}$$

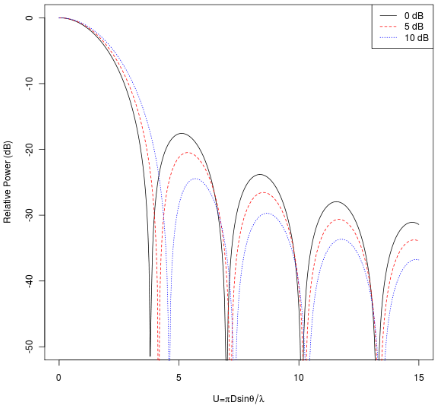
with point source sensitivity χ_{PSS} (≈ 460 K/Jy), flux density per beam $S_{\nu,beam}$ and where K describes a correction for non point-like sources:

$$K = \frac{\int_{source} P \Psi d\Omega}{\int_{source} \Psi d\Omega} = \begin{cases} \frac{1}{1+x^2} & x = \frac{\theta_s}{\theta_b} \quad \text{for Gaussian source} \\ \frac{1-\exp(-x^2)}{x^2} & x = \frac{\phi \ln 2}{\theta_b} \quad \text{for disk source} \end{cases}$$

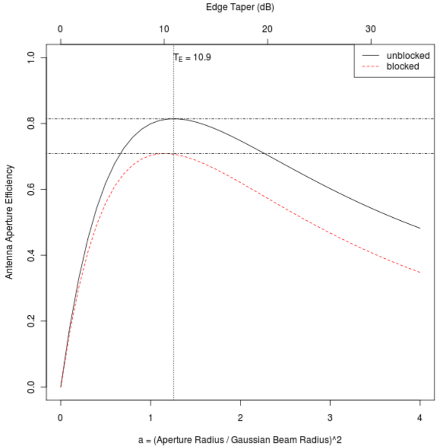
where Ψ is source distribution, P is beam pattern

Theoretical expectations

- theoretical beam profiles for different edge taper



- theoretical aperture efficiency and blockage



Validation against ground based telescopes

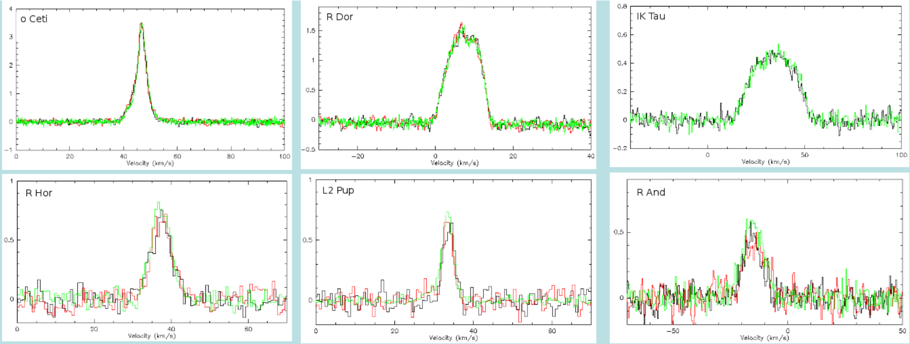
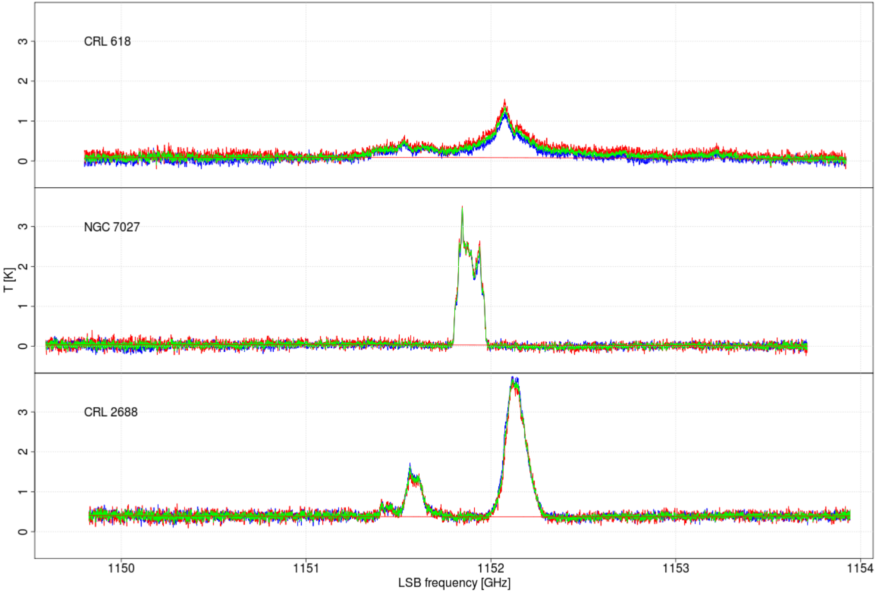
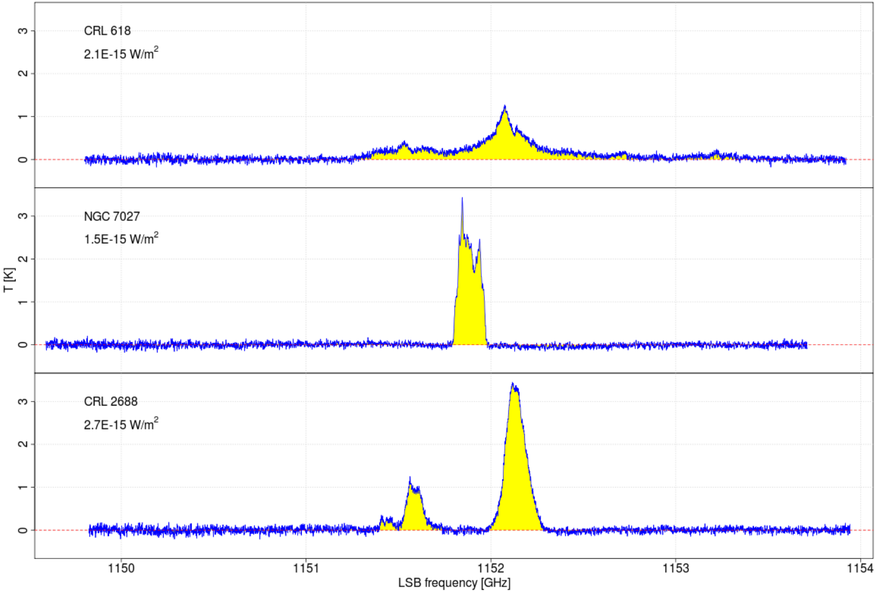


Figure: Measurements performed with HIFI of 6 AGB stars, in the CO(6-5) transition at 691 GHz. Black and red: HIFI, green: APEX


CRL 618
NGC 7027
CRL 2688
T [K]
0
1
2
3
1150
1151
1152
1153
1154
LSB frequency [GHz]


CRL 618
2.1E-15 W/m²
NGC 7027
1.5E-15 W/m²
CRL 2688
2.7E-15 W/m²
T [K]
0
1
2
3
1150
1151
1152
1153
1154
LSB frequency [GHz]

Ongoing work

- optimize pipeline for all switching schemes: matching techniques, order of operations
- understand H/V differences in terms of pointing, different beam efficiencies and/or sideband gains
- understand and treat baseline ripple (standing waves)
- derive a less pessimistic upper limit on sideband gain uncertainties
- make HIFI beam maps available
- LO warm-up studies, stability