The Heterodyne Instrument for the Far-Infrared (HIFI) and its data

*D. Teyssier*

*ESAC*

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Outline

1. What was HIFI and how did it work
2. What was HIFI good for – science cases
3. The HIFI calibration scheme and its accuracy
4. The HIFI PSF
5. Top-level documentation
What was HIFI?

- The **HIFI** instrument used the principles of the **super-heterodyne** detection.
- In such a system, the sky signal (**RF**) is combined to that of a synthetic source (the **Local Oscillator – LO**) tuned to a very nearby frequency, in a non-linear electronic device (the **mixer**).
- The mixing of the two signals creates a **beat** of the two frequencies, that pulses at a much lower frequency (the **Intermediate Frequency – IF**), but holds the amplitude and phase of the original signal (**coherent detection**).
- This operation is called **down-conversion**, and is used in numerous domestic devices (radio, TV, etc).
What was HIFI (2) ?

- Intrinsically, the sky frequency domain down-converted from RF to IF is not unique: two spectral ranges at \([F_{LO} - F_{IF}]\) and \([F_{LO} + F_{IF}]\) are covered simultaneously.

- The two ranges are called the **Lower Side-Band** (LSB) and the **Upper Side-band** (USB) and the information they contain are folded onto each others, merged into what is called a **Double-Side-Band** (DSB) spectrum. **Single-Side Band** (SSB) systems can be designed by rejecting one side-band.

- The spectral resolution is ultimately limited by the LO stability, but in practice it is defined by the spectrometer (backend) used to sample the signal at the IF. It can be as high as \(R \sim 10^7 (\lambda/\Delta\lambda)\).

- The backend also sets the **instantaneous** spectral coverage.
HIFI main characteristics

- **Single pixel** on the sky, in **two polarizations**
- **7 mixer** bands (14 LO sub-bands) covering the **488-1272 GHz** (236-614 µm) and **1430-1902 GHz** (158-210 µm) tuning ranges

<table>
<thead>
<tr>
<th>LO (GHz)</th>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
<th>Band 4</th>
<th>Band 5</th>
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<tbody>
<tr>
<td>488</td>
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<td>1120</td>
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<tr>
<td>1272</td>
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<td>1430</td>
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<td>1700</td>
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<td>1902</td>
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</table>

- **Two types of spectrometers** were simultaneously available

<table>
<thead>
<tr>
<th>Spectrometer</th>
<th>Wide-Band Spectrometer (WBS)</th>
<th>High-Resolution Spectrometer (HRS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covers the whole IF (2.4 or 4 GHz)</td>
<td>Variable spectral resol.: 0.125, 0.25, 0.5 and 1 MHz (0.02–0.8 km/s)</td>
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<tr>
<td>Spectral resol.: 1.1 MHz (0.2–0.8 km/s)</td>
<td>IF coverage from 0.25 to 2 GHz</td>
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</tbody>
</table>

**LO Band 1-5 (GHz)**

- Band 1: 488
- Band 2: 640
- Band 3: 800
- Band 4: 960
- Band 5: 1120
- Band 6: 1272
- Band 7: 1430

** LO Band 6-7 (GHz)**

- Band 6: 1700
- Band 7: 1902

**FLO (GHz)**

- IF bandwidth: 4 GHz
  - Beam: 44” – 17”
- IF bandwidth: 2.4 GHz
  - Beam: 15” – 11”
The HIFI observing modes

1 – Position Switch
   - Mode I – 1: Point-PositionSwitch
   - Mode I – 2: DBS, FastChop-DBS

2 – Dual Beam Switch
   - Mode I – 2: DBS
   - Mode II – 2: DBS-Raster, FastChop-DBS-Raster, DBS-Cross, FastChop-DBS-Cross
   - Optional continuum optimisation

3 – Frequency Switch
   - Mode I – 3: FSwitch, FSwitch-NoReference
   - Mode II – 3: OTF-FSwitch, OTF-FSwitch-NoReference
   - Optional sky ref measurement

4 – Load Chop
   - Mode I – 4: LoadChop, LoadChop-NoReference
   - Mode II – 4: OTF-LoadChop, OTF-LoadChop-NoReference
   - Optional sky ref measurement

AOT I: Single Point Observations
AOT II: Mapping Observations
AOT III: Spectral Scan
HIFI and the *Herschel* spectrometers

Image credit: C. Pearson (RAL, SPIRE Instrument team)
With line widths sub-km/s to some tens of km/s, high resolution is the only way to distinguish otherwise blended lines and Hyper Fine Structure (HFS).

Resolving spectral profile allows to understand the dynamics of the observed regions (infall, outflows, P-Cygni, self-absorption, etc.)
The final HIFI products (from level2 upwards) are calibrated in the so-called $T_A^*$ intensity scale, and are so-called Single Sideband intensities.

- This scale is, however, HIFI-specific and cannot be directly compared to spectra obtained by other facilities – conversion to adequate scales/units are necessary for that (e.g. main beam temperature $T_{mb}$, or flux densities Jy).
- Although HIFI data are primarily calibrated for line intensity, the continuum measured by HIFI can also be used with good accuracy.

**Space-craft radial velocity**

- The HIFI products have they frequency corrected from the space-craft velocity along the source line-of-sight.
- For fixed targets, it brings the frequency scale in the LSR.
- For moving targets, it brings the frequency scale in the frame of the target.
- Note that no products are given in velocity scale.

**USB/LSB scales**

- The HIFI pipeline creates two products: a USB and an LSB spectrum.
- The two products are not only mirror spectra of one another wrt the LO frequency – intensity calibration can vary in either side-band.
The **absolute** calibration accuracy varies with the band and frequency range:

- Conservative figures of **2-4%** in bands 1-5, and **5-6%** in bands 6-7 (random error), plus a systematic **5%** uncertainty due to planetary model.
- The **relative** calibration accuracy (**repeatability**) is in the range **3-10%**.
- The **continuum** calibration uncertainty will vary with the observing mode and the tuned frequency:
  - **Fast-referencing** schemes (DBS, Load-Chop) provide accurate measures of the continuum (\(~10\%\)), with degradation in the least-stable detector bands (bands 6-7) – **On-the-fly mapping** offers poorer accuracy.
  - **Frequency-switching** data **cannot** recover the continuum information.
## Calibration uncertainty and science-readiness

### Flux Uncertainty

<table>
<thead>
<tr>
<th>Absolute</th>
<th>Repeatability</th>
<th>Science Readiness of Standard Products</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bands 1 to 5 (SIS mixers)</strong> – goal 3%, baseline 10%</td>
<td>2-4% internal instrumental error (random) + 5% (systematic) Planet model</td>
<td>HIFI data intrinsically in an instrument-internal scale ($T_A^*$) – beam coupling losses to source need to be assessed by user</td>
</tr>
<tr>
<td></td>
<td>3-6% (point-source), reduced to 3% if pointing offset can be corrected</td>
<td>Majority of HIFI products are science-ready (modulo the above conversion)</td>
</tr>
<tr>
<td><strong>Bands 6 to 7 (HEB mixers)</strong></td>
<td>5-6% internal instrumental error (random) + 5% (systematic) Planet model</td>
<td>Main residual artefacts are baseline distortion (mostly standing wave), affecting ~20% of the standard products (2/3 being from point-mode observations)</td>
</tr>
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<td></td>
<td>11% (point-source), reduced to 9% if pointing offset can be corrected</td>
<td></td>
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</tbody>
</table>
**High-Resolution Spectrometer**
- Frequency calibration entirely relying on accuracy of the *master oscillator (master clock)*
- The frequency accuracy range from \( \sim 30 \) kHz (band 1) to \( \sim 150 \) kHz (band 7)

**Wide-Band Spectrometer**
- Frequency calibration based on regular internal *COMB measurement*. Accuracy of the COMB reference relies on the master oscillator
- COMB fitting allows frequency resolution accuracy of **100 kHz or better**
The HIFI beams (1)

- The HIFI beam can be approximated to first order to a 2-D Gaussian
  - In the real world, the PSF has extended side-lobes to the level of $\sim -17$ dB and below – *this can hold a significant fraction of the flux for extended emission, esp. at high frequencies*
  - Diffraction-limited HPBW range from **43''** down to **11.2''** at upper end of B7
  - Coupling efficiencies are band- and polarization-dependent

### HIFI coupling efficiencies

<table>
<thead>
<tr>
<th>Mixer</th>
<th>$f$ (GHz)</th>
<th>$\eta_{mb}$</th>
<th>$\eta_A$</th>
<th>HPBW (')</th>
</tr>
</thead>
<tbody>
<tr>
<td>1H</td>
<td>480</td>
<td>0.62</td>
<td>0.65</td>
<td>43.1</td>
</tr>
<tr>
<td>1V</td>
<td>480</td>
<td>0.62</td>
<td>0.63</td>
<td>43.5</td>
</tr>
<tr>
<td>2H</td>
<td>640</td>
<td>0.64</td>
<td>0.64</td>
<td>32.9</td>
</tr>
<tr>
<td>2V</td>
<td>640</td>
<td>0.66</td>
<td>0.66</td>
<td>32.8</td>
</tr>
<tr>
<td>3H</td>
<td>800</td>
<td>0.62</td>
<td>0.63</td>
<td>26.3</td>
</tr>
<tr>
<td>3V</td>
<td>800</td>
<td>0.63</td>
<td>0.66</td>
<td>25.8</td>
</tr>
<tr>
<td>4H</td>
<td>960</td>
<td>0.63</td>
<td>0.64</td>
<td>21.9</td>
</tr>
<tr>
<td>4V</td>
<td>960</td>
<td>0.64</td>
<td>0.65</td>
<td>21.7</td>
</tr>
<tr>
<td>5H</td>
<td>1120</td>
<td>0.59</td>
<td>0.54</td>
<td>19.6</td>
</tr>
<tr>
<td>5V</td>
<td>1120</td>
<td>0.59</td>
<td>0.55</td>
<td>19.4</td>
</tr>
<tr>
<td>6H</td>
<td>1410</td>
<td>0.58</td>
<td>0.59</td>
<td>14.9</td>
</tr>
<tr>
<td>6V</td>
<td>1410</td>
<td>0.58</td>
<td>0.60</td>
<td>14.7</td>
</tr>
<tr>
<td>7H</td>
<td>1910</td>
<td>0.57</td>
<td>0.56</td>
<td>11.1</td>
</tr>
<tr>
<td>7V</td>
<td>1910</td>
<td>0.60</td>
<td>0.59</td>
<td>11.1</td>
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</tbody>
</table>
Each polarisation (H/V) is measured by separate detection chains

- The aperture associated to each polarisation has its own alignment
- The H/V co-alignment is not strictly perfect and a slight mis-alignment exists for each mixer band
- In effect HIFI observes at the position of a synthetic aperture in the middle of the respective H/V aperture
- This allows to mitigate the differences due to pointing errors on a particular polarisation
- Separate positions are then assigned to each polarisation in the data processing
- You should bear this in mind if averaging H and V data for SNR improvement
- Can lead to significant H/V intensity imbalance
**On-line documentation**

- Herschel Explanatory Legacy Library (HIFI handbook, quick-start guide, etc):
  [http://www.cosmos.esa.int/web/herschel/legacy-documentation-hifi](http://www.cosmos.esa.int/web/herschel/legacy-documentation-hifi)

- HIFI cookbooks:

- The HIFI Data Reduction Guide:
  [http://herschel.esac.esa.int/hcss-doc-14.0/index.jsp#hifi_um:hifi-um](http://herschel.esac.esa.int/hcss-doc-14.0/index.jsp#hifi_um:hifi-um)

- The HIFI Calibration wiki page
  [http://herschel.esac.esa.int/twiki/bin/view/Public/HifiCalibrationWeb](http://herschel.esac.esa.int/twiki/bin/view/Public/HifiCalibrationWeb)

**Other references**

- “Tools of Radio-astronomie”, Rohlfs & Wilson, 2004
- Roelfsema et al., A&A 537, A17, “In-orbit performance of Herschel-HIFI”
QUESTIONS ?
THE FOLLOWING PROVIDES COMPLEMENTARY MATERIAL ABOUT THE HIFI CALIBRATION AND ASSOCIATED PIPELINE STEPS
The ultimate goal of the data calibration is to recover the original source signal from the total signal measured by the detectors.

The detection chain function involves (\textit{time-dependent}) transformations by the \textit{optics}, \textit{electronics}, and the \textit{environment} between the source and the telescope (esp. the atmosphere for ground-based facilities).
**HIFI Flux Calibration – a bit of maths**

- **HIFI** works with **differential signals**, allowing to cancel out to 1st order the telescope and instrument background (so-called $T_{rec}$).
- The instrument response is expressed as a **band-pass** function, measured on two internal (**hot** and **cold load**) black-bodies.
- As such, the HIFI data are calibrated as **brightness temperature** ($J_v = B_v(T)$).

$$J_{sou} - J_{OFF} = \frac{1}{\eta_{sou}\eta_l G_{inst}} [C_{sou} - C_{OFF}]$$

- **Source and reference brightness temperature** ($K$, Double-Side-Band)
- **Example of an HIFI band-pass function**
- **Source and reference counts**
- **Forward efficiency**
- **Source efficiency**

**Instrument response**

$$G_{inst} = \frac{C_h - C_c}{(\eta_h + \eta_c - 1)[J_h - J_c]}$$

**Coupling to the loads**

**Hot and cold load counts**
The HIFI calibration is thus based on a three points (hot, cold, blank sky OFF) measurement scheme

- Unlike for the ground-based radio-telescopes, the OFF is not used for atmosphere calibration, but rather for standing wave mitigation
- The rate at which those points are visited depends on the drift characteristics applying to each of the 14 detector bands

The standard HIFI products are calibrated on the so-called $T_A^*$ scale

- Calibration onto a single-sideband scale require correction from the side-band ratio (SBR)
- Source coupling correction depends on the source extent compared to the beam – many radio-astronomers convert their data into a main beam temperature:
  \[ T_{mb} = T_A^* \frac{\eta_I}{\eta_{mb}} \]
HIFI pipeline: Double Beam Switch ex. (1)

Pipeline steps for DBS observations:
Reference and OFF subtraction
HIFI pipeline: Double Beam Switch ex. (2)

1. **Total power**
   - Hot load
   - Cold load
   - Counts vs. IF Frequency (MHz)

2. **Double diff.**
   - Band-pass spectrum
   - ON-OFF Phase 1 – Phase 2
   - Band-pass corrected

3. **Double diff.**
   - ON-OFF Phase 1 – Phase 2

Pipeline steps for DBS observations:
- *bandpass calibration*

From previous step

**Level1**
Pipeline steps for DBS observations:
side-band calibration and average

Collection of all ON-OFF

Level2

All spectra in USB frequency scale

All spectra in LSB frequency scale

Level2 USB

Level2 LSB