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

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Outline

- What is HIFI and how is it working
- What is HIFI good for – science use cases
- How is HIFI calibrated and what are the accuracies
- The HIFI PSF
- Some references
What is HIFI? (1)

- The **HIFI** instrument uses 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 is 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 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>Band</th>
<th>Frequency (GHz)</th>
</tr>
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<tbody>
<tr>
<td>Band 1</td>
<td>488</td>
</tr>
<tr>
<td>Band 2</td>
<td>640</td>
</tr>
<tr>
<td>Band 3</td>
<td>800</td>
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<tr>
<td>Band 4</td>
<td>960</td>
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<td>Band 5</td>
<td>1120</td>
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<tr>
<td>Band 6</td>
<td>1272</td>
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<tr>
<td>Band 7</td>
<td>1430</td>
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<td>1700</td>
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</table>

- **IF bandwidth**: 2.4 GHz
- **Beam**: 15” – 11”

- **Two types of spectrometers**, simultaneously available
  - **Wide-Band Spectrometer (WBS)**
    - Covers the whole IF (2.4 or 4 GHz)
    - Spectral resol.: 1.1 MHz (0.2–0.8 km/s)
  - **High-Resolution Spectrometer (HRS)**
    - Variable spectral resol.: 0.125, 0.25, 0.5 and 1 MHz (0.02–0.8 km/s)
    - IF coverage from 0.25 to 2 GHz

- **HEB mixers**
- **SIS mixers**
The HIFI observing modes

<table>
<thead>
<tr>
<th>Referencing scheme</th>
<th>AOT I Single Point Observations</th>
<th>AOT II Mapping Observations</th>
<th>AOT III Spectral Scan</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Position Switch</td>
<td>Mode I – 1 (\text{Point-PositionSwitch} )</td>
<td>Mode II – 1 (\text{OTF} )</td>
<td>Mode III – 2 (\text{SScan-DBS} ) (\text{SScan-FastChop-DBS} )</td>
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<tr>
<td></td>
<td>Mode I – 2 (\text{DBS} ) (\text{FastChop-DBS} )</td>
<td>Mode II – 2 (\text{DBS-Raster} ) (\text{FastChop-DBS-Raster} ) (\text{DBS-Cross} ) (\text{FastChop-DBS-Cross} )</td>
<td>Mode III – 2 (\text{SScan-DBS} ) (\text{SScan-FastChop-DBS} )</td>
</tr>
<tr>
<td>2 – Dual Beam Switch</td>
<td>Mode I – 3 (\text{FSwitch} ) (\text{FSwitch-NoReference} )</td>
<td>Mode II – 3 (\text{OTF-FSwitch} ) (\text{OTF-FSwitch-NoReference} )</td>
<td>Mode III – 3 (\text{SScan-FSwitch} ) (\text{SScan-FSwitch-NoReference} )</td>
</tr>
<tr>
<td><em>Optional continuum optimisation</em></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>3 – Frequency Switch</td>
<td>Mode I – 4 (\text{LoadChop} ) (\text{LoadChop-NoReference} )</td>
<td>Mode II – 4 (\text{OTF-LoadChop} ) (\text{OTF-LoadChop-NoReference} )</td>
<td>Mode III – 4 (\text{SScan-LoadChop} ) (\text{SScan-LoadChop-NoReference} )</td>
</tr>
<tr>
<td><em>Optional sky ref measurement</em></td>
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<td></td>
<td></td>
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<tr>
<td>4 – Load Chop</td>
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<tr>
<td><em>Optional sky ref measurement</em></td>
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</tbody>
</table>

See also complementary information in the tutorials about mode specifics
HIFI and the Herschel spectrometers

Image credit: C. Pearson (SPIRE ICC)

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The Herschel spectrometers: resolution

Why does high-resolution spectroscopy matter?

- 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
- Resolving spectral profile allows to understand the dynamics of the observed regions (infall, outflows, P-Cygni, self-absorption, etc)
HIFI flux and frequency calibration

- 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 level2 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 the space-craft velocity along the source line-of-sight
  - For **fixed target**, 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 level2 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
HIFI flux calibration accuracy

- **HIFI flux calibration accuracy**
  - The *absolute* calibration accuracy varies with the bands and frequency ranges – the main contributors to the calibration errors are the *side-band ratio* and the accuracy of the *planetary models* used to derive efficiencies
  - Conservative figures of 5-10% in bands 1-2, 10-15% in bands 3-5 and 15-20% in bands 6-7
  - The *relative* calibration accuracy is still being assessed in details, but the flux repeatability of the HIFI data is usually good to better than 5-10%
  - The *continuum* calibration accuracy will mostly 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 continuum accuracy
    - *Frequency-switching* data *cannot* recover the continuum information

*See also complementary material at the end of this presentation*
**HIFI frequency calibration accuracy**

- **High-Resolution Spectrometer**
  - Frequency calibration entirely relying on accuracy of the *master oscillator*
  - The frequency accuracy range from ~30 kHz (band 1) to ~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 \(-17\) 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 polarisation-dependent
The HIFI Beams (2)

- **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**
Some references

• “Tools of Radio-astronomie”, Rohlfs & Wilson, 2004
• Roelfsema et al., A&A 537, A17, “In-orbit performance of Herschel-HIFI”
• Mueller et al. 2014, “The HIFI beam: Release #1 – release notes”
• Comito et al., A&A 395, 357, “Reconstructing reality: Strategies for sideband deconvolution”

On-line documentation

• HIFI observing mode cookbooks:
  http://herschel.esac.esa.int/hcss-doc-12.0/load/hifi_um/html/hdrg_cookbooks.html
• HIFI Data Reduction Guide:
  http://herschel.esac.esa.int/hcss-doc-12.0/index.jsp#hifi_um:hifi-um
• HIFI Calibration wiki page
  http://herschel.esac.esa.int/twiki/bin/view/Public/HifiCalibrationWeb
• Observing mode Release and Performance Notes
  http://herschel.esac.esa.int/twiki/pub/Public/HifiCalibrationWeb/HifiObservingModesPerformance_110926a.pdf
QUESTIONS ?
THE FOLLOWING PROVIDES COMPLEMENTARY MATERIAL ABOUT THE HIFI CALIBRATION AND ASSOCIATED PIPELINE STEPS
Data calibration: general concept (1)

• The ultimate goal of the data calibration is to recover the original source signal from the total signal measured by the detectors

\[ C = F [S_{sou} + S_{sky}] + C_{tel} + C_{inst} \]

• 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 (1)

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

- **HIFI** works with **differential signals**, allowing to cancel out to 1\(^{\text{st}}\) order the telescope and instrument background (so-called \( T_{\text{rec}} \)).
- 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** \([J_{\nu}=B_{\nu}(T)]\)

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

Source and reference brightness temperature (K, Double-Side-Band)

Source and reference counts

Instrument response

Example of an HIFI band-pass function

Coupling to the loads

Hot and cold load counts

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HIFI flux calibration (2)

- 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-side-band** 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**:
    
    $T_{mb} = T_A^* \frac{\eta_l}{\eta_{mb}}$

$$[J_{sou} - J_{OFF}]_{SSB} = \frac{[J_{sou} - J_{OFF}]_{DSB}}{G_{ssb}} \leftarrow \text{SBR}$$
The HIFI pipeline: DBS example (1)

**Pipeline steps for DBS observations:**
Reference and OFF subtraction

- **ON-source phase 1**
- **OFF-source phase 1**
- **ON-source phase 2**
- **OFF-source phase 2**

**Counts**

**Total power**

**Simple diff.**

- **ON-OFF phase 1**
- **ON-OFF phase 2**

**Double diff.**

**ON-OFF Phase 1 – Phase 2**

**Level0.5**

**Level1**

Counts

IF Frequency (MHz)

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The HIFI pipeline: DBS example (2)

Pipeline steps for DBS observations: bandpass calibration

From previous step

Level1

ON-OFF
Phase 1 – Phase 2
Band-pass corrected

Double diff.

Band-pass spectrum

Double diff.

Hot load
Cold load

Counts

IF Frequency (MHz)

5500 6000 6500 7000 7500 8000

Total power

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