

Herschel/HIFI In-flight Commissioning and Performance

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Abstract— The Herschel Space Observatory was successfully launched on the 14th of May, 2009, lifting into space the Heterodyne Instrument for the Far-Infrared (HIFI). After the standard early orbit operations on the Space-craft, the instrument was switched on for the first time on the 24th of May, kicking off an instrument Commissioning period of more than a month and a half. We present here the outcome of this Commissioning campaign, including the measured in-flight performance of the instrument. Among the challenges encountered during this period was the need to optimize the stability of the signal provided by the Local Oscillator (LO) chains in some of the frequency bands, in particular that covering the singly Ionized Carbon (C+) line at the upper edge of the HIFI range, and one of the backbones of the science program of the instrument. The same concept also allowed significant improvements in the upper end of the 3b LO chain. Another noticeable achievement was the very good co-alignment measured between the mixer beams in the respective H and V polarizations offered by HIFI, allowing for more than a simple build-in redundancy, as the observing efficiency will really benefit from the combination of the two mixers.

I. INTRODUCTION

Herschel [1] is the fourth ‘cornerstone’ mission in the ESA science programme. With a 3.5 m Cassegrain telescope it became on the 14th of May 2009 the largest space telescope ever launched. It allows photometry and spectroscopy observations in approximately the 55-672 μm range, bridging the gap between earlier infrared space missions and ground-based facilities. Aboard Herschel, the Heterodyne Instrument for the Far-Infrared (HIFI [2]) offers very high-resolution (up to $R > 10^7$) spectroscopy with a continuous coverage between 488 and 1272 GHz (SIS mixers), and 1430 and 1902 GHz

(HEB mixers), as well as a simultaneous coverage of up to 4 GHz with its two backend spectrometers (an Acousto-Optic Spectrometer, and a Digital Auto-correlation Spectrometer).

HIFI is suitable for investigating interstellar gas, for example in star-forming areas and in the gas expelled by dying stars. In the far-infrared and the submillimetre areas where HIFI is working, a wide range of molecules absorb radiation, including water. HIFI is suitable for capturing this radiation and can unravel it into a spectrum in which the characteristic fingerprints of all the different molecules can be seen. This instrument can be used to determine exactly what the gases are composed of and the temperature and pressure they are at. Furthermore, HIFI is highly suitable for measuring the speed of gas.

In this paper, we present the early phases of the HIFI operations that focussed on the Commissioning of the instrument, and the assessment of its performances.

II. THE HIFI COMMISSIONING CAMPAIGN

A. The Early Mission Phases

Immediately after its successful launch on the 14th of May 2009, Herschel entered the so-called Launch and Early Operation Phase (LEOP) during which most of the Spacecraft functionalities are verified. HIFI was switched on exactly 10 days after the launch, and started a Commissioning Phase which, shared with the other two instruments on-board Herschel (PACS and SPIRE), took about almost two months. About 440 hours of instrument data were collected during this phase.

The Commissioning Phase was immediately followed by a Performance Verification (PV) Phase, which concentrated on the validation of the various observing modes. This campaign was unexpectedly interrupted on August 2nd by a fatal failure of one of the warm electronic units controlling the Local Oscillator (LCU). We refer to [3] for more details about the mechanisms that lead to the loss of this unit. It took about 5 months of deep laboratory investigations, and preparation of an alternative operation scheme, before HIFI was started again on the 10th of January 2010, using its redundant electronics. A short regression-Commissioning campaign was performed, which confirmed the perfect health of the newly started instrument. As of today, HIFI is working nominally and the operation scheme designed to recover from similar upsets as the one that occurred on the Prime LCU has proven to be fully adequate.

B. The HIFI Commissioning Phase

The Commissioning campaign was broken down in the following way:

- **Instrument functional and health checks:** those tests were done immediately after the instrument power-on, and were dedicated to checking that all units had survived the launch. Of particular importance were the functional checks of the mechanical components of HIFI, namely the Martin-Pupplett assemblies used in the diplexer bands, and the internal chopper, which allows to observe various lines-of-sight on the sky at a fast rate, but also to couple the mixer beams to the internal calibration loads. Those activities were run in real-time contact with the instrument, from the European Space Operation Centre (ESOC) located in Darmstadt, Germany. The rest of the operations was run off-line, based on time-tagged sequences of telecommands uploaded on-board on a daily basis.
- **Instrument characterisation:** those measurements focussed on the characterisation of the instrument operation settings for optimum heterodyne performance (IF chain settings, mirror and diplexer settings, LO power tables, etc).
- **Instrument performances:** those measurements focussed on the parameters defining the figures of merit of HIFI as a heterodyne system (sensitivity, stability, standing waves, direct detection, etc). Those numbers are presented in the following section.
- **Instrument Astronomical Observing Template (AOT) pre-validation:** although the bulk of the observing mode validation was encompassed in the PV campaign, a subset of the so-called Astronomical Observing Templates (AOT) was needed in order to map the loci of the instrument apertures with respect to the Spacecraft pointing unit (i.e. the star trackers).
- **Focal Plane Geometry (FPG):** those measurements are necessary in order to relay the HIFI beam positions on the Herschel Focal Plane to the position of the Spacecraft boresight, and eventually derive all alignment parameters needed to adequately point on astronomical sources. These measurements offered HIFI its first-light spectra (Fig. 1).

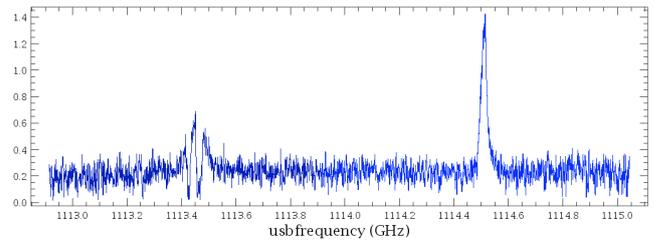


Fig. 1 One of HIFI first-light measurements in one of the polarization channels connected to the Wide-Band Spectrometer (WBS). The intensity scale is not fully calibrated in this plot.

III. INSTRUMENT IN-FLIGHT PERFORMANCES

A. Instrument sensitivity

The HIFI sensitivity was assessed using the standard Y-factor technique, measured towards the two internal loads with respective physical temperatures of 100 K (Hot load) and 10 K (Cold load). Because of the absence of atmosphere, and thanks to a telescope forward efficiency near to unity, the receiver noise temperatures obtained in this fashion offer sensitivity figures very close to the system noise temperature. Fig. 2 summarizes the distribution of the DSB receiver noise temperatures as measured over the full HIFI tuning range.

All mixers offer state-of-the-start sensitivity, in line with the performances reported by the various mixer groups at the time of delivery to the PI institute. While the SIS bands feature some variations over their operating ranges, the HEB mixers show a relatively flat noise distribution over almost 500 GHz of frequency coverage. There is some LO power shortage observed at isolated frequencies, but the bulk of the targeted range has been achieved.

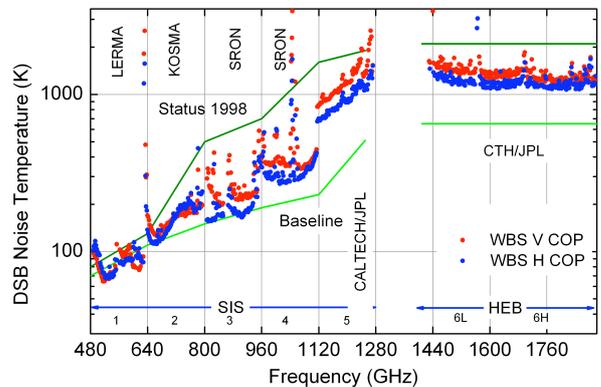


Fig. 2 HIFI Double-Side-Band receiver noise temperatures, together with an indication of what institute manufactured and provided the corresponding mixers. Also shown are the temperatures as measured 10 years before launch, as well as the baseline values at the time of the instrument proposal.

B. Instrument stability

The instrument stability performance was measured using the Allan variance technique (e.g. [4]). This is a standard technique to characterise the stability of spectroscopic instruments used in astronomical observations. In particular, the period for switching between source and reference measurement is often derived from the Allan minimum time.

We used the unified Allan variance computation scheme proposed by [5], which allows to trace total-power and spectroscopic fluctuations within the same framework. This definition of the instrument stability time allows to characterise the instrument even in the case of a fluctuation spectrum shallower than $1/f$, as measured for the total power fluctuations in high-electron-mobility transistors.

In order to map all switching cycles involved in the HIFI observing modes, the following Allan times were mapped across the HIFI tuning range:

- Total power Allan times
- Spectroscopic (or System) Allan times
- Differential Allan times for *i)* measurements between the two internal loads, *ii)* measurements between two positions on the sky (in use in the so-called *Double-Beam-Switching* (DBS) mode), *iii)* measurements between the sky and the internal cold load (in use in the so-called *Load-Chop* mode), and *iv)* measurements taken in *Frequency-Switching* (FSW) mode

Because of the long durations needed for those measurements (at least twice the expected Allan time), the number of frequency points sampled for a given mixer band remains limited, so that isolated stability degradations are difficult to fully cover. In general, it is observed that gain fluctuations represent the main cause of instrumental instabilities, leading to large differences between the stability times relevant for measurements aiming at an accurate determination of the continuum level and for purely spectroscopic measurements. Fast switching loops (using the internal chopper – up to 4 Hz) are needed for a reliable determination of the continuum level, while most spectroscopic measurements can be set up in such a way that baseline residuals due to spectroscopic drifts are at a lower level than the radiometric noise.

Total power Allan times are found to be of the order of 10-30s at a resolution of 1 MHz, although in some areas of the HEB bands, they can be less than 2-3s. In bands using diplexers for the LO injection, a degradation is observed at both ends of the IF, due to a higher contribution from the LO excess noise. Spectroscopic Allan times are in the range 60-400s at the best location of the IF, and usually 3-4 times worse when considering the whole IF. Finally, differential Allan times are in most of the cases longer than the measurement times (1800s) setting a lower limit on the real figure. There are some exceptions to this when using the FSW referencing scheme, especially in HEB bands.

C. Standing Waves

Standing waves are one of the main artefacts that can result from gain drifts as they generally arise from the non-cancellation of the band-pass power modulation when combining the on-source and references phases of an astronomical measurement. Those power modulations can take place between optics (e.g. between horns, loads, mirrors, or combinations of those latter) or within electronics (e.g. impedance mismatch). See also [6].

For HIFI, as on most radio-telescopes, the main optical paths susceptible to give rise to noticeable standing wave systems are:

- 1) Between the mixer horn and the secondary mirror: the measurements have shown that this standing wave is hardly seen in any of the HIFI spectra – it was only detected to a very low level in dedicated measurements done in the band with the largest beam. This positive effect is very likely due to the presence of a dedicated scatter cone added in the centre of the Herschel secondary mirror (see Fig. 3).

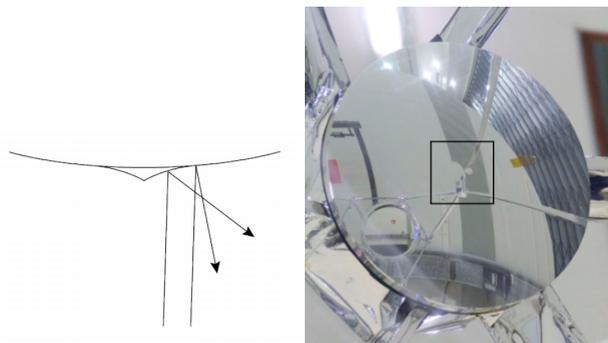


Fig. 3 *Left*: simple sketch depicting the shape of the scatter cone implemented on the Herschel secondary mirror. *Right*: picture of the Herschel secondary mirror, with its scatter cone. The location of the cone is indicated by the square in the centre.

- 2) Between the mixer horn and the internal loads: despite of the absorption coating (~ -45 dB) covering the internal Hot and Cold loads, residual standing waves can be seen especially when observing strong continuum sources. This standing wave, of period around 100 MHz, is however relatively well behaved and can usually be removed with standard sine-wave fitting at data-processing level
- 3) Between the mixer horn and LO horn: although this standing wave does not show up directly on the spectral baseline, it provokes a modulation of the LO power feeding the mixer and can affect in a similar fashion the side-band gain ratio of DSB measurements. Its characteristics can be measured by sweeping the LO frequency with a fine granularity and measure the variation of the mixer current (a direct measure of the LO pumping power). Such a measurement is illustrated in Fig. 4.
- 4) Between the mixer horn and the edge of some of the roof-top mirrors in the band using diplexers, giving rise to a weak ripple of period around 650 MHz.

On top of those, an electrical standing wave is generated in the HEB bands, most likely because of the absence of isolators between the mixer and the low noise amplifier. Unlike the optical standing wave, this ripple cannot be described as a simple sine wave. It appears with a main period of about 320 MHz, but its structure shows more skewed wave morphology, together with a period modulation. The amplitude of this standing wave scales with the difference in mixer currents between two observing phases (impedance mismatch), and can therefore be worse for FSW observations. A full description of this effect, and its possible cures, has been presented in [7].

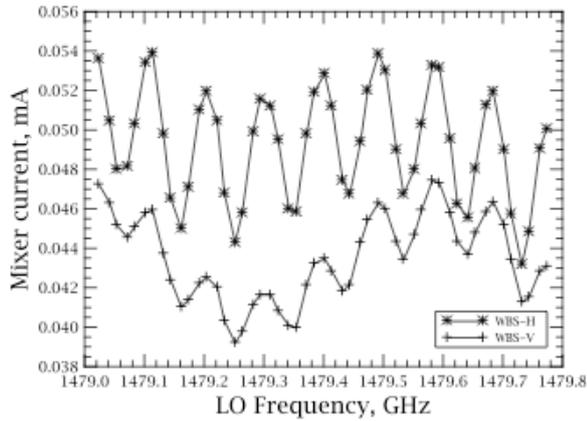


Fig. 4 Example of a measurement of the LO power modulation due to standing waves between mixer and LO horns.

D. Spectral purity

There are several frequencies in HIFI where the local oscillator has been shown to produce more than one frequency, leading to the presence of potential lines at unknown and possibly unstable frequencies. Those impurities are believed to be due to oscillations in the first, and sometimes, second stage multipliers of the Local Oscillator.

1) Oscillation theory

All multipliers that use a capacitor to terminate the bias port at the RF frequencies can oscillate if the RLC of the capacitor and attaching lead and its phase shift are a sub-harmonic of the input frequency. Simplistically this is an analog of the famous mechanical problem of small pendulum forcing a large pendulum. It will work very well if the frequency of the large pendulum is a sub harmonic of the small one.

The RF works as a charge pump for the RLC circuit. The amount of charge pumped depends on the bias point with bias closer to zero generally producing more current. This would be a monotonic function if the input match of the multiplier were independent of bias, however the input match degrades away from the optimal bias condition so there is often a peak in the RF pumped IV curve. The bias circuit oscillation has the effect of moving the bias point at the oscillation frequency allowing for there to be substantial gain in the oscillation. Fig. 5 shows the IV curve of a 200 GHz doubler in oscillation and not in oscillation. Note that the IV curve has the same shape but is compressed in the oscillating case.

2) Purification of the LO signal

The HIFI Local Oscillator chains were designed in order to leave a full control on the multiplier and gate bias settings. The following two options have been considered to purify the affected frequency areas:

- force the multiplier to operate in a varactor mode with a sub-threshold level of rectified current. Ideally the mode would be pure varactor with zero current; however, due to non-ideality in the diodes this really never possible. Fortunately several of the doublers in use (e.g. band 7b) are varactors and were

designed to have little current at its optimal bias point. A major concern to reverse biasing the multiplier is allowing the RF voltage swing to probe the reverse breakdown region. In this case it was known that the IV characteristics of the diode will change and this change will not be reversible. The HIFI design approach was to avoid all hints of reverse current and not take any chances with a degradation process that was poorly understood

- force the multiplier to work in a varistor mode, i.e. well in the second hump of the IV curve (e.g. first stage multiplier in bands 5a/5b)

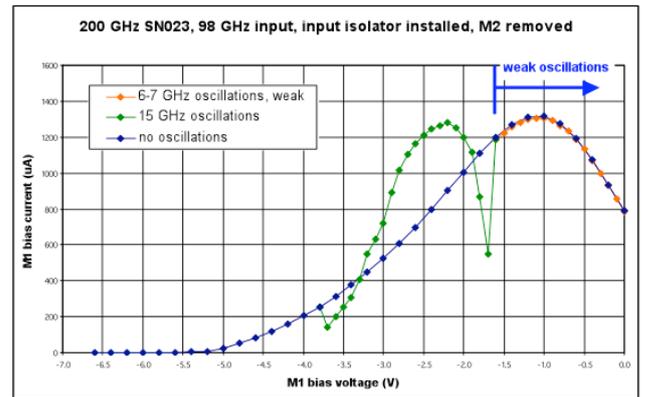


Fig. 5 IV curve of oscillating and non-oscillating 200 GHz doubler

E. Spurious Signals

The LO multiplier oscillations can also give rise to free-running spurious signals which will appear in the calibrated spectra as strong spikes and can in the worst case saturate all pixels of one spectrometer sub-band.

While the weakest and narrowest spurs can usually be eliminated at data processing levels, some other spurs have been treated at the multiplier level by changing their bias settings. Fig. 6 shows the example of a strong spur in band 1a close to one very important water line, and how biasing the first multiplier more negative significantly helped in reducing the spur intensity. It is noted however that a compromise must often be found as such changes on the multiplier biases can reduce the available LO output power, and therefore jeopardize the mixer pumping.

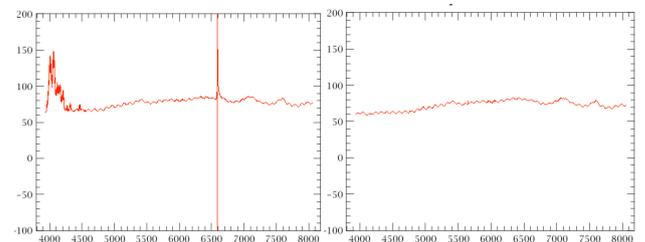


Fig. 6 Example of an LO spur removal by multiplier bias change in band 1a at 551 GHz. *Left*: receiver noise temperature at the nominal bias, featuring a strong spur. *Right*: same with a more negative multiplier bias, showing the removal of the spurious signal.

IV. POINTING PROPERTIES

The pointing performance offered by the instrument is the combination of two contributions. On the one hand, the capability of the Spacecraft to accurately stare at a targeted line-of-sight is fully driven by the performance of its star-tracker system. On Herschel, the so-called *Absolute Pointing Error* (APE) was measured to be of the order of 2 arcsec on the sky, i.e. fully within the specifications. On the other hand, the capability of the instrument to get its beam well coupled to the targeted source depends on the accuracy with which the positions of its aperture are known with respect to the frame defined by the Star-tracker. Ensuring the latter is the purpose of the Focal Plane Geometry (FPG) measurements.

A. HIFI FPG campaign

The in-flight assessment of the HIFI aperture was highly relying on the very accurate measurements that had been performed on the ground during the Instrument-Level Test (ILT) campaign, see e.g. [8], [9]. During those measurements, the aperture positions were measured with respect to a reference (alignment cube) belonging to a common reference frame, but most importantly, the various bands were paired in clusters for which the relative positioning was measured with an accuracy better than 0.7 arcsec on the sky. The results of this campaign are illustrated in Fig. 7.

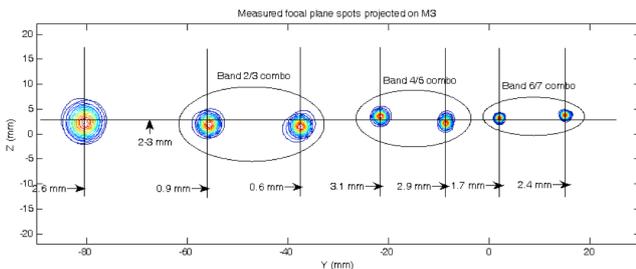


Fig. 7 Projection of the beam intensity distribution onto the HIFI pick-up mirror (M3) as measured during the Instrument-Level Tests.

This legacy results allowed to starting the in-flight FPG measurements with only one aperture per cluster. The measurements were done in two steps:

- A coarse mapping was performed over an area around the expected aperture location on the sky, allowing for mis-pointing margins. For this, a sampling slightly worse than a Nyquist sampling was used. Only one aperture per cluster was considered at the time
- After correcting the offset measured from the coarse mapping, a finer mapping was repeated with a smaller sampling and extent. This time, all 7 bands were measured.

The typical map sizes and sampling for the above steps are illustrated on Fig. 8. Fig. 9 shows an example of such measurements on Saturn in bands 1 and 6.

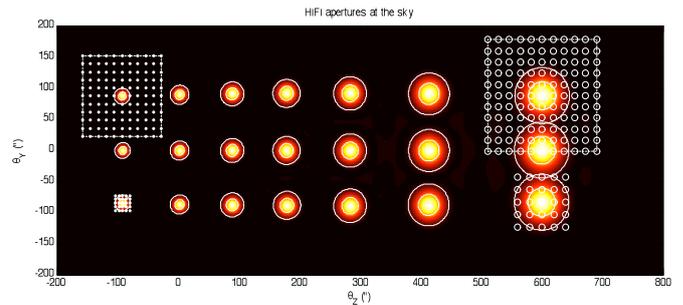


Fig. 8 Illustration of the HIFI aperture positions on the sky, together with the footprints of the raster map pixels performed in the framework of the coarse (upper coverages) and fine (lower coverages) focal plane geometry measurement campaigns.

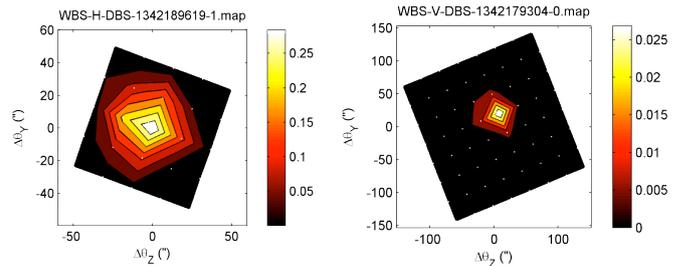


Fig. 9 Example of Saturn measurements in band 1 (491 GHz) and 6 (1625 GHz), used to determine the offsets of the corresponding HIFI apertures.

B. Beam co-alignment

HIFI offers for each receiver two polarisation channels that can be measured simultaneously. While they provide a hardware redundancy to cover contingency failures, they can also be combined to decrease the noise level achieved in spectral measurements by a factor $\sqrt{2}$. This assumes that both polarisations are looking at the same point on the sky. Because they correspond to two physically different mixers and their associated optics, the co-alignment of the respective apertures on the sky adds a potential error.

The co-alignment was measured using the map information collected in the respective polarisation channels. The results are summarized in Table 1. The co-alignment is found to be very good, and in perfect agreement with what was measured pre-launch. However, in order to mitigate the global pointing error when combining the two polarisations, it was decided to not favour any of the channels and rather use an synthetic aperture located in the centre of the two polarisation beams. The resulting coupling losses in such an approach are limited, and listed in Table 1.

TABLE I
BEAM CO-ALIGNMENT RESULTS

| Band | F (GHz) | FWHM (") | ΔHV_{ILT} in Y;Z (") | ΔHV_{CoP} in Y;Z (") | Coupling loss (%) |
|------|---------|----------|------------------------------|------------------------------|-------------------|
| 1 | 480 | 44.3 | -4.5;+1.5 | -6.2;+2.2 | 0.8 |
| 2 | 640 | 33.2 | -4.3;-1.5 | -4.4;-1.3 | 0.7 |
| 3 | 800 | 26.6 | -5.1;-4.3 | -5.2;-3.5 | 1.9 |
| 4 | 960 | 22.2 | -1.5;-2.2 | -1.2;-3.3 | 0.9 |
| 5 | 1120 | 19.0 | +1.5;+3.6 | 0.0;+2.8 | 0.8 |
| 6 | 1410 | 15.2 | +0.7;0.0 | +0.7;+0.3 | 0.1 |
| 7 | 1910 | 11.2 | +0.7;-1.5 | 0.0;-1.0 | 0.2 |

C. Chopper angle calibration

In one of HIFI's most used observing modes (DBS), the internal chopper mirror is used to move the beam to a reference Off position on the sky within 3 arc minutes away from the On-target position. Since moving the internal mirror changes the light path for the incoming waves the possibility of residual standing waves exists. By slewing the telescope so that the source appears alternatively in both On and Off chopped positions, the impact of standing wave differences is eliminated to a first order.

The whole scheme assumes that there is a perfect match between the distance on the sky involved between the two chopper positions, and the distance involved in the telescope slew. Since the FPG measurements have been taken in the DBS mode, it is possible to create two separate maps corresponding to each telescope position, and therefore derive any offset between the source positions in each coverage. This offset is used to recalibrate the exact telescope slew distance needed to match the intrinsic chopper angle on the sky. This is particularly important since there is some curvature involved when chopping away from the on-axis line-of-sight and this effect varies with the HIFI band. Fig. 10 illustrates this result, showing an excellent agreement between measured and theoretical throws on the sky.

V. CONCLUSIONS

The HIFI in-flight Commissioning campaign has taken about 2 months and involved a team of more than 40 scientists, with a short regression test period following the HIFI re-start after the LCU failure in August 2009. The instrument performances are similar or better than pre-launch, meeting all top-level specifications. The science data quality is very good, albeit more challenging in the higher frequency bands (HEBs), and data artifacts are similar to those encountered in other radio-telescopes on the ground. On-going efforts in the area of spectral purity is made possible by a system design flexible enough to allow the last-fine tunings in space.

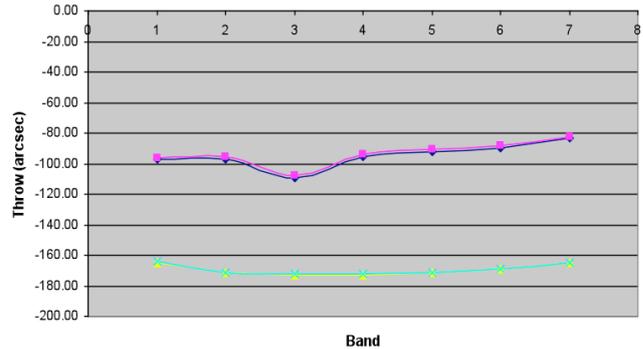


Fig. 10 Chopper throw distances on the sky. *Upper curves*: theoretical (diamonds) and measured (squares) distances for a so-called half-throw, i.e. a chopper throw between the secondary (M2) centre and one of the borders of M2. *Lower curves*: theoretical (triangles) and measured (crosses) distances for a so-called full-throw, i.e. a chopper throw between the two opposite borders of M2.

ACKNOWLEDGMENT

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