HIFI Pre-launch Calibration Results

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***Abstract*— This contribution presents the ground calibration campaign of the HIFI Flight Model instrument conducted at the SRON-Groningen premises. This campaign has been conducted over more than a year and a half, with a core period of 9 months where the complete flight model was available in the laboratory. The calibration of the instrument has been organized according to four main topics: i) spectral calibration, ii) beam characterisation, iii) photometry calibration, iv) stability.**

We present here the strategy used in each of these activities and give the first outcomes of the campaigns, especially in the perspective of the future calibration of the astronomical data, and how these results will be propagated onto the flight early and routine activities.

I. Introduction

HIFI is the heterodyne instrument to be flown on-board the Herschel Space Observatory. With 7 mixer bands spanning the 480–1910 GHz frequency window, its calibration as a whole is a real challenge, especially in bands making use of HEB technology, which will be put in orbit for the first time during this mission. The calibration was approached as a topical characterisation campaign, as is described in the following sections.

II. Spectral calibration

The characterisation of the spectral properties of an heterodyne instrument is a key issue for the final frequency calibration of the astronomical data. The spectral behaviour of the full instrument will be highly related to the performances of the Local Oscillator Unit (LO) as the signal produced by this latter has implications at several levels of the detection chain. First of all, the master oscillator (which has an accuracy of 1 part in 10^7) will provide the lock frequency to the High-Resolution Spectrometer (HRS) internal oscillators, as well as to the internal comb used in the Wide-Band Spectrometer (WBS). It therefore drives the absolute frequency calibration accuracy offered by the spectrometers. Because the LO signal is not a purely monochromatic line, it will degrade the spectral properties of the instrument, both at the level of spectral responses (resolution element shape, spurious response in the down-converted product) and spectral signals (spontaneous emission from the LO). They are described in the following sections.

A. Spectral Response

The spectral response of the instrument is the combination of the responses of the spectrometers themselves, and of that of the LO injected line. The objectives of the tests conducted were as follows:

- Verify the absolute frequency resolution of the instrument
- Verify the required instrument line-shape
- Verify the frequency accuracy of the instrument
- Determine the IF up-converted LO frequency (an up-converter was necessary in the HEB bands in order to bring the 2.4-4.8 GHz IF range of these bands into the standard 4-8 GHz IF expected by the spectrometers)

For this a strong and narrow line was injected into the system on the sky port, and swept over the spectrometer resolution element with steps of 31 kHz. The test signal was provided by an Agilent synthesizer operating between 15 and 16 GHz, which was then fed into a comb generator.

B. WBS

The shape of the WBS channel response can be described to a large degree by a Gaussian function, with Lorentzian and asymmetric wings. The specification on the corresponding resolution bandwidth (width of a boxcar filter of equal maximum transmission) is of 1.1 MHz.

Fig. 1 below shows the measured response of a WBS channel. One can immediately see that the shape presents a strong wing on the red side, and has a resolution bandwidth well above the specification (1.650 MHz). Overall, resolution bandwidths in the range 1.310 and 1.797 MHz have been measured. This effect was later identified as being due to the laboratory conditions in which the measurements were taken.

The ideal shape and resolution bandwidth is indeed expected for vacuum conditions, at a temperature of 10 degree Celsius. Measurements were indeed performed in open air, at 20 degree Celsius, and turned out to be totally consistent with similar measurements performed prior to the unit delivery (see Fig. 2).

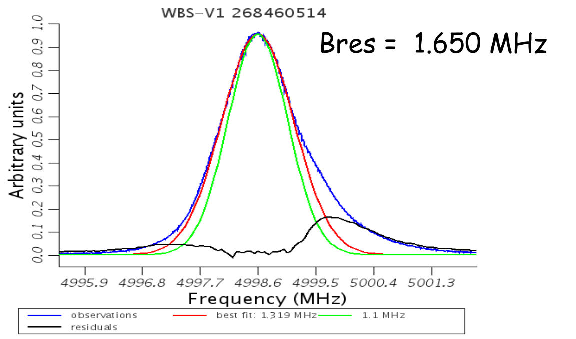

Fig. 1 Profile of the WBS resolution channel measured by a injected line swept over the channel width. (blue). Various fits and residual are shown.

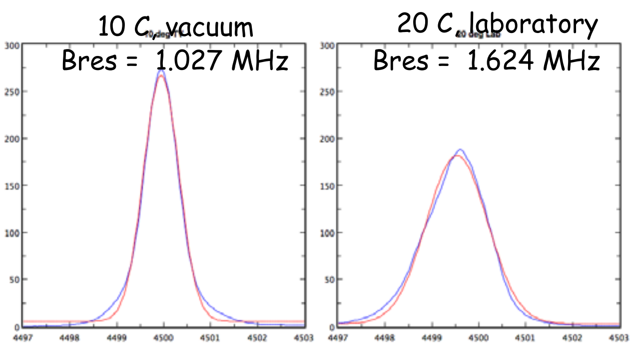

Fig. 2 Same as Figure 1 in different laboratory environments, measured by the WBS team prior to delivery to the SRON AIV team.

C. *HRS*

Due to its digital nature, the HRS provides an optimal intrinsic resolution of 125 kHz. This resolution is in practice degraded due to the non-perfect sharpness of the LO line injected to the mixer. Figure 3 illustrates one of the measurements obtained for band 1a. It is interesting to note the high signal-to-noise level that can be achieved in such experiment, allowing to assess the level of side-lobes contribution due to the Hanning windowing of the correlation function applied in the HRS. Table 1 summarizes the resolutions measured for several of the bands.

The measurements show that the HRS resolution is well specifications for all bands but 2a, 3b and 4a.

D. *Spurious Characterization*

The spectral purity of the instrument depends on the level of all significant spurious signals and spurious responses present in the data. Un-catalogued instrument spectral artefacts could indeed be misinterpreted as astronomical features.

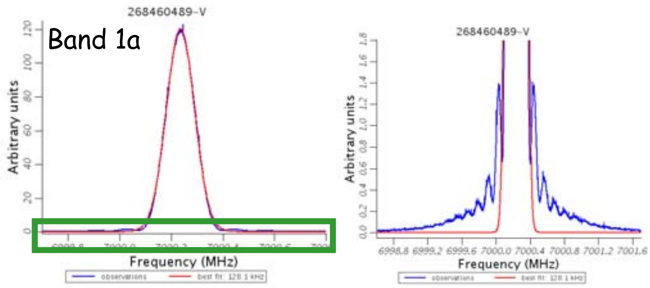

Fig. 3 Same as Figure 1 for the HRS. The details of the rectangular area are shown on the right, illustrating the level of side-lobe contribution.

TABLE IV
HRS MEASURED RESOLUTIONS AND ACCURACIES

Band	1a		2a		2b		3a		4b		6b	
	H	V	H	V	H	V	H	V	H	V	H	V
FWHM kHz	125	128	216	216	171	170	156	158	157	153	186	184
Specs	160		180		180		190		230		280	
Accur. (kHz)	21		31.4		31.6		37.6		40.5			
Specs	53		69		69		85		117			

E. *Spurious Signals*

A spurious signal is a spectral feature which is present in the spectrometer output in the absence of any spectral feature in the signal entering the instrument while it is e.g. looking at a clean black body. These signals can be harmonically related to the LO, internally generated, or picked up.

A catalogue of those spurs was produced based on a systematic analysis of all available spectra, with a particular emphasis on the high-granularity noise temperature survey presented in section IV. Figure 4 summarizes the occurrences of such signals. In general some few narrow lines are observed for very specific LO frequencies. Some broader lines are also seen, often associated with poor mixer pumping quality (LO excess noise)

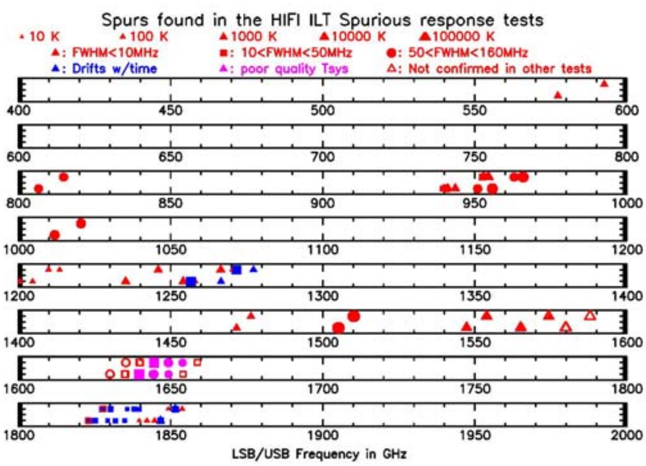

Fig. 4 Overview of the spur locations over the HIFI frequency range.

F. Spurious Responses

A spurious response is a ghost spectral feature present in the spectrometer output which is related to a spectral feature in the signal entering HIFI, but which appears at the wrong frequency. Any occurrence of such lines would imply an incorrect calibration on any astronomical lines observed. The image side-band of a DSB mixer is an example of spurious response. Causes for such effects are usually strong harmonics or oscillations in the LO chain.

We have concentrated here on mono-chromatic responses to a given line injected at the sky port of the instrument. A coherent source was stepped from 15 to 16 GHz (step size 0.04-0.05 GHz) and a comb generated harmonics (30 to 96) of this source. For band 7b (1719-1910 GHz), a monochromatic source (SIII harmonic 108 of a source frequency tuned between 16.38 and 18.01 GHz) was used.

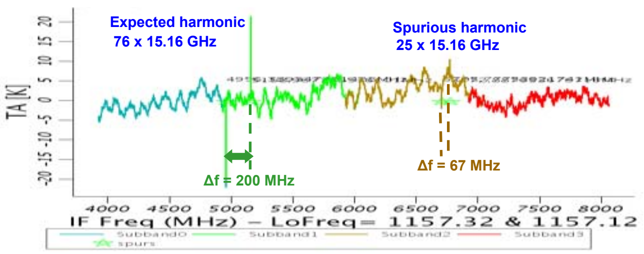

Fig. 5 Example of a spurious response measurement in frequency switching mode. The injected line is seen on the left, while the feature on the right is a ghost, arising from a lower harmonic.

Figure 5 illustrates the sort of measurement used to hunt spurious responses in the system. The frequency switch mode was used to calibrate the instrument band-pass, allowing also to scale the harmonic contribution based on the frequency throws observed between two ghosts spikes.

The scan over the full HIFI range has revealed three main categories of spurious responses:

- Weak LO "leaks" of level below 0.1% of the original signal
- Medium LO "leaks" of level of a few % of the original signal
- Strong LO "leaks" which can be in excess of 50% of the original signal. Those were mostly observed at the upper end of band 3b, 5b and 7b. These LO impurities have been found to be due to oscillation in a doubler which makes that more than one tone is eventually mixed. Further tests proved that more negative multiplier biases could restore most of the purity, albeit at the cost of some LO output power.

Figure 6 gives an overview of where the above leaks have been encountered.

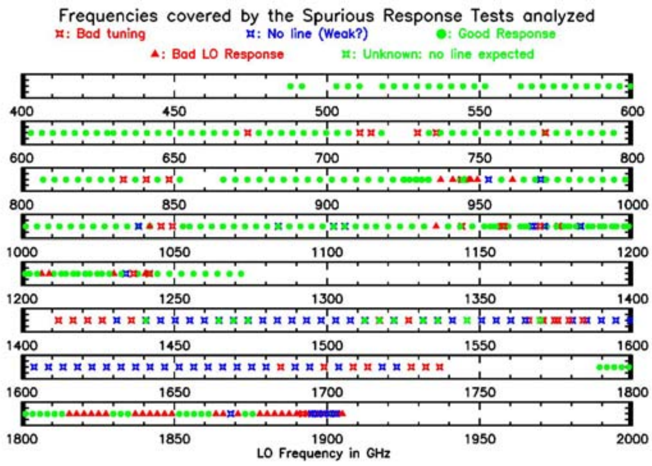

Fig. 6 Overview of the area of affected spectral purity

III. Beam Characterization

The beam characterization of the 14 mixer line-of-sight is a fundamental pre-launch activity as it provides the absolute positions of the HIFI beams with respect to the telescope theoretical bore-sight, a measurement which in turn will be used in order to calibrate the absolute pointing of each of the HIFI bands. In addition it allows the first estimates for beam efficiency prediction.

The measurement setup used for this activity has already been introduced in more detail by Jellema et al. [1]. It is based on a vacuum beam scanner located on top of the HIFI FM test cryostat, which allows both phase and amplitude measurements. Fig 7 illustrates this device.

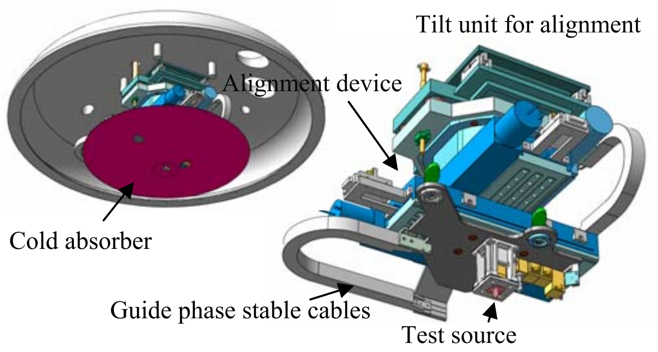

Fig. 7 Drawings of the beam scanning system

The re-constructed beam positions and patterns in the absolute S/C coordinate system are shown in Figure 8. The (quasi-)optical alignment is found to be very good, and optical losses will stay below 6%. The co-alignment is generally 20-30% of the waits size, which means 10-15% of the FWHM at the sky. This means that the losses per polarization channel when re-pointing to the average position at the sky will be of typically 1-3%. This is the approach that HIFI has finally taken in order to define the official aperture the S/C shall point to in orbit, assuming that both polarizations will always be (weight-)averaged by the astronomer.

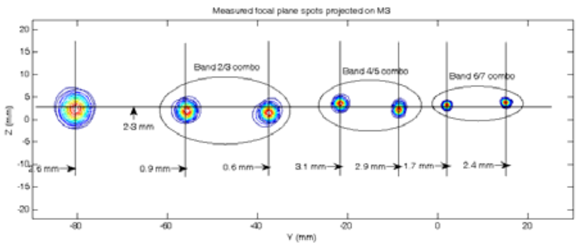

Fig. 8 Absolute positions and energy distribution of the HIFI beams as measured during the ILT.

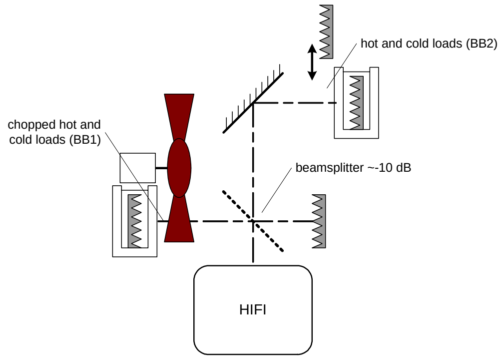

Fig. 9 Measurement setup for the linearity experiments

IV. Photometry Calibration

The photometry calibration is of upmost importance for the interpretation of the astronomical data, and in particular for comparison with models. HIFI has an absolute photometric calibration goal of 3%, with a baseline at 10%. This is a very challenging requirement, even in the absence of atmosphere. The following equation illustrates the various contributors to the error budget:

$$J_{source} - J_{OFF} = \frac{1}{G_{ssb}\eta_l + \omega_{ssb}} \frac{\eta_c + \eta_h - 1}{\eta_{sf}} \times [\ldots]$$

- ηc and ηh are the mixer beam coupling factors to the internal cold and hot loads. 1% error on these numbers translates into an error between 0.2 and 5% (depending on frequency) and of 1% respectively on the absolute calibration
- ηsf is the mixer coupling to the sky. Its accuracy will largely rely on the error made on the planet model in use to convert observed intensities into physical units. Current Mars and Uranus models are believed to be trustable to about 5%
- G_{ssb} represents the contribution from the side-band ration applying to the DSB mixers in use. 1% error on this number translates into 0.5% error on the absolute calibration

A. System linearity

As HIFI will be observing astronomical sources of varying line and continuum intensities, the linearity of the photometric scale in both domains has to be addressed. The measurement setup is illustrated in Figure 9. Various pairs of thermal loads were used in order to simulate various regimes of continuum background, on top of which a synthesized line could be injected when necessary.

B. Line linearity

The above setup was used in order to observe an injected line (equivalent temperature in the range 0-2000K) against a continuum load switchable between 10 and 100K. The non-linearity measured over the various line contrasts is shown in Figure 10. The measurement accuracy is seen to improve with higher line contrast, the best range being 50-250K. The average non-linearity in bands 1 to 6 is found to be -0.5 +/- 2.9 % for the WBS, and 0.15 +/- 1.5% for the HRS. Overall, the line linearity is within 2%, implying a good line calibration for all type of source intensity.

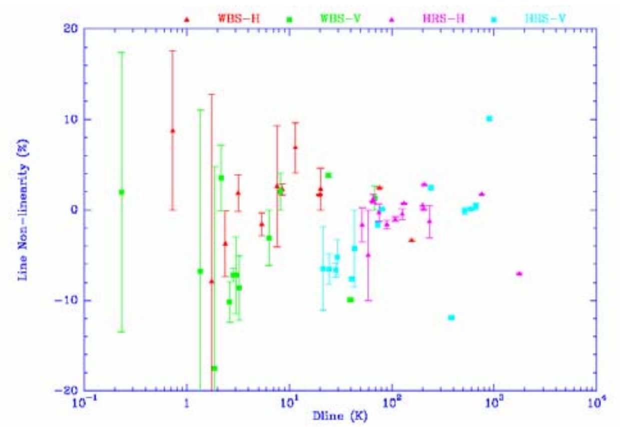

Fig. 10 Results of the line linearity measurements. Error bars are observed to decrease with the line contrast (Δline).

C. Continuum linearity

In this experiment, the 2 pairs of loads are used to provide a variable continuum source between 200 and 300K. Here the measurements were seen to suffer more significantly from system un-stability of the continuum gain on short time scale, so that the current picture of the continuum linearity is still affected by important error bars (see Figure 11). The linearity is found to be on average -2 +/- 6%. Other measurements made with a faster referencing scheme were taken later but are not yet analysed at the time of writing this paper.

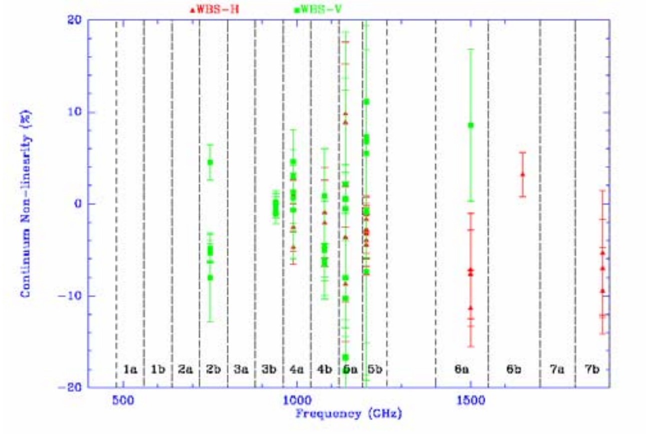

Fig. 11 Current results of the continuum linearity measurements.

V. Radiometry Properties

A. Internal load beam coupling

The absolute calibration of HIFI will rely on observations of well-known solar system bodies such as Mars of Uranus, which will be used in order to derive the overall beam coupling to the source at the sky (aperture and beam efficiencies). However, this calibration will be bootstrapped to the internal loads, which provide the routine photometric calibration of any astronomical observation.

Because the use of these sources as "relay"-calibrator relies on the accurate knowledge of the radiated temperature to the mixer, the coupling of this latter to the apertures of these loads is fundamental. While the cold load of HIFI (thereafter called the CBB) is a tilted absorbing plate at sink temperature (around 10K), the hot load (thereafter called the HBB) consist of a narrow slit in V-shape design in order to act as a trapping cavity (see Figure 12). This cavity is heated up to a temperature of order 100K, therefore its size has been reduced to the maximum in order to limit the heat load into the FPU. Both load surfaces are coated with SiC grains on black Skycast. The coupling to these two loads will depend on the overall alignment of all optics from mixer to cavity.

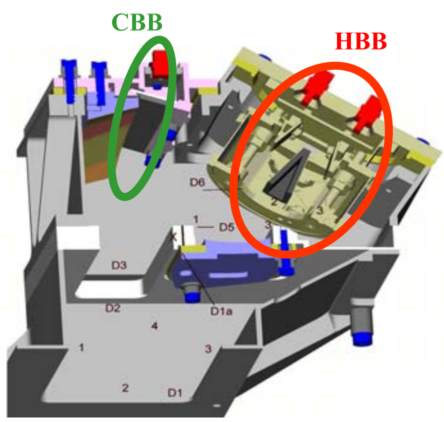

Fig. 12 Drawing of the Calibration Source Assembly (CSA) inside the HIFI FPU

In order to measure the coupling to these loads, absolute external photometric calibrators were designed so that the radiated temperature seen by the mixer on the internal load could be calibrated on an absolute temperature scale. The external absolute hot black body (AHBB) consists of a wide LN2-cooled coated cylinder with a titled top surface (30 degrees), allowing to encompass all possible beam positions on the HIFI pick-up mirror (M3). Its emissivity was measured to be better -45dB. The cold reference was a shutter located inside the test cryostat, right on top of the pick-up mirror, and offering a titled coated surface at sink temperature. Figure 13 illustrates the test setup.

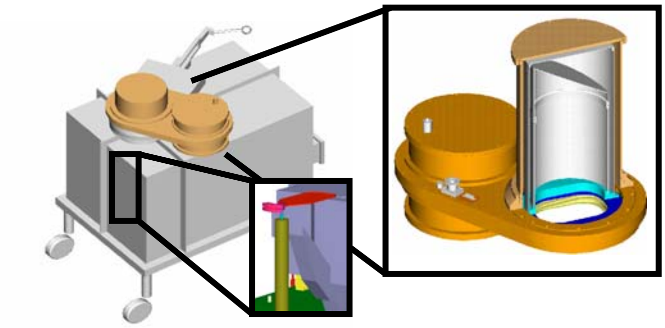

Fig. 13 Measurement setup for the internal load coupling experiment. Left: FM test cryostat with absolute cold (middle) and warm (right) external loads

The coupling was measured over the full HIFI range, with a granularity of 4 GHz. Results are shown in Figure 14 for the H-polarization mixers.

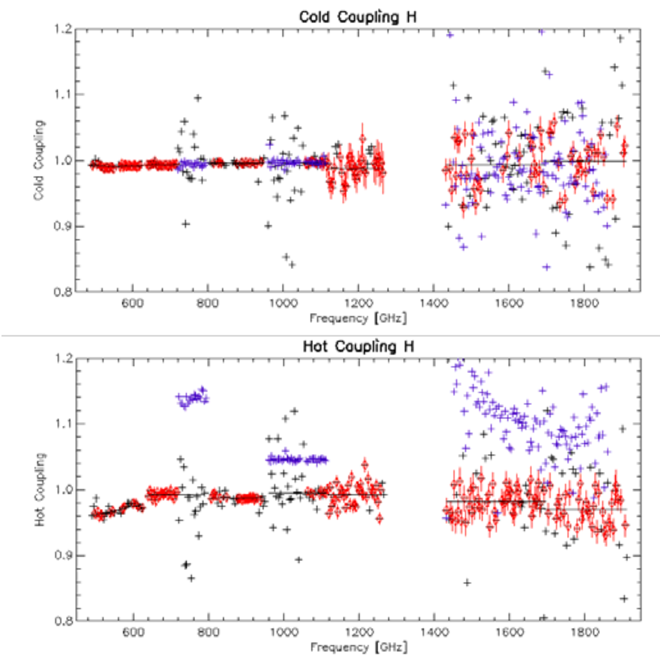

Fig. 14 Results of the internal load coupling measurements. Red symbols indicate the points used in the computation of the mean coupling (in solid line). Blue crosses indicate measurements done in another configuration, and discarded from the analysis.

Couplings are found to be very close to unity for all bands, which is as expected from theory. The coupling to the hot load has however a rising trend with increasing frequency, indicative of possible beam spill-over on the edges of the cavity at the highest wavelengths. A stronger scatter was observed in the data collected on the HEB bands, an effect due to the poorer total power stability offered by these bands. The coupling was however treated as a single number averaged over the whole mixer band range. Errors on the coupling are found to be less than 1% in bands 1 to 4, and up to 10% in the higher bands.

B. System noise temperature

As a by-product of the above measurements, the mixer band-pass response can be derived in the form of the system noise temperature. This provides the overall picture of the instrument sensitivity over its operational range. This measurement was later repeated on a finer grid (1 GHz). The results are shown in Figure 15. Note that these measurements are performed in complete vacuum, so that no further correction than the beam coupling factor derived above is necessary to infer the effective noise temperatures.

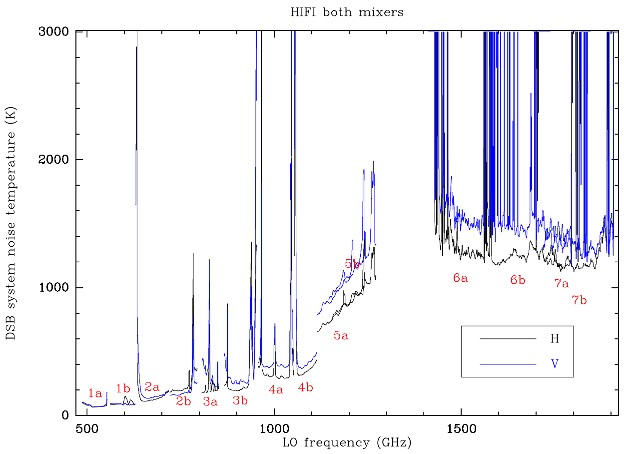

Fig. 15 System noise temperature as a function of LO frequency

The T_{sys} performances are totally compliant with the original requirements, offering unprecedented sensitivity in all covered bands. The results also reveal some gaps, in particular in the HEB bands, consequences of the introduction of attenuator windows on the LO path for stability purpose, resulting in areas of LO output power shortage. We refer to Jellema et al. [2] and Kooi et al. [3] for further details on this particular topic. Note however that, due to the possibility to adjust the LO tuning over the USB or LSB, as well as over the available 4 GHz IF band, most of those gaps disappear when the sensitivity is plotted against the sky frequency of a targeted line. This is illustrated on Figure 16.

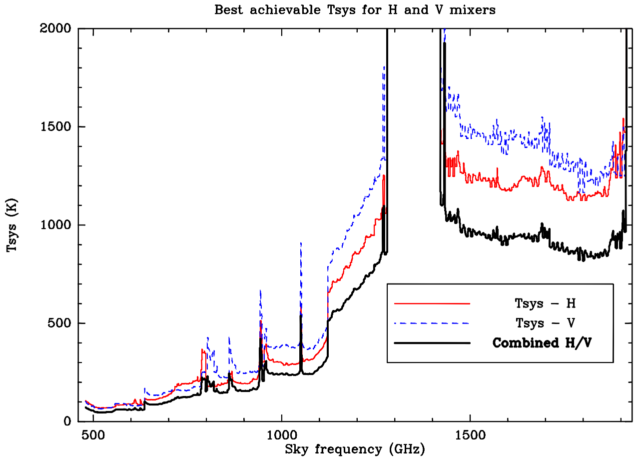

Fig. 16 System noise temperature as a function of sky frequency. The solid black line shows the achievable noise when combining both polarizations

VI. *Gas-cell measurements*

Gas-cells offer a unique laboratory source for validation of spectroscopy experiments as they allow a fair control of the spectroscopic features to be fed into the system, and offer infinite frequency coverage due to the versatility of available molecular species. As such they allow an end-to-end qualification of the heterodyne detection system.

A. Side-band ratio assessment

One of the most important parameters for the photometric calibration of lines in a DBS system is the side-band gain ratio of the mixers at the frequency of operation. Methods based on laboratory side-band rejection systems (using Martin-Pupplett interferometers) are difficult to implement in such compact configurations such as the one of HIFI. Another alternative consisting in using laboratory gas cells has proved to be fairly successful in previous experiment, as e.g. during the calibration of the SWAS satellite (e.g. Tolls et al. [4]).

In such an experiment, a spectral line is located in one of the side-bands, while the other side-band is supposed to be free of spectral features. When the line is saturated, and the respective side-band gains are perfectly balanced, the DSB spectrum should appear as a single line absorbing exactly half of the continuum fed to the DSB mixer. Any deviation from this half level indicates a departure of the side-band gain ratio from unity. The most challenging aspect of such measurements is the availability of spectral lines of sufficient strength over very large and fine sampled frequency coverage. A description of the specific HIFI gas-cell design can be found in Teyssier et al. [5]. The measurement setup is illustrated in Figure 17.

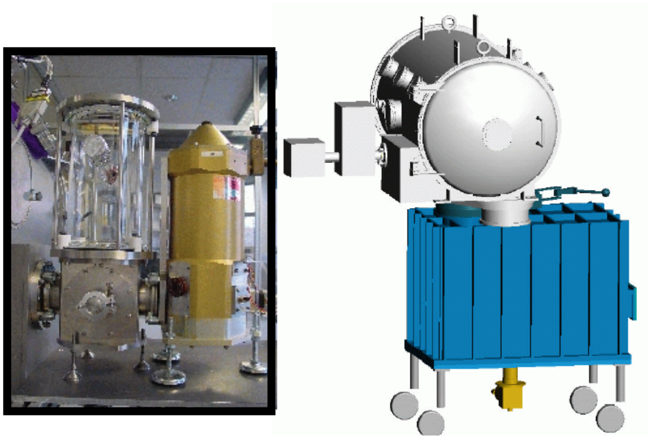

Fig. 17 Left: gas-cell and its associated black body. Right: illustration of the measurement setup for the gas-cell experiment.

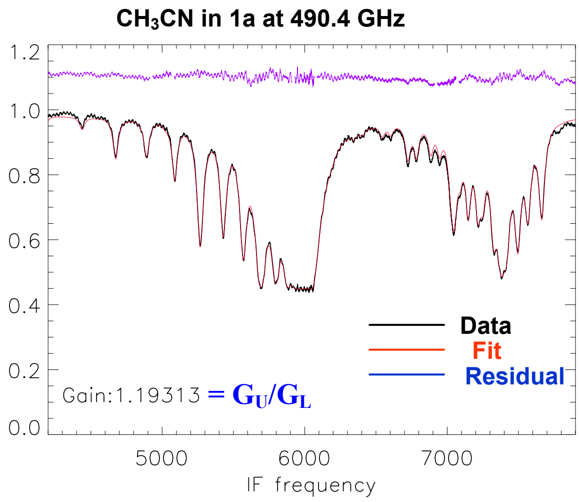

Fig. 19 Example of side-band ratio retrieval based on modelled line profile fitting on a transition of CH_3CN in band 1a.

The data-set collected was fairly massive (over 6000 spectra in a dozen of molecules) and the analysis of the side-band ratios is still on-going at the time of writing this paper. A first crude overview was performed based on a quick-look assessment of the line absorption dip over the survey. The outcome of this coarse computation is shown in Figure 18. A lot of uncertainties are affecting such a automatic, the largest being related to the baseline quality of a part of the data-set, as well as to the non-saturation of a large fraction of the transitions probed. This leads to the large scatter seen all over the considered range.

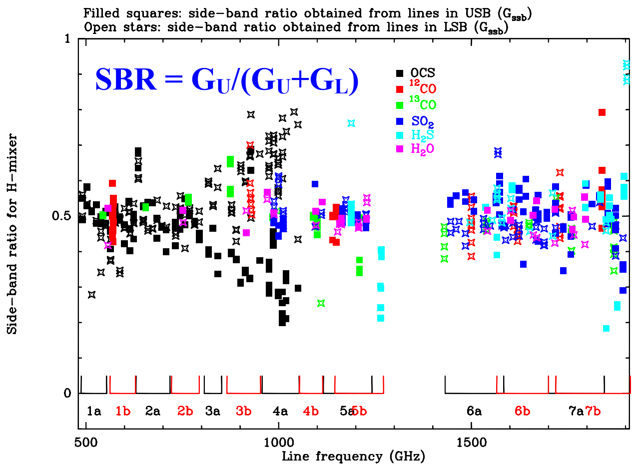

Fig. 18 Side-band gain ratio as measurement with the crude quick-look method (see text for details)

We are currently working toward a more accurate approach, whereby a complete model of the line profile is computed based on the physical conditions of the gas in the cell (pressure, temperature, cell path length). This technique allows much more accurate determination of the side-band ratio (down to below 1% in most stable and sensitive bands). An example of such retrieval is illustrated in Figure 19 (courtesy of E. Dartois).

B. *Spectral surveys*

With its wide and continuous spectral coverage, HIFI will dedicate a significant part of its scientific program to spectral surveys. The achievement of such complete coverage requires the guarantee that the instrument can be optimally tuned over the whole frequency range. We conducted such a un-biased survey using the methanol molecule, which features a very dense spectrum all over the HIFI range. The ultimate goal of such a measurement is also to validate specific data processing tools dedicated to the de-convolution of the DSB spectra using redundant measurements over the IF bandwidth (e.g. Comito et al. [6]). Figure 20 shows the result of such a de-convolution performed on the data observed in the band 3 of HIFI (courtesy of C. Comito).

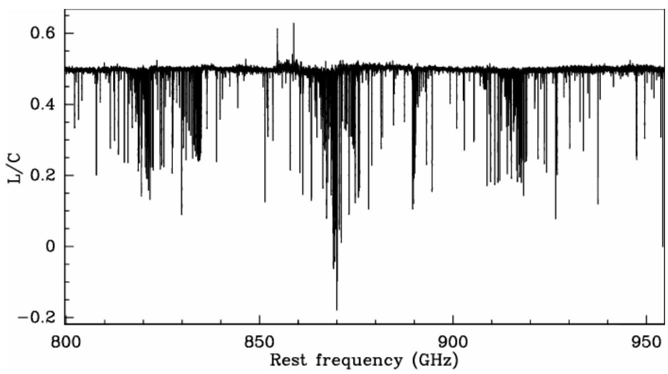

Fig. 20 SSB spectrum obtained from the de-convolution of the methanol spectral survey in band 3.

VII. Stability

We refer to Kooi et al. [3] for a detailed description of this topic.

CONCLUSIONS

The pre-launch calibration campaign of the HIFI instrument has been a collaborative effort spanned over a period of a year and a half, with a core period of nine months where the full flight instrument was available to the team. It has been an intensive learning period where some on-the-fly redesign or addition of flight hard-ware became un-avoidable even little time before its delivery to ESA in June 2007. The campaign has collected an impressive amount of data which will still offer material for study over the next years. The big picture is that of an instrument very well into its performance specifications, and offering an absolute calibration within the initial goal of 3-10% in the first half of the frequency coverage. In the HEB bands in particular, it is expected that this accuracy will rather be in the range 10-20%. Overall, it makes HIFI the most accurate heterodyne instrument ever built in the bands overlapping those of other ground-based facilities, and clearly the new reference for the frequency ranges where it will offer pioneering science.

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