HIFI Flight Model Testing at Instrument and Satellite Level

P. Dieleman[1,*], W. Luinge[1], N.D. Whyborn[2], D. Teyssier[3], J.W. Kooi[4], W.M. Laauwen[1], and M.W.M de Graauw[2]

[1]SRON Netherlands Institute for Space Research, Groningen, the Netherlands

[2]Atacama Large Millimeter/sub millimeter Array, Las Condes, Chile.

[3]European Space Astronomy Centre, 28691 Villanueva de la Cañada, Madrid. Spain

[4]California Institue of Technology, MS 320-47 Pasadena, California 91125, USA

* Contact: P.Dieleman@sron.nl, phone +31-50-3638286

***Abstract*— This article gives an overview of the tests performed on the HIFI instrument before and after integration in the Herschel satellite. The test results are compared to the performance requirements. Overall, HIFI complies well with the original requirements. As an example of unexpected test results the effect of unwanted feedback in the amplification circuit on the data quality is discussed.**

I. Introduction

The Heterodyne Instrument for the Far-Infrared (HIFI)[1] is one of three instruments on board of the ESA Herschel satellite[2]. It spans a frequency from 480 – 1260 and 1410 to 1910 GHz, with a spectral resolution of up to 140 kHz. HIFI has 7 dual-polarisation mixer bands. Bands 1-5 consist of SIS mixers, bands 6 and 7 use HEB mixers[3]. The local oscillator (LO) frequency range is split into 14 frequency bands, each with its own LO chain. The downconverted Intermediate Frequency (IF) signal is fed to two types of spectrum analyser; to an Acousto-Optic Spectrometer (WBS) with an IF band of 4-8 GHz and a resolution of 1.1MHz and to an auto-correlator (HRS) with an adjustable IF bandwidth up to 2 GHz and a resolution of up to 140kHz.

Before delivery to HIFI system, all individual units were fully qualified and performance tested[4]. In this article the results of the Instrument Level Test (ILT) of HIFI as an integrated instrument are presented.

II. Science Drivers and Requirements

Main HIFI science driver is the detection of water lines, especially in the frequency range where the atmospheric absorption hampers the observation from ground. The second driver is the ability to perform line surveys to determine molecular complexities in active regions. From these drivers the instrument specifications are derived, see table 1. In this table the associated tests to verify these requirements are listed as well.

TABLE II
HIFI Requirements and Corresponding Tests

Category	Specification	Test
Functional	Chopper accuracy < 1 arcsecond Tuning duration < 20 seconds	SIS magnet tuning IF amplifier noise LO power tuning Diplexer tuning
Radiometry	flux calibration <10%, (3% goal) RF range 480-1250, 1410-1910 GHz IF range 4 GHz Noise temperatures as specified	Internal Calibrator Line linearity Continuum linearity Tsys survey RF paths standing waves Side band ratio Heterodyne validation Stability validation
Spectral Purity	Spurious <25 dB below signal No spurious in difference spectrum	Spurious signals Spurious responses
Frequency response	Spectral resolution <160 – 350 kHz Resolving power $>3 \cdot 10^6$ Frequency calibration $< 1 \cdot 10^7$ 95 % of energy within 2 ·FWHM	Resolution Frequency accuracy Line shape
Amplitude Stability	Allan variance < 1.5 times theoretical value	Total power Spectroscopic
Observational modes	Frequency switch > 90 MHz Beam switching using chopper	Frequency switch Chopper speed
	System engineering	LO purification* IF Feedback**

Radiometry and gas cell measurements are described in [5], and stability results in [6].
* The LO appeared to have a significant spurious frequency in 2 frequency ranges. The LOU settings were optimised to minimise this effect, but further optimization is required
** IF feedback is described later in this article.

III. HIFI TEST ENVIRONMENT

Since HIFI is a flight instrument, the test environment main criteria were temperature, temperature stability and pressure. The Focal Plane Unit (FPU) with the 14 mixers is cooled in a dedicated cryostat, with 2, 4 and 6K levels for the mixers, intermediate strapping and FPU housing respectively. The Local Oscillator Unit (LOU) was operated in a cryostat at 130K. This is the temperature the LOU will reach when cooled by a radiator in space. The electronics units including the backends will have a temperature close to room temperature. These were mounted in a closed cooled cabinet at ambient pressure.

Figure 1 shows the setup with FPU and LOU cryostat.

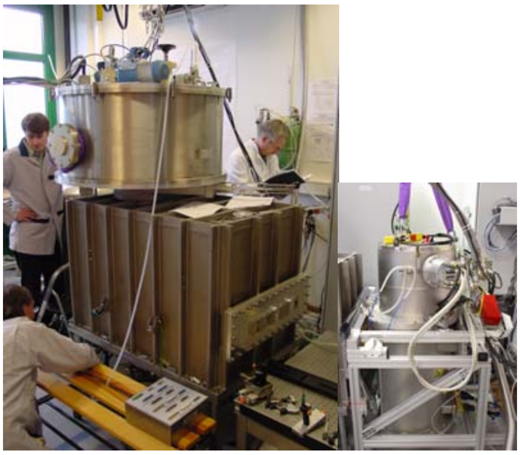

Fig.1. The square cryostat on the left houses the FPU. The right photograph shows the LOU cryostat mounted in a frame to provide alignment adjustments. The round vacuum tank on top of the FPU cryostat houses a scanner for beam measurements.

The LO signal was coupled to the FPU via a nitrogen flushed compartment. This was intended to stabilise the LO power input to the mixers and hence achieve the expected stability in flight. The flow also served to flush away any water adsorbed on the cryostat windows, thus achieving flight-representative LO power values on the mixers. All calibration sources were operated in vacuum. This was achieved either via a reimager, or by mounting the calibration source close to the FPU entrance mirror. The reimager is a vacuum tank of 1 m^3 with relaying optics, which maps the diverging beam of the FPU to a small collimated beam. Figure 2 shows the reimager in use.

Fig. 2. At the left a cryostat with a vacuum Hot/Cold load is shown, which is coupled via a gas cell and the large reimager vacuum tank to the FPU cryostat.

Operating HIFI was done remotely by an operator in a separate room, to minimise temperature variations in the room by airflows. In particular stability tests were programmed overnight for this reason. The test commands were sent to HIFI via a simulated onboard satellite computer. External equipment was readout and commanded via the same console, to fully automate and synchronize tests. The measurement data from HIFI and the test equipment was gathered in one database, for ease of correlation analysis.

IV. HIFI TEST RESULTS

The radiometric calibration, frequency accuracy and stability results are described elsewhere [3,5,6]. The final analysis on LO purity is ongoing, hence this results section will focus on the functional and engineering test results.

A. *Functional test results*

An important aspect of SIS operation is the proper setting of the magnetic field. Early in the mixer testing the mixer core material appeared hysteretic. To arrive at the proper field at the junction the magnet coil was never operated at negative currents and always commanded to a large positive current before going to the optimum setting. The effect of hysteresis was minimised by this approach. The reproducibility of this tuning was good enough to allow the automated tuning to be limited to a small region around the expected optimum magnet coil current. Figure 3 shows such a tuning using the measured IF power versus commanded magnet current. The mixer bias voltage used for this measurement was 50 µV away from the Shapiro step voltage.

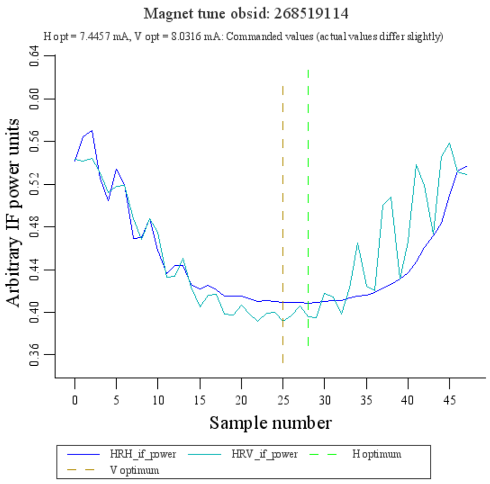

Fig. 3. Magnet tuning of band 1. The vertical axis gives the IF power, the horizontal axis the magnet current steps. The fast oscillation is due to the additional larger loop in the 2-junction structure. Still the algorithm finds the best setting of the magnet current.

The reproducibility of his method appears very good, independent of frequency and LO pump level. Related to this topic is the use of deflux heaters. All HIFI SIS mixers have heaters to heat the superconducting materials (Nb or NbN) above their critical temperatures. Although in flight it is not expected that significant varying magnetic fields will be present, especially in the on-ground testing this can occur. A large number of magnet tunings before and after defluxing has been taken up to now, and no clear indication of changed optima has been noticed. This hints toward a minimum expected use of the heaters in flight, thereby reducing overhead and He consumption.

The IF noise temperature is measured using the standard high-low mixer bias technique. The resulting IF noise spectra are shown in Figure 4.

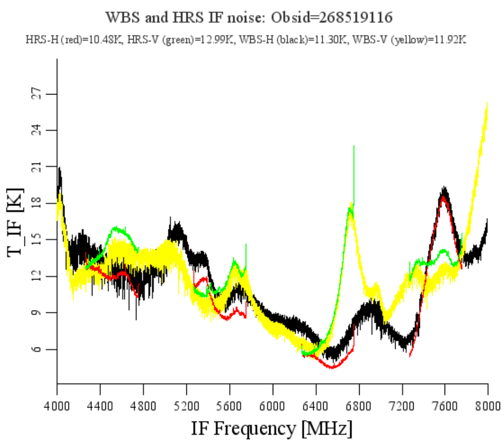

Fig. 4. IF noise temperature of band 2, Horizontal and Vertical polarisation mixers, measured by HRS and WBS each. Clearly the HRS and WBS spectrum per mixer polarisation overlap well, showing that the main contribution to the noise comes from the mixer-1st IF amplifier sections, and that the backend contributions are negligible due to the large IF amplification of 60 dB.

The LO power tuning is performed in 2 steps: Firstly the LO power is scanned over its full range by varying the drain voltage of the last power amplifier. From this measurement the optimum setting is chosen, Step 2 is a fine-tune of this setting before each measurement. The exact LO power is a sensitive function of temperature of the chain. Since the dissipation and hence the temperature drift in the LOU chain is significant, a tuning of the LO power in a small region around the previously found optimum is required. To reach the equilibrium temperature quickly, the fine-tune starts at a high drain voltage, and since during the scan the mixer current is monitored, the scan stops when the correct current is reached. This method avoids frequent retuning of the drain settings. The effect of LO warm-up on instrument stability is described in [6].

B. *Engineering test results*

During instrument tests it became apparent that when moving mechanical elements in the FPU cryostat and in the FPU itself, additional lines in the IF spectra could be seen. Since all measurements were performed with black thermal radiators in vacuum, these lines could not be originating from these sources. Since this effect was even present when the internal chopper was moved, the requirement that spurious signals shall not present in a difference measurement with 100 seconds integration, was violated. Investigations showed that the cause lies in the significant IF amplification. The occurrence of the unwanted lines in the spectra is explained as follows: The mixer IF signal is amplified by an 25 dB amplifier close to the mixer, and a second amplifier with up to 35 dB gain in a separate housing at the side of the FPU. This housing is fairly open for the IF field, and part of the signal is emitted into the cryostat. This is via wall reflections fed back to the 1st amplifier where it interferes constructively or destructively, depending on its phase. If now the FPU chopper moves, the path length is changed and hence the phase. Therefore the difference spectrum on/off source or Hot/Cold using the internal calibrators shows additional offsets. The reason that these offsets show up as lines is that the FPU cryostat has typical dimensions of 1 m^3, which together with the ~6 GHz IF frequency causes box modes, separated by 20 MHz, depending on the exact path. An example of such a difference spectrum is shown in Figure 5.

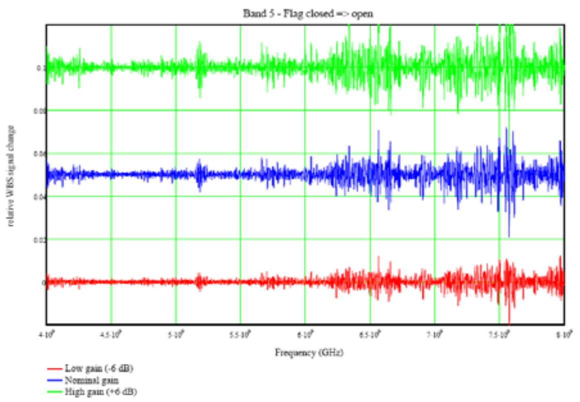

Fig. 5. Ratio of spectra taken for a mixer without LO power applied, at 2 chopper positions, as function of IF amplifier gain. Vertical axis: relative power, Horizontal axis: IF frequency. The offset is intentional. Clearly with higher IF gain (red-blue-green curves) the IF feedback effect increases.

This IF feedback effect must be present in many receivers, but since most of the ground-based observatories have moveable elements outside the cryostat, the effect is stable and hence not visible in difference spectra.

A solution was found in taping the outside of the 2nd IF amplifier housing with Aluminium tape, which minimises the leakage of the IF signal. Figure 6 shows the IF-2 housing with Al tape.

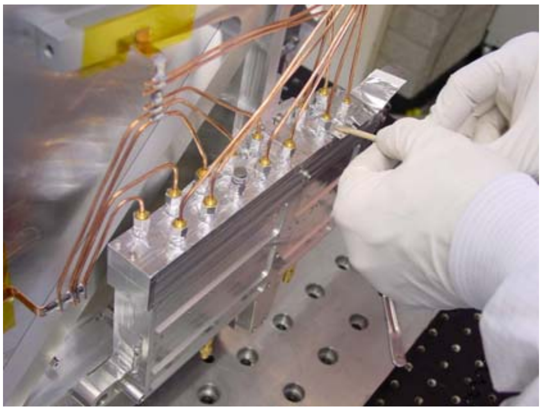

Fig. 6. The IF amplifier housing being covered with Al tape. An additional box was produced that facilitated the wrapping of the IF connectors.

The effect as function of area of the IF-2 housing covered with Al tape is plotted in Figure 7. On the long term the remainder of the effect can be calibrated out in flight, since the effect is reproducible with chopper angle, and the chopper reproducibility is very good.

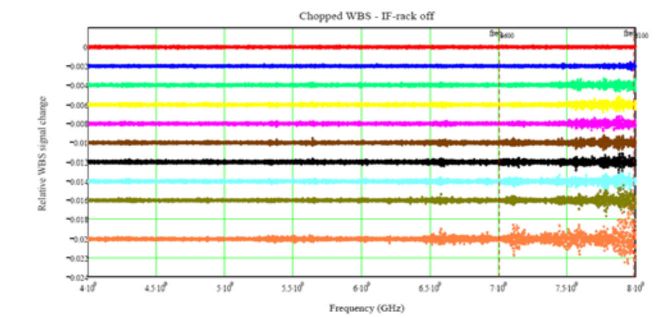

Fig. 7. Plot layout as in Fig. 5. The higher traces are taken with a larger area covered with Al tape. Clearly the IF signal seeps out of every part of the IF2 amplifier housing; the feedback effect is lowered for every additional part that is taped.

V. HIFI – HERSCHEL INTEGRATION STATUS

A. Integration test results

HIFI was delivered July 10, 2007 to EADS-Astrium Friedrichshafen[7] for integration with the Herschel satellite. Two aspects needed hardware modifications:

After electrical integration it appeared that a significant current ripple is present in the 28V power supply line from the solar panel simulator to the HIFI LO Control Unit. The ripple had a frequency of 600 Hz and an amplitude of 300 mA peak-peak, on a total of 1A. A filter to damp the oscillations was designed and fabricated by the HIFI team and mounted on the satellite. The filter functioned well; no ripple could be perceived.

A second hardware change concerned a cryostat window heater. From earlier missions it is known that significant quantities of water escaping from the vast area of the satellite isolation layers can freeze at the coldest points. The coldest spots are the windows in the Herschel cryostat. These windows enable LO power injection to the mixers. If water would freeze here the effect on LO power loss is significant[8]. Removing the ice needs a temperature of the window of at least 170 K to avoid excessive heating durations[9]. Hence a dedicated construction with additional windows on a thermally insulated holder was devised. Recently this unit passed thermal testing successfully and is now ready for integration with the satellite.

In Figure 8 the fully assembled Herschel satellite is shown.

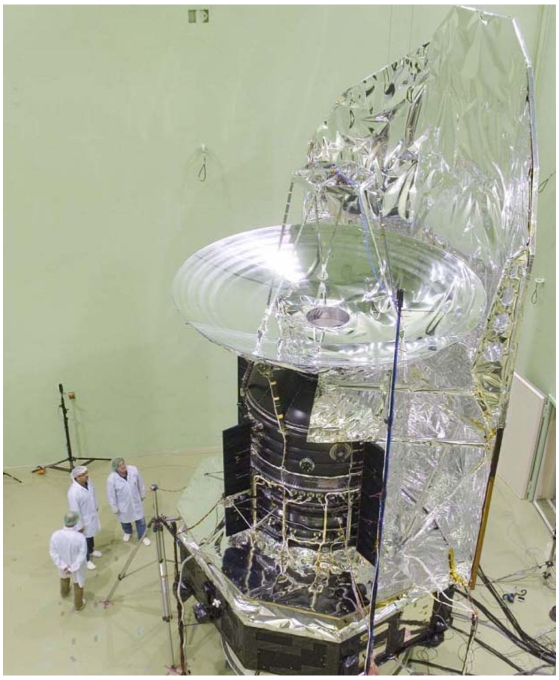

Fig. 8. The Herschel satellite in fully assembled configuration ready for acoustic testing.

B. Performance test results

The first performance tests were executed in April 2008. The LOU is at ambient temperature during these tests, which results in a lower output power compared to that at the operational temperature in flight. The second effect is that the LOU is misaligned to anticipate the shrinkage of the support structure at operational temperature. Bands 6a, 7a and 7b could therefore not be performance tested due to lack of LO power. The other bands showed that the noise temperature spectra are unchanged with respect to those seen during ILT. The previously mentioned IF feedback effect was reduced by a factor of 3, most likely because of the larger volume and absorbing contents of the Herschel cryostat compared to the HIFI ILT FPU cryostat.

CONCLUSIONS

The HIFI ILT and Herschel integration phases are nearly complete. Preliminary performance tests with warm LOU show that HIFI is healthy and performing well. The final confirmation will be in the Thermal Vacuum test, where the LOU will be operated at flight representative temperatures

ACKNOWLEDGMENT

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