Performance of HIFI in flight conditions

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***Abstract*— HIFI, the Heterodyne Instrument for the Far-Infrared is one of three instruments on board the ESA Herschel mission, planned for launch in May 2009. The HIFI instrument was tested in representative flight conditions during the Thermal Balance / Thermal Vacuum (TBTV) test in ESA's Large Space Simulator (LSS) last December 2008. In particular HIFI's local oscillator could finally be tested over its full frequency range.**

The system noise temperature is similar to that found during instrument testing at the laboratory. Stability is measured to be slightly worse for the SIS bands and better than before for the HEB mixers, the latter most likely due to the absence of vibrations of mechanical cryocoolers. A new diplexer calibration approach was used, LO purity tests around 930 and 1900 GHz to remove spurious signals were successfully performed. Standing waves in both the signal-and LO optical paths were measured to provide input for spectrum baselines optimization schemes.

***Index Terms*—Submillimeter wave receivers, superconductor-insulator-superconductor devices, quasioptical mixers, Infrared spectroscopy.**

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 – 1270 and 1430 to 1901 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 LO is placed outside the cryostat to limit the heat load on the helium. A dedicated radiator will cool the LO to 125 K once in flight (see Fig. 1). 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 140 kHz.

HIFI was delivered to ESA for integration onto the Herschel satellite in June 2007. HIFI was fully integrated by April 2008. Most of the performance tests were executed in the summer of 2008. However n these tests the LO frequency coverage was limited, since the LO is mounted outside the cryostat and is hence at ambient temperature in normal clean room test environment. The available LO power at room temperature is insufficient for the band 6 and 7 HEB mixers. The Herschel Thermal Balance / Thermal Vacuum test was therefore the first opportunity to test the HIFI over its full frequency range. In this article the calibration scheme, some optimizations and the final performance as measured during the TBTV test are reported.

II. HERSCHEL THERMAL BALANCE TEST

November 2008 the Herschel satellite was lowered into the LSS, (Fig. 1) and the cool-down of the Large Space Simulator (LSS) [4] at the ESA test center ESTEC started.

The entire satellite was radiatively cooled in the LSS. Thermal equilibrium at 130 K was reached after 5 days for the LO. To save time a dissipative heater was used to avoid cooling the LO to its equilibrium temperature without dissipation. The heater power was set to the average LO dissipation in operation. Throughout the TBTV tests and in flight the dissipation of the LO was kept constant, either by operating the unit or by using this heater.

The warm units (spectrometers, electronic control and supply units) cooled to 5ºC in 24 hours, after which satellite heaters prevented further cooling. After HIFI switch-on, the temperature went up to 10 - 20ºC within 24 hours.

The thermal equilibrium temperature of the HRS appeared to be too low to maintain the clock speed of the HRS ASICs; satellite heaters were used to increase the temperature at the mounting interface to 25ºC. The thermal stability requirement of 0.3 mK/s of the WBS and HRS spectrometers units is guaranteed by a PID control.

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Fig. 1. Herschel lifted to be placed into the LSS. The 3.5 meter telescope is covered by a protection cloth. The rear side of the solar panel is covered by multilayer thermal insulation (MLI) blankets. The black central cylinder contains the 2500 liters He and the focal plane units of the instruments. The lower section, covered with black MLI contains the warm electronics that will be kept at room temperature by their own dissipation . Clearly visible is the LO radiator close to the solar panel, this will allow the LO to cool to 125 K in flight.

III. HIFI TUNING

After thermal equilibrium was reached and a series of health checks was successful performed, the diplexers and LO settings could be tuned to provide optimum signal coupling and LO power to the mixers.

Diplexers in the Focal Plane Unit provide LO and signal coupling for 4 mixer bands. These diplexers are unbalanced and hence need re-adjustment once without gravity in flight.

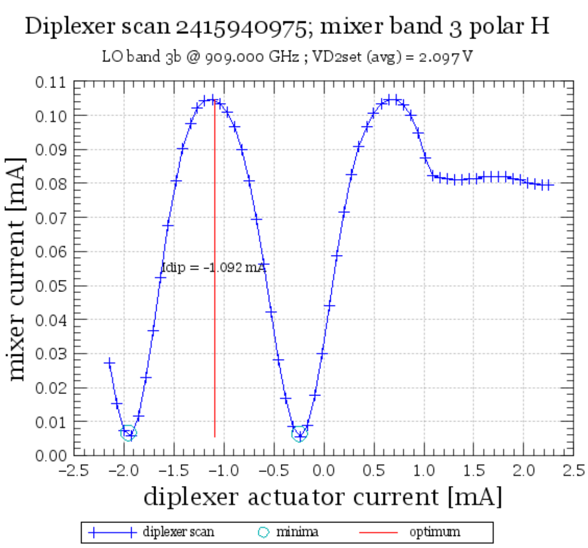

Fig. 2. A typical example of a diplexer scan. In this case the diplexer hits the end-stop beyond 1 mA, hence the flat region. The optimum is calculated as the average of the minima.

The diplexer calibration starts with a coarse tuning to optimize the LO – mixer coupling. Fig. 2 shows the result of a coarse diplexer scan.

Since neither the optimum LO power not the optimum diplexer setting is known a priory, the diplexer scan is executed for 7 LO power settings to hit at least one proper setting. The LO output power is controlled by the drain voltage setting of the 2nd power amplifier in the chain, before the multipliers. In Fig. 3 the mixer current as function of LO drain voltage (Vd2) is shown for mixer band 4 and LO subband 4a.

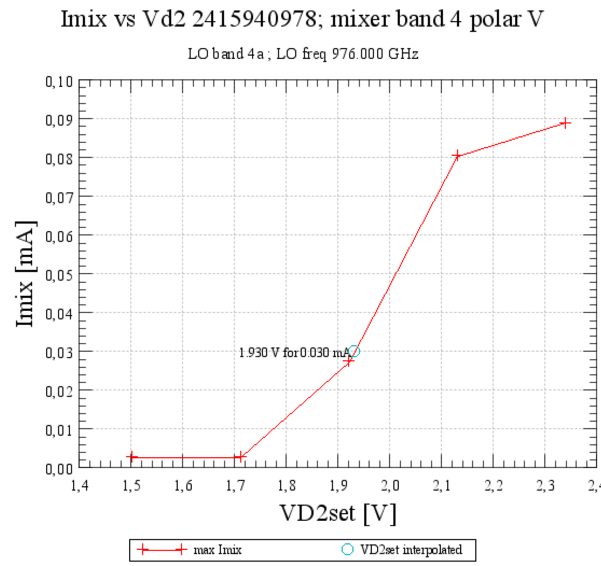

Fig. 3. The relation between 2nd power amplifier drain voltage and mixer current. The interpolated drain voltage setting is indicated as well.

This Vd2-mixer current relation is needed for the diplexer fine calibration, in which the diplexer setting for the signal path is optimized. The reason to include this test is that the LO alignment may differ from the signal path alignment. Since the diplexer function is based on path lengths variation, and the path length is dependent on the angle of the beam, any unequal alignment of the two beams would result in a different diplexer optimum setting. The signal path coupling optimization is performed by measuring the noise temperature using the internal hot-cold calibration loads for 20 diplexer settings around the expected optimum. A typical result of the diplexer fine calibration can be found in Fig. 4.

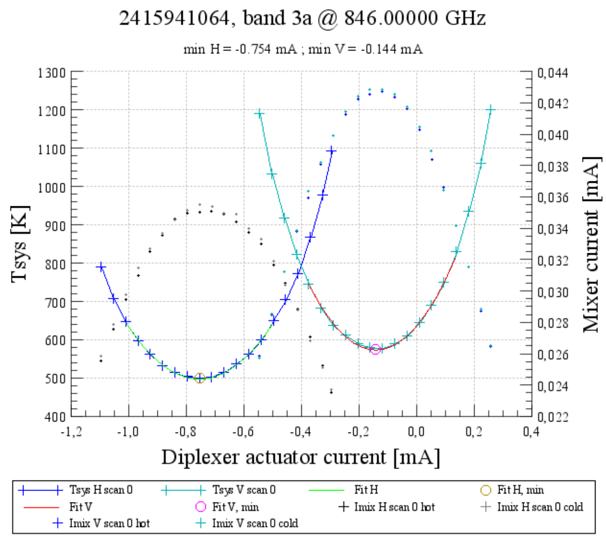

Fig. 4. Noise temperature versus diplexer setting for the H and V polarizations. The optima for the signal path are quite close to those found for the LO path.

The resulting diplexer calibration relation is shown in Fig. 5.

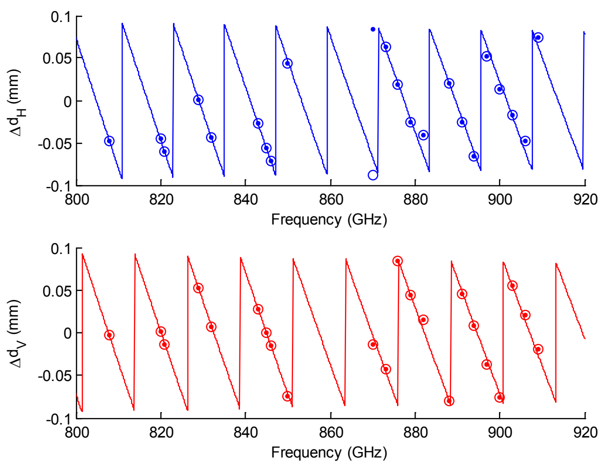

Fig. 5. Saw-tooth result for the diplexer setting as function of LO frequency. Clearly the model (line) fits the data (open circles) very well.

Generally the fine-tuning confirmed the course calibration results. Deviations were too small to be discerned mainly because of the limited accuracy of the noise temperature measurements due to standing waves and drift. The final accuracy is better than 2% of a wavelength, and hence the signal coupling losses are negligible.

The LO settings need adjustment with respect to the ILT found values since the LO attenuator values were different from those used in ILT, furthermore the output power is dependent on the LO temperature and the LO harness was now at 100 K rather than room temperature. The LO output power was calibrated by scanning the Vd2 and measuring the resulting mixer current for every 2 GHz over the full HIFI bandwidth. This procedure is performed with the diplexer already at the optimum LO coupling setting. The result is similar to that presented in Fig. 3, but with 10 points for optimum interpolation accuracy. An example of the HEB mixer current for the full LO power for LO subband 6b is shown in Fig. 6.

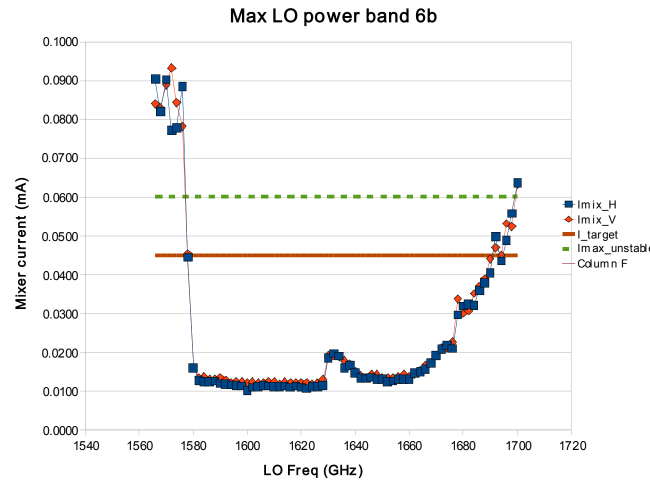

Fig. 6. Mixer current versus LO frequency for the maximum LO power. The brown line indicates the mixer current for best noise temperature. Clearly there is ample LO power over a 120 GHz range in this LO subband.

IV. HIFI Performance Test

With the diplexers and LO well tuned, the mixer magnet settings for maximum suppression of Josephson noise could be optimized. The method is described in [5]. The results are similar to those previously measured at ILT and during Herschel integration with the LO at room temperature.

The system sensitivity of HIFI was measured using the internal hot (100K and cold (10K) calibration loads for every 2 GHz. External loads or line signals could not be used since the Herschel cryocover was not opened during the TBTV test. The result is shown in Fig. 7. The noise temperature is similar to that measured in the Instrument Level Tests (ILT) just before delivery to ESA. At a number of frequencies the LO settings could be optimized to achieve an increased pump level at the mixer compared to ILT, so drop-outs at isolated frequencies could be removed. Since two mixers (horizontal and vertical polarization) function simultaneously, one could add the spectra and arrive at a combined system noise temperature that is square root 2 lower than the individual noise temperature, provided the noise temperatures and stabilities are similar.

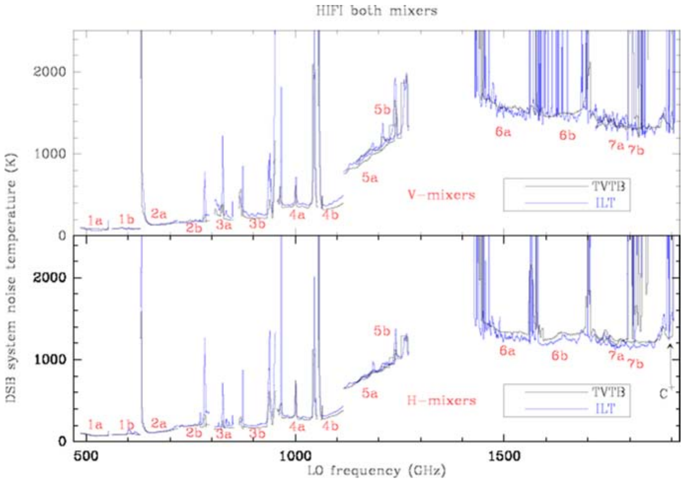

Fig. 7. System noise temperature as function of LO frequency. The plotted noise temperature values are the median values over the IF range.

V. LO PURITY

In the instrument level tests in the laboratory just before delivery it was found that LO subbands 3b and 7b had frequency regions where most of the LO power produced was not at the commanded frequencies. This behavior became apparent not only from dedicated spurious signals tests with external signal sources, but also by examining the diplexer scans in these frequency ranges. The diplexer can act as a Fourier transform spectrometer (FTS), albeit with a limited frequency resolution since the optical path length modulation is a mere 2 to 7 wavelengths. Since in the LSS an external signal source could not be used, the LO purity level could only be determined by diplexer scans. The diplexer model established as a result of the diplexer coarse test is then used to determine the mechanical path length and hence the LO frequency.

A typical example of the LO impurity is the spare band 3b output spectrum as shown in Fig. 8. The spare band 3b chain exhibited very similar behavior and hence the recipe to cure the problem could be determined and tested offline as a preparation for the TBTV test.

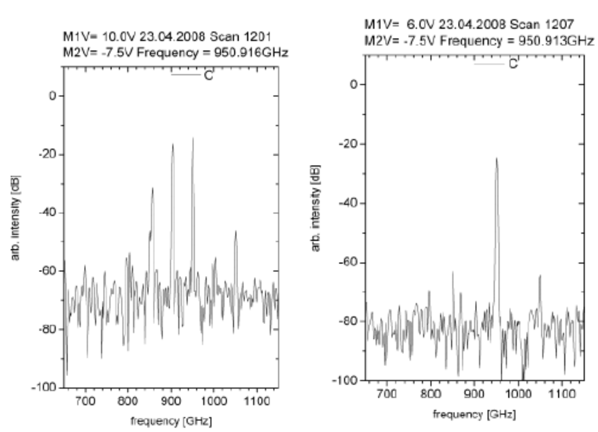

Fig. 8. LO output spectra measured with an FTS on the spare 3b LO chain. Commanded frequency is 950.916 GHz. The left plot shows the multi-tone with the default multiplier settings, the right plot shows the cleaned-up spectrum with settings optimized for single tone at the correct frequency.

It was found that the 1st (M1) and often also the 2nd multiplier (M2) stage bias voltages directly impact the purity of the LO signal.

The 3b TBTV purity test consisted of collecting the voltages and currents of the chain as well as taking diplexer scans for a 2-D grid of M1 and M2 voltage settings. A second parameter relating to the LO purity appeared to be the M2 current. For 3b the M1 needed to be biased more forward, M2 needed sometimes a more reverse bias voltage. To ensure these settings would not affect the lifetime of the multipliers, the 3b spare chain was lifetime tested at a worst case 8μA M2 reverse current for twice the expected flight operation time.

The test result is good: 9 out of 12 LO frequencies could be purified and the expectation is that the last 3 can be cured as well with extrapolated M2 voltages.

LO subband 7b was known to have purity problems above 1890 GHz. Unfortunately most of the observation proposals are centered around the CII line of 1901 GHz, that requires an LO frequency between 1897-1898 to measure the line in the upper side band. The purity effort in TBTV concentrated on this line. For band 7b it was found in ILT that the cure lies in operating the 1st multiplier at more negative voltage bias. However the LO band 7b was already used with M1 voltages close to half the reverse breakdown voltage, the general 'rule of thumb' safe limit to avoid damage to the diode. Hence the importance of lifetime tests was emphasized. A test was performed on a 200 GHz flight spare multiplier. In this test the device survived more than -9V of reverse bias with 100mW of RF. Although the I,V curve of the diode did change substantially, it stabilized and the output power hardly changed after 1000 hours of testing. The input power of the flight multiplier will be below 100mW, and the reverse bias will be -8.5 V or less. The 7b purity test was successful: the CII line is now clean.

For the diplexer bands 3,4,6 and 7 diplexer scans were taken for every 2 GHz with the aim to examine the LO purity. In this diplexer survey no new impure regions were found, except for bands 7a and 7b. Fig. 9 shows that regions a few GHz wide are present in these bands that show deviating LO frequencies. Curing these fell outside the scope of the TBTV test. With the knowledge obtained these can be addressed, although this will have to be in flight.

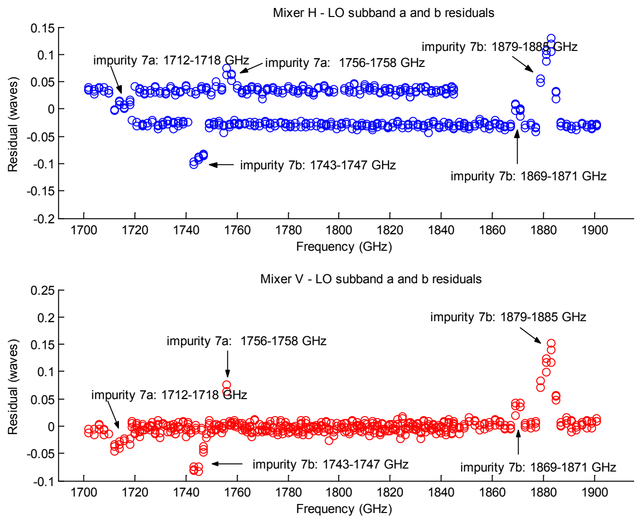

Fig. 9. Deviation of the measured versus commanded LO frequencies in terms of wavelength fractions. The CII (1900 GHz) region is clean.

VI. Standing Wave Tests

Dedicated tests were performed to find amplitude and periods of standing waves in both the LO and signal paths. The method chosen is to measure the mixer current and take I spectra during a retune the LO in steps of 14 MHz, with the mixer and diplexer tuned for the middle frequency of the range. For the signal path, the IF spectra were divided by the first spectrum and an FFT was calculated. The thus normalized IF spectrum is shown in Fig. 10.

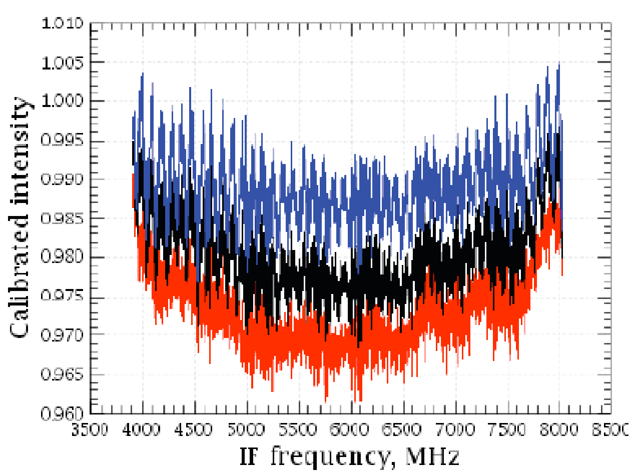

Fig. 10. Normalized spectra used in the signal standing wave calculation. The deviation from 1 is an indication of the mixer current and IF impedance match variation over the LO frequency range of 0.5 GHz.

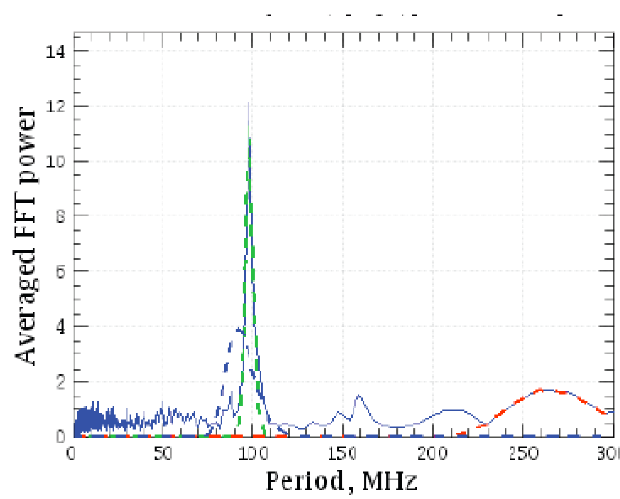

Fig. 11. FFT of the IF spectrum of Fig. 10. The peak at 92 MHz corresponds to the optical path length of 1.63 meters between the mixer and internal hot calibration source. The cold source – mixer distance is shorter (1.53 m), resulting in a frequency of 98 MHz.

The standing wave in the mixer – LO path was measured by monitoring the mixer current during the LO frequency retuning. The resulting curve shows a clear sinusoidal pattern, as can be seen in Fig. 12.

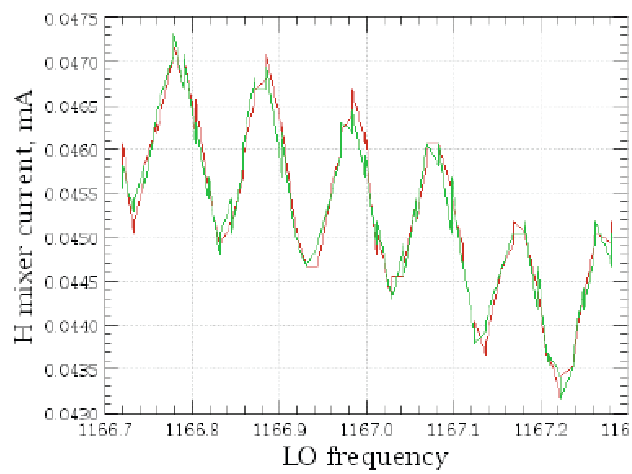

Fig. 12. Mixer current versus LO frequency. The frequency is typically 92 MHz, since the length of the mixer – LO path is (unintentionally) identical to the mixer – hot source.

Main standing waves found when looking at the Cold or Hot calibration loads are presented in Table 1.

TABLE I HIFI STANDING WAVE FREQUENCIES

Dominant Frequency	Path	Other frequencies
92 MHz	Mixer – Hot source	320, 650 MHz
98 MHZ	Mixer – Cold source	320, 650 MHz
92 MHz	Mixer – LO	320, 650 MHz

The higher frequencies are seen in the diplexer bands only, and the 650 GHz corresponds to 22 cm which is the distance between the diplexer rooftop and the mixer. The 320 MHz may be due to the combined rooftop reflection and the interaction between the 2 mixer – LO paths, which causes an additional total coupling modulation.

The aim of the standing wave test is not only to measure the magnitude of the standing waves as such, but also to indicate the optimum frequency throw for frequency switched observations. Frequency switching is a popular observing mode for heterodyne systems since both in the "on" (At LO frequency f_1) as in the "off" (LO frequency $f_2=f_1+f_{throw}$) state the signal can be observed and dead time is minimized [7]. The frequency throw was chosen equal to the mixer – LO standing wave frequency of 92 MHz. This to ensure the mixer is pumped to the same mixer current level for f_1 and f_2 and that the difference in LO dissipation between f_1 and f_2 is minimal, providing a thermal drift as low as possible. Unfortunately most HIFI bands exhibit a slope on top of the sine, as seen in Fig. 12. For this reason retuning of the LO power is required when going from f_1 to f_2, and the resulting small difference in mixer currents and LO dissipations for the 2 frequencies does affect the baseline quality [6].

The HIFI stability was measured extensively, for various observing modes. The results are described in [6]. Generally the stability especially for the bands 6 and 7 is better than measured during the instrument level tests. The main reason may be the absence vibrations from mechanical cryo-coolers in the Large Space Simulator, which caused significant path length and hence LO power modulations in ILT where both the FPU and LO cryostats were cooled by separate mechanical coolers.

VII. HIFI STATUS AND OUTLOOK

The HIFI TBTV tests finished December 10th. After warm-up the satellite was moved to the Ariane Espace Launch site in Kourou, French Guyana. March 9th the last HIFI health check was performed, confirming that HIFI survived transport in good health and is ready for launch. The Herschel launch is expected to be in May 2009. One week after launch HIFI will be cooled down to its equilibrium temperature and can be switched on. The commissioning phase duration is 2 months, in which part of the TBTV tests are repeated to obtain the final flight performance of HIFI

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