

The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI): Instrument and Pre-launch Testing.

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Abstract

This paper describes the Heterodyne Instrument for the Far-Infrared (HIFI), to be launched onboard of ESA's Herschel Space Observatory, by 2008. It includes the first results from the instrument level tests. The instrument is designed to be electronically tuneable over a wide and continuous frequency range in the Far Infrared, with velocity resolutions better than 0.1 km/s with a high sensitivity. This will enable detailed investigations of a wide variety of astronomical sources, ranging from solar system objects, star formation regions to nuclei of galaxies.

The instrument comprises 5 frequency bands covering 480-1150 GHz with SIS mixers and a sixth dual frequency band, for the 1410-1910 GHz range, with Hot Electron Bolometer Mixers (HEB). The Local Oscillator (LO) subsystem consists of a dedicated Ka-band synthesizer followed by 7 times 2 chains of frequency multipliers, 2 chains for each frequency band. A pair of Auto-Correlators and a pair of Acousto-Optic spectrometers process the two IF signals from the dual-polarization front-ends to provide instantaneous frequency coverage of 4 GHz, with a set of resolutions (140 kHz to 1 MHz), better than < 0.1 km/s. After a successful qualification program, the flight instrument was delivered and entered the testing phase at satellite level. We will also report on the pre-flight test and calibration results together with the expected in-flight performance.

Keywords: Astronomy, Far Infrared, Sub-millimetre, Space Instrumentation, Heterodyne receiver, Spectrometer.

1. Introduction

HIFI, the Heterodyne Instrument for the Far Infrared, is one of the three instruments to be placed in the focal plane of the 3.5 meter telescope on board of "Herschel", the fourth cornerstone of ESA's Horizon 2000 program. The Herschel space mission, scheduled for launch in 2008, is designed to study the universe in one of the last unexplored regions of the electromagnetic spectrum. The main scientific goals for the Herschel mission are in the area of evolution of galaxies and star and planet formation. [1]

As Herschel is an observatory-type mission, HIFI needs to be versatile to be able to address many key themes in modern astrophysics. Therefore the instrument is designed to provide very high spectral resolution over the widest possible frequency range. With the limited collecting area of a 3.5 m telescope utilisation of state-of-the-art superconducting mixers with near quantum-noise limit system noise temperatures are required for adequate sensitivity. The very high spectral resolution, provided by the heterodyne technique, will also be important to disentangle the contribution from the various emission regions often contained in the relatively large beam of the Herschel telescope. HIFI is not the first heterodyne space instrument for Astronomy. SWAS and ODIN are both smaller heterodyne space missions that explored mainly a limited frequency range around 550GHz, and which had detection of inter- and circumstellar Water and molecular Oxygen as key science objectives

2. Scientific Rationale for Herschel-HIFI

The scientific themes for HIFI are mainly related to the understanding of the cyclic interrelation of stars and the interstellar medium in galaxies. On the one hand, stars – and planetary systems - are formed through gravitational collapse of interstellar molecular clouds. On the other hand, the interstellar medium is formed from the ejecta - enriched by newly synthesised elements - of dying stars. This complex interplay between stars and the ISM drives the evolution and, thus, the observational characteristics of the Milky Way and other galaxies, all the way back to the earliest proto-galaxies at high red-shift. Although HIFI will have capabilities to address many key topics in modern astrophysics, there are three areas for which HIFI will be unique: Observations of water lines, the molecular complexity of the Universe and Observations of red-shifted [CII].

2.1 Observations of Water

Water is a key ingredient in many environments, including young stellar objects, late type stars, planetary nebulae, dense molecular clouds, interstellar and circum-stellar shocks, solar system objects such as comets, planets and

satellites, and circum-nuclear disks in Active Galactic Nuclei; essentially in any dense and warm environment. Water is a cornerstone molecule in interstellar chemistry and it can be a dominant reservoir of elemental oxygen in the gas phase. Because of its many levels, water is also an important coolant, which can dominate the energy balance of the gas in such regions. This occurs in a very subtle way through a delicate balance because the radiation field can couple different parts of the cloud, leading to complex line profiles, hence requiring high spectral resolution. Of course, the many water levels with their different Einstein A-values also provide a powerful diagnostic of the physical conditions in the emitting gas. While some other space-borne instruments have measured only a few transitions of H₂O, HIFI will cover an unparalleled number of water lines that are sensitive to a wide range of physical conditions at high spectral resolution. Within the broad field of water studies, the HIFI consortium has singled out the “water trail in star-forming regions” as a key project for HIFI. The aim is to follow the origin and evolution of water from dark dense, pre-stellar cloud cores, through the onset of collapse, the formation of the YSO and its circum-stellar disk, and the eventual incorporation into planetesimals and eventually planets. Because of atmospheric conditions, studies of interstellar and circum-stellar water are unique to space and, particularly to HIFI with its high spectral resolution at sub-millimetre wavelengths where the most important water transitions reside.

2.2 The Molecular Universe

Over the last decade, it has become increasingly clear that molecules are an important component of the interstellar medium even outside the shielded environments of molecular clouds. Because of its exceptional spectral coverage, HIFI is eminently suited to study the molecular universe, including large organic molecules, through spectral line surveys. Such studies will provide an unbiased view of the molecular inventory of a wide range of objects. Moreover, the large number of lines of individual molecules present in these spectra will allow detailed study of the physical conditions in

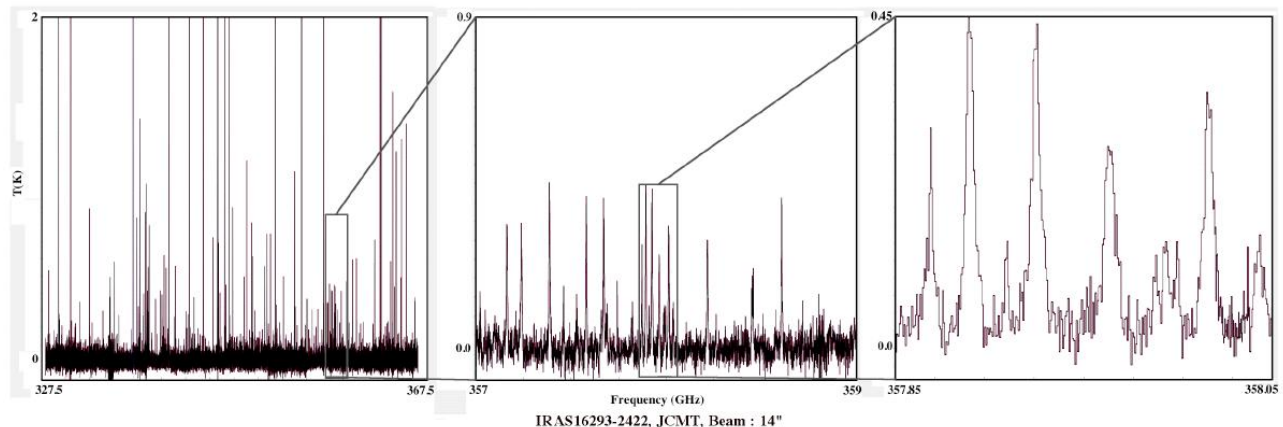


Figure 1. Sample spectra of a spectral scan towards IRAS 16293-2422 with the JCMT. The survey was performed at a spectral resolution of about 0.6 km/s. The brightest line is about 25 K (truncated in the plot to enhance faint lines) the emitting gas. The origin and evolution of the molecular universe starts with the injection of material by stars in the later stages of their evolution. After subsequent processing of this material in the interstellar medium by the prevalent possibly other planetary systems in the universe is a key problem within astrophysics. Through complete spectral line surveys, unhindered by telluric absorption in the sub-millimetre, HIFI can measure the molecular inventory of a wide range of evolutionary stages of interstellar clouds, under a variety of excitation conditions like ultraviolet radiation fields and strong shocks, to where evolution ends resulting into newly formed stars and their budding planetary systems. Understanding this pre-biotic evolution and its relationship to the origin of life on Earth is one of the main objectives. HIFI will provide also a unique opportunity to search for the ro-vibrational transitions associated with low-lying vibration modes of complex species, like Carbon chains and Polycyclic Aromatic Hydrocarbon molecules (PAHs) which dominate the mid-infrared spectra of circum-stellar region. An example of the richness of the spectral data we expect, is shown in figure 1. (E.Caux et al. private communication). Here the line density is on average 20 lines /GHz.

2.3 Red-shifted CII

HIFI is currently the only instrument which can survey the red shifted [CII] 158 micron line, the dominant cooling line of interstellar gas and a direct probe of massive star formation, through the very important red shift-range of 0.5-3 when

galaxy evolution was in full swing. Because of its high luminosity, this line can be observed to very high red shift and will provide a direct measure of the FUV starlight in dusty galaxies, which is important for galaxy evolution. SOFIA will be limited by sensitivity and telluric absorption through this red shift range. Red shifts beyond 1.5 can be studied using ALMA, but not contiguously. There is overlap with PACS in this range but HIFI will provide spectrally resolved lines, disentangling emission and absorption, and velocity structure within galaxies. Moreover, HIFI makes it possible to directly compare line profiles of e.g. CO and HI. In any case, because the 0.5-3 red shift interval is crucial for the evolution of galaxies, the formation of their disks, and the production of metals, observation of the [CII] line in this red shift range will be a fundamental contribution of HIFI to the field of galaxy evolution.

3. Instrument Design Concept

The Heterodyne Instrument for the Far-Infrared Space Observatory [2] onboard the Herschel Space Observatory has been optimised to address the astronomical key questions discussed above and these require all high spectral resolving powers and sensitivity. By combining the high spectral resolving power of the radio heterodyne technique with near quantum-noise limited sensitivity from superconductor physics and applying state-of-the-art in microwave technology, it was now possible to construct an instrument with the following capabilities:

- Continuous frequency coverage from 480 to 1250 GHz in five bands, while a dual sixth band will provide coverage for 1410-1910 GHz
- Resolving powers up to 10^7 (300 – 0.03 km/s)
- Detection sensitivity close to the theoretical quantum noise limit.

HIFI instrument consists of five major sub-systems, shown in the block-diagram of figure 2.

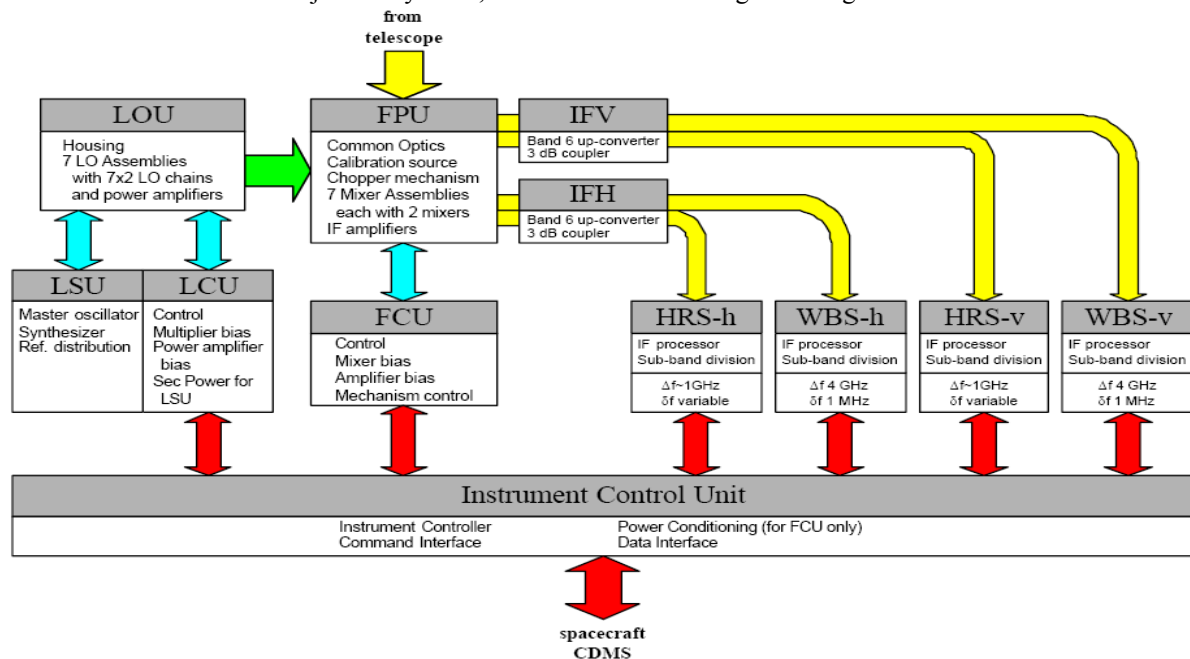


Figure 2. HIFI blockdiagram showing the various sub systems and their interconnections.

1. The focal-plane sub-system comprises the focal-plane unit (FPU) inside the cryostat. This contains relay optics, diplexers for LO injection, a focal-plane chopper, mixers, low-noise IF pre-amplifiers, and calibration sources. A FPU control unit (FCU), located at the Service module (SVM), supplies the bias voltages for mixers and IF preamplifiers in the FPU and controls the LO diplexers, the focal plane chopper mechanism and the calibration source.
2. The local oscillator sub-system comprises the local oscillator unit (LOU) located on the outside of the cryostat. The LOU contains 7 Local Oscillator Assemblies (LOA), each contain two LO multiplier chains and their feeding power amplifiers/triplers. These chains are fed by a common LO Source Unit (LSU) and generate the LO signals which are coupled into the FPU via 7 windows in the cryostat wall. The Local Oscillator Source Unit (LSU) and a Local Oscillator

Control Unit (LCU) are located in the service module (SVM) and contain the reference frequency source and the bias supplies and controls of the local oscillator.

3. A Wide-Band Spectrometer (WBS) [2] consists of a pair of 4 GHz-wide Acousto-Optic Spectrometers (AOS) with a frequency resolution of about 1 MHz and a bandwidth of 4 GHz for each of the two polarisations. They are located in the SVM.

4. A High-Resolution Spectrometer (HRS) [2] consists of a pair of auto-correlator spectrometers and will provide several combinations of bandwidth and frequency resolutions. The HRS is divided into 4 sub-bands, each of which can be placed anywhere within the full 4 GHz IF band. The HRS modules will also be located in the SVM.

5. An instrument control unit (ICU) within the SVM interprets commands from the satellite tele-command system, controls the operation of the instrument, and returns science and housekeeping data to the satellite telemetry system.

4. Focal Plane Sub-System

4.1 The Focal Plane Unit

The focal-plane unit (FPU) [3] is the cryo unit of the focal plane subsystem to be located on the optical bench inside the Herschel cryostat. It contains relay optics for the sky signals that is common for all mixer bands and that includes also a

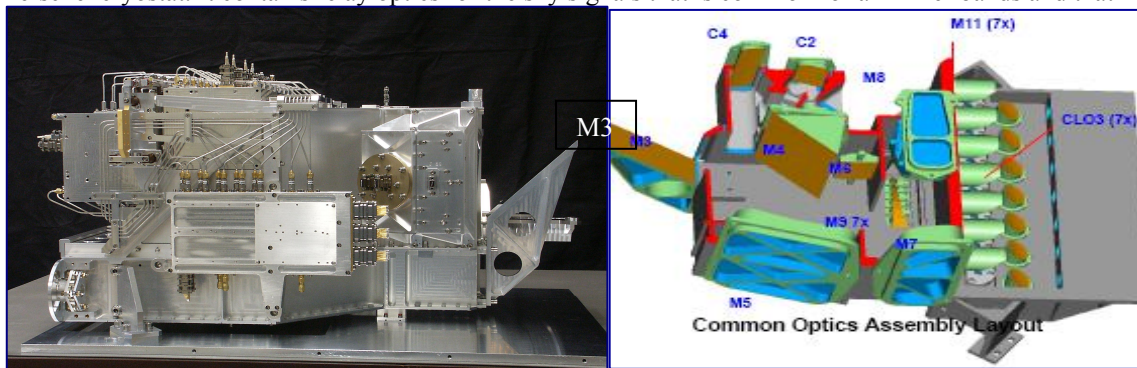


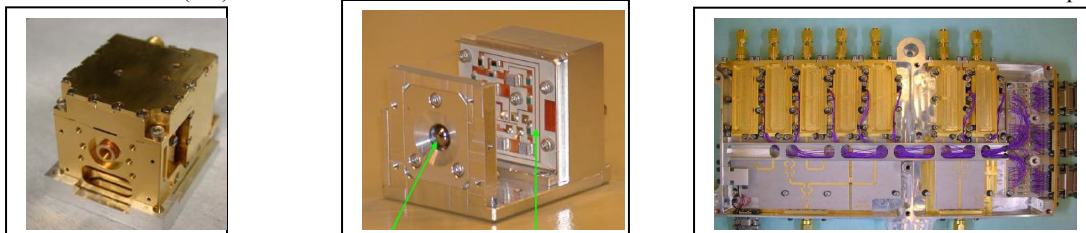
Figure 3. HIFI flight model Focal Plane Unit together with the lay-out of its Common Optics Assembly, in mirrored composition. Note, mirrors #3, which direct the radiation from the telescope into the FPU, are just next to each other, in the middle of the page.

focal plane chopper. It holds also the mixer sub assemblies (see below), the diplexers for LO injection, a low-noise IF pre-amplifiers box, and calibration sources. A FPU control unit (FCU), located at the Service module (SVM), supplies the bias voltages for mixers and IF preamplifiers in the FPU and controls the LO diplexers, the focal plane chopper mechanism and the calibration source. It is a frequency independent design where the waist positions are frequency independent and where alignment can be carried out with visible light. The optics is all reflective. Al used for all the mirrors and is the same as used for the mechanical structure. Figure 3 shows a diagram of the Common Optics Assembly together with a picture of the flight model of the FPU after its assembly has been completed.

4.2 The HIFI Signal Chain

There are 7 mixer bands (see figure 4) that cover the overall HIFI frequency range, each with two mixer sub-assemblies (MSA). One mixer band will operate at a time. The pair of mixers in a mixer band operate at orthogonal polarisation. It also provides redundancy for the frequency bands. The MSA's contain mechanical supports, mixers, diplexers and polarisers as well as IF amplifiers, and are mechanically mounted on the FPU. The block diagram of the HIFI signal chain showing all components for one polarisation is shown in figure 5.

Figure 4. HIFI Mixer for band-1 (left) and for band-6 (right) with the flight model of the IF-2 box with contains 2 times 7 amplifiers.



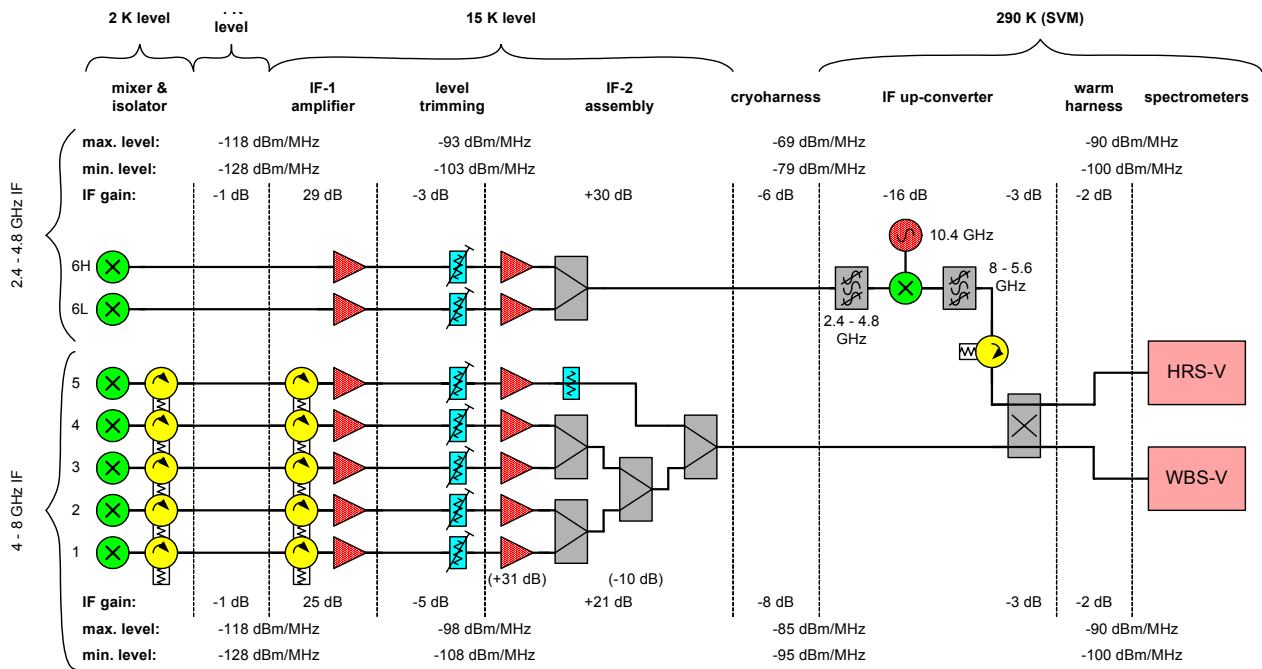


Figure 5. Block diagram of the HIFI signal chain showing all components for one polarisation

With the HIFI mixers covering such a wide frequency range several dedicated developments were needed to optimise the sensitivity for each mixer band. Therefore they have been developed in several European and US laboratories. For a summary see table 1. The achieved performances are presented in figure 6. The flight mixers were delivered in 2005 and early 2006 and integrated in the MSAs and these were subsequently integrated in the Focal Plane Unit.

Table 1. Overview of frequency ranges and technologies for the HIFI mixer bands. See a.o.[4,5,6,7,8,9].

Mixer band	Frequency range	Mixer Element	Matching circuit	Feed/coupling structure	Mixer Laboratory	Development
1	480 – 640 GHz	SIS Nb-Al ₂ O ₃ -Nb	Nb on Nb microstrip	corrugated horn and waveguide	LERMA	Paris, France
2	640 – 800 GHz	SIS NbTiN-Al ₂ O ₃ -Nb	Al on NbTiN microstrip	corrugated horn and waveguide	KOSMA	Koeln, Germany
3	800 – 960 GHz	SIS NbTiN-Al ₂ O ₃ -Nb	Al on NbTiN microstrip	corrugated horn and waveguide	SRON	Groningen, Netherlands
4	960 – 1120 GHz	SIS NbTiN-Al ₂ O ₃ -Nb	Al on NbTiN microstrip	corrugated horn and waveguide	SRON	Groningen, Netherlands
5	1120 – 1250 GHz	SIS NbTiN-AlN-NbTi	Al on NbTiN microstrip	lens and twin slot antenna	CalTech/JPL	Pasadena, USA
6	1410 – 1703 GHz	HEB NbN phonon cooled	Al co-planar waveguide	lens and twin slot antenna	Chalmers Univ.	Gothenborg, Sweden
67	1703 – 1910 GHz	HEB NbN phonon cooled	Al co-planar waveguide	Lens and twin slot antenna	Chalmers Univ.	Gothenborg, Sweden

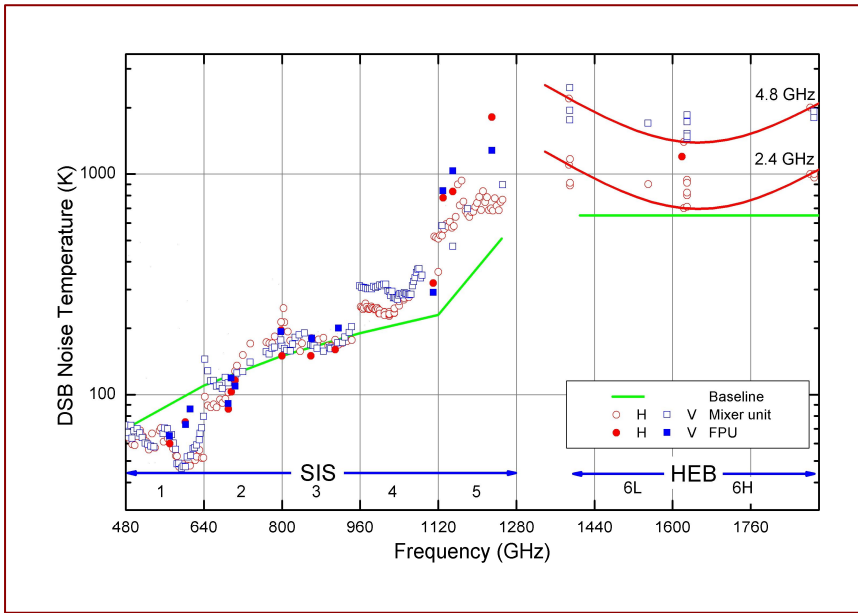


Figure 6 showing the performances for the HIFI mixers in Double-Side-Band Noise Temperatures as function of frequency for the seven HIFI mixer bands. The open symbols give the test results at mixer unit level for the two polarizations. The filled symbols are the mixer performances after integration in the MSA's and Focal Plane Unit. All SIS bands (1-5) have a 4-8 GHz IF range. The two HEB IF bands cover 2.4-4.8 GHz. There is still a strong IF frequency dependence for the noise temperatures, which range from about 900 K to about 1500 K that is represented by the two curved lines. The SIS IF bands are flat for the entire 4-8 GHz range. The straight lines represent the baseline performance values that were set at the start of the project, assuming a successful development of the SIS and HEB device materials. The expectations were apparently set too high for bands 5 and 6. Nevertheless, the achieved sensitivities for all HIFI frequency ranges represent the state-of-the-art for this type of mixers.

5. The Local Oscillator Sub-System

The LO block diagram is given in figure 7 together with the multiplication scheme [10]. Each mixer frequency band is covered by two chains in the corresponding LOAs. See figure 8. The tuning ranges are achieved with a broadband, high-power mm-wave amplifier as input source for the varactor frequency multiplier chains. The demonstrated output powers of the amplifiers are sometimes over 400 mW in the 75-100 GHz frequency range. Planar Schottky diodes are used for all the stages of the varactor multiplier chains [4]. These provide not only high power-handling capability and a wide bandwidth, but improved also considerably the reproducibility and stability, needed for a satellite project.

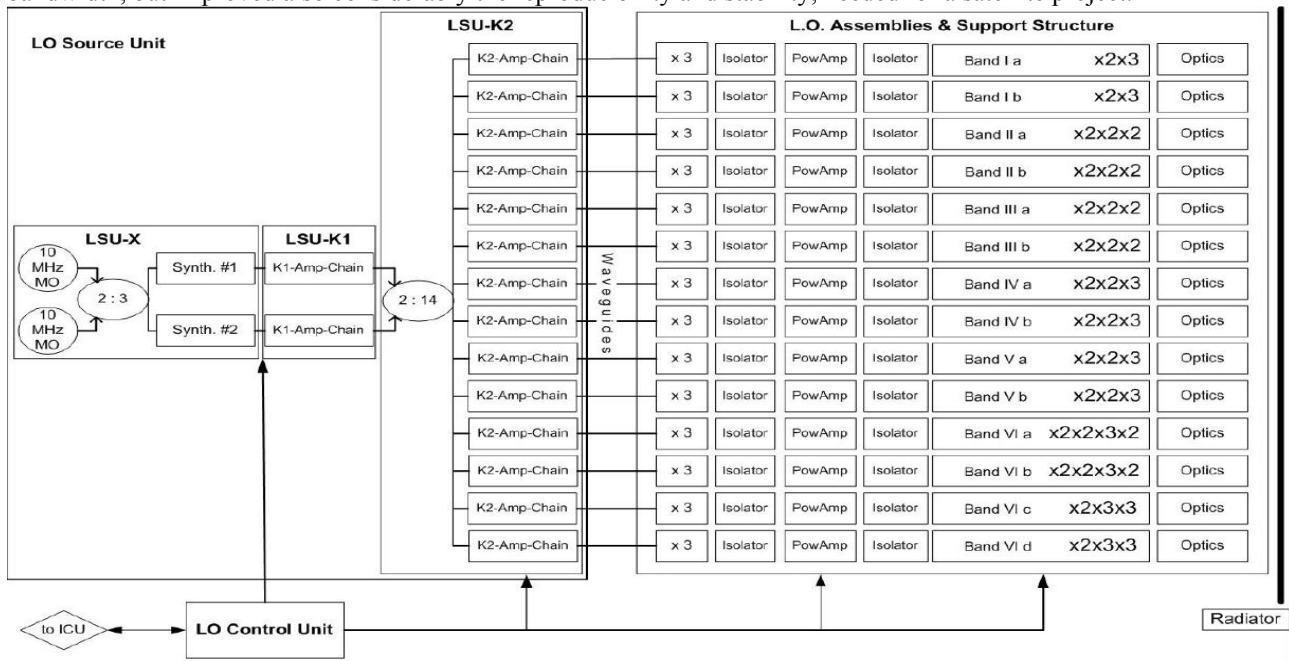


Figure 7. The LO subsystem block diagram. The left part comprises the Local Oscillator Source Unit that provides the reference frequency and Ka band input power for the 14 multiplication chains.

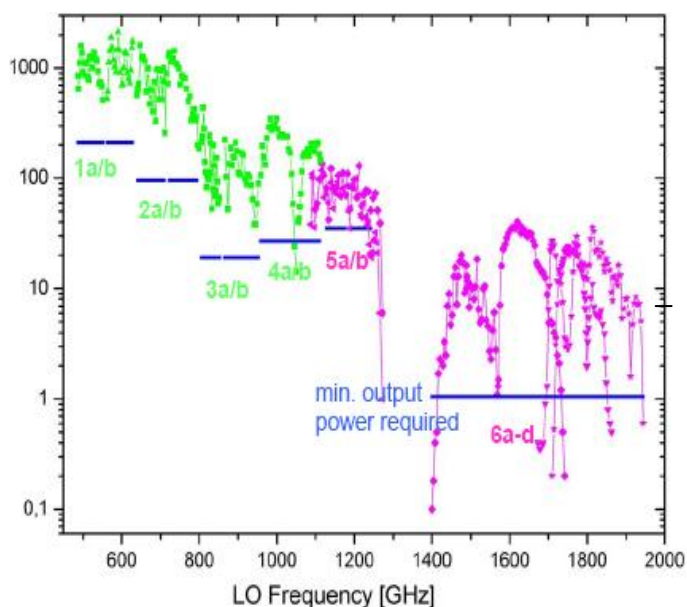


Figure 8. LOA with two multiplication chains, starting from the right with power amplifiers followed by the multipliers (middle) and output optics (left)

Figure 9. Output power versus frequency for the 14 multiplication chains. The horizontal lines indicate the minimum requirements as was estimated at the start of the project. With improved mixer sensitivity, the provided LO chain outputs are an order of magnitude for the lower bands. See a.o. [11,12]

As can be seen from figure 9, the output powers of the LO chains are all high enough to pump all mixers over the entire frequency range as was also demonstrated during testing.

6. The HIFI spectrometers and Instrument Control Unit

6.1 The High Resolution Spectrometer (HRS)

The High Resolution Spectrometer of HIFI is a set of digital autocorrelation spectrometers [13,14]. The IF input signal is analyzed in sub-bands of 230 MHz wide, after an analog down-conversion. The HRS implements real-time signal processing functions onboard of the satellite at electronic level and a subsequent software signal processing on the ground. The HRS is made of four main sections, three hardware units and one software section: 1) An analog section to up and down convert the IF input signal, 2) A signal digitalization section, 3) An autocorrelation computing section, 4) A software data processing section.



Figure 10. One of the two HRS flight units for HIFI

Mode	high Resolution	Normal Resolution	Low Resolution	Wide Band
Number of Bands	1 1	2 2	4 4	8 8
Bandwidth	250 235	250 235	250 235	500 470
FWHM (MHz)	0.14 0.125	0.27 0.25	0.54 0.5	1.1 1.0

Table 2 HRS main performance requirements and achieved values. Lower values in each row are for demonstrated performance,

After analogue processing and digitization, the autocorrelation functions of the input astronomical signal are computed using correlation modules made up of ASIC's. These correlation functions are sent to the ICU (Instrument Control Unit) via an FPGA and then to the ground to be processed with dedicated software modules. There are essentially three software modules: 1) Specific processing of the autocorrelation spectrometers, to obtain the power spectrum from the input signal autocorrelation function, 2) A power calibration processing to calibrate the observed input signal spectrum

in terms of power, 3) A set of routines to test and characterize the HRS. The bandwidth and resolution of the HRS flight units are summarised in table 2 together with its main requirements.

6.2 The HIFI Wideband Spectrometer (WBS): Acousto-Optical Spectrometer (AOS)

The HIFI Wideband Spectrometer (WBS) for HIFI is an Acousto-Optical Spectrometer (AOS) [15]. AOS have become a standard tool in radio astronomy for spectroscopic observations in the mm/submm frequency range. Because of the relatively simple design of an AOS it is a very suitable instrument for space applications, and the recent developments of AOS for SWAS with 1.4 and ODIN with 1 GHz bandwidth have demonstrated that this technology is mature enough for space applications in general. The figures for power consumption, weight, or volume show that other technologies like digital correlators or filter banks do not yet provide comparable performance, at least for large bandwidth applications in the GHz range and large numbers of frequency channels at the same time. For Herschel the requested instantaneous frequency coverage in the HIFI instrument is 4 GHz in total with a frequency resolution of about 1 MHz. For two polarisations this means that approximately 16,000 frequency pixels for full Nyquist sampling are required. The maximum bandwidth of acousto-optical deflectors is limited due to the rather strong acoustic attenuation in the crystal materials at higher frequencies. In 1998 1.2 GHz was approximately the maximum bandwidth of an AOS with 1 MHz frequency resolution and thus a hybrid solution with an IF processor was necessary. So 4 times 1 GHz was chosen for full frequency coverage. This was achieved by putting four sets of transducers on the same crystal. See figure 11 for the WBS block diagram. The principle components of an AOS are given below, in figure 12. The resulting spectral resolution for the HIFI AOS is 1.1 MHz.

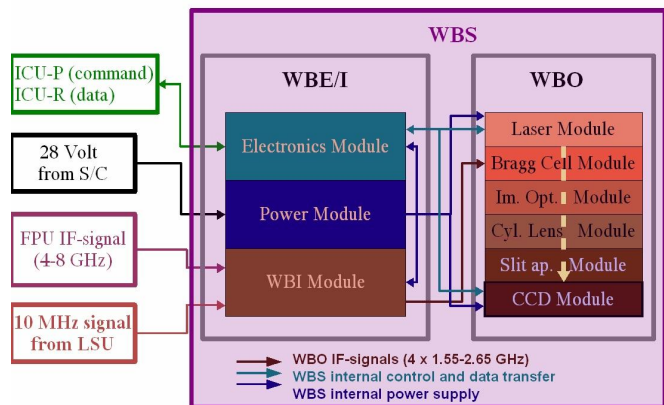
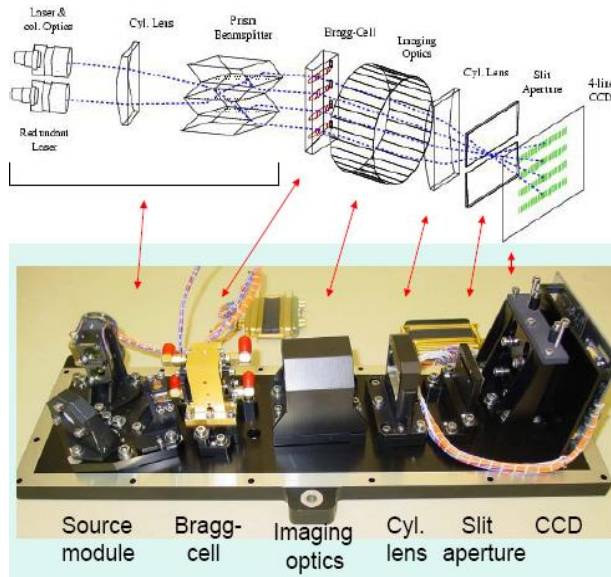


Figure 11. Block diagram of the WBS with its inputs and main electronic (WBE/I) and optical (WBO) units.

Figure 12. One of the two WBO units of the flight model WBS are shown with a cartoon of the unit above, indicating the main components of the AOS

6.3 The HIFI Instrument Control Unit

The ICU is the only subsystem that interfaces electrically with the spacecraft for telemetry and telecommand. See figure 13 for its block diagrams. It distributes electrical power to the FCU, it takes care of the command execution and synchronization, it packages the telemetry and provides the health-autonomous mode. The ICU electronics consists of a single box, positioned in the warm part of the S/C and as close as possible to the FCU, LCU, WBS-V, WBS-H, HRS-V and HRS-H sub-systems.

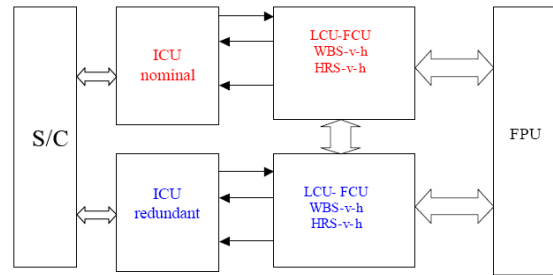
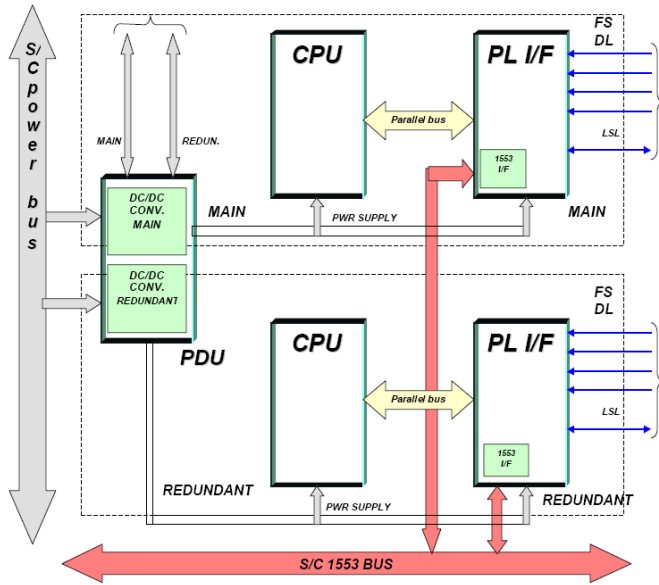


Figure 13. HIFI ICU block diagrams: the right figure shows the general block diagram and the interface relations with the other HIFI subsystems together with the redundancy concept. The left figure shows the main internal components.

The interface with the spacecraft will be able to handle a baseline data rate of ~100 kbit/s and will be compliant with the MIL-STD-1553B standard, with the ICU acting as a Remote Terminal and the CDMS as the bus controller. The ICU design concept and hardware has a very high degree of commonality with the data processing units from PACS and SPIRE.

7. Instrument Level Testing

Instrument level tests were carried out in the first 7 months of 2007. Of the Spectral tests, Continuum Linearity, Line linearity, Spurious response, Spurious signals, and Standing Waves were the characteristics studied. For Radiometry we took a usual hot-cold as function of frequency and LO power, while Gas-Cell spectral measurements of a number of gasses were taken to determine the Side-band ratio, again as function of frequency.

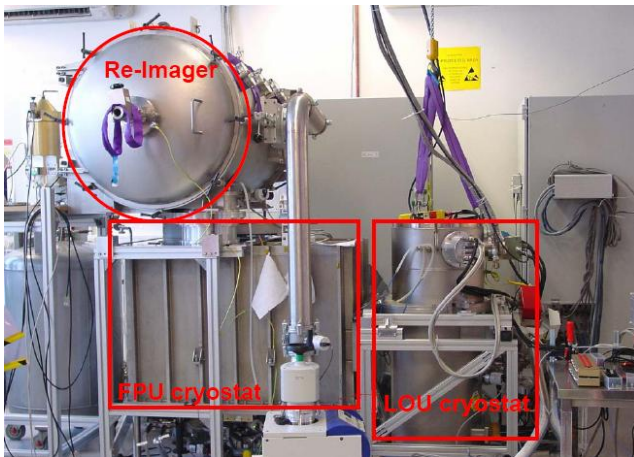


Figure 14. HIFI instrument Level Test set-up, containing a FPU cryostat, (left below) a LOU cryostat (right), a re-imager/telescope simulator (top left) and 2 electronic racks for the warm electronics boxes that are all to be located at the Herschel satellite Service Model (SVM).

Figure 14 shows the test set-up for the instrument level tests. It contains a large cryostat for the focal plane unit simulating Herschel's cryo-temperature conditions, a cryostat for the LO providing similar temperatures as expected for the LOU when mounted on the exterior of the Herschel cryo-vessel in orbital conditions, and a Herschel telescope simulator to provide radiation from hot and cold black bodies, from a gas cell and from coherent sources for spurious studies. Two thermally regulated electronic racks are used as the ground test Service Module (SVM).

The test results showed in general compliance with the requirements that were derived from the scientific user requirements document. However not all tests could be carried out as planned. We did not have all the equipment and time to carry out the continuum and line linearity. Also the ILT test conditions could not simulate completely the space environment as we had to use cryostat windows for the LO and ground support cables between the LCU and LSU to LOU. Besides, the mechanical coolers for the cryostats introduced electrical and vibration effects on the instrument stability.

The spurious response tests showed several undesired features. A complete catalogue has been made compiled and will be available to the astronomer through HSPOT. Standing waves effects have been analyzed. One of the strongest effects are related to the extra set of windows in the LO cryostat and thermal filters in the LO path. As these effects determine the frequency throw used in frequency switching mode the standing waves need to be re-measured in orbit.

One of the main surprises was found in the LO-mixer interaction. It appeared there was far too much LO power for proper mixer pumping in all of the bands except for band-5. As the LO pump level is tuned by the power amplifier in the LO chains the high level of attenuation required brought the power amplifier tuning in an unstable regime and this affected the instrument stability in a very serious way. To remedy the situation external optical attenuators were developed for each mixer band and these are placed in the baffle unit that also carries the heaters for the LO window de-icing. This unit is placed between the LOU and the Herschel cryostat external wall. The attenuator levels introduced vary from 15db for band-1 till 2 db for band-7. With these attenuators in place the HIFI instrument stability is mostly within the requirement range except for a few frequency spots that need further attention and bias adjustments of LO components in the LO chains like the bias of multipliers.

Extensive gas cell measurements were made to determine the side band ratio for each mixer band. The gasses used were OCS, CO, SO₂, H₂S, CH₃CN and CH₃OH. For CH₃OH a complete spectral scan was made over all frequencies covered by HIFI. Some sample spectra are shown in figure 14. The preliminary derived ratios showed for the middle of the mixer bands a 1:1 ratio. More analysis is needed to assess in detail the ratios for the band edges.

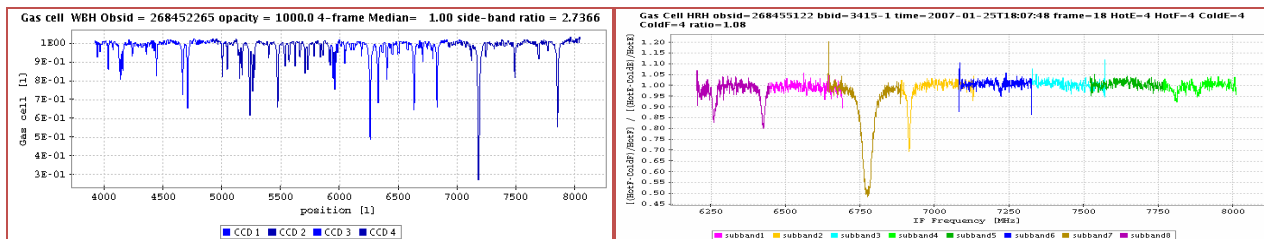


Figure 15. Sample spectra of taken by HIFI during ILT. The left spectrum is a WBS spectrum of methanol at 1016 GHz. At the right is a HRS spectrum of sulfur dioxide at 1696 GHz.

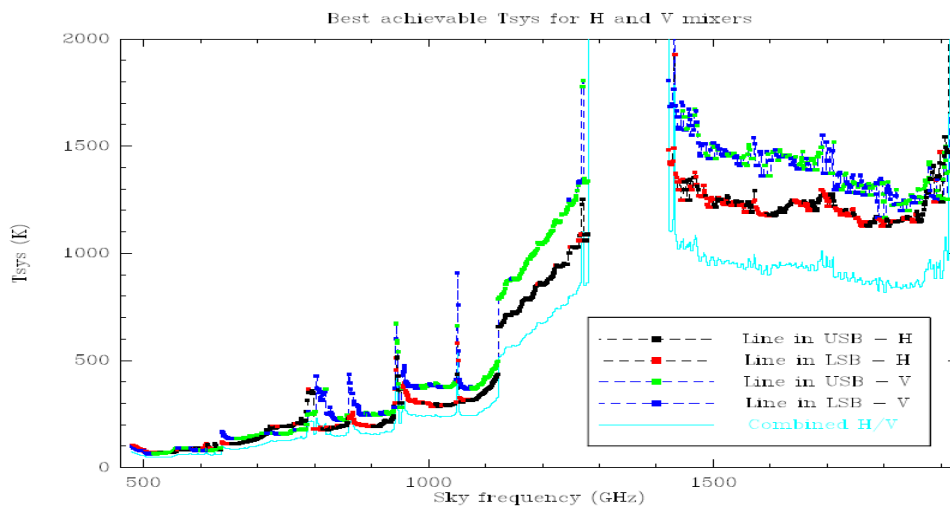


Figure 16. HIFI's T_{sys} for USB and LSB for H and V polarisation and for the combined mixers outputs.

Finally we show in figure 16, the results of the Hot/Cold load measurements that give HIFI system noise temperature. These are given for the cases the lines are in the upper or lower sideband and for both polarisations (H and V). The H/V combined sensitivity is shown as well.

8. Observing Modes and Astronomical Observing Templates (AOT)

8.1 HIFI Observing Modes.

The intended observing modes for the Herschel-HIFI instrument are constructed around possible ways to take near-real-time reference spectra. These data are required to correct for the (non-constant) relative spectral response of the IF pass-band of the heterodyne spectrometer. These reference modes are: a) position switch, b) dual beam switch, c) frequency switch and d) load chop. These reference modes are used for the three HIFI AOTs: 1) Single Point Observations, 2) Mapping Observations and 3) Spectral Scans. As the observing efficiency is strongly depending on the length of time spent to take a reference spectrum, the ratio of slewing time versus instrument stability time will be an important factor in the decision process for selecting the optimal observing mode.

8.1.1 Position Switch.

With the telescope a single pixel HIFI beam is pointed alternately at a target position and at a reference position. The reference position is usually chosen to be a nearby area of the sky that is devoid of emission in the band being used. If the reference position is to have also emission, then the reference position must be calibrated too. The reference position must be sampled with a frequency to allow compensation of drifts in the signal chain.

8.1.2 Dual Beam Switch (DBS)

In this mode an internal chopper mirror within HIFI is used to move the beam to a reference Off position on the sky. The reference Off position can be set up to 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 exist. By moving the telescope in such a way that the source appears in both (On-Off) chop positions, the impact of standing wave differences is expected to be eliminated to a large extent. There are two chopper speeds. The faster chop is available for observations for low spectral resolutions where effects of instrumental drifts might be expected to distort baselines and increase noise.

8.1.3 Frequency Switch

In this mode, following an observation at a given On frequency, the local oscillator frequency is changed by a small amount (a few tens of MHz). The shift in frequency is small enough that the lines of interest remain observable at the two LO frequencies. Effectively, therefore, this makes for a very efficient mode since target emission lines are observed in both ON and OFF positions. Subtraction of the Off spectrum from the On means that we remove the baseline, but significant ripples may still remain in the On – Off measurement.

8.1.4 Load Chop.

In this reference scheme, an internal cold source is used as a reference. The chopping mirror alternately looks at the target on the sky and an internal source of radiation. This is particularly useful when there are no emission-free regions near the target that can be used as reference in either dual beam switch or position switch mode or where frequency switch can not be used due to the frequency structure of the source.

8.2 HIFI Astronomical Observing Templates (AOT)

8.2.1 Point Source AOT

This AOT is designed for “pointed” observations and in certain cases to make very small maps. It can utilise all four observing modes as described above.

8.2.2 Mapping AOT: On-The-Fly (OTF) and Raster mapping

On-the-fly mapping is probably the most efficient means of collecting data to map emission over a large region of sky. Data are taken continuously while the telescope is scanned back and forth across the target with data readouts taking place at a scanning distance similar to the beam size at the frequency of observation. A single emission-free point

reference position measurement is used as an Off measurement. As a single optical path is used, standing wave effects are expected to be minimal. Frequency Switching is also available for OTF mapping. When Raster Mapping is carried out the DBS is the available mode.

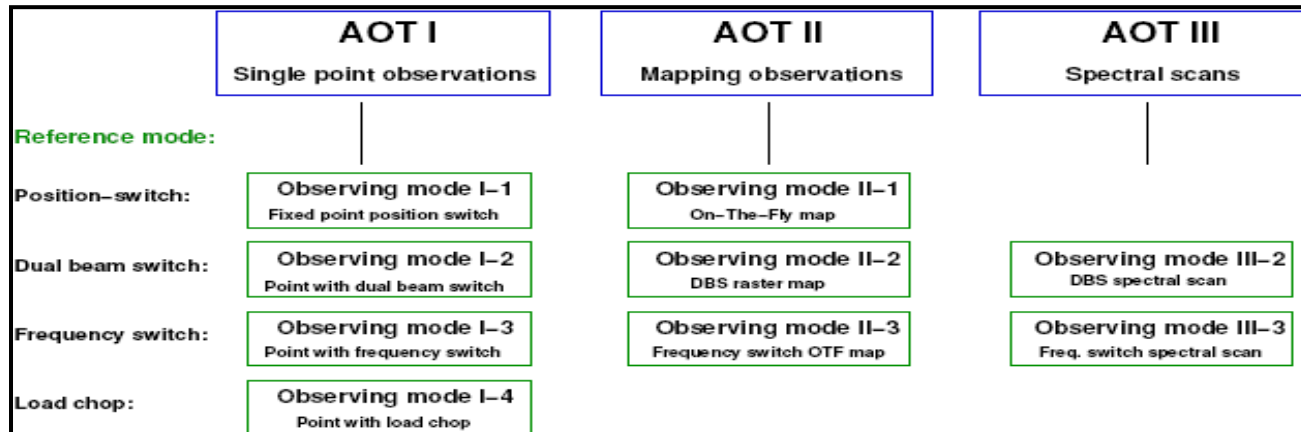


Figure 14. Overview of HIFI observing modes and AOT's as they will be implemented in the satellite commanding and data reduction software. The test results indicate that the load chop mode might also be interesting for AOT-II and AOT-III.

8.2.3 Spectral Scans AOT

This AOT is designed for making spectral scans for a part or the whole of a frequency band. Typically these are made at LO frequencies that are 1GHz or so apart. There are two observing modes available here. For each observing frequency setting, dual beam switch or frequency switch measurements can be made, resulting in fully calibrated dual sideband spectra at each of the LO settings. The creation of a single sideband spectrum is afterwards achieved by a de-convolution routine during data processing.

9. HIFI expected performance

The functional tests and calibrations indicated that the scientific capabilities can be expected close to what has been designed. An overview of the expected sensitivities is given in table 3. These are 5 sigma values for an hour of integration except for the frequency scans. Here 1 sigma values are given for integration times of 4 hours or 10 hours of observing time spent per band for bands 1-5 or bands 6L/H. More definite values will be available only after a successful launch, after the in orbit Performance Verification.

Mixer Band		1	2	3	4	5	6
Frequency Range (GHz)		480-640	640-800	800-960	960-1120	1120-1250	1410-1910
T _{sys} (SSB) (K)		160	320	480	730	2000	2500
Flux Limit (5σ, 1hr; R=10e4) (mK)		5,0	9	12	17	43	46
Flux Limit (5σ 1hr; R=10e4) (Jy)		2,3	4	5,5	8	20	22
Line Flux Limit (5σ; 1hr; R=1e4) (10e ⁻¹⁸ W/m ²)		1,3	3	5	8	24	34
Line Scan (Δv=1 km/s DBS) (mK)							
1σ, 4 hrs/band(1-5), 10 hrs for 6L/H		12	23	30	42	95	290

Table 3. Expected performance for the various HIFI bands as derived from the mixer unit tests and the first Instrument Level Tests carried out in the period January to July 2008. More details can be found in HSPOT, the ESA Herschel user interface tool

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References

- [1] G. Pilbratt, "Herschel Mission; this volume.
- [2] T. de Graauw, F. P. Helmich, "Herschel-HIFI: The Heterodyne Instrument for the Far-Infrared", in *The Promise of the Herschel Space Observatory*, edited by G. L. Pilbratt et al., ESA SP-460, pp. 45-51, 2001.
- [3] B. D. Jackson, K. J. Wildeman, N. D. Whyborn on behalf of the HIFI Focal Plane Consortium, "The HIFI Focal Plane Unit", *Proc. 13th International Symposium on Space Terahertz Technology*, pp. 339-348, 26-28 March 2002, Harvard University, Cambridge, Massachusetts, USA.
- [4] Brian D. Jackson, Gert de Lange, Tony Zijlstra, Matthias Kroug, Jacob W. Kooi, Jeffrey A. Stern, and Teun M. Klapwijk, "Low-noise 0.8-0.96- and 0.96-1.12-THz superconductor-insulator-superconductor mixers for the Herschel Space Observatory," *IEEE Trans. on Microwave Theory and Techniques*, vol 54, no. 2, pp. 547-558, Feb. 2006.
- [5] Brian D. Jackson, Gert de Lange, Tony Zijlstra, Matthias Kroug, Jeffrey A. Stern, and Teun M. Klapwijk, "Niobium titanium nitride-based superconductor-insulator-superconductor mixers for low-noise terahertz receivers", *Journal of Applied Physics*, vol 97, no. 11, pp. 113904-113912, Jun. 2005.
- [6] Y. Delorme, M. Salez, B. Lecomte, I. Péron, F. Dauplay, A.Féret, J.Spatazza, J.-M. Krieg, K. Schuster, "Space-qualified SIS mixers for Herschel Space Observatory HIFI band-1instrument", *16th Int.Symp.on Space THz Technology; Göteborg; Sweden; May 2-4 2005*
- [7] Salez M. Delorme Y.; Peron I.; Lecomte B.; Dauplay F.; "A 30% bandwidth tunerless SIS mixer of quantum-limited sensitivity for Herschel/HIFI band 1", *SPIE Proc.Vol.4855*, 2002; 02
- [8] S. Cherednichenko, M. Kroug, P. Khosropanah, A. Adam, H. Merkel, E. Kollberg, D.Loudkov, B. Voronov, G. Gol'tsman, H.-W. Huebers, H. Richter, "1.6 THz HEB mixer for far infrared space telescope (Herschel)", *Physica C*, vol.372.pp.427-431, Aug. 2002.
- [9] S.Cherednichenko, V.Drakinskiy, T.Berg, "THz HEB heterodyne receivers for space and ground based radio astronomy", *Proc. Europ. Microwave Assoc.*, vol.1, no.3, 2005.
- [10] J.C. Pearson, R. Guesten, Th. Klein, N.D. Whyborn, "Local oscillator system for the heterodyne instrument for FIRST (HIFI)", *SPIE Vol. 4013*, p. 264-274,2000.
- [11] A. Maestrini, J.S. Ward, H. Javadi, C. Tripon-Canseliet, J. Gill, G. Chattopadhyay, E. Schlect and I. Mehdi, "Local Oscillator chain for 1.55 to 1.75 THz with 100-uW peak power," *IEE Microwave and Wireless Component Letters* 15, 871 (2005)
- [12] J.S. Ward, G. Chattopadhyay, A. Maestrini, E. Schlect, J.Gill, and I. Mehdi, "1400-1900 GHz local oscillators for the Herschel Space Observatory," *Proc. 14th Int. Symp. Space THz Technology*, 94 (2003)
- [13] Caïs P., Ravera L., Lagrange D., Giard M., Baudry A., Myvial J.Y., "First spectra from a new, wide band, hybrid digital spectrometer for the FIRST-HIFI instrument", *International journal of infrared and millimeter waves*, (1998).
- [14] M. Belgacem, L. Ravera, E. Caux, P. Caïs & A. Cros: "The high resolution versatile digital spectrometer of HIFI-HSO", *New Astronomy* 9, 43, 2003.
- [15] R.Schieder, O.Siebertz, C.Gal, M.Olbrich, F.Schloeder, R.Bieber, F.Schmuelling, V.Tolls, J.Horn, "Toward Very Large Bandwidth with Acousto-Optical Spectrometers" *SPIE 4855*, 313-324, 2002.