HERSCHEL-HIFI: THE HETERODYNE INSTRUMENT FOR THE FAR-INFRARED

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Abstract

The science requirements for and the capabilities of the Heterodyne Instrument for the Far-Infrared (HIFI) are given. It is shown that the HIFI design can satisfy the science requirements and will be able to do, unhindered by telluric lines and varying atmosphere, many unique observations.

Key words: Missions: Herschel – Instrumentation: spectrographs – Techniques: spectroscopic – Infrared: general – Radio lines: general – Submillimetre

1. Introduction

Over the last decades there has been a growing use of the submillimetre region as the region where physical and chemical processes in dusty places can be best studied. Starting from the millimetre region where the lowest rotational line of CO lies up to about 1 THz, observations of many molecules are possible and nowadays common practice. However, the submillimetre wavelength region, as viewed from the Earth's surface, only consists of small windows in which the transmission varies between one to zero, with generally less transmission at higher frequencies. At these frequencies, atomic and ionic fine-structure lines and a plethora of rotational molecular lines (in particular those of light hydrides) can be found. Together, these lines form excellent probes of the physical and chemical conditions in many regions, varying from places of planet formation to the surroundings of nuclear engines of active galaxies.

The advancements in heterodyne mixing devices have provided low-noise, high-gain instrumentation with a natural, very high spectral resolution. This is of prime importance when to avoid line confusion, within the expected forests of lines, and to study dynamically evolving regions. Ground-based observatories have the advantage of large mirrors and/or the possibility of interferometric observations. Space-borne observations will, however, have the advantage that e.g. water can be studied in astrophysically important environments, which is impossible from even the best submillimetre sites. The absence of telluric lines allows for spectral line-surveys in the whole submillimetre region instead of the relatively small atmospheric windows, whereas the thermally stable location of L2, implies that calibration can be better than ever achievable from the ground.

All these factors together stress the need for a cryogenic space-borne heterodyne instrument with a large spectral working range. Here, we will list the science requirements on the instrument and its compliance with these. The conceptual design, its operating modes and its expected sensitivity will be given.

2. Science Objectives

A number of key scientific themes of modern astrophysics is related to understanding the cyclical interrelation of stars and the interstellar medium of galaxies (Fig. 1). On the one hand, stars and planetary systems are formed through the gravitational collapse of interstellar molecular clouds, on the other hand, the interstellar medium is formed from the ashes, enriched by newly nucleo-synthetised elements, of dying stars. This complex interplay between stars and the ISM drives the evolution and, thus, determines the observational characteristics of the Milky Way and other nearby and far away galaxies.

The unifying aspect of these research areas is the presence of copious amounts of cool molecular gas and dust, which reprocesses essentially all radiation from central objects to far-infrared (FIR) and sub-millimetre (sub-mm) wavelengths. Furthermore, most molecules possess many rotational transitions in the sub-mm range. Here the important light hydride molecules are often uniquely observable, as are the fine-structure lines of atoms, ions, and their isotopes. These transitions provide an effective probe of the physical conditions (density, temperature) of the emitting gas. A wide spectral coverage is needed for such studies because it allows the simultaneous analysis of a large number of transitions of a species and its isotopes, thereby confirming its identification and determining its abundance. Such studies will also be greatly assisted by the complete absence of telluric absorption and good relative calibration, which are prerequisites for accurate determinations of line ratios. In particular there is a need for space-borne observations to detect many transitions of H_2O, since this molecule plays such a dominant role in the energy balance as well as the chemical evolution of a wide variety of objects and is almost unobservable due to telluric emission.

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ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

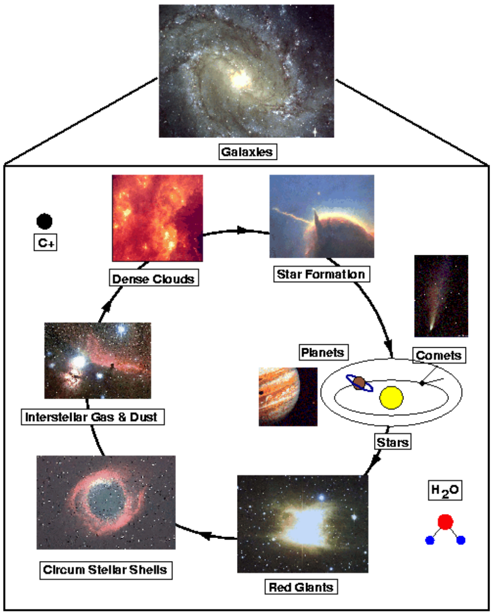

Figure 1. Gas and dust are cycled through interstellar matter in the Milky Way, a variety of physical and chemical processes continuously drive the chemical evolution of the Galaxy; small photographs adapted from D. Malin and IPAC.

In addition, as confirmed by COBE (Cosmic Background Explorer), the powerful FIR emission of distant dusty galaxies is red-shifted to sub-mm wavelengths.

Many studies also require the very high spectral resolution permitted by heterodyne instruments as this is essential to overcome spectral confusion and line blending. Moreover, when studying dynamically evolving regions, velocity information is often indispensable in unravelling the contributions from the multiple components present. This resolution is also needed for the detailed study of planetary atmospheres and cometary material.

These science drivers can be translated in the following requirements on HIFI:

- HIFI should have high (10^{6-7}) spectral resolution to overcome spectral confusion and line blending, and to preserve and detect the kinematic information in line profiles
- HIFI should have a large instantaneous bandwidth to measure lines from extra-galactic objects in one frequency setting and to allow for fast spectral surveys
- HIFI should have state-of-the art mixing devices or better to detect faint (isotopic) lines
- HIFI should be able to measure at least upto 1910 GHz (158 μm) to measure the [C II] line within the Milky Way and in nearby galaxies

Such an instrument not only would fulfill these requirements but is also particularly apt for studies ranging from collapsing molecular clouds forming new stars and planetary systems, stellar winds associated with dying stars, the origin and evolution of the general ISM, galactic nuclei to nearby and distant dusty galaxies.

HIFI will directly address a wide range of key questions including the following:

1. HIFI will probe the physics, kinematics and energetics of star forming regions through their cooling lines, including H_2O, the major coolant.
2. HIFI will survey the molecular inventory of such diverse regions as shocked molecular clouds, dense Photo-Dissociation Regions (PDRs), diffuse atomic clouds, Hot Cores and proto-planetary disks around newly formed stars, winds from dying stars and toroids interacting with AGN engines.
3. HIFI is particularly suited to search for low-lying ro-vibrational transitions of complex species such as PAHs and, thus, to investigate the origin and evolution of the molecular universe.
4. HIFI can provide the out-gassing rate of comets through H_2O rotational lines and determine the vertical distribution of H_2O in the giant planets.
5. HIFI can measure the mass-loss history of stars which, rather than nuclear burning, regulates stellar evolution after the main sequence, and dominates the gas and dust mass balance of the ISM.
6. HIFI will measure the pressure of the interstellar gas throughout the Milky Way and will resolve the problem of the origin of the intense galactic [CII] 158 μm emission measured by COBE.
7. HIFI can determine the $^{12}C/^{13}C$, and $^{14}N/^{15}N$ isotope ratios as a function of galactic radius in the Milky Way and other galaxies, through the hyperfine splitting of atomic fine-structure lines. One can thus constrain the parameters of the Big Bang and explore the nuclear processes that enrich the ISM.
8. HIFI will measure the FIR line spectrum of nearby galaxies as templates for distant, possibly primordial galaxies.

3. The HIFI instrument

3.1. Introduction

The Heterodyne Instrument for the Far-Infrared, HIFI, has been optimised to address the astronomical key questions discussed above which all require high spectral resolving powers and high sensitivity. By combining the high spectral resolving power of the radio heterodyne technique with quantum noise limited detection from superconductor physics and the state-of-the-art in microwave technology, it is now possible to develop an instrument with the following capabilities:

- continuous frequency coverage from 480 to 1250 GHz in five bands, while a sixth and seventh band will provide coverage for 1410-1910 GHz,
- resolving powers up to 10^7 (300 - 0.03 km/s)

– detection sensitivity within a factor 3 of the theoretical quantum noise limit. Both polarisations of the astronomical signal will be detected for maximum sensitivity.
– calibration accuracy within 10%, with a goal of 3%

In order to cover the wide frequency range with high sensitivity, HIFI is designed to have 7 mixer bands and 14 LO subbands. The first five frequency-bands will each contain a pair of mixers using superconductor-insulator-superconductor (SIS) tunnel junctions. Channels 6Low and 6High will contain two mixers based on the recently developed fast hot-electron bolometers (HEB). The instrument will operate at one frequency at a time in both polarisations; i.e. only one of the frequency bands will be active. For the Local Oscillator (LO), solid-state varactor/varistor frequency multipliers will be used. HIFI will have an instantaneous bandwidth of 4 GHz analysed in parallel by two types of spectrometers: acousto-optic spectrometers and autocorrelators.

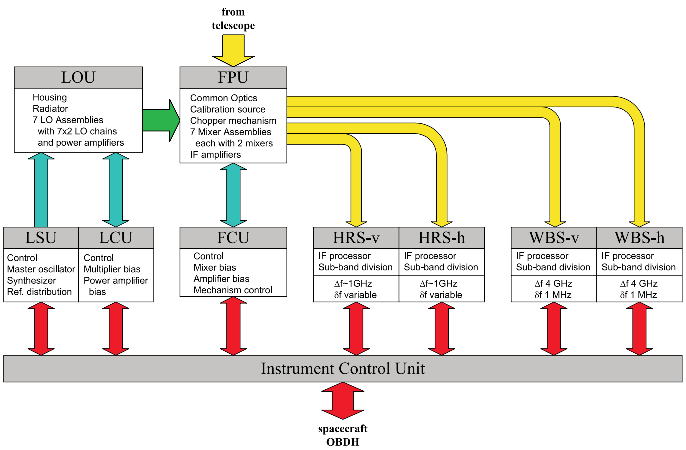

Figure 2. Block diagram of the HIFI instrument

HIFI consists therefore of five major sub-systems:

1. The focal-plane sub-system comprises the focal-plane unit (FPU) inside the cryostat and the FPU control unit (FCU) located in the service module (SVM). The FPU contains a.o. mixers and low-noise IF HEMT preamplifiers. The FCU supplies the bias voltages for mixers and IF preamplifiers in the FPU and controls the FPU.
2. The local oscillator sub-system comprises the Local Oscillator Unit (LOU) located on the outside of the cryostat, the Local Oscillator reference frequency Source Unit (LSU) and a Local Oscillator Control Unit (LCU), both located in the service module. The LOU generates the LO signals which are coupled into the FPU via windows in the cryostat wall.
3. The wide-band spectrometer sub-system (WBS) consists of a pair of AOS spectrometers with a frequency resolution of 1 MHz and a bandwidth of 4 GHz for each of the two polarisations. It is located in the SVM.
4. The high-resolution spectrometer sub-system (HRS) consists of a pair of auto-correlator spectrometers and will provide several combinations of bandwidth and resolution. It is also located in the SVM.
5. The instrument control unit sub-system (ICU), located in 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.

In order to materialize the high sensitivity of the superconducting mixers a high opto-mechanical, thermal and electrical stability, throughout the whole instrument is required.

3.2. Focal Plane Sub-System

In order to cover the challengingly wide frequency range, the FPU employs a highly modular design consisting of:

– a common optics assembly (COA) which contains the optical elements which are common to the 7 optical beams and serves as the support structure for the chopper, calibration assembly, and local oscillator optics
– 7 mixer assemblies (MA) containing the optical elements, mixers and IF components specific to each of the 7 frequency bands.

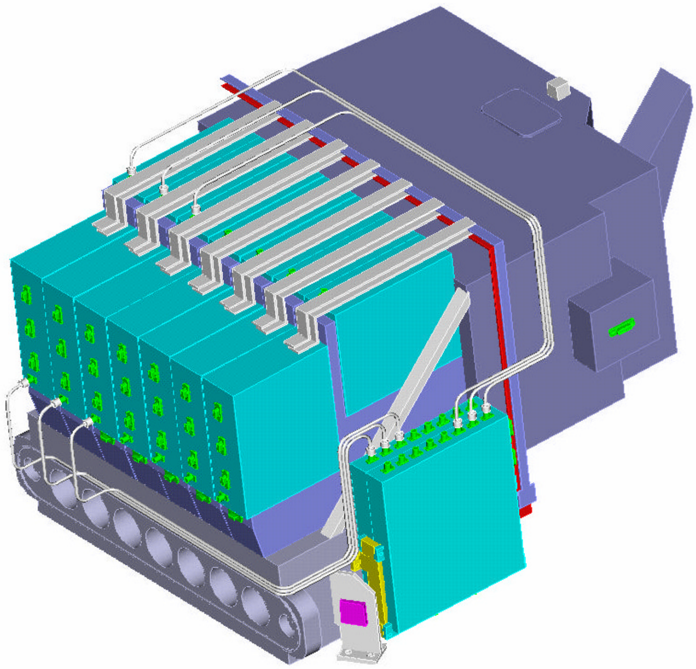

Figure 3. View of the common optics assembly in the instrument

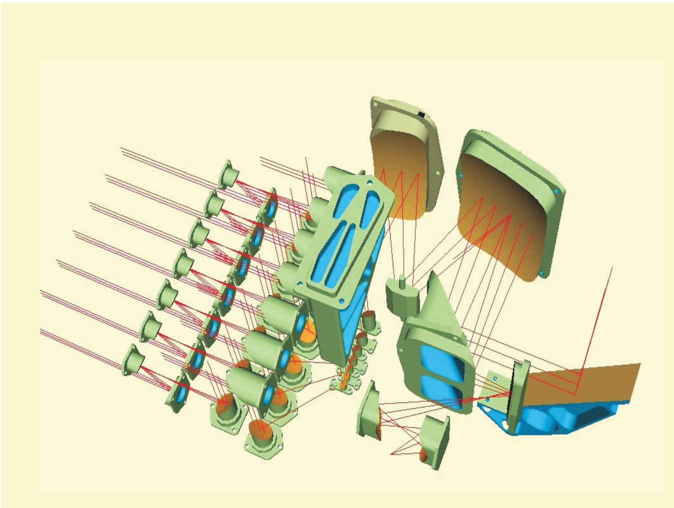

Figure 4. View of the beams in the common optics assembly

The Common Optics Assembly (COA) contains the optics from mirror M3 in the telescope focal plane through to but excluding the Mixer Assemblies (MA). The COA mechanical structure provides also the support for the chopper, the calibration assembly and some optics for the local oscillators. The telescope focal plane mirror (M3) acts as a folding mirror. The telescope focal plane is re-imaged in the main optics by means of a Gaussian telescope at unit magnification implemented by an Offner system. Between its two mirror sections a flat chopper mirror is positioned in the pupil plane. After the imaging mirror a flat mirror folds the beam towards a stack of 7 field-splitting mirrors placed at an image of the focal plane. These 7 mirrors differ in orientation so that the seven resulting beams are separated in direction creating seven 50 mm equidistant optical axes for the 7 mixer assemblies. The focal length of the individual band splitting mirrors can be chosen to alter the system exit pupil location while keeping the focal plane image in the same position.

Finally, the beams from the band splitting field mirrors (7x) are re-imaged into the mixer assemblies, which are mounted onto the Main Optics structure in a stack. The housing of the COA and the mirrors will be machined from a single block of aluminium giving rigidity and dimensional stability.

Most observations with HIFI will be made using beam switching. A focal-plane chopper within the instrument will switch the telescope beam between the astronomical source and a nearby reference position. The focal-plane chopper in HIFI will have a maximum beam throw (separation between source and reference position) of 3 arcminutes on the sky and will chop at frequencies up to 5 Hz. The mechanism moves a mirror between four positions: two positions on the sky and two calibration positions. The required rotation for the present optical design is 4.6°.

A calibration assembly is located just near the entrance opening of the common optics assembly. It provides two black body sources with adjustable temperature in the range 15-100 K. The end-to-end calibration of the system including the telescope will be accomplished by observation of astronomical sources of known strength. The accuracy achieved will depend upon pointing accuracy but should be better than 10%. The goal is to achieve an instrumental calibration accuracy of 3%.

The LO beams are coupled through vacuum windows in the Herschel cryostat wall and directed into the respective MA's by a set of folding mirrors. We have chosen to use 7 separate sub-windows, each optimised for the transmission of its LO band. The Local Oscillator Unit (LOU) itself is located outside the dewar at an optical distance of more than 650 mm from the HIFI FPU.

3.3. Mixer Assemblies

The HIFI mixers are located in Mixer Assemblies (MA). There will be 7 MA's, each covering a certain frequency range with two mixers, yet only one MA will operate at any time. The pair of mixers in individual MA's will operate at orthogonal polarisation. The MA's contain mechanical supports, mixers, diplexers as well as IF amplifiers, and are mechanically mounted on the FPU. The optical input to an MA consists of a signal beam and a LO beam. In the MA box the signal beam will be split into 2 polarisations for the 2 mixers. The LO beam will also be split into 2 beams with suitable linear polarisation to be coupled to the mixers. The combining of the signal and LO beams will be done by a beam-splitter for the two lowest frequency bands, and by tuneable diplexers in the higher bands where less LO power is available. This gives rise to two different optics layouts for the MA boxes, but they will be identical externally.

Each mixer is followed by a dedicated IF preamplifier at an IF centre frequency of 6 GHz and a bandwidth of 4 GHz. Since only one pair of mixers will operate at any time power combiners are used to feed the signals from bands 1 to 4 into a single pair of coaxial cables, as is also done for the signals from bands 5, 6 and 7. The choice of band is made by activation of the required pair of preamplifiers. The first stages of the IF preamplifiers are to be cooled to 15 K as well as the second stages.

Mixer technologies for fabricating sensitive heterodyne mixers favour the use of wave-guide mixers for the lower frequency bands, while the higher frequencies will use lenses and planar antennas such as double slot lines. However both solutions are compatible with the chosen mechanical and optical configurations. The HIFI frequency bands, sensitivities and foreseen mixer elements are given in Table 1.

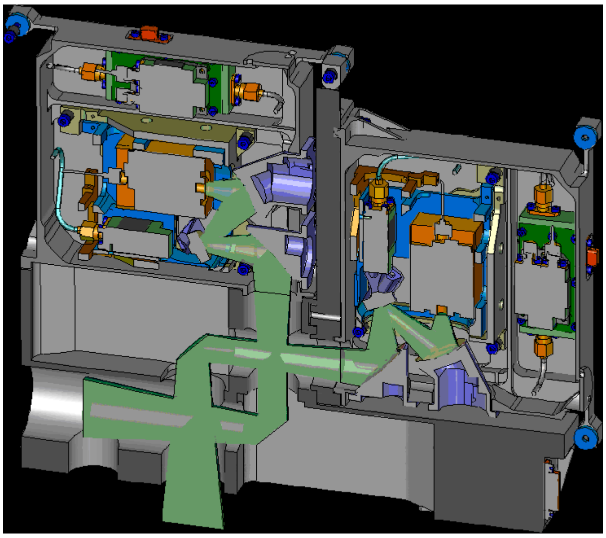

Figure 5. View of a mixer assembly

Table 1. HIFI DSB base line receiver noise temperature for the probable mixer types. The last column indicates the baseline mixer type: WG - waveguide, QO - quasi-optical.

Band	Range (GHz)	T_{noise} (DSB) (K)	Mixer Technology	Mixer Type
1	480	70	Nb-SIS	WG
	640	110		
2	640	110	NbTiN-SIS	WG
	800	150		
3	800	150	NbTiN-SIS	WG
	960	190		
4	960	190	NbTiN-SIS	WG
	1120	230		
5	1120	230	NbTiN-SIS	QO
	1250	510		
6Low	1410	650	NbN-HEB	QO
	1700	780		
6High	1700	790	Nb-HEB	QO
	1920	870		

3.4. Local Oscillator Sub-System

A block diagram of the LO signal generation is given in Fig. 6. The local oscillator sub-system (LO S/S) consists of the following units:

- The LO Source Unit (LSU), which contains the stable LO reference frequency source and whose output is split over 14 waveguides, each feeding one of the chains in the LOA's with signals in the 26-41 GHz range.
- The local oscillator unit (LOU), which is located outside the cryostat and supplies the LO signal for the mixers inside the FPU. It consists of a mechanical support structure to support a cooler radiator and seven LO multiplier assemblies. The 7 Local Oscillator Assemblies (LOA) for bands 1-5, 6-Low and 6-High, each contain two LO multiplier chains and their feeding power amplifiers/triplers
- The LO control electronics (LCU), which is sited in the SVM and which also supplies the electrical and microwave signals needed by the LOU, monitors the LO system, and reports its status to the ICU.

The LOA's are arranged with a spacing of 50 mm between the optical axes of adjacent LOA's yielding one optical plane per mixer assembly. The LOA's are mounted onto the LOU mechanical support structure.

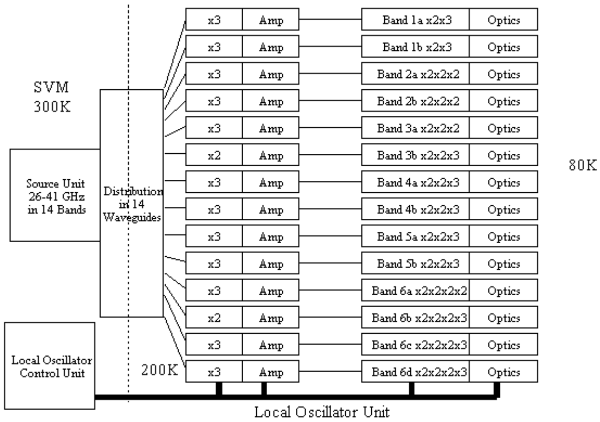

Figure 6. Block diagram of LO signal generation for the 7 LO bands. The source unit and control unit are located in the SVM.

3.4.1. Multipliers

The LOA's consist of optics with a focusing/re-imaging mirror and a wire grid beam combiner and two almost identical LO sources oriented with orthogonal polarisations. Together these two sources are to provide full frequency coverage of a particular mixer band. The chosen arrangement of two LO sources pumping two mixers on orthogonal polarisation can be implemented using polarising beam splitters. Note that only one LO source is operational at any given time and that this LO pumps two mixers operating on orthogonal polarisation.

The LO frequency bands are given in Table 2. The listed tuning ranges can be achieved when a broadband, high-power mm-wave source is used to drive the frequency multiplier chain (Huang et al. 1997). High-power mm-wave amplifiers, have been successfully applied in LO sources at 100 GHz. The demonstrated output powers of over 400 mW in the 75-115 GHz frequency range exceed by far what is available with Gunn devices.

Table 2. Local Oscillator bands for HIFI

	Power Amplifier Bands			
Multipl.	71–79 (GHz)	80–92 (GHz)	88–99 (GHz)	92-106 (GHz)
x2	142–158	160–184	176–198	184–212
x2x2	284–316	320–368	352–396	368–424
x2x3		480–552		552–636
		Band 1a		Band 1b
x2x2x2		640–736	704–792	736–848
		Band 2a	Band 2b	Band 3a
x2x2x3	852–948	960–1104	1056–1188	1104–1272
	Band 3b	Band 4a	Band 4b	Band 5
x2x2x2x2			1408–1584	1472–1696
			Band 6a	Band 6b
x2x2x3x2	1704–1896			
	Bands 6c/d			

4. The Spectrometer Sub-Systems

The HIFI back-end consists of a pair of wide-bandwidth spectrometers (WBS) and a pair of tuneable high-resolution spectrometers (HRS). The systems perform spectral analysis of the IF signals coming from the active mixers in the FPU and sends the resulting spectra, along with housekeeping data, to the instrument control unit (ICU) for forwarding to the s/c data handling system. Commands from the ICU are given to the spectrometer sub-systems to set HRS configuration, IF levels, integration times, etc.

The proposed HIFI back-end is designed to have a high degree of redundancy and so that in the worst cases failure results in limited loss of capability. Their frequency resolution and coverage characteristics are given in Table 3. The WBS will consist of two separate acousto-optic spectrometer (AOS) units utilising a technology similar to the spectrometers, flown on NASA's SWAS and Sweden's ODIN satellite. Each unit has the capability to analyse a 4 GHz band with a spectral resolution of about 1 MHz. The 4 GHz signal input band is divided by the WBS IF processor into four 1.1 GHz wide sub-bands with a centre frequency of 2.1 GHz. These sub-bands are then merged.

Table 3. HIFI backend parameters for one polarization

Backend	Mode	Res. (MHz)	Sub-band width (GHz)	Band-sections
WBS	normal	1	1	4
HRS	normal	0.27	0.250	4
	high	0.14	0.250	2
	emergency	0.54	0.500	4

The HRS will provide several resolution/bandwidth combinations and will be based on Digital Auto-Correlation Spectrometers. It will use a combined frequency and time multiplexed design. Two sets of four auto-correlators will be used, one per IF channel. The analogue to digital conversion is performed by a sampler clocked at 550 MHz with a resolution of 2 bits (3 levels). A serial to parallel converter separates the signal into two output data streams at 275 MHz clock-rate each feeding a correlator block. It will be possible to configure each HRS into 4 independent sub-bands allowing high-resolution observations of up to 4 independent astronomical spectral line regions located within the 4 GHz IF bandwidth.

5. Observing Techniques and Templates

Three HIFI observing techniques are foreseen:

- Total power observing with no internal switching. This mode may be used in combination with telescope movements such as position switching where the telescope (and satellite) is moved between two or more pointing positions on a time-scale of about 100 s, or on-the-fly mapping where the telescope performs a raster scan across the astronomical source.
- Beam switching where the focal plane chopper in the Focal Plane Unit switches the beam between two positions upto 3 arcmin. apart on the sky at a rate of 1 Hz. This mode will be used for point-like astronomical sources, and optionally for on-the-fly mapping of extended objects.
- Frequency switching where the LO frequency is switched between two values spaced by up to a few 100 MHz at a rate of 1 Hz. This may be used to observe sources with narrow spectral features.

For observing with HIFI two astronomical observing templates (AOT) are foreseen:

1. AOT 1: pointed observations taking a spectrum over a frequency range equal to or larger than the standard 4 GHz band
2. AOT 2: mapping observations at a single LO setting

Peaking-up observations, to determine the location of the peak of the (line) emission, may be implemented as an additional AOT or could be added to AOT1. Such observations may be needed to correct for telescope pointing inaccuracies. In both AOTs a menu will give the observer the opportunity to select the frequency range(s), the observing technique(s) and the parameter settings for the instrument and telescope pointing (mapping).

6. Expected Performance

As an example a calculation has been performed for the limiting noise resulting from a (DSB) chopped observation of 1, 3, 30 and 300 minutes. The observing time is without overheads taken into account.

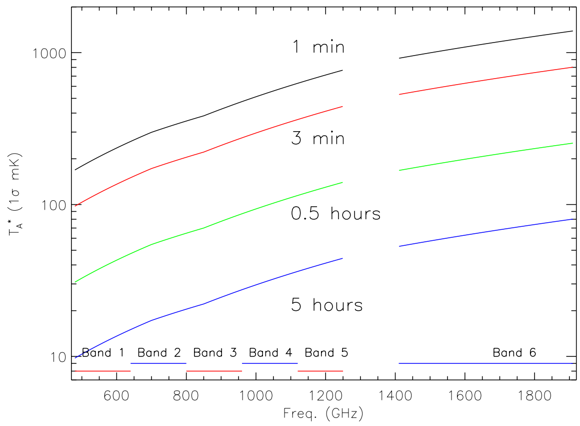

Figure 7. Expected 1 sigma noise for base-line sensitivity to be reached in 1 minute, 3 minutes, half an hour and 5 hours of integration.

Acknowledgements

HIFI is built by a large consortium of institutes spread out over many countries:

- The Netherlands: SRON Groningen/Utrecht, DIMES, University of Delft
  Responsibilities: Management, integration, test and calibration instrument and Focal Plane subsystem; ICC; Focal Plane subsystem, including control unit; Mixers bands 3 and 4
- United States of America: JPL/CalTech, Pasadena, University of Amherst
  Responsibilities: Mixers and multiplier chains for bands 5 and 6; Power amplifiers for all LO bands; Transistors for pre-amplifiers
- Germany: KOSMA, 1. Physikalisches Institut, Köln, Max-Planck Institut für Radioastronomie, Bonn, Max-Planck Institut für Aeronomie, Lindau
  Responsibilities: Mixers band 2; Wide Band Spectrometer; Management, integration and test for Local Oscillator subsystem; LO structure, assemblies, multipliers for band 1,2,3 and 4
- France: CESR Toulouse, LRM-DEMIRM, Paris, Observatoire de Bordeaux
  Responsibilities: Mixers band 1; High Resolution Spectrometer
- Italy: CAISMI-CNR, Firenze, IFSI, Frascati
  Responsibilities: Instrument Control subsystem; Optics (incl. Bragg crystal)
- Spain: Centro Astronómico de Yebes/OAN
  Responsibilities: Cryo pre-amplifiers
- Switzerland: ETH, Zürich
  Responsibilities: Common Optics Assembly/Mixer Assemblies; HEMTS and pre-amp system
- Sweden: Onsala/Chalmers TH, Göteborg
  Responsibilities: Back-up development cryo pre-amplifiers; HEB mixers; Beam tests of mixers and assemblies
- Poland: Space Research Center, Warszaw
  Responsibilities: Local Oscillator Control Unit
- Canada: CSA
  Responsibilities: LOU reference frequency source

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