HIFI information for the Herschel Calibration Workshop

Version 1 of 24/11/04, by

Abstract

This document contains information on HIFI, its sensitivity, the most important science goals and the instrument calibration

Document: ICC/2004-11
1 of 24/11/04
9 pages

Document approval

Prepared by:	Frank Helmich, Csaba Gal	24 November, 2004
Checked by:	Calibration Group	
Authorized by:		

Distribution

ESA:
A. Heras — ESTEC

HIFI steering committee
Th. de Graauw — SRON

HIFI project:

Revision history

Version	Date	Changes	Author
Issue 1	28/10/2004	First version	C.Gal/F.P. Helmich

Applicable documents

Doc. ref.	Title

Reference Documents

Doc. ref.	Title
SRON-G/HIFI/SP/1998-01	HIFI Instrument Specification
PT-HIFI-02125	Instrument Interface Document, part B
SRON-G/HIFI/SP/2000-01	Science User Requirements Document
LRM-ENS/HIFI/PL/2000-01	HIFI Calibration Plan
HIFI-ICC/2002-034	The intensity calibration for HIFI
L3AB/HIFI/CAL/2003-02	Frequency calibration frame work
HIFI-ICC/2003-20	Spatial response
HIFI-ICC/2003-008	HIFI observing mode descriptions
L3AB/HIFI/CAL/2003-01	Solar system bodies as calibration sources
LRM-ENS/HIFI/SP/2000-001	Calibration sources for FIRST/HIFI

Contents

Introduction

Purpose of this document to provide a general overview on the science goals of HIFI, its sensitivity and show the possible observing modes. Finally, a short introduction into the calibration strategy is given. This document does not replace any other document in the HIFI document tree.

1.1 HIFI as a heterodyne instrument

HIFI is only different from ground-based telescopes like the 3m KOSMA telescope, the IRAM 30m (Pico Veleta), the Caltech Submillimeter Observatory (CSO, Hawai'i), and the James Clerk Maxwell Telescope (JCMT, Hawai'I) in the sense that there is no atmosphere between the telescope and the source. So, many of the principles used on ground-based telescopes, can be re-used for HIFI. It is this knowledge that is extensively used within HIFI and especially in the HIFI calibration group. However, the lack of atmosphere also means that HIFI is likely much more stable than any ground receiver and thus that the calibration accuracy is much better than ever achievable on ground. Moreover, HIFI has a larger instantaneous bandwidth than existing groundbased instruments resulting in a more challenging overall calibration. This led to the notion that for HIFI, standing waves could be addressed in a much better way than ever before and thus a much more extensive description was needed than e.g. the often-used calibration scheme of Ulich & Haas (ApJS 30, 247,1976) and Kutner and Ulich (ApJ 250, 341,1981) or Penzias & Burrus (AR&AA 11, 51,1973). This led to a much more thorough description than ever before in the HIFI calibration framework, which consist of an intensity part, a spatial part (the beam) and a frequency part (spectral properties). With this frame work the HIFI calibration group is confident to reach the 10% radiometry accuracy from the HIFI specification document. However, this strictly relies on accuracy of models of planets and asteroids, which ultimately determine our knowledge of the conversion from currents and potentials into flux density or equivalently Rayleigh-Jeans approximations of the brightness temperature.

1.2 Overview

In this document first an overview will be given of the science goals of HIFI, then a description of the instrument is given, its observing modes and sensitivity. The calibration will be outlined, with especially those aspects necessary for the Herschel calibration workshop. Goal for HIFI is to improve the accuracy of, in particular, Solar System Objects models in order to improve the overall calibration.

2 Science goals for HIFI

HIFI, the heterodyne instrument for the far-infrared, is one of the instruments for the Herschel Space Observatory, one of the cornerstones of ESA's Horizon programme. It is designed to study the Universe in one of the last unexplored regions of the electromagnetic spectrum from space. It will do so with an unprecedented spectral resolution and sensitivity. Since it is an observatory type instrument it needs to be versatile to be able to address many key themes in modern astrophysics.

These themes are for HIFI mainly related to the understanding of the cyclic interrelation of stars and the interstellar medium of 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 ashes – enriched by newly synthesized elements – of dying stars. This complex interplay between stars and 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 redshift.

In several areas HIFI has unique capabilities

- In particular, while some space-borne instruments will measure or have measured only a few transitions of water, HIFI will cover an unparalleled number of water lines that are sensitive to a wide range of physical conditions at high spectral resolution. From the few existing data, it is already clear that water plays a dominant role in the chemical evolution as well as in the energy balance of a wide variety of objects, including regions of star and planet formation, shocks, hot cores, winds from dying stars, diffuse interstellar clouds, toroids around active galactic nuclei, and comets and planetary atmospheres. With its high spectral resolution, only HIFI is able to determine the true strength of the self-absorbed water lines.
- Because of the exceptional spectral coverage, HIFI is eminently suited to study the molecular universe, including light hydrides as key species in the interstellar chemistry and large organic molecules, through spectral line surveys
- HIFI is currently the only instrument which can survey the redshifted [CII] 158 micron line, the dominant cooling line of interstellar gas and a direct probe of massive star formation, locally and through the very important redshift-range of 0.5-3 when galaxy evolution was in full swing.

2.1 Other key science areas

HIFI is an excellent instrument to probe the physics, chemistry, and dynamics of the ISM, near and far, in great detail. It will therefore have an impact on a wide range of astrophysical problems. The science areas highlighted above as unique were selected because no other instrument will be able to address this science with competitive sensitivity. The great strength of HIFI is however in its versatility and therefore it will be equipped to address many newly emerging science issues.

The original HIFI proposal and the later Guaranteed Time programmes have identified a number of science areas where HIFI can make important contributions. Some of these are:

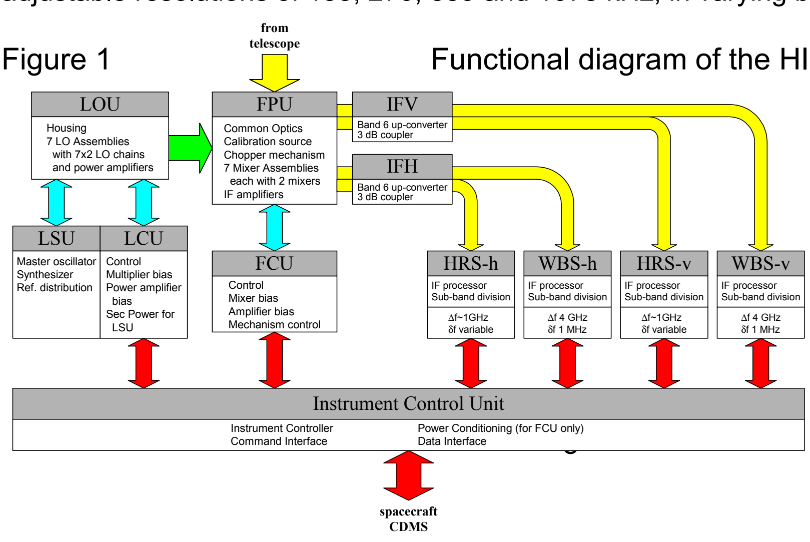
- The interstellar medium and star formation in galaxies. HIFI can address the nature of the interstellar medium in galaxies, its role in the evolution of galaxies, and the processes controlling the formation of stars on a global scale. Such studies will also provide the templates required to understand observations of the era of galaxy formation at high redshift, but also studies of the thermal balance locally are possible with observations of the fine-structure lines, CO, H_2O and other hydrides.
- The diffuse ISM in the Milky Way. The structure and dynamics of the diffuse ISM in the Milky Way is central to studies of galactic evolution driven by star formation. HIFI will measure the pressure of the interstellar gas throughout the Milky Way, isotope abundance gradients, and the molecular inventory of diffuse interstellar gas.
- Late stages of stellar evolution. Water and CO are excellent tracers of the warm envelopes of stars at the end of their evolution, and therefore provides tools to study these regions close to the central star.
- Comets. Comets are among the most pristine objects preserved in the solar system. HIFI can measure directly the outgassing rate of comets, and derive clues to their origin.

3 Description of the HIFI instrument

HIFI is a heterodyne instrument, which means that the signal from the source is mixed with an internally generated signal (the Local Oscillator or LO signal). The two signals are fed into a mixer in which the sky signal is down converted to the difference frequency which is much easier amplified. All spectral information is, however, conserved and the output, the Intermediate Frequency (IF), can be fed into spectrometers to obtain a very high spectral resolution (down to 0.1 MHz) spectrum over an IF range of 4 GHz. Down conversion works in such a way that not only the signal band is down converted, but at the other side of the LO frequency a similar band is down converted (the image band). The IF consists thus of a combination of the two side bands. This has consequences for science planning, because the wanted line in the signal side-band may be blended with unwanted lines from the image side-band. It also has consequences for the calibration, both in straightforward sense, but also through subtle effects.

In figure 1, one can see the functional diagram, where on the left hand side the local oscillator signal is generated in 14 so-called LO subbands, in the middle, the Focal Plane, the signal from the sky is combined with the LO signal and fed into 2 (2 polarizations) of the 14 available mixers at one time. The out coming IF signal is fed into a series of backends, for each polarization there is a 4 GHz wide Wide Band Spectrometer (WBS), which has a resolution of about 1.1 MHz, and there is a High Resolution Spectrometer (HRS), which has adjustable resolutions of 135, 270, 539 and 1078 kHz, in varying bandwidths.

Figure 1 Functional diagram of the HIFI instrument



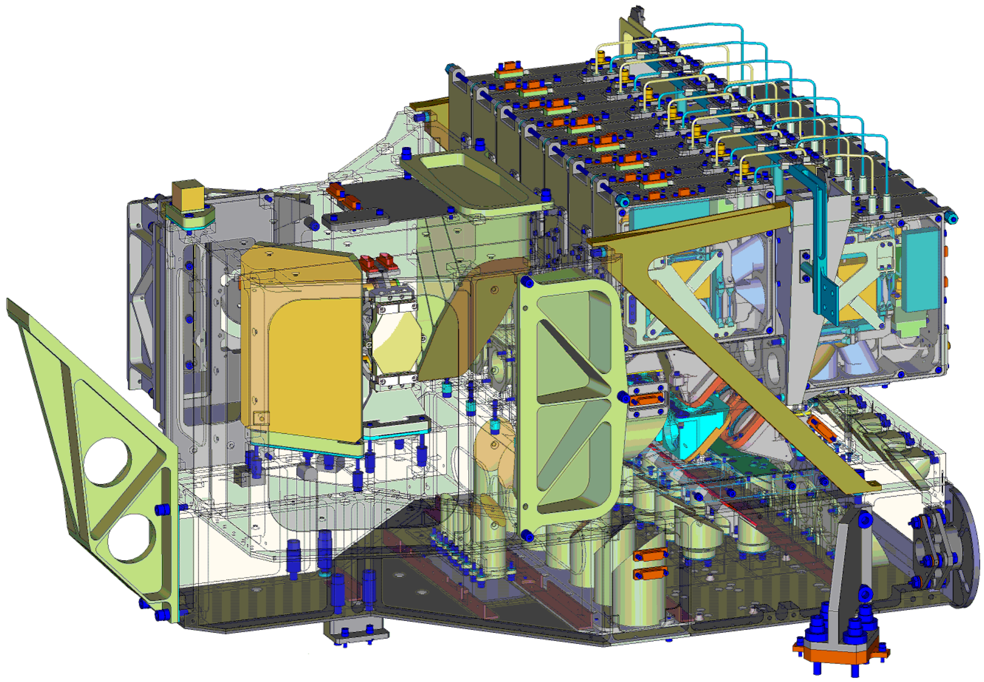


Figure 2 The HIFI focal plane unit. Clearly the pick-off mirror M3 is visible (left) and the modular design of the mixer units (top-right). All mixers share the common optics in the middle and the same calibration source unit (not shown).

The pick-off mirror M3 is used to direct the beam from the mixers to the celestial source. Each mixer pair therefore is at a slightly different position on M3 and thus on the sky. Simultaneous measurements are therefore excluded. HIFI spans almost a factor of 4 in frequency. With constant size of the telescope this implies that at its lowest frequency HIFI's beam size is about 45 arcseconds on the sky. At 1.9 THz, the largest frequency it is 12 arcseconds. Band 1 ranges from 480-640 GHz; Band 2 from 640-800 GHz; Band 3 from 800-960 GHz; Band 4 from 960-1120 GHz; Band 5 from 1120-1250 GHz and Band 6 from 1410-1910 GHz.

4 Observing modes and sensitivity

In general observations with HIFI will be done in modes where the source is observed followed by an observation of a reference. This reference may be a blank piece of the sky chosen by either moving the telescope (nodding) or by moving the internal chopper (chopping) or a combination of these two. Other reference measurements are observations of the cold internal load (load chop), or by switching the LO signal by a small amount to a slightly different frequency (frequency switch). It is clear that for different observations different reference strategies will be chosen. It is the task of the HIFI Instrument Control Center Group to provide a scheme of the best possible combination schemes of source and reference observations.
Moreover, all observations consist of a sequence of source, reference *and* calibration measurement loops. These loops are set up to correct for the different kinds of instabilities that will occur in the instrument. In the Herschel Calibration Workshop most likely only one of these set-ups is important, the Double Beam Switch mode used for point like sources, where

the chopper is used to switch between source and sky-off position and after a certain period this whole procedure is repeated but the off position is now at exactly the other side of the source position (the beams have switched to the other side). Again chopping is done and thus double difference measurements can be made, whereby most (especially the standing waves), if not all, instrumental effects will cancel. Frequency-switched and position-switched observations will be done for larger source sizes. HIFI is essentially a single pixel instrument, so mapping either has to be done in a specified raster, or by taking spectra while moving the telescope (either can be combined with chopping). The latter method is generally called on-the-fly-scanning, or in ESA speak, line scanning. Both mapping methods can make use of an external off-position as reference or a frequency switch.

4.1 Time estimator recipe

The description of observing modes is very elaborate and as an approximation the time estimator recipe gives some feeling about HIFI's sensitivity. These numbers are also used by HIFI's scientists to estimate what there scientific (key)programmes would need.

Definitions:

- T_{sys}: System temperature, use Single Side Band (SSB) numbers everywhere
- Delta_nu: frequency resolution (Hz)
- T_{tot}: Total observing time (s)
- A: Overall efficiency factor

Depending on the observing modes, the efficiency factor (A) is:

- 0.25 for frequency switching
- 0.125 for chopping (which includes the Double Beam Switch and Position Switch)
- 0.5 for very long OTF scans (more than 2 samples)
- 0.3 for short OTF scans

System temperatures (T_{sys}(SSB)) are:
Band 1-5 (480-1250 GHz): T_{sys}(SSB)= (200*nu/500 GHz) (K)
Band 6 (1410-1910 GHz):): T_{sys}(SSB)= 1600 K

And with the common radiometer equation: $T_{rms} = T_{sys}$/sqrt(A*delta_nu*T_{tot})

If we are able to combine the two polarizations the noise can be lowered by sqrt(2). This may be best justified in bands 1-5.

For completeness, the point source continuum sensitivity is about 450 Jy/K at 500 GHz for bands 1-5 and 600 Jy/K for band 6.

5 Calibration of HIFI

The radiometric calibration accuracy is set to be 10% with a goal of 3%. Below some aspects of the HIFI calibration are listed.
A thorough description is available in the HIFI calibration Framework documents.

All methods chosen have taken the following into account:

- We can exploit the advantage of a missing atmosphere

- Due to the large IF all continuum sources will show considerable sideband imbalances

- Standing waves are expected in several parts of the optical paths between LO, mixer and sky, in particular between mixer and secondary. They are not treated within the standard formalism (Penzias & Burrus, Ulich & Haas, Kutner & Ulich)
- The HIFI internal loads are at 15K and 100 K for the cold and hot load resp.

Using these assumptions a 3-point calibration (like on IRAM, the HHT, KOSMA etc.) can be constructed, which consists of the use of the cold load, the hot load and the blank sky (OFF), in one calibration measurement. This procedure allows determining the band-pass, the receiver noise, the forward efficiency and a signature of the instrumental standing waves to be measured simultaneously. It also gives higher calibration accuracy than the standard two-point calibration. Another advantage would be, but this has to be tested in space, that the analysis of the spectral ripple in the blank sky measurement allows to fit the standing wave behaviour by using a model.

Spectrally the calibration is straightforward since the spectrometers are locked to the master (LO) oscillator through highly accurate oscillators/clocks via phase lock loops. The only exception is in band 6 (1410-1910 GHz) where the up-converter for the different IF is unlocked. Some drifts may be present in the frequency, but this is known to be temperature dependent and the drifts will be monitored. The filter curves of the individual frequency channels are well determined during ground tests and from theory. These can also partly be checked in orbit by internal comb measurements.

Spatial calibration is very important in-orbit, because this cannot be exercised on the ground in full detail. The calibration starts of with quasi-optical modelling of all the HIFI beams, up to their position on the sky and this would bring the beam profile very likely within 10% accuracy. However, during the launch things may have shifted slightly and thus the beams of HIFI have to be checked very carefully. Also the aperture efficiency can *only* be accurately deduced from astronomical observations. This is where the models of astronomical sources, and especially the very bright Solar System objects, come into play. The aperture efficiency is best derived from dedicated calibration measurements of Uranus and/or Ceres. The beam profiles can be determined by obtaining deep maps on Mars and/or Saturn/Jupiter. Note that normal stars are excluded because these are not bright enough. Also note that neither Mars nor Uranus are visible all the time due to strong visibility constraints of Herschel. It is therefore of great importance to prepare for models of a number of sources, including the largest asteroids.

Body (1)	Date (2)	D ["] (3)	freq [THz] (4)	T_B [K] (5)	$S_{nu,tot}$ [Jy] (6)	$S_{nu,beam}$ [Jy] (7)	T_A*(SSB) [K] (8)	SNR 1 sec (9)	T_{int}^{20dB} [sec] (10)	T_{int}^{30dB} [sec] (11)
Saturn	15-5-2007	16.9	1.9	135	55100	29691	116.3	291	0.118	12
Mars	1-10-2007	9.8	1.9	226	36200	28840	112.9	282	0.125	13
Mars	1-7-2007	6.4	1.9	222	14922	13531	53.0	133	1	57
Uranus	1-7-2007	3.6	1.9	60.0	662	642	2.51	6	240	7hour
Ceres	1-1-2008	0.6	1.9	169	94	94	0.37	1	197min	329hour
Saturn	15-5-2007	16.9	0.5	131	4835	4609	20.31	564	0.031	3
Mars	1-10-2007	9.8	0.5	226	2928	2880	12.69	353	0.080	8
Mars	1-7-2007	6.4	0.5	222	1210	1202	5.30	147	0.462	46
Uranus	1-7-2007	3.6	0.5	77.0	118	117	0.52	14	48	81min
Ceres	1-1-2008	0.6	0.5	169	8	8	0.04	1	173min	288hour

Table 1: Time estimate for observations of Solar System bodies with Herschel-HIFI. The upper part is for 1.9 THz, the lower part for 500 GHz. Column [3] gives the planetary diameter at the time of observation (column [2]). Column [4] gives the observing frequency. Column [5] is the brightness

temperature used for the calculation of total fluxes given in [6]. Fluxes per beam are listed in [7] and used to derive the antenna temperature expected with HIFI in column [8]: this is simply given by the total flux per beam $S_{nu,beam}$, divided by the point source sensitivity. Column [9] gives the corresponding signal-to-noise ratio after 1 sec of on+off integration time. Beware that all additional times are neglected here! Columns [10] and [11] give the integration times needed to achieve signal-to-noise ratios of 20dB and 30dB respectively.

5.1 Error budget

Using all calibration equations from the frame work document and from the observing modes calibration document an error budget can be made. In this budget one immediately sees that there are two major sources of error outside the instrument and two in the instrument. In the instrument these are the cold load coupling and the side-band ratio. Both can amount up to 5% accuracy, but also both can be measured in the laboratory. Outside the instrument Herschel's pointing plays a major role, but this is hopefully to improve. Last large error source is the knowledge on models for astrophysical sources. The calibration group assumes that the continuum of Uranus (just as other objects like the asteroids) is known to within 5%. One of the objectives of this workshop is to bring this and other numbers down by improvement of our knowledge on these objects and by improving the models themselves.

5.2 Solar System Objects

As stated above, knowledge on Solar System objects play a crucial role in resulting accuracy of HIFI's radiometry calibration. Therefore the continuum and atmospheric models for these sources need to be as good as possible. HIFI is intending to make very frequent observations of the Giant Planets, Mars and the brightest asteroids in order to make the calibration as uniform as possible. Modellers can assist in defining what the crucial parameters are in their models. Together observations can then be defined to improve the model and thus HIFI's calibration.

5.3 Line emission objects

In the calibration scheme of HIFI extensive use is made of continuum sources. These provide an easy and relatively quick way of obtaining the relevant calibration parameters. However, the calibration group has also a need for standard spectra in which strong, point-like, line sources are observed. These can be planetary atmospheres but better candidates are AGB sources. These sources have relatively intense CO (and sometimes HCN or H_2O) emission over the whole frequency range available to HIFI. In monitoring these CO lines over the whole life time of Herschel, the calibration group has the means to determine any degradation or systematic long-term drifts, albeit the variability of these sources is not known.

A Further reading

The HIFI website can be found at http://www.sron.nl/divisions/lea/hifi/index.html
The HIFI science is also described on http://www.sron.rug.nl/hifiscience
The HIFI ICC has its web pages at http://www.sron.rug.nl/hifi_icc