The HIFI Focal Plane Unit

B.D. Jackson, K.J. Wildeman, and N.D. Whyborn
on behalf of the HIFI Focal Plane Consortium
SRON National Institute for Space Research
Postbus 800, 9700 AV Groningen, The Netherlands

ABSTRACT

The Heterodyne Instrument for the Far-Infrared (HIFI) is a heterodyne spectrometer being built for the European Space Agency's Herschel Space Observatory, with seven receiver channels covering the 480-1250 and 1410-1910 GHz frequency ranges. This paper provides an overview of the HIFI Focal Plane Unit (FPU) design, with particular emphasis placed upon an overview of the primary elements in the FPU's signal chain.

1. THE HERSCHEL SPACE OBSERVATORY

The Herschel Space Observatory (see Fig. 1) is a cryogenic space telescope being built by the European Space Agency to study the universe in the far-infrared and the submillimetre (60-670 um) [1-3]. To fulfil its scientific goals, Herschel will carry three scientific instruments: two imaging arrays with low-to-medium spectral resolution (PACS [4] and SPIRE [5]); and a high-resolution heterodyne spectrometer (HIFI) [6,7]. To maximize the sensitivity of these instruments, the Herschel telescope will be passively cooled to ~ 80 K, while a superfluid helium bath will cool the satellite's optical bench and the instruments' detector elements to 10-15 K and < 3 K, respectively. The instruments' warm control electronics, together with the satellite's command and control system and HIFI's intermediate frequency spectrometers, will be located in the satellite's service module, below the cryostat, while the HIFI local oscillator unit will be mounted on the side of the cryostat, with the local oscillator beams injected into the focal plane unit through windows in the cryostat.

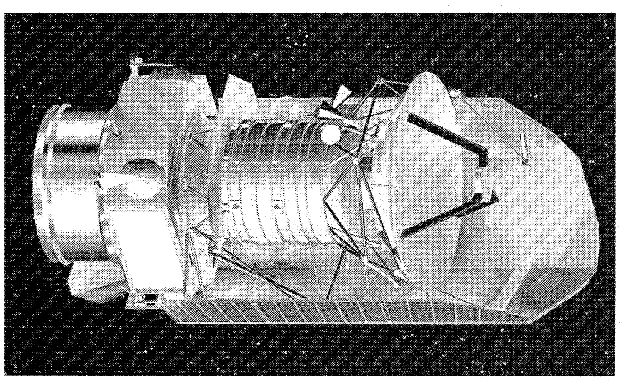


Fig. 1 – The Herschel Space Observatory

2. THE HETERODYNE INSTRUMENT FOR THE FAR-INFRARED (HIFI)

The Heterodyne Instrument for the Far-Infrared (HIFI) is a high-sensitivity, single-pixel heterodyne spectrometer that will be used to study a wide range of objects in the local solar system, our own galaxy, the interstellar medium, and both nearby and distant galaxies [6]. The primary characteristics of the HIFI instrument are:

- complete spectral coverage of 480-1250 (with 5 SIS mixer bands) and 1410-1910 GHz (with 2 HEB mixer bands);
- a spectral resolution of 0.14 to 1 MHz;
- high sensitivity, with $T_{N,rec} \sim 4hf/k_B$;
- a 4 GHz instantaneous band-width in both the upper and lower sidebands;
- dual polarization operation; and
- a calibration accuracy of at least 10% (with a goal of 3%).

As seen in Fig. 2, HIFI has five major sub-systems: the Local Oscillator Sub-System (LOSS); the Focal Plane Sub-System (FPSS); the Wide-Band Spectrometer (WBS); the High-Resolution Spectrometer (HRS); and the Instrument Control Unit (ICU).

Within the LO sub-system, a tuneable, spectrally pure 24-36 GHz signal is generated in the Local Oscillator Source Unit. This signal is then frequency-multiplied to 71-106 GHz, amplified, and further frequency-multiplied to the desired RF frequency in the Local Oscillator Unit. The result is a spectrally pure LO signal with a tuneable frequency and power level. Fourteen multiplier chains are used to cover the full HIFI spectral range, with two chains per Focal Plane mixer channel. The LO beams are fed into the Focal Plane through 7 windows in the Herschel cryostat.

Inside the Focal Plane Unit (FPU), the incoming astronomical signal is split into 7 beams. Each of these signal beams is optically combined with its corresponding LO beam, and then split into two linearly polarized beams that are coupled into 2 mixer units. Each of the mixer units generates an intermediate frequency (IF) signal that is amplified within the FPU prior to leaving the cryostat.

The IF output signals from the FPU are coupled into two IF spectrometers. The Wide-Band Spectrometer (WBS) is a four-channel acousto-optical spectrometer that samples the full 4-8 GHz output of the FPU with 1 MHz resolution, while the High-Resolution Spectrometer (HRS) is a high-speed digital auto-correlator that samples a narrower portion of the IF band with a higher resolution.

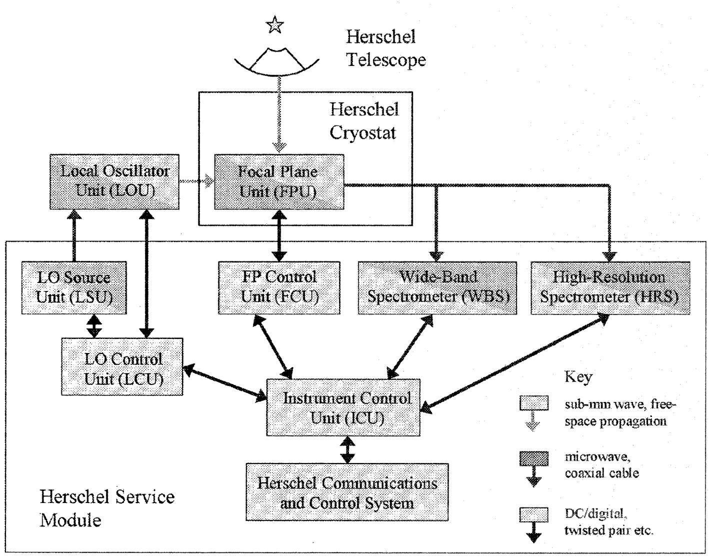


Fig. 2 – Block Diagram of the HIFI Instrument

Each of the 4 HIFI sub-systems includes a warm electronics unit. These four control units are, in turn, commanded by a single Instrument Control Unit, which also interfaces with the satellite's on-board command and control system.

3. THE HIFI FOCAL PLANE UNIT

The HIFI Focal Plane Sub-System consists of the Focal Plane Unit (the FPU, located on the Herschel optical bench) and the Focal Plane Control Unit (the FCU, contained in the satellite's warm service module).

The Focal Plane Unit (see Fig. 3) consists of six major assemblies: the Common Optics Assembly (COA); the Diplexer Assembly; the Mixer Sub-Assemblies (MSA's, of which there are 14); the second-stage IF amplifier box; the Focal Plane Chopper; and the Calibration Source Assembly.

The complexity of the Focal Plane sub-system is demonstrated by the large consortium of institutes that are contributing to its design, construction, and testing: ~ 20 groups from ~ 14 institutes (see Table 1, on the following page).

3.1 FPU Design Constraints

The design of the Focal Plane Unit is constrained by a number of important design requirements. In particular, the inputs to the FPU optical design are:

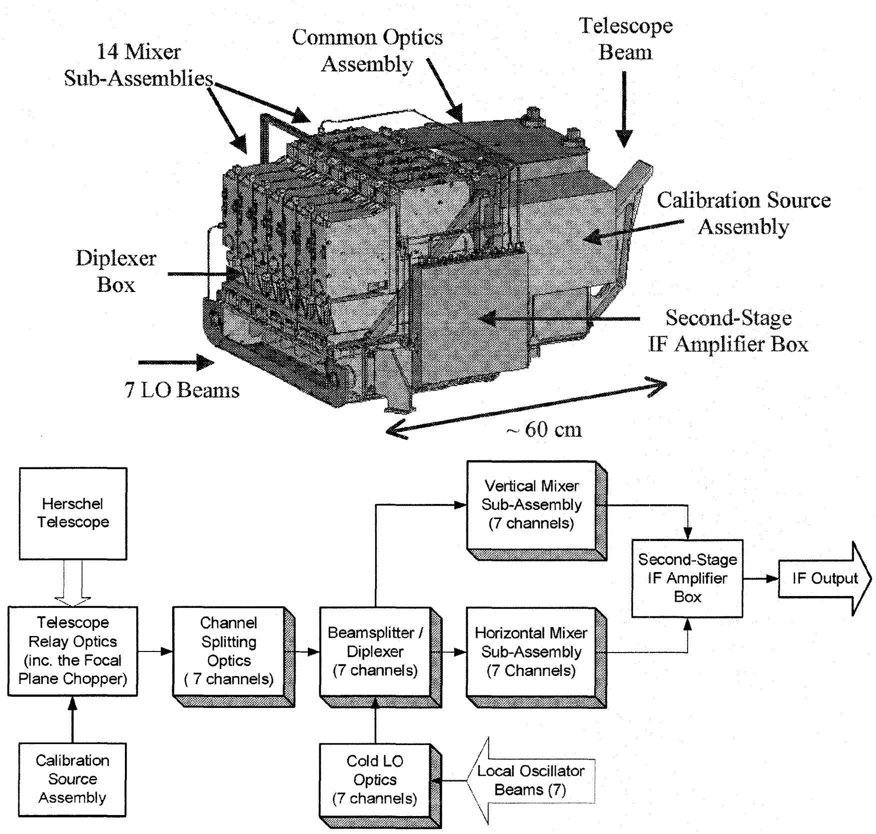


Fig. 3 – The HIFI Focal Plane Unit

Table1: The HIFI Focal Plane Sub-System Consortium

Country	Institute(s)	Responsibilities
The Netherlands	SRON	Management, System Integration and Testing, System Engineering, FCU, Mechanisms
	SRON, TPD, MECON	COA, Diplexer Box, MSAs, Calibration Source
	SRON, DIMES	Band 3 and 4 Mixers
France	LERMA, IRAM	Band 1 Mixer
Germany	KOSMA	Band 2 Mixer
	DLR (Berlin)	Band 6L Mixer Beam Measurements
USA	JPL/NASA	Band 6H Mixer, IF Amplifier HEMTS
	JPL, CalTech	Band 5 Mixer
Sweden	CTH	Band 6L Mixer, Band 1-4 MSA Beam Measurements, IF Amplifier Design
Spain	YEBES	First-stage IF Amplifier
Switzerland	ETH	Second-stage IF Amplifier, COA and MSA Construction
Ireland	NUI	Quasi-optical Design Analysis

- It is assumed that fundamental mode gaussian beams can approximate the RF beams produced by the mixers, the LOs, and the telescope.
- The Herschel telescope is a Ritchey-Chrétien telescope with a 3.5-m primary mirror and a 0.31-m secondary. The secondary is 1.6 m in front of the primary and 2.6 m from the telescope focal plane (yielding a geometrical F/D ratio of 8.68 for the edge-rays incident on the focal plane).
- The FPU produces seven optical beams (one per channel) that are spatially separated in the telescope focal plane, resulting in an angular separation of the optical beams on the sky.
- The telescope secondary is an aperture-stop in the optical system, truncating each of the HIFI signal beams at –11-dB (independent of frequency).
- The 7 LO beams enter from the back of the focal plane unit. Each beam has a 7.5 mm waist located ~ 200-250 mm from the input to the FPU, with the beams spaced by 50 mm.
- The optical imaging quality of the system should be high (a fundamental gaussian passing through the system should suffer distortion losses ≤ 1 %).

In addition to the optical interfaces, the mechanical and thermal interfaces to the spacecraft places the following constraints on the FPU design:

- The total FPU mass is ~ 46 kg.
- The total FPU volume is 50 x 70 x 40 cm^3.
- The average heat-load of the FPU on the cyrostat is ~ 20 mW on the instrument's 10 K level, 7 mW at 4 K, and 5 mW at 2 K (during operation).
- The FPU should survive the high vibration levels present during launch.

Finally, the HIFI model philosophy generates two additional, but related requirements:

- After integration of the FPU, it should be possible to repair or replace critical components within 1 month (i.e. mixers and mechanisms).
- After integration, it should be possible to upgrade the FPU if ongoing development yields a significant improvement in mixer sensitivity.

3.2 The Common Optics Assembly

The Common Optics Assembly (COA, see Fig. 4), is the basis of the FPU structure, and mounts directly on the Herschel optical bench. Its optical design consists of 3 blocks: the telescope relay optics, the channel-splitting optics, and the cold local oscillator optics.

The telescope relay and channel-splitting optics relay the instrument's seven signal beams from the Herschel focal plane into the diplexer box. This is done with 6 common mirrors (the telescope relay optics, shared by all channels), followed by 7 sets of three mirrors (the channel-splitting optics). The telescope relay and channel splitting optics have three primary functions:

- They produce an image of the telescope secondary on the fourth mirror in the chain, enabling the implementation of a focal plane chopper.
- They produce an image of the focal plane on the first mirrors in the channel-splitting optics. Because the instrument's seven beams are separated in the focal plane, this allows the beams to be split by seven isolated mirrors with different orientations.
- In each channel, they create an image of the telescope secondary within the diplexer box. This image is a frequency-independent waist that is relatively large, to minimize diffraction losses within the diplexers.

The waists of the seven beams entering the FPU from the LO unit are re-imaged by the

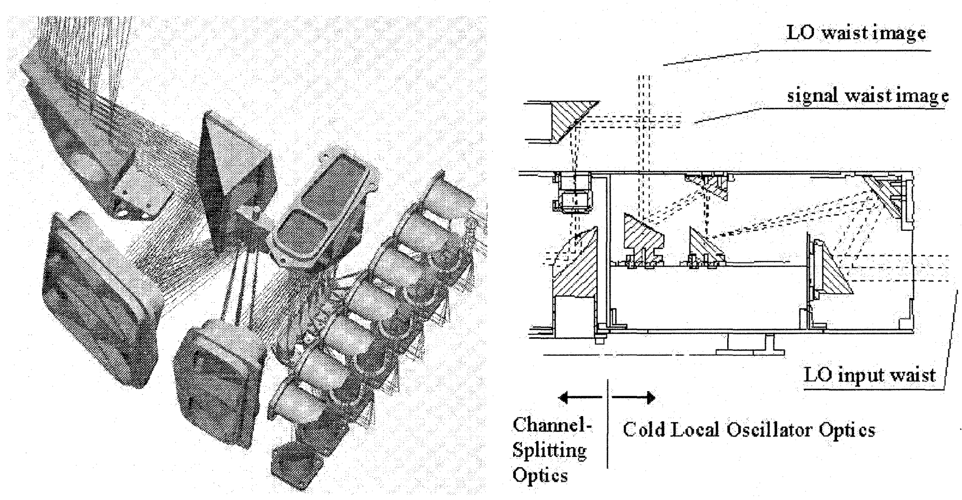
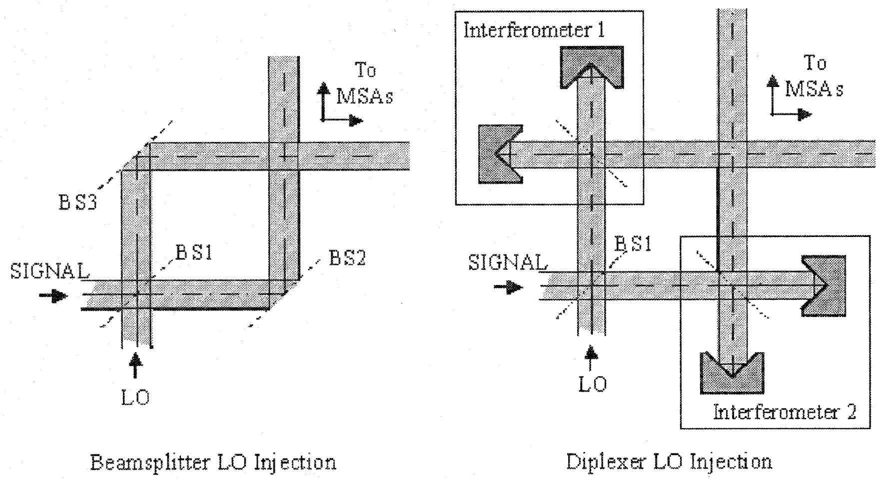


Fig. 4 – The Common Optics Assembly. The left-hand image shows the mirror configuration of the telescope relay optics (the first six common mirrors) and the channel-splitting optics (the 7 sets of three smaller mirrors). The right-hand image shows the layout of a single channel of the cold local oscillator optics.



(a) (b)

Fig. 5 – Local Oscillator Injection Schemes

cold local oscillator optics, producing frequency-independent waists in the diplexer box that match the signal beam waists produced by the channel-splitting optics.

3.3 The Diplexer Assembly

Within the diplexer assembly, each of the 7 signal beams is combined with its corresponding LO beam, creating two linearly polarized output beams per frequency channel. Each linearly polarized beam is then directed into a Mixer Sub-Assembly.

At low frequencies, where relatively high LO powers are available, the combining is done with three polarizing beamsplitters per channel. As indicated in Fig. 5a, the first beamsplitter is placed at the intersection of the LO and signal beams, creating two mixed beams (one contains the "horizontally" polarized signal beam plus the "vertically" polarized LO beam, while the second contains the inverse). Each of the mixed beams then hits a second beamsplitter, whose polarization is defined to reflect 90 % of the signal power and 10 % of the LO power (the remaining signal and LO power are absorbed in a beam-dump). This 90%/10% coupling of signal and LO powers is achieved by setting the polarization of BS1 18° from the vertical, while BS2 is horizontally polarized and BS3 is vertically polarized. Increased coupling of signal power to the mixers can be achieved by rotating the polarization of BS1 closer to the vertical (although this also reduces the LO power coupling).

At high frequencies, where LO power is scarcer, a Martin-Puplett diplexer is used for LO injection (see Fig. 5b). Once again, the first beamsplitter creates two beams containing LO and signal power in orthogonal polarizations (the polarization of BS1 is vertical in this case). The following pair of beamsplitters in Fig. 5a are then replaced with a polarizing Michelson interferometer that rotates the polarization of the LO beam relative to that of the signal beam, creating a linearly polarized output (one interferometer is used for each mixer). In this manner, the coupling of both the LO and signal powers to the mixers are high, although mechanisms are needed to tune the interferometers for use at different frequencies.

3.4 The Mixer Sub-Assembly

Each of the 14 linearly polarized outputs from the diplexer box enters a Mixer Sub-Assembly (MSA) that includes:

- three mirrors that focus the optical beam from the diplexer into the mixer;
- a mixer unit (SIS mixers in bands 1-5 and HEB mixers in bands 6L and 6H);
- a low-noise IF amplifier (plus two IF isolators that suppress reflections in the cable between the mixer and the amplifier);
- low-frequency filtering for the mixer's DC bias lines; and
- a mechanical structure that isolates the 2 K mixer from the 10 K FPU

The resulting MSA design (see Fig. 6) is a densely packed ~ 5x12x15 mm^3 box. The design's complexity is driven by a number of factors, including the need for a compact design and the desire for a low-distortion, all-reflective optical design. In particular, this second requirement necessitates the use of at least two mirrors (the second mirror compensates for distortions introduced by the first mirror). In practice, a three-mirror system is used because it is more compact than a comparable two-mirror design.

3.5 The IF2 Box

Prior to leaving the FPU, the IF outputs of the 14 mixer sub-assemblies pass through a 14-channel second-stage amplifier (the IF2 Box). The extra gain provided by this additional amplifier is needed to overcome the losses in the IF cables between the FPU and the spectrometers (~ 5 m of stainless steel cable will be used to minimize the heat-load on the cryostat). In addition, the IF2 box has several extra functions:

- equalizing the output powers of mixers in different bands;
- offsetting the frequency-dependence of the IF cable losses; and
- combining the 14 mixer outputs into 4 cables to reduce the thermal load on the cryostat.

3.6 The Focal Plane Chopper

The fourth mirror of the telescope relay optics is the focal plane chopper. The chopper mirror is mounted on flex pivots that allow it to rotate around the centre of its optical

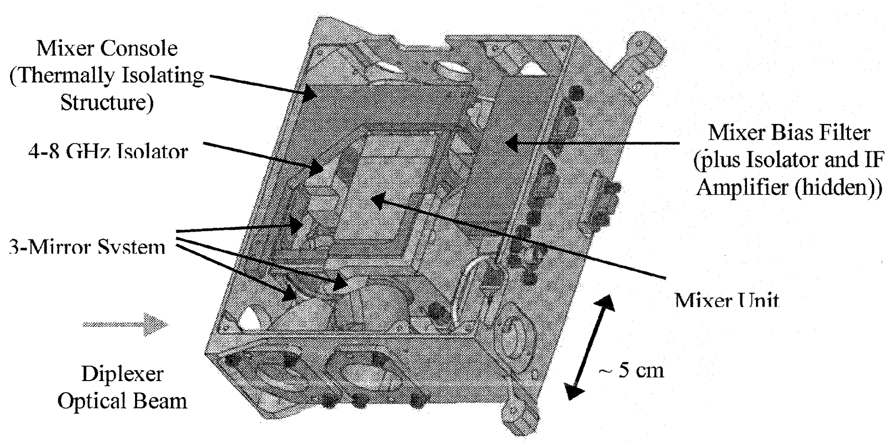


Fig. 6 – The Mixer Sub-Assembly

surface (in one direction). Because the mirror is located at an image of the telescope secondary, tilting the chopper results in a tilt of the beam on the sky. The primary uses of the chopper are to scan the beam on the sky (in one direction), and to redirect the instrument's optical beam into the on-board calibration source.

3.7 The Calibration Source Assembly

Mounted on the side of the COA, the calibration source assembly contains a lightweight blackbody cavity (the calibration source) that can be heated to 100 K, plus a set of mirrors that focus the optical beam from the FPU into the cavity. The calibration source assembly provides two stable blackbody signal loads that are used to verify the calibration of the instrument's sensitivity (one load is at ~ 10 K, while the second is at an adjustable temperature between 10 and 100 K). The HIFI signal beam is steered into the calibration source by using an extreme position of the focal plane chopper.

4. THE HIFI MIXER UNITS

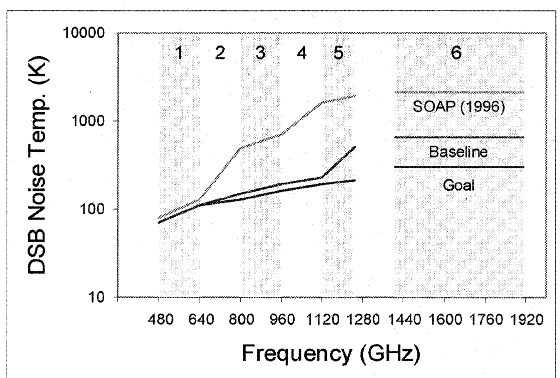
4.1 Performance Requirements

The ultimate sensitivity of the HIFI instrument will be largely determined by the sensitivity of the SIS and HEB mixers at the heart of the FPU. For this reason, ambitious goals have been set for the performance of these mixers. In particular, with a goal of $T_{N,rec} \sim 4\ hf/k_B$ defined for the sensitivity of the integrated instrument, the goal sensitivities of the HIFI mixers are $T_{N,mixer+IF} \sim 3.5\ hf/k_B$ (including the noise contributions of the IF chains). In general, this goal has been achieved in SIS mixers at lower RF frequencies (below 700 GHz). However, the desire to achieve this sensitivity over broad RF and IF bandwidths, and at much higher RF frequencies, makes this a significant challenge. This is highlighted by the plot in Fig. 7 of the goal sensitivities of the HIFI mixers versus the best-reported sensitivities at the time of the submission of the HIFI proposal to ESA (in 1996).

Band	Frequency (GHz)	Mixer Type
1	480-640	SIS, WG
2	640-800	SIS, WG
3	800-960	SIS, WG
4	960-1120	SIS, WG
5	1120-1250	SIS, QO
6L	1410-1710	HEB, QO
6H	1710-1910	HEB, QO

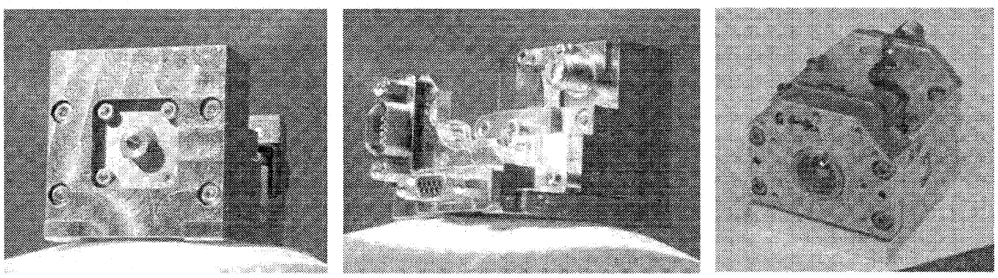
Note: WG = waveguide mixer
QO = quasi-optical mixer

(a)



(b)

Fig. 7 – HIFI Band Definition and Mixer Sensitivity Goals. Note that the baseline and goal sensitivities are defined as the effective input noise of a receiver with loss-less optics (i.e. only the mixer and IF chain noise contributions are considered). Also, note that the 1996 State-of-the-Art Performance (SOAP) generally corresponds to narrow-band mixers at low IF. A clear split between the SOAP and Goal sensitivities is seen above 640 GHz.



(a) (b) (c)

Fig. 8 – Two Prototype HIFI Mixer Units. (a) and (b) front- and rear-views of the band 4 mixer (from SRON), with its corrugated horn visible in (a), (c) is a front-view of the prototype band 6H mixer (from JPL/NASA), with its quasi-optical lens visible.

4.2 Interfaces and Other Requirements

The HIFI mixers are compact units with well-defined optical, mechanical, and electrical interfaces designed to facilitate rapid integration into the mixer sub-assemblies. This has required the inclusion of a number of features that are not present in laboratory-based SIS or HEB mixers. In particular, while a typical lab mixer includes:

- a RF beam-forming element (a waveguide horn or a quasi-optical lens-antenna);
- a SIS or HEB mixing element;
- a superconducting electro-magnet (for SIS mixers only); and
- an IF output connector that is also used as the DC bias connector,

a HIFI mixer will also include a number of additional features:

- a built-in bias-T to split the IF output from the DC bias input;
- a five-wire bias network (to allow the actual mixer bias to be monitored, while also providing ESD protection and EMC filtering on the bias lines);
- a resistive de-flux heater (for the SIS mixers only); and
- absolute alignment of the mixer's quasi-optical RF beam.

Furthermore, the mixer units must be rugged enough to survive 4-5 years of instrument and satellite integration and testing, the satellite launch, and 4-5 years of in-flight operations. This requires that the mixer units be able to survive, without suffering a loss of calibration, low-level ESD events, several days of vacuum bakeout at 80°C, a large number of thermal cycles to 2 K (~ 25 are foreseen for the flight units), high vibration levels, and irradiation by energetic particles.

Fig. 8 includes pictures of two prototype HIFI mixer units.

5. CURRENT STATUS AND EXPECTED DEVELOPMENT SCHEDULE

The HIFI instrument has a three-stage development program, including a development model, a qualification model, and a flight model.

At present, the mixer and IF amplifier development programs are wrapping up, with development model hardware deliveries scheduled for the spring of 2002. The construction and integration of the development model FPU is expected to be complete by the summer of 2002 and will be followed by ~ 6 months of instrument-level testing in the second half of 2002.

The development model program will be followed by a qualification program, which will demonstrate the compliance of the as-built hardware with the requirements of space qualification (including, in particular, formal environmental testing of both individual units and the integrated instrument). At lower levels of integration (i.e. units that are deliverable to the FPU), the qualification program has already begun, with completion expected by the end of 2002. The qualification program for the integrated FPU will begin in mid-2002, and will last until the second half of 2003.

The construction of flight hardware will begin in the second half of 2002, with the units at a lower level of integration being delivered in mid 2003, so that the integration of the FPU can take place in the second half of 2003. Testing of the integrated instrument is planned for the second half of 2004.

6. ACKNOWLEDGEMENTS

The authors would like to thank the HIFI Focal Plane Sub-System consortium for their significant contributions to this project (see Table 1).

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