HETERODYNE INSTRUMENT for FIRST (HIFI): PRELIMINARY DESIGN

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ABSTRACT

We describe the preliminary design of the proposed Heterodyne Instrument for FIRST *(HIFI)*. The instrument will have a continuous frequency coverage over the range from 480 to 1250 GHz in five bands, while a sixth band will provide coverage for 1410-1910 GHz and 2400-2700 GHz. The first five bands will use SIS mixers and varactor frequency multipliers while in the sixth band a laser photomixer local oscillator will pump HEB mixers. *HIFI* will have an instantaneous bandwidth of 4 GHz, analysed in parallel by two types of spectrometers: a pair of wide-band spectrometers (WBS), and a pair of high-resolution spectrometer (HRS). The wide-band spectrometer will use acousto-optic technology with a frequency resolution of 1 MHz and a bandwidth of 4 GHz for each of the two polarisations. The HRS will provide two combinations of bandwidth and resolution: 1 GHz bandwidth at 200 kHz resolution, and at least 500 MHz at 100 kHz resolution. The HRS will be divided into 4 or 5 sub-bands, each of which can be placed anywhere within the full 4 GHz IF band. The instrument will be able to perform rapid and complete spectral line surveys with resolving powers from 10^3 up to 10^7 (300 – 0.03 km/s) and deep line observations.

Keywords: space instrumentation, heterodyne receiver, far-infrared spectrometer, submm spectrometer,

Part of the SPIE Conference on Advanced Technology MMW, Radio, and Terahertz Telescopes
Kona, Hawaii • March 1998 SPIE Vol. 3357 • 0277-786X/98/$10.00

1. INTRODUCTION

The proposed Heterodyne Instrument for FIRST, *HIFI*, has been optimised to address a number of astronomical key questions requiring high spectral resolving powers and sensitivity[1]. Combining the high spectral resolving power of the radio heterodyne technique with quantum noise limited detection from superconductor physics and with the state-of-the-art in microwave technology, makes it possible to develop an instrument for FIRSTwith: a continuous frequency coverage over the range from 480 to 1250 GHz in five bands, while a sixth band will provide coverage for 1410-1910 GHz and 2400-2700 GHz, and an unrivalled spectral resolution and ultimate sensitivity. This instrument will be able to perform rapid and complete spectral line surveys with resolving powers from 10^3 up to 10^7 (300 – 0.03 km/s) and deep line observations.

This instrument will fully exploit the recent rapid pace of development in sub-mm wavelength mixer technology[2] to give sensitivity close to the theoretical limit. The first five frequency-bands will each contain a pair of mixers using superconductor-insulator-superconductor (SIS) tunnel junctions. Both polarisations of the astronomical signal will be received for maximum sensitivity. Channel 6 will contain two mixers based on the recently-developed fast hot-electron bolometers (HEB) using thin superconducting films with one mixer for each sub-band. The instrument will operate at one frequency at a time; i.e. only one of the frequency bands will be active. For Local Oscillator (LO) sources varactor frequency multipliers (band 1-5) and laser photomixers (band 6) will be used.

HIFI will have an instantaneous bandwidth of 4 GHz analysed in parallel by two types of spectrometers: a pair of wide-band spectrometer (WBS), and a pair of high-resolution spectrometer (HRS). The wide-band spectrometer will use acousto-optic technology with a frequency resolution of 1 MHz and a bandwidth of 4 GHz for each of the two polarisations. The HRS will employ either a digital auto-correlation spectrometer (ACS) or a chirp transform spectrometer (CTS) and will provide two combinations of bandwidth and resolution: 1 GHz bandwidth at 200 kHz resolution, and at least 500 MHz at 100 kHz resolution. The HRS will be divided into 4 or 5 sub-bands, each of which can be placed anywhere within the full 4 GHz IF band.

HIFI will consist of three major sub-systems and an instrument controller (see Figure 1):

1. The focal-plane sub-system comprises the focal-plane unit (FPU) inside the cryostat, containing relay optics, mixers, low-noise IF HEMT pre-amplifiers, a focal-plane chopper, and a calibration source; and the FPU control unit (FCU) which 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.

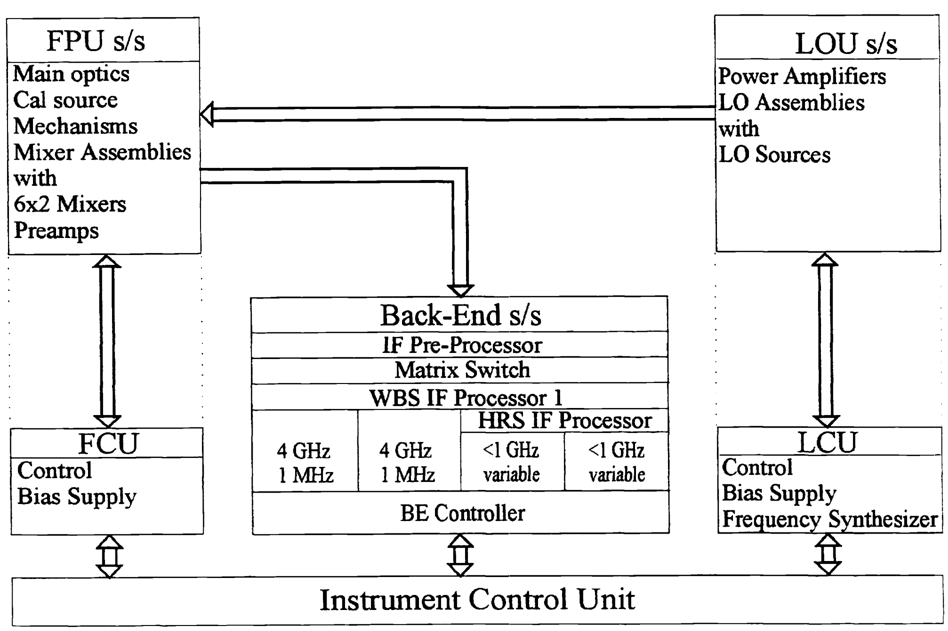


Figure 1. Block diagram of the *HIFI* instrument

2. The local oscillator sub-system comprises: the local oscillator unit (LOU) located on the outside of the cryostat generating the LO signal which is coupled into the FPU via a window in the cryostat wall; and the local oscillator control unit (LCU) in the service module (SVM) which controls the frequency of the local oscillator with a precision of 1 part in 10^8.
3. A back-end sub-system (BES) within the SVM. This contains the IF processor, WBS, HRS, and backend control system (BCS).
4. An instrument control unit (ICU) within the SVM which interprets commands from the satellite telecommand system, controls the operation of the instrument, and returns science and housekeeping data to the satellite telemetry system.

2. FOCAL PLANE SUB-SYSTEM

Extremely flat and stable spectral baselines are a stringent requirement for the *HIFI* instrument in order to be able to study the very weak broad emission and absorption lines of distant galaxies and to perform broadband spectral surveys. Thus, special emphasis is placed on the design of the optics in the HFPU to avoid generation of standing waves. It also includes a chopper mechanism to switch between two positions on the sky, and will allow the standard dual beam switch techniques for standing wave elimination. In addition, it will be necessary to mount the first IF amplifiers very close to the mixers and to carefully control the thermal environment of critical components.

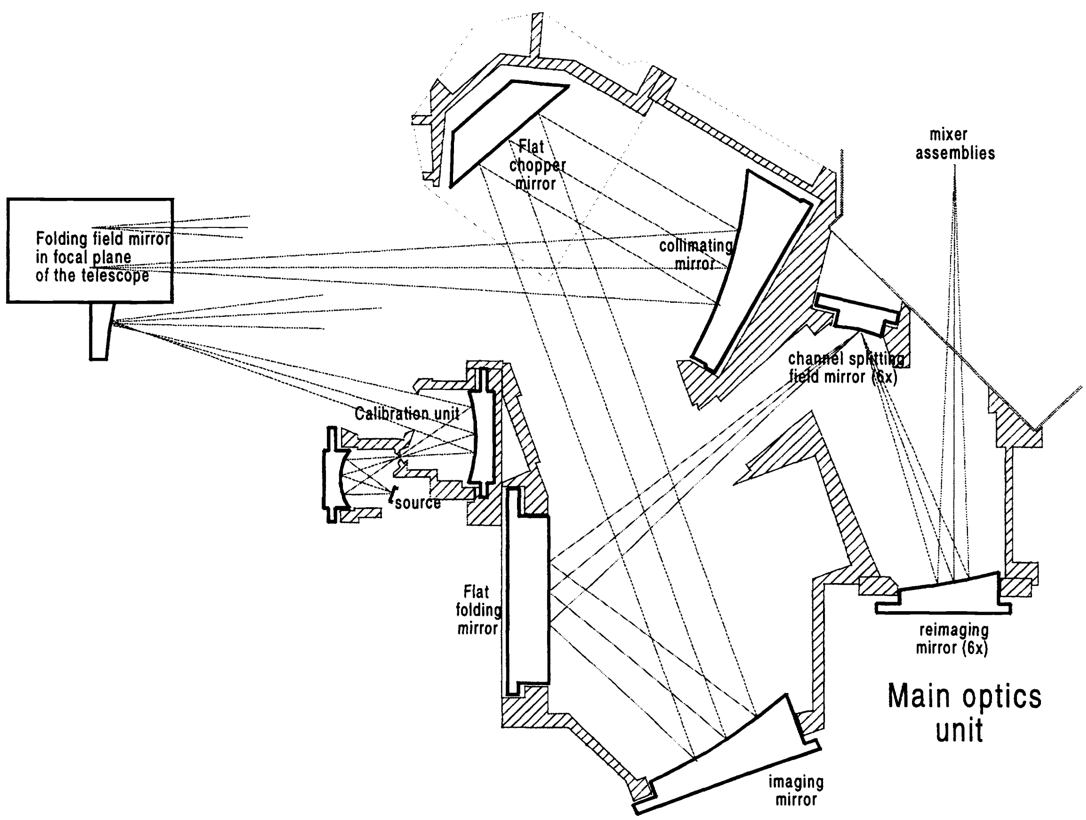


Figure 2 *HIFI* Common Optics Layout

The instrument measures radiation in two polarisations in 5 contiguous bands covering the frequency interval 480 to 1250 GHz and in a single polarisation in two sub-bands around 1.7 THz and 2.5 THz. There are 6 optical beams coming from the telescope, one for each of the 5 dual-polarisation bands and one for the two high-frequency sub-bands. There are 7 beams coming from the LO Unit, one for each band or sub-band. See Figures 2 and 3.

The FPU employs a highly modular design consisting of:

- a common optics assembly (COA) which contains the optical elements which are common to the 6 optical beams and serves as the support structure for the chopper, calibration assembly, and local oscillator optics
- 6 mixer assemblies (MA) containing the optical elements, mixers and IF components specific to each of the 6 instrument bands

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 local oscillator optics.

The telescope focal plane mirror (M3) acts as a folding mirror and also as a field mirror to reduce the optical path length towards the pupil image (= image of the telescope secondary mirror) for packaging reasons. The telescope focal plane is re-imaged in the main optics by means of a Gaussian telescope at unit magnification implemented by a collimating mirror and an imaging mirror, both with a focal length of 280 mm. Between these two mirrors a flat chopper mirror is positioned in the pupil plane.

After the imaging mirror a flat mirror folds the beam towards a stack of 6 field splitting mirrors placed at an image of the focal plane. The centres of these mirrors are located on a line, oriented perpendicular to the plane shown in Figure 2. These 6 mirrors differ in orientation so that the six resulting beams are separated in direction. 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 (6x) are re-imaged into the mixer assemblies, which are mounted onto the Main Optics structure in a stack.

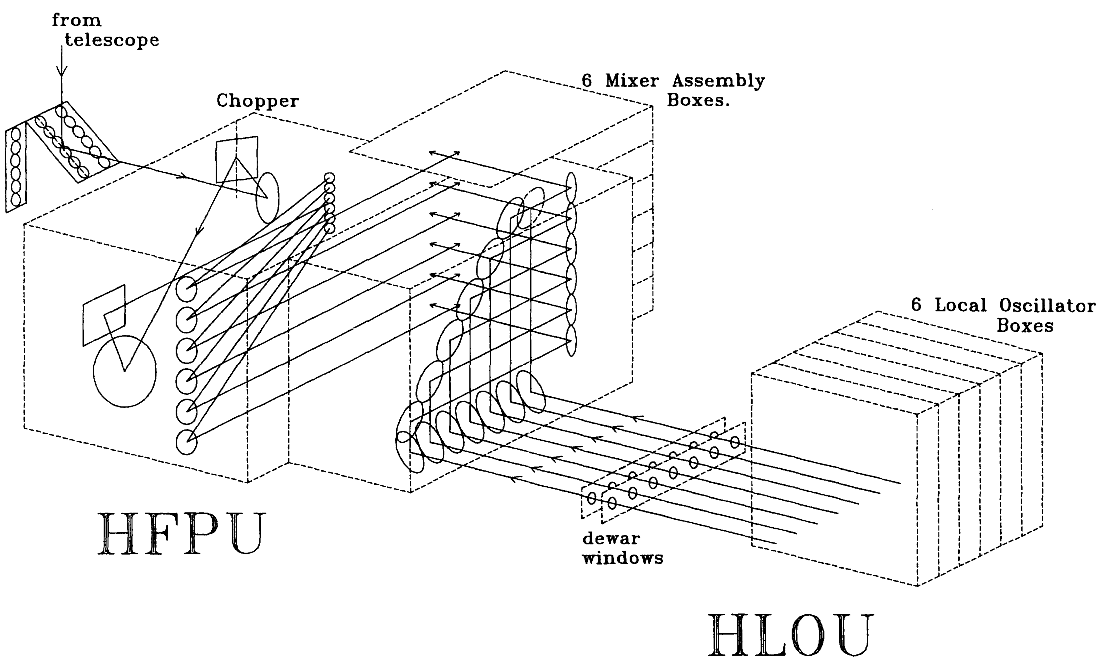


Figure 3. Perspective view showing the LO beams between LO and Mixer Assemblies

The housing of the COA and the mirrors will be machined from a single block of aluminium giving rigidity and dimensional stability. All mirrors will be bolted from the outside onto the housing using 3 fixation points. If necessary shims will be used to adjust the alignment. This construction technique was used very successfully in the SWS flown on ISO.

The Chopper-Mechanism and Calibration Assembly: 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 spectrometer system will measure the difference in emission between the two positions. The focal-plane chopper in *HIFI* will have a beam throw (separation between source and reference position) of 3 arcmin. on the sky and will chop at frequencies up to 1 Hz. The mechanism, which uses flex-pivots, is similar to the scanning mechanism flown in SWS and LWS on board ISO. The mechanism moves a mirror between three positions: two sky positions and a third calibration position. The required rotation for the present optical design is 4.6°.

A calibration assembly is located just above the entrance opening of the Common Optics Assembly. It provides a black body source with adjustable temperature in the range 15–100 K. This unit couples to the instrument via a part of M3 and is selected for calibration measurements by suitably positioning the chopper mirror. The auxiliary optics in the calibration unit minimises the surface area of the source so as to reduce the heat load on the cryostat. The goal is to achieve an instrumental calibration accuracy of 3 %. 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 %.

Local Oscillator Optics: The Local Oscillator Unit (LOU) itself is located outside the dewar at an optical distance of more than 650 mm from the *HIFI* FPU. The LO beams are coupled through vacuum windows in the dewar wall and directed into the respective MA's by a set of folding mirrors. See also Figure 3. We have chosen to use 7 separate sub-windows, each optimised for the transmission of its LO band. The sub-windows will be small to reduce the thermal load on the cryostat due to radiation; each beam will be focussed to a minimum waist at the window location.

Mixer Assemblies: The *HIFI* mixers are located in Mixer Assemblies (MA). There will be 6 MA's, each covering a certain frequency range with two mixers, only one MA will operate at any time. The pair of mixers in individual MA's will operate at orthogonal polarisations. The MA's contain mechanical supports, mixers, diplexers and polarisers as well as IF amplifiers, and are mechanically mounted on the FPU. Thermal straps connect the mixers and 1st stages of the IF amplifiers to the "1.7 K level", and the 2nd stage IF amplifier to the "15 K level". A connection to the "4.3 K level" is used to heat-sink an internal wiring harness. A 0.5 K adsorption cooler will be included in band 6 MA for the aluminium HEB mixers.

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 polarisations to be coupled to the mixers. The combining of the signal and LO beams will be done by a beamsplitter for the two lower 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.

IF Preamplifiers: the IF pre-amplification scheme is shown in Figure 4. Each mixer is followed by a dedicated IF preamplifier – 6 bands times 2 polarisations giving 12 pre-amplifiers in total.

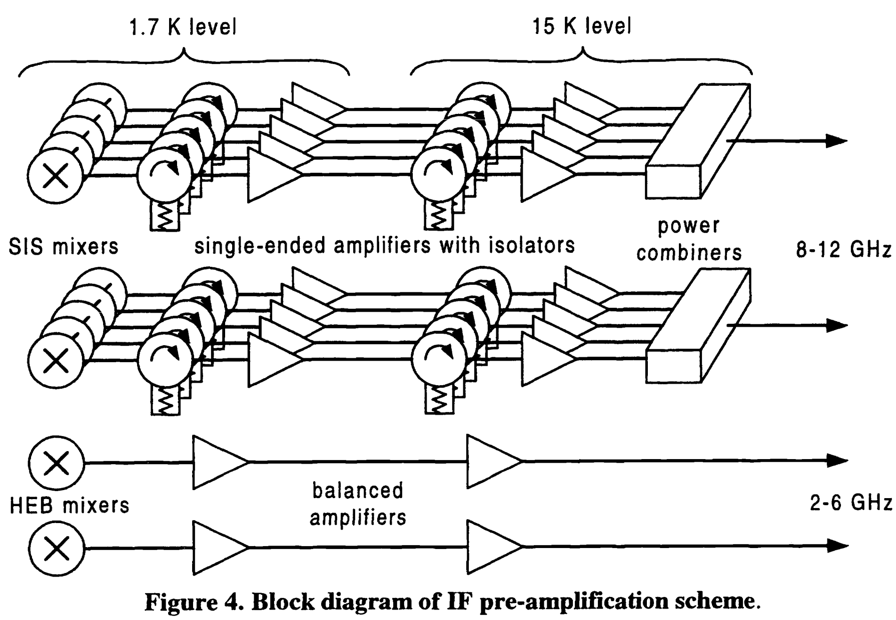


Figure 4. Block diagram of IF pre-amplification scheme.

For the SIS mixers of bands 1 to 5, these operate at an IF of 10 GHz, while band 6 will use HEB mixers and have an IF centre frequency of 4 GHz. Since only one pair of mixers will operate at any time, we propose to use power combiners to feed the signals from bands 1 to 5 into a single pair of coaxial cables – the choice of band is made by activation of the required pair of preamplifiers. The IF signals from band 6 will be fed into a second pair of IF cables. This arrangement reduces the number of coaxial cables between the front-end and the IF processor to four, with a consequent reduction in thermal load. A total IF gain of 38 dB or more is required in the FPU to overcome cable and other losses and to render the noise contribution of the back-end system insignificant. To avoid problems with feedback and instability, a cascade of two amplifiers will achieve the desired amplification. The baseline is to cool the first stages of the IF preamplifiers to 1.7 K and to operate the second stages at 15 K where there is a higher heat-lift capacity. An option to integrate the first preamplifier stage into the mixer to obtain the maximum possible sensitivity will be studied.

Mixers: Existing technologies for fabricating sensitive heterodyne mixers favour the use of waveguide 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 proposed frequency bands, sensitivities and foreseen mixer elements are given in Table 1. Sensitivity values are given for three cases: (i) presently achieved values with state-of-the-art performance (SOAP); (ii) Baseline values to be achieved after the development years from 1998 to 2000; (iii) Goal values, expected to be achievable after further improvements before delivery of the FM in 2004. The use of new detector materials such as NbTiN makes the expected improvement in sensitivity possible. The SIS mixers need an adjustable magnetic field of a few hundred Gauss, which is provided by small superconducting electromagnet coils. These magnets are integrated in or close to the mixers. To remove trapped flux from the junction, an on-chip heater resistor is used to warm up the mixer chip just beyond the superconducting transition temperature of the SIS junction materials momentarily. The HEB mixers of band 6 do not need a magnetic field.

Table 1. *HIFI* DSB receiver noise temperature for 3 cases and probable mixer types: (i) State-Of-the-Art Performance (SOAP), (ii) Baseline values and (iii) Goal values. The last column indicates the baseline mixer type: WG – waveguide, QO – quasi-optical.

Band	Range,	DSB Noise temperature, K			Mixing element technology			Mixer type
	GHz	SOAP	Baseline	Goal	SOAP	Baseline	Goal	
1	480 640	80 130	70 110	70 110	Nb–SIS	Nb–SIS	Nb–SIS	WG
2	640 800	130 500	110 150	110 130	,,	NbTiN–SIS	NbTiN–SIS	WG
3	800 960	500 700	150 190	130 160	,,	,,	,,	WG
4	960 1120	700 1600	190 230	160 190	,,	,,	,,	WG
5	1120 1250	1600 1900	230 510	190 210	,,	,,	,,	WG
6a	1410 1910	2100 2100	650 650	300 300	Nb–HEB	Nb–HEB	Al–HEB	QO
6b	2400 2700	2500 2500	800 800	450 450	,,	,,	,,	QO

3. LOCAL OSCILLATOR SUB-SYSTEM

The local oscillator (LO) part of the *HIFI* instrument consists of the following units:

- The local oscillator unit (LOU), which sits outside the cryostat and supplies the LO signal for the mixers inside the FPU. The LOU will be arranged in 6 local oscillator assemblies (LOA's) with a spacing of 50 mm between the optical axes of adjacent LOA's yielding one optical plane per mixer band which eases alignment and gives a high degree of modularity. The LOA's are fixed to a mechanical support structure. Each LOA feeds both polarisations of the corresponding FPU's mixer band.

- 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.

There are two types of local oscillator assemblies (LOA), the standard version for bands 1–5 using frequency multiplier chains, and a photomixer version for band 6.

LO Band 1-5 Multipliers: LOA's for band 1-5 consist of a small optics part with a focusing mirror and a wire grid beam combiner and two almost identical LO sources oriented with orthogonal polarisations. Together these two sources provide full frequency coverage of the particular mixer band. The chosen arrangement of two LO sources (one operational) pumping two mixers on orthogonal polarisations can be implemented using polarising beamsplitters. We exploit the high IF frequency and DSB mixer operation to reduce the tuning range requirement for the LO. We have assumed a band overlap of 2 GHz between adjacent mixer bands. Note that only one LO source is operational at any given time and that this LO pumps two mixers operating on orthogonal polarisations.

Table 2. Proposed mixer, local oscillator and amplifier frequency bands
(* the baseline for band 6 is to use photomixer LO sources; with multipliers as back-ups)

Mixer		LO		Multiplier	LO amplifier
Band	operating range, GHz	band	tuning range, GHz	Stages	Frequency band, GHz
1	480–642	1a 1b	492–550 572–630	x2x2x2 x2x2x2	61.5–68.8 71.5–78.8
2	640–802	2a 2b	652–710 732–790	x2x2x2 x2x2x2	81.5–88.8 91.5–98.8
3	800–962	3a 3b	812–870 892–950	x2x2x3 x2x2x3	67.7–72.5 74.3–79.2
4	960–1122	4a 4b	972–1030 1052–1110	x2x2x3 x2x2x3	81.0–85.8 87.7–92.5
5	1120–1250	5a 5b	1132–1174 1196–1238	x2x2x3 x2x2x3	94.3–97.8 99.7–103.2
6	1410–1910 2400–2700	6a 6b	1414–1906 2404–2696	x2x2x2x3* x2x2x2x3*	58.9–79.4 100.2–112.3

The mixer and LO frequency bands are given in table 2. We expect that the tuning range of the final LO sources will be larger than given in the table, in which case the overlaps between the coverage of upper and lower LO sources provide redundancy. The listed tuning ranges can be achieved when a broadband, high-power mm-wave source is used to drive the varactor frequency multiplier chain. High-power mm-wave amplifiers[3], manufactured by TRW, have been successfully applied in LO sources at 500 GHz. The demonstrated output powers of over 300 mW in the 75-100 GHz frequency range exceed by far what is available with Gunn devices.

Taking into account coupling losses, the required LO power for 1250 GHz is estimated to be 5 μW, which seems feasible with varactor frequency multipliers. Output powers of 20 μW up to 1.5 THz have been measured. Generally, at lower frequencies, planar and whisker-contacted multipliers show similar performance. However, considering the reproducibility needed for a satellite project, the high power-handling capability and the wide bandwidth needed for the *HIFI* LO's, planar Schottky diodes will be used for at least the first stage of the varactor multiplier chains. As backup, for the high-frequency multiplier stages, whisker-contacted multipliers will be used. Although the whisker contact is difficult to manufacture, it presents a 'free' parameter for matching the diode to the embedding circuitry, which is important at high frequencies.

LO Band 6 Laser Photomixer: in the Laser Photomixer Local Oscillator two near-IR laser beams are combined in a photomixer to generate a difference frequency in the THz region[4]. The current system concept is composed of four different components; the laser sources, the optical processing hardware, the control electronics, and the photomixer assembly (see Figure 5).

Two laser sources are currently under evaluation: a Distributed Bragg Reflector (DBR) laser diode with external optical feedback, and an external cavity diode laser. In both cases the laser source includes a laser with its respective optical feedback mechanism and the necessary isolation and optics to couple the radiation into Polarisation Maintaining (PM) single mode fibre.

The optical processing unit is assembled from fibre-optic components, and includes two Electro Optic Modulators (EOM), a number of directional couplers, a wavemeter, a Cs reference cell, a number of photo detectors, an Ultra Low Expansion (ULE) high finesse cavity and an optical amplifier (MOPA). A MOPA amplifier has demonstrated the ability to amplify two laser signals separated by more than 10 GHz.

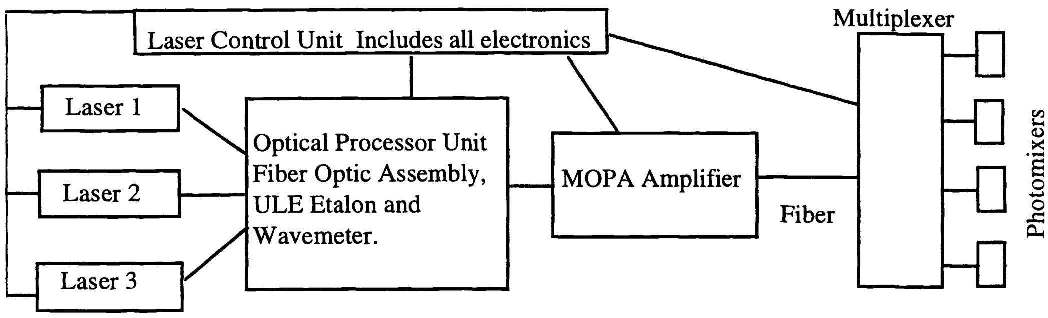


Figure 5. Laser photomixer LO source block diagram

The control electronics supply the current and feedback to the lasers, and provide the necessary signal processing to control the laser source frequencies. A microprocessor controls the operation of the laser frequency locking system. To date, a line width (FWHM) of 500 kHz has been demonstrated along with all-day lock times using 852 nm DBR lasers. The ability to generate any offset frequency to 100 kHz within the 1.5 THz tuning range of the lasers has been demonstrated. Optical feedback experiments at Caltech have demonstrated that a 100 kHz line width is possible.

The current baseline is to use a system with three external-cavity lasers. The reference laser and the offset laser would be fixed tuned gratings (tuning bandwidth ~60 GHz), while the second cavity locked laser would be a tuned grating device (tuning bandwidth ~10 THz). The two fixed tuned devices would lie near the 371 THz Cs line and would use that to determine the cavity order for the reference laser and tune the microwave frequency offset around the cavity order picked. The cavity order of the second laser would be determined by a wavemeter with a resolution better than a free spectral range. The free spectral range of the etalon will be measured to better than the required part in 10^8 accuracy. Several suitable calibration methods are known and the actual calibration procedures will be developed and evaluated this year.

The photomixer assembly will include a fibre multiplexer feeding a set of fibre-coupled photomixers. Each photomixer will be integrated with a planar antenna on high resistivity Si lens to couple out the sub-mm radiation efficiently. Photomixers have been demonstrated[4] to provide sufficient output power to drive the HEB mixers at the frequencies needed for band 6. Further photomixer development is currently focused on improving device performance and reliability by research in the areas of faster materials, increased output power and efficiency, and increased input power handling. The current plan is to use local heaters to warm the photomixers to above 250 K so that 852 nm lasers can be used.

All of the laser system except the photomixers will reside in the SVM. Transmission of the signal to the photomixer will take place in PM fibre, which has a loss of less than 3 dB/km.

4. BACK-END SUB-SYSTEM

General Description: the *HIFI* back-end sub-system (BES) consists of an IF processor, a pair of wide-bandwidth spectrometers (WBS), a pair of tuneable high-resolution spectrometers (HRS), and a pair of data processing and control units, the Backend Control System (BCS). The system performs spectral analysis of the IF signals coming from the active mixers in the FPU and sends the resulting spectra, along with house-keeping data, to the instrument control unit (ICU) for forwarding to the s/c data handling system. Commands from the ICU are given to the BCS to control the Back-End configuration, set IF levels, integration times etc.

The characteristics of the proposed *HIFI* spectrometers are listed in Table 3. The WBS will use acousto-optic spectrometer (AOS) technology similar to the spectrometers, to be flown on NASA's SWAS and Sweden's ODIN satellite. The HRS will provide two resolution/bandwidth combinations and will either be based on Digital Auto-Correlation Spectrometers (ACS), or Chirp Transform Spectrometers (CTS). It will be possible to configure each HRS into 4 or 5 independent sub-bands allowing high-resolution observations of up to 4 or 5 astronomical spectral line features within the 4 GHz IF bandwidth. The *HIFI* Back-End is designed with a high degree of redundancy and so that in the worst cases failure results in limited loss of capability.

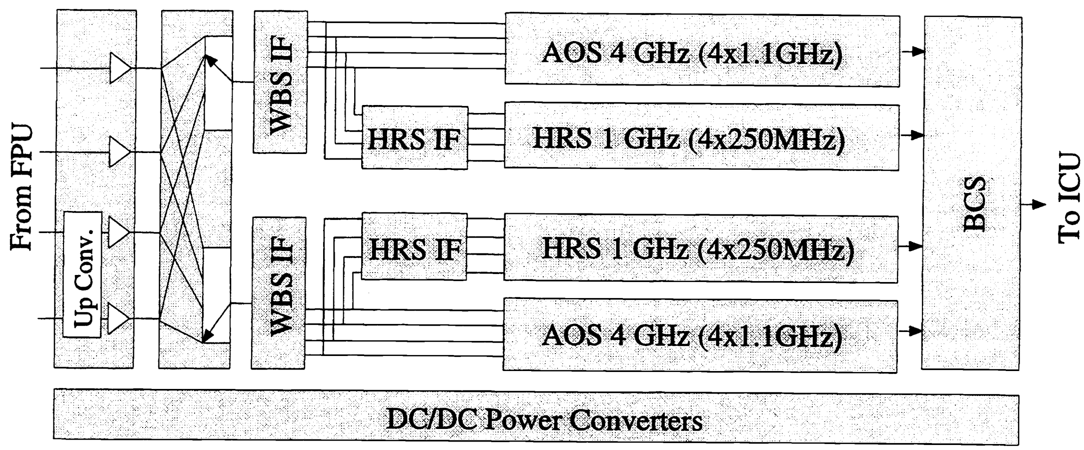


Figure 6. *HIFI* Back-end sub-system block diagram showing the IF processors, spectrometers and control

Wide Band Spectrometers: the WBS consists of two separate AOS units. Each unit has the capability to analyse a 4 GHz band with a spectral resolution of about 1 MHz. The 4 GHz 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 analysed by either a single four-channel array AOS or four independent AOS's, each with a bandwidth of 1.1 GHz. A frequency accuracy of about 0.1 MHz will be obtained by periodically measuring internally generated comb spectra. A 100 MHz overlap ensures that it will be possible to correct for potential baseline offsets between the sub-bands caused by limited stability or very long integration times between reference measurements. The expected performance of the WBS subsystem is shown in Table 3.

Table 3. WBS performance based on 4-band array-AOS

parameter	value	Notes
Total bandwidth (-3 dB)	4 GHz	4 times 1.1 GHz, including overlap
Pixel frequency spacing	0.5 MHz	
Noise fluctuation bandwidth	1.5 MHz	
Spectroscopic Allan variance minimum time	> 800 s	Temperature variation < 1°C/hour
Frequency linearity	< 0.2 MHz	deviation after compensation
Gain compression	< 1%	
Cross-Talk between bands	< - 30 dB	
Noise dynamic range	10 dB	

The baseline array AOS uses one Bragg cell with four independent acoustic beams illuminated by a single laser diode, one common opto-mechanical set up and a four-line linear CCD. The advantages are improved thermal tracking of the performance of the 4 sub-bands since a common laser and Bragg cell are used, and a compact, lightweight unit due to the use of a single optical path. The array-AOS approach needs a small number of components that increases the reliability of the spectrometer. An array-AOS has already been built at the University of Cologne for ground based application. The overall stability of the AOS depends strongly on the temperature stability of the system. This must be better than 1°C/hour to achieve a spectroscopic Allan variance minimum near 1000 s. The AOS has to operate at a temperature lower than 15°C to ensure a MTBF above 3 years for the near-infrared laser diodes (0.8 μm).

Auto Correlation Spectrometers: In the ACS, the main processing and detection is done in the time domain after digitisation. In such a device, the signal processing uses high-speed digital electronics, presenting the advantages of stability and system integration. The *HIFI* ACS will use a combined frequency and time multiplexed design, allowing reduced power consumption. Two sets of four auto-correlators will be used, one per IF channel. Each ACS analyses a 250 MHz bandwidth, giving a total bandwidth of 1 GHz. 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 GHz clock-rate each feeding a correlator block. The overhead to accommodate time multiplexing is small because of the large number of channels in each bank (2048 or higher).

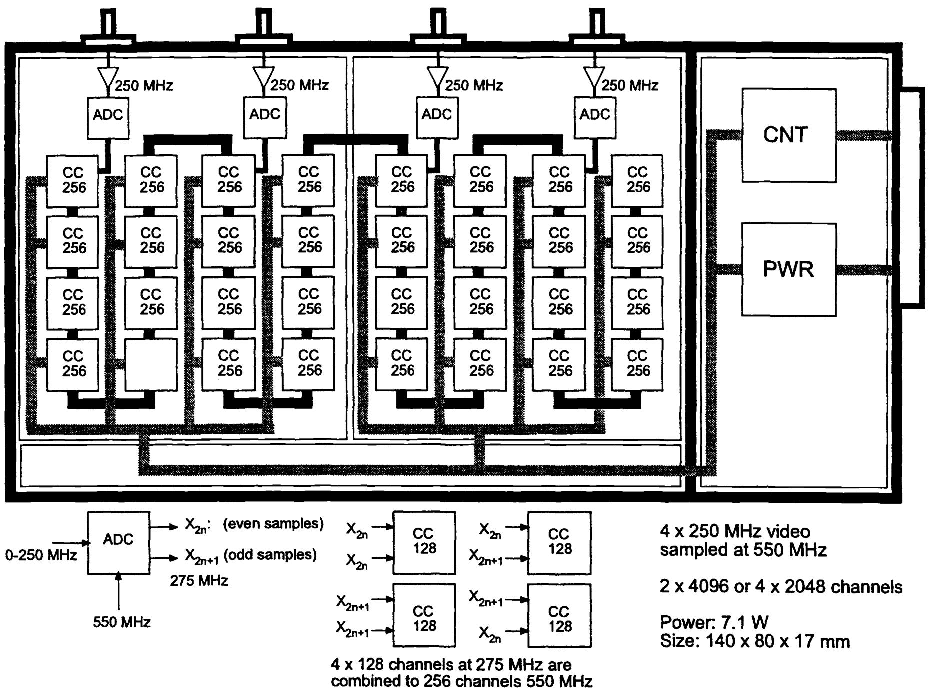
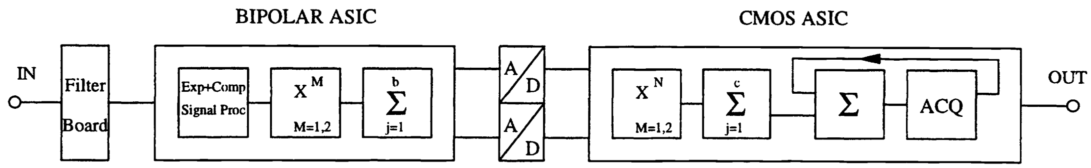


Figure 7. Block diagram of the ACS

The resolution can be set by the BCS, configuring the ACS to analyse each band with a cascade of one to eight correlators. The resolution requested in the normal mode (200 kHz) is obtained by cascading eight correlator chips of 256 channels for each ACS, for a total of 16,384 channels. The very high-resolution mode (100 kHz) is obtained by configuring the HRS in 2 sets of 2 ACS, each set using 8192 channels in two bands of 250 MHz. After each integration, the data are transferred to the readout register of the correlator chip. The integration time is adjustable from 20 ms to 500 ms. The Fourier transform of the measured auto-correlation function will be derived on the ground.

Chirp Transform Spectrometers: the functional principle of the CTS is based on the Chirp Transform Algorithm, which is equivalent to the Fourier Transform. In the basic implementation of the CTS, a chirp signal, generated by impulsing a dispersive Surface Acoustic Wave (SAW)-filter (expander), is mixed with the IF signal, provided by the heterodyne receiver and convolved with a matched SAW filter (compressor)(see). The SAW filters determine bandwidth and spectral resolution of the CTS. So-called Single Bounce Reflective Array Compressors (SBRAC) with 200 MHz bandwidth and 20 microseconds dispersion time, which have been developed for the ROSETTA-MIRO spectrometer, will be used for *HIFI*.



Case 1: M=1; b=1; N=2; c=1,2,3,...,20 Case 2: M=2; b=1,2,3,...,20; N=1; c=1

Figure 8. Block diagram of the CTS (ASIC version

Back-end Control and Data Flow: the *HIFI* data flow is large but still compatible with the FIRST on-board data storage and down-link capacity, as is discussed below. The number of channels operating at the same time is about 36,000: 16,000 for the WBS and 20,000 for the HRS; and we will use a 32-bit DSP for data processing. The maximum data volume per integration is 144 Kbytes. This can be easily reduced by a factor of 2 without losing information. To fit the telemetry data rate of 40 kbits/sec, the on-board integration time has to be adapted. A standard 10 or 20 second integration time seems feasible. The on-the-fly mapping mode requires smaller integration times, but here only sub-spectra will be needed thus reducing considerably the number of channels to be processed.

5. REQUIRED SPACECRAFT RESOURCES

Table 4: Summary Required Spacecraft Resources

	FP Sub-System	LO Sub-System	BE Sub-System	Instr. Control Unit
Volume (litres)	48	25	19/31	7
Mass (kg)	29	13	27/32	5
Power 2K	4/6.5 mW	-	-	-
4K	1.1/0 mW	-	-	-
15K	24 mW	-	-	-
100K	-	6 W	-	-
SVM	13 W	20 W	97/93 W	15 W
Cryo-Harness: 404 leads		Command Rate: 2kb/s, 2hrs/day		
Cryo-Coax cables: 4		Telemetry Rate: 40 kb/s continuous		
HLOU Harness: 226 leads		Pointing: 1.9" APE required at highest frequencies		
Window in cryostat wall for LO injection		Cooling for AOS unit below 15°C		

6. OBSERVING TECHNIQUES AND TEMPLATES

Observing Techniques: 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 HFPU switches the beam between two positions 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.

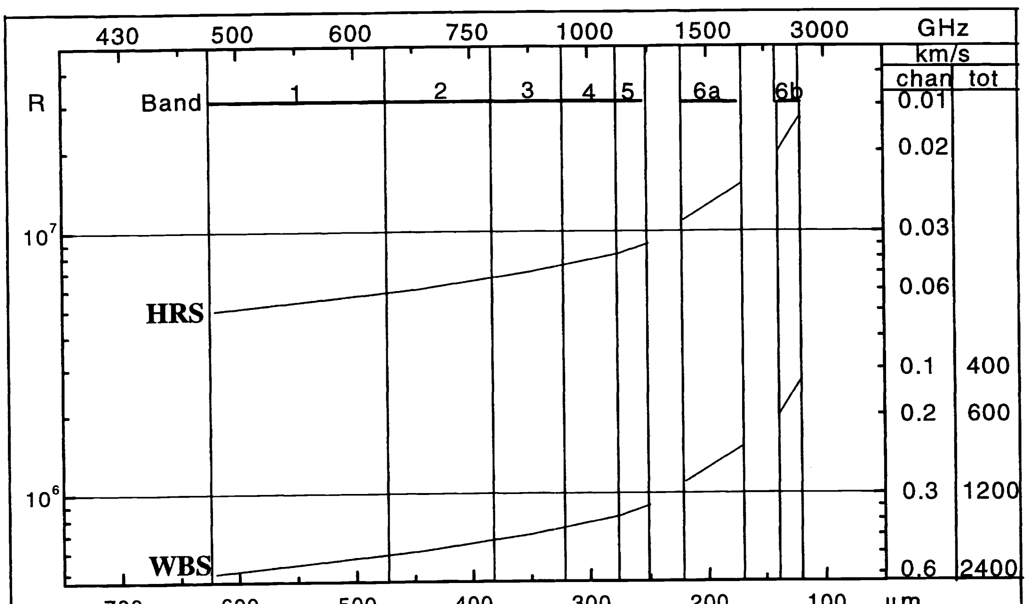
For observing with *HIFI* two astronomical observing templates (AOT) will be used:
AOT 1: pointed observations taking a spectrum over a frequency range equal to or larger than the standard 4 GHz band

AOT 2: mapping observations at a single frequency 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).

7. EXPECTED PERFORMANCE

Figure 9 shows the resolution capabilities of the HIFI together with the expected sensitivities.



Band	1	2	3	4	5	6a	6b	Units
Beamwidth (HPBW)	39	30	25	21	19	13	9	arcsec
Receiver Noise (DSB, goal)	84	120	160	190	210	300	460	K
Flux Limit (5σ, 1 hr, R=10^4)	1.5	2.0	2.3	2.5	2.7	4.6	5.6	Jy
Flux Limit (5σ, 1 hr, 10^4)	3.4	4.4	5.1	5.6	6.0	10	12	mK
Line Flux Limit (5σ,1 hr,10^4)	0.9	1.4	2.0	2.6	3.2	7	14	10^{-18} W/m²
Linescan (1σ,24 hrs δf=1MHz)	16					34	41	mK

Figure 9: The instrument capabilities of HIFI. The vertical axis at the right gives velocity resolution for channels (chan) of the WBS and HRS spectrometer. The total (tot) instantaneous velocity coverage of HIFI is given as well.

8. REFERENCES

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3. P-P. Huang, T-W. Huang, H. Wang, et al., "A 94-GHz 0.35-W Power Amplifier Module", IEEE TMTT, **45**, 2418-2423, 1997.
4. S. Verghese, K.A. McIntosh, and E.R. Brown, "Optical and terahertz power limits in the low-temperature-grown GaAs photomixers", Appl. Phys. Lett, **71**, pp 2743-2745, 1997.