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FIRST – Far Infra-Red and Submillimetre Space Telescope

Payload Definition Document (PDD)

"common model payload"

prepared for the FIRST Science Advisory Group (SAG) by the

FIRST Payload Working Group (PWG)

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Contents

1 FIRST – Far Infra-Red and Submillimetre Space Telescope

1.1 Introduction and purpose of this document

The Far Infra-Red and Submillimetre Space Telescope (*FIRST*) is the fourth "cornerstone" (CS4) mission in the European Space Agency (ESA) long term space science plan "Horizon 2000". The mission selected for implementation in November 1993 was based on a spacecraft with mechanical cryo-coolers for payload cooling. Later it has been investigated whether Infrared Space Observatory (*ISO*) cryostat technology could be used to advantage for payload cooling. Presently, industrial system definition studies will be performed in parallel for both spacecraft options, commencing in November 1995 and scheduled to be completed by the end of the summer of 1996.

The purpose of the present document, the Payload Definition Document (PDD), "common model payload", is to give a definition of the model payload to be used by the industrial consortia in the course of these studies.

1.2 The FIRST concept and mission

FIRST is intended to open up the last major part of of the electromagnetic spectrum, the submillimetre and far-infrared (approximately 1 mm (= 300 GHz) – 100 μm (= 3 THz)) range, which is still mainly inaccessible for observational astronomers. It is intended to be a multi-purpose mission offering unique capabilitites to a large part of the astronomical community.

1.3 The initial System Definition Study

In the period 1990 – 91 a System Definition Study (SDS) was carried out, which resulted in a spacecraft concept with two modules with relatively simple interfaces. The service module (SVM) contained the supporting structure and spacecraft thermal control, solar array, electrical subsystems, attitude and reaction subsystems as well as some payload electronics. The payload module (PLM) was made up of a passively cooled non-deployable 4.5 m Cassegrain submillimetre telescope, with the attitude measurement sensors attached, inside its (inflatable space rigidized) thermal shield. The whole telescope assembly was attached to the superfluid helium cryostat, the focal plane instrument assembly being located inside its vacuum vessel.

The *FIRST* spacecraft must carry a complement of instruments for high and medium resolution spectroscopy, imaging and photometry over the submillimetre and far-infrared range. The model payload used in the course of the SDS comprised a total of four incoherent and heterodyne detection instruments. The Far Infrared Spectrometer (FIS) and the Far Infrared Photometer (FIP) both were direct detection instruments, employing a combination of photoconductors and bolometers. The Sub-THz Receiver (STR) and the THz Receiver (THR) were single-channel heterodyne receivers employing SIS mixers and solid state local oscillators. These instruments are described in the SDS PDD.

A dual Ariane 5 launch into geostationary transfer orbit was foreseen. The intended operational orbit was a highly elliptical (1000 × 70600 km), low inclination (10°), 24 hour orbit, potentially offering a maximum of approximately 17 hours of science operations per orbit. The launch mass was 3400 kg and the lifetime, determined by the boiloff rate of the helium in the cryostat, was expected to exceed 3 years.

1.4 The "Rider Study"

Since the total cost to completion of a mission employing the SDS generated spacecraft was found to be outside the allowable ESA financial envelope, a rescoped spacecraft employing mechanical cryo-coolers for payload cooling, a 3 m diameter telescope with a rigid thermal shield, a payload complement with a reduced number of scientific instruments, and less stringent pointing requirements were studied in 1992 – 93, with a view to offer a less costly alternative. The outcome is described in detail in the *FIRST* "Red Report", ESA SCI(93)6. This report also describes the scientific objectives and the model payload. This was the mission used for selecting *FIRST* for implementation as CS4 in November 1993.

In summary, the resulting mission employs a spacecraft with a passively cooled telescope with a monolithic 3 m diameter main reflector and a fixed sunshield, and payload instruments cooled by mechanical cryo-coolers offering a 4 K environment. The model payload contained two instruments: a Multi-Frequency Heterodyne receiver (MFH) for very high resolution spectroscopy in selected bands in the range 250 – 600 μm, and a Far Infra-Red instrument (FIR) for spectroscopy in the range 85 – 300 μm, and photometry in the range 85 – 900 μm. The FIR detectors operated at temperatures of 1.6 K (photoconductors) and 0.15 K (bolometers), respectively, demanding additional cooling which was to be provided by an internal ^{3}He/^{4}He dilution cooler.

This spacecraft would still be injected by a dual Ariane 5 launch into an *ISO* type 24-hour HEO orbit. With a nominal mission duration of 2 years, consumables would be sized for 6 years, taking advantage of the extended operational lifetime offered by the mechanical coolers.

1.5 The "Cryostat Backup Study"

In view of the fact that a cryostat spacecraft had been considered at an earlier stage, and that the *ISO* development had been successful with the flight model in final testing phase, it was felt prudent at this stage to restudy this option, maximising the use of *ISO* knowhow and technology in doing so.

The study was limited to the payload module. The model payload used consisted of three instruments and is decribed in the "Backup Cryostat Study" PDD. It was performed in 1994 – 95 and the result made it plausible that that a cryostat *FIRST* could possibly be a viable option from scientific, technical and financial points of view.

2 The present System Definition Studies

Since there are now two spacecraft options, a cryo-cooler and a cryostat based one, which have been studied to different degrees of detail at different times, it has been decided to perform system definition studies of both options beginning in November 1995 and scheduled to be completed by the end of the summer of 1996.

Both spacecraft options are considered in the mission frame of the originally selected CS4 mission in terms of launcher, orbit, etc. However the cryo-cooler option will take into account recent cryo-cooler developments, and improved design. The cryostat option will be based on the previously performed payload module study using *ISO* technology.

Both spacecraft designs will accomodate the same 3 m diameter Cassegrain telescope with fixed sunshade and the same model payload, referred to as the "common" model payload, which is described in this document.

3 Overview of the "common" model payload

3.1 Introduction

It must be emphasized that the payload described in this document is a model payload. The purpose of the model payload is to give the industrial contractors a concrete example of what an actual science payload could look like, in order that the feasibility of its accomodation can be reliably assessed, and critical areas where the requirements of the payload is driving the spacecraft design can be identified.

The actual payload, i.e. the payload which will be carried on the *FIRST* spacecraft, will only be selected by ESA after the community response to an "Announcement of Opportunity" (AO) has been thouroughly assessed and competetively evaluated in terms of scientific capabilities, technical feasibility and associated development risk, and compatibility with the selected spacecraft design and mission requirements.

The selected payload instruments will then have to be developed, constructed, tested, and funded by the successful institutes/consortia prior to delivery to ESA, and subsequent integration with the spacecraft. Thus, the actual flight science payload can, in principle, differ from the model payload used in the present study, however, in several important respects it cannot drive the spacecraft design more than what the model payload does.

3.2 Generalities, constraints, and baseline payload

The *FIRST* mission is designed to offer observational opportunities in one of the last major poorly explored parts of the electromagnetic spectrum, the submillimetre and the far infrared. This part of the spectrum lies between the radio and infrared domains. The radio astronomical detection techniques steadily progress towards higher and higher frequencies whereas the infrared detectors push towards longer and longer wavelenghts; these two techniques meet in the spectral domain of *FIRST*.

For high frequency millimetre/submillimetre spectral line radio observations normally coherent (heterodyne) detection techniques are used. The astronomical signal and a stable local oscillator signal are both fed to a mixer element where their difference frequency signal is generated, selected and then amplified, further conditioned, and finally analysed in a spectrometer.

For spectral line observations in the far infrared normally photoconductor detectors are used, the frequency selecting device then is placed before the detector in the optical chain. For photometric (continuum) observations bolometer type detectors are generally used throughout the submillimetre while both bolometers and photoconductors are used in the far infrared.

The optimal choice of instrument for a given observation is a complicated function on observing frequency, spectral resolution, spatial coverage and sensitivity needed, instrument performance and limiting background. Both types of instruments, the coherent (heterodyne) and the incoherent (direct detection) need cooling, however, their thermal, and other, interface requirements to the spacecraft are different. Since *FIRST* is intended to be a multi-purpose mission capable of addressing a wide range of different observations, a number of instruments of various designs are desirable. The *FIRST* Payload Working Group (PWG) has chosen the following baseline:

- One heterodyne instrument, to be referred to as the "HET". It performs high and very high resolution spectroscopy in the 490 – 1130 GHz band using a multichannel SIS mixer receiver with solid state local oscillators and ("hybrid") digital autocorrelator and acousto-optical spectrometers.

- One incoherent photoconductor instrument, to be referred to as the "PHOC". It performs spectroscopy and photometry in the 85 – 200 μm region using a 16×16 stressed "bulk" Ge:Ga photoconductive detector array and Fabry-Pérot interferometers.
- One incoherent bolometer instrument, to be referred to as the "BOL". It performs photometry in the 200 – 900 μm region and, in addition, spectroscopy in the 200 – 400 μm region using two bolometer detector arrays and Fabry-Pérot interferometers.

3.3 Accomodation of the science payload

The three instruments must share the focal plane, none will be positioned on the optical axis. Note that the telescope has a fixed subreflector. They are allocated a section of the focal plane each, in such a way that the sun direction is perpendicular to the dividing lines in the focal plane, cf. Figures 1 and 2 below.

The payload instruments will be mounted on a cooled mounting bench inside the payload module. The temperature of this interface will be in the range 15 – 23 K, depending on spacecraft configuration.

Although the "normal" position for the payload instruments during ground operations would be horizontal with respect to gravity, there is a requirement on the payload that it can operate being tilted 90°. Some degradation in performance could be acceptable, however, tilting of the payload module must not in any way endanger the integrity or safety of either the instruments themselves or the spacecraft.

Comment: When this payload was initially designed the assumption was that FIRST would have a f/10 telescope. This has subsequently been revised to f/9, and recently finally to f/9.59. These changes will imply some changes to the internal instrument optics which (at this point) have not been worked through into the instrument designs. However, this is unimportant as far as the system study contractors are concerned.

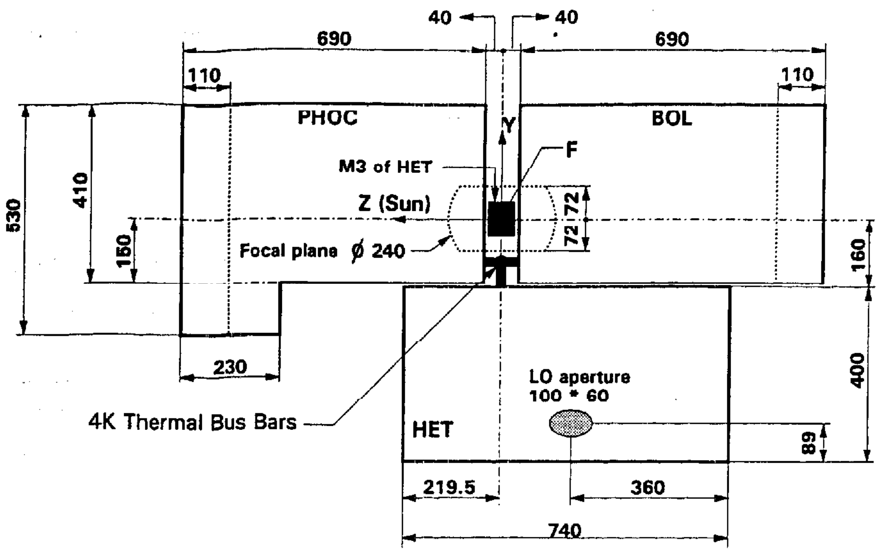

Figure 1: The *FIRST* focal plane, top view towards (−x)
The division of the focal plane between the three instruments as seen from above. The 4 K bus bars can be seen protruding to a common point just above the base plate. The sun direction is perpendicular to the lines splitting the focal plane between the instruments. Units are in mm.

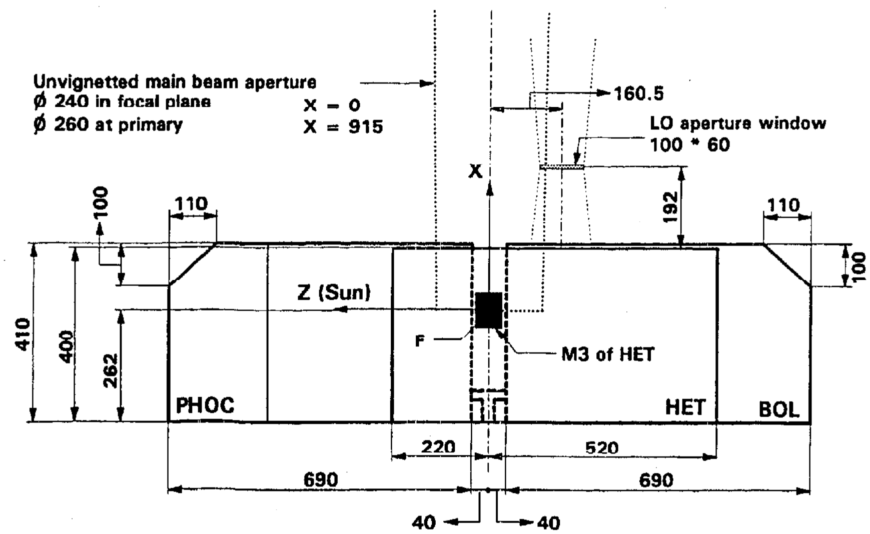

Figure 2: The *FIRST* focal plane, side view towards (+y)
The division of the focal plane between the three instruments as seen from one side. The instruments are mounted on a cooled mounting plate.

4 The heterodyne (HET) instrument

4.1 Introduction

The underlying idea behind coherent detection is to frequency translate the passband of the astronomical signal under observation to a much lower frequency. This is done by mixing the astronomical signal with a locally generated very stable monochromatic signal, the local oscillator (LO) signal, and extracting the difference frequency, the intermediate frequency (IF), for further processing. Such a system is known as a heterodyne (superheterodyne) receiver.

Heterodyne detection offers two important advantages. It enables observations of astronomical signals at frequencies so high that no amplifiers are available at the signal frequency. In addition, it provides isolation between the signal input and the very high gain amplifier system needed to further condition the signal. The price that has to be paid is that the mixing process itself (generally) involves a conversion loss of signal, and that a suitable LO signal has to be generated.

The mixer element must be as non-linear as possible, currently in ground-based submillimetre observatories Schottky diodes and superconductor-insulator-superconductor (SIS) junctions are being used. The SIS is preferable because of its higher sensitivity, much lower LO power requirements, and possibly lower conversion loss; in the model payload described here only SIS mixers are used. A good coupling must be achieved between the sources of the astronomical and LO signals, normally by quasioptical means, and the mixing element which can be mounted either in a waveguide structure or in an "open" mount.

The IF signal is very weak and must be amplified close to the mixer before it can be passed on to other equipment. After further amplification and signal conditioning, the signal is analysed in a spectrometer which measures the signal strength in typically about 1000 frequency channels. The choice of IF frequency is dependant on the required IF bandwidth with sensitivity decreasing with increasing IF frequency. Typically the achievable bandwidth for low noise transistor amplifiers is $20 - 40\,\%$. In *FIRST* the required bandwidth is 2 GHz with a goal of 4 GHz which dictates an IF frequency of about 10 GHz.

The SIS mixing element must be physically cooled down to about 4 K or lower. This means that in the case of a cryostat spacecraft, the mixer array should be strapped to the superfluid helium cryogen tank. For best sensitivity the first IF amplifier must also be cooled to under 23 K. However, the quasi-optics and subsequent electronics (IF chain), as well as the spectrometer, can be operated at ambient temperature ("warm"). Internal calibration loads are necessary.

4.2 Science requirements

Very high spectral (velocity) resolution necessitates the use of heterodyne techniques. A velocity resolution of a fraction of a $\mathrm{km\,s^{-1}}$ is required, which corresponds to R ($= \nu/\delta\nu = \lambda/\delta\lambda$) $\sim 10^6$. Spectral coverage, preferably continuous, from the atomic carbon C^0 (CI) line at 492 GHz to at least the para-H_2O $1_{11} \rightarrow 1_{00}$ ground-state line at 1113 GHz, nominally to 1200 GHz. Sensitivity must be state-of-the-art, the sensitivity of HET observations will be limited by the instrument itself, not by the telescope background.

4.3 Heterodyne instrument description

4.3.1 Overall capabilities

The HET instrument was designed with versatility in mind, since the model payload is just an example of a possible instrument. It is a multichannel receiver which, depending on how the various channels are allocated in frequency, could be configured as either a multifrequency receiver covering a wide frequency band, or alternatively, some channels could be allocated to the same frequency for redundancy and/or multibeam operations over a somewhat more limited total spectral range.

The instrument consists of a quasi-optical beam guide system coupling the astronomical signal from the telescope to the mixer array after combining it with the LO signal. The quasi-optical system also performs the functions of filtering out the image frequency response of the mixers, cancelling radiometer drifts by chopping, and contains a system for calibrating the radiometer temperature scale.

Since the bandwidth of currently available mixers in the submillimetre range is limited to 5 – 10 %, we have chosen to use an array of 9 mixers to give full spectral coverage between roughly 500 GHz and 1.1 THz. If broader bandwidth mixers become available in the future, then it is possible to provide a limited imaging capability by including several mixers at the same frequency within the array. Also if the packing density can be increased, then more mixers could be included in the available space on the focal plane. The mixer array has 9 SIS mixers in a 3×3 rectangular configuration chosen to reduce the size of the foot-print of the HET in the focal plane of the telescope. This array is cooled to 2 K by a strap to the helium tank in the case of a cryostat spacecraft, or by connection to the 4 K cooling bus of the mechanical cooler spacecraft. (It would be to advantage if the cryo-cooler spacecraft design incorporated a dedicated 2 K cooler similar to the one in the PHOC).

The low noise IF pre-amplifiers are mechanically mounted on the nominally 20 K plate close to the mixer array and are operated at 15 – 23 K depending on cooling scheme. The quasi-optics including the image termination and the calibration unit also are mounted on the 20 K plate. The second stage of the IF system is mounted on the radiation cooled CVV of the cryostat or one of the shields of the mechanically cooled payload and is operated at 80 – 313 K. The unit containing the LO sources is located on the outside of the payload module, and operated at its equilibrium temperature. The rest of the IF chain and the backend spectrometers are housed in ambient temperature ("warm") compartments of the spacecraft payload and service modules.

The backend spectrometers are of two types. The combination of both digital auto-correlation spectrometers (DACS) and acousto-optic spectrometers (AOS) allows a spectral resolution to be selected between 250 kHz and 2.5 MHz, and offer up to 2000 (possibly 4000) spectral resolution channels.

4.3.2 Instrument description

The HET instrument consists of:

1. A cold focal-plane unit, containing quasi-optics and IF pre-amplifiers mounted on the nominally 20 K plate, and a 9 element SIS mixer array at 2 – 4.5 K.

2. The LO unit which is located between the payload module and the telescope and connected via a system of mirrors and a window to the focal plane unit.

3. The second stage of the IF system located on the outside of the payload module (PLM) but within 2 m of the cold IF pre-amplifiers.

4. The PLL control for the LO unit, to be located in the service module (SVM) but within 5 m of the LO unit.

5. The "warm" IF unit, to be located in the service module (SVM) but within 5 m of the second stage IF amplifiers.

6. The spectrometers, a prime and a redundant DACS, and a prime and a redundant AOS, located in the service module, not more than 5 m away from the "warm" IF amplifiers.

7. The control electronics, located in the service module.

8. The cable harness.

In the remainder of section 4.3 each of the various items above are described in further detail. For a summary of masses and sizes cf. section 4.4.

4.3.3 Optical design and quasioptical elements

The HET receiver optic system (cf. Table 1) performs the following functions: it re-images the f/9 focal plane of the telescope onto the f/2.75 receiver mixer array, and combines the local oscillator signal from the LO units with the astronomical signal from the telescope with the minimum of loss. Because the various channels of the HET will cover a wide range of frequencies from about 500 GHz to 1100 GHz it is essential that the common optics must also work over this wide range. To achieve this the common optics make use of Gaussian telescopes which have the property of frequency independence. A Gaussian telescope consist of two focusing optical elements separated by the sum of their focal lengths. Such a system behaves as a telescope with a magnification given by the ratio of the elements focal lengths.

Three Gaussian telescopes are used in the proposed optical system (cf. Figures 3, 4, 5, and 6) Focusing mirrors 5 and 6 form one Gaussian telescope to couple the beams from the Cassegrain focal plane to the mixer array. The magnification of this telescope is 3.3× in order to match the f-number of the mixer array to that of the *FIRST* telescope. The focusing mirrors 10 and 9 as well as 6 and 7 form two pairs of Gaussian telescopes which couple the local oscillator signal from the LO units to the mixers.

The mirrors would be machined aluminium with a thickness of about 10 mm and may be gold plated to improve their reflectance. Excess material can be machined away from the back sides to reduce mass. The focusing mirrors will be sections of ellipsoids of revolution and would be manufactured in a numerically controlled milling machine.

Because the bandwidth of each of the mixers and local oscillator units is likely to be restricted and similar, it is logical to use a separate LO unit with each individual mixer. So an arrangement of lenses and mirrors mounted in front of the LO unit optimises the coupling between each LO and mixer pair. It is unnecessary to use a frequency independent optical system at this point since the tuning range of each channel is likely to be about 5 – 10%.

A polarisation rotating diplexer is used in order to combine the LO and astronomical signals with the minimum of loss. This device can be tuned to accept signals of one polarisation at the signal frequency and of the opposite polarisation at the LO frequency (they will differ by approximately 10 GHz). Thus, by injecting the LO signals with the opposite polarisation to the astronomical signal,

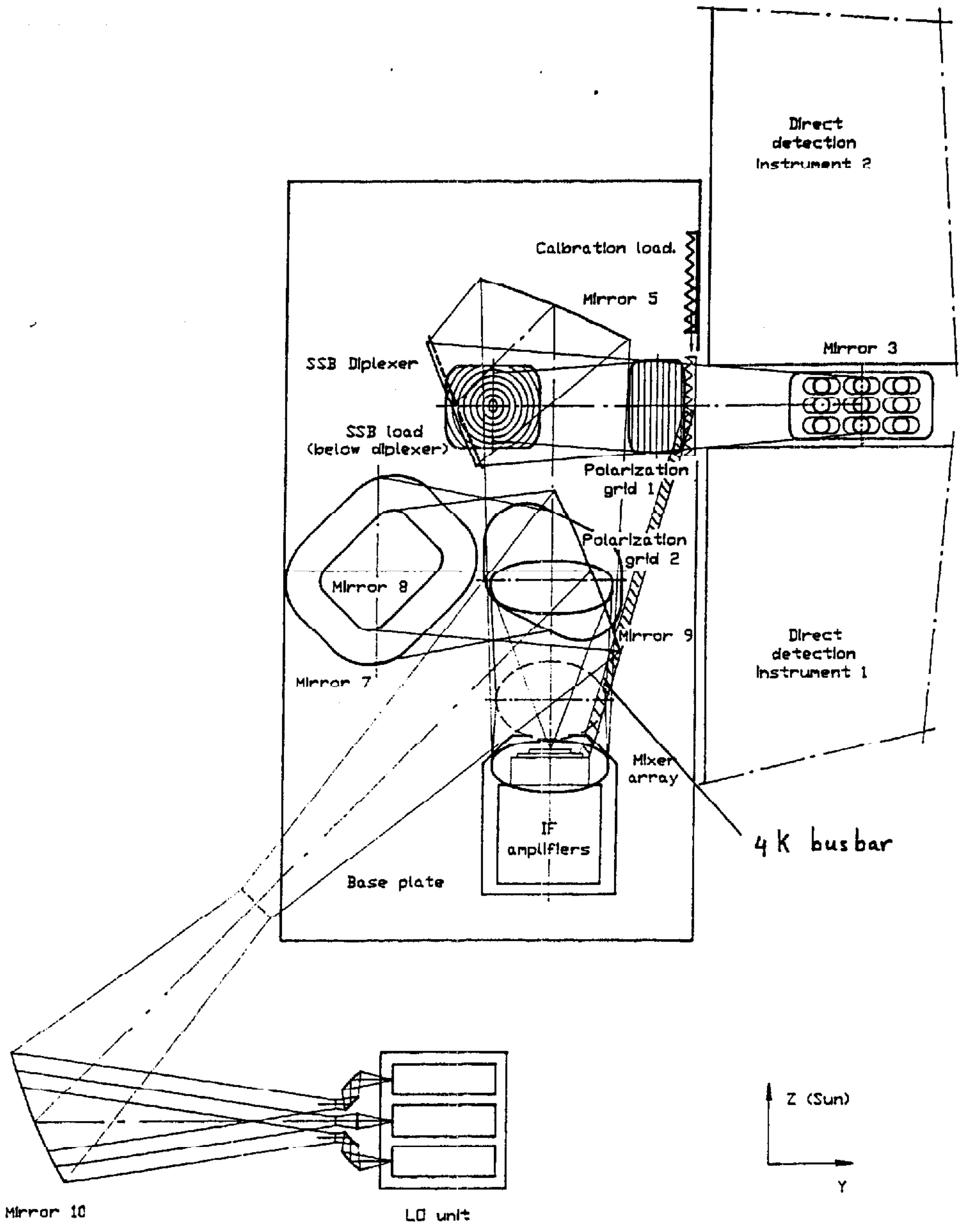

Figure 3: HET top view towards (−x)

HET instrument layout looking down from the telescope secondary showing the position of mirror M3 in the telescope focal plane, the optical system and the detector array relative to the direct detection instruments.

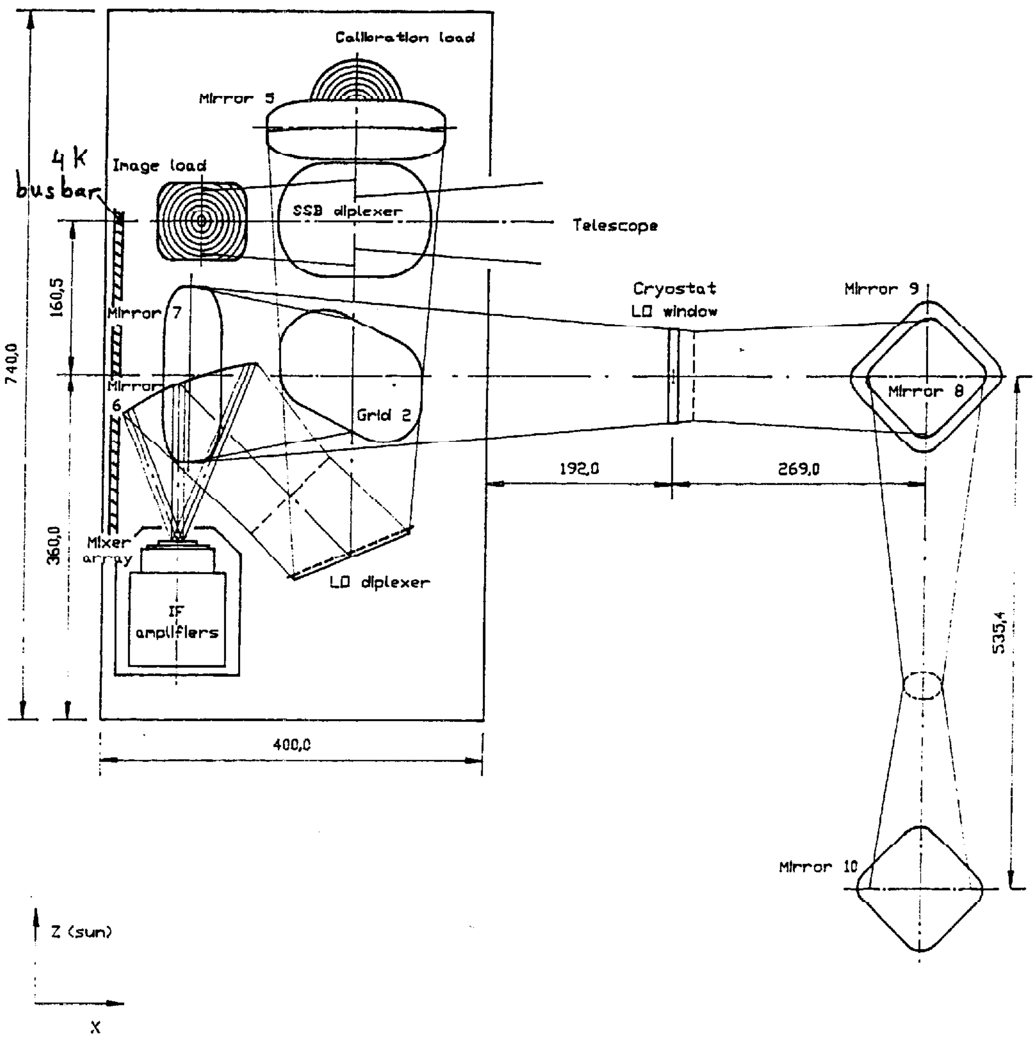

Figure 4: HET side view towards (+y)

HET instrument layout looking from the left side showing the optical system with the local oscillator beam path and cryostat window.

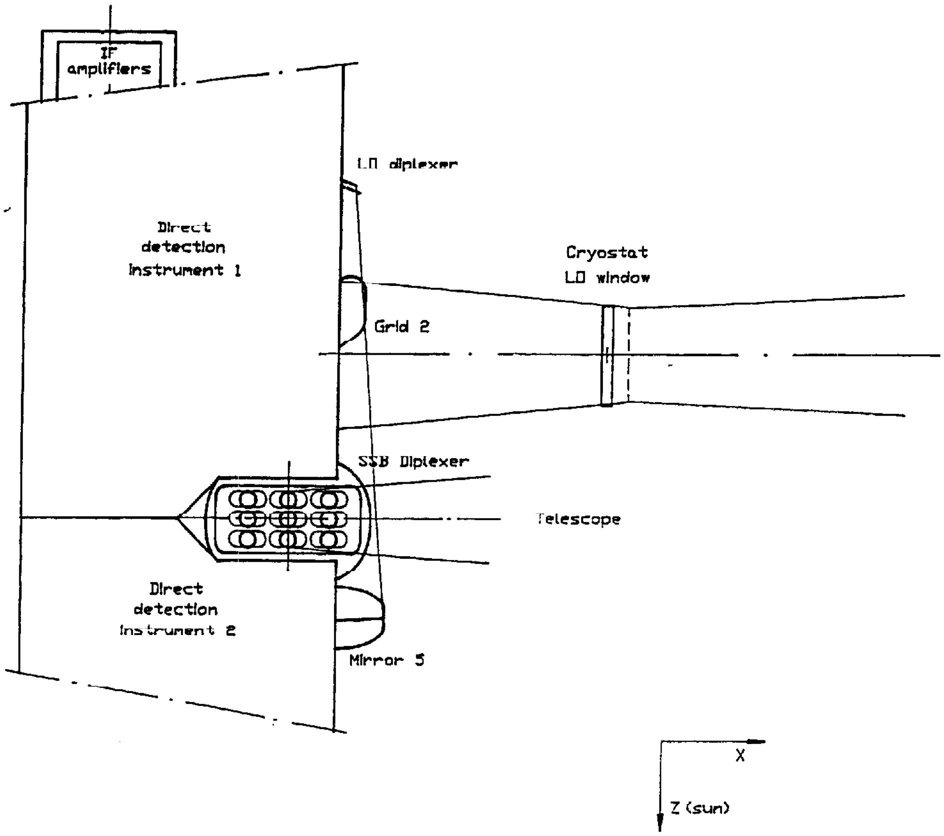

Figure 5: HET side view towards (−y)
HET instrument layout looking from the right side showing the focal plane and relative position of the direct detection instruments.

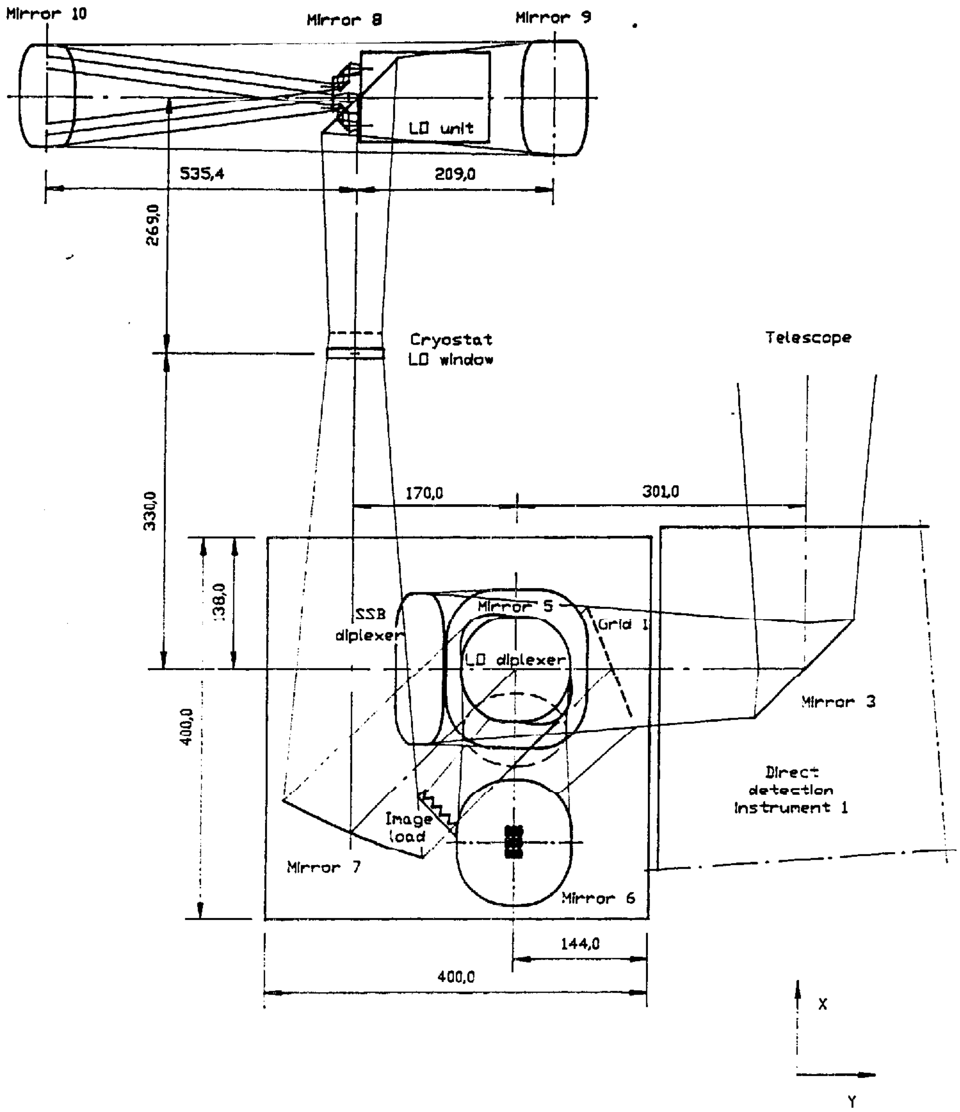

Figure 6: HET sunward view towards (+z)

HET instrument viewed towards the sunward side showing the position of the LO units in relation to the rest of the receiver, and the direct detection instruments.

they can be combined and coupled to the mixers. A motor is needed to tune the LO diplexer to the desired signal frequency.

The mixers in the array will be sensitive to two frequencies called the signal and image frequencies – these differ by twice the intermediate frequency or 20 GHz in this case. To avoid confusion from unwanted signals in the image band, it is necessary to filter out the image frequency. This is accomplished by polarising grid 1 and a second polarisation rotating diplexer: the SSB diplexer.

The polarising grids could be made from many parallel gold plated tungsten wires stretched across a metal frame. The wire diameter would be about 25 μm and the pitch about 100 μm. The diplexers could consist of two back-to-back wedges of a dielectric material, such as quartz or polythene, in contact such that the effective thickness can be varied by sliding the two wedges past each other. The back side of one wedge would be metalised with gold and the front side of the other would support an etched polarising grid.

To calibrate the intensity of the signals detected by the HET a calibration unit will be placed between mirror 3 and polarising grid 1. This will contain a temperature controlled black-body source which may be moved into the beam. Comparing the detected radiometer outputs when looking at two sources at different temperatures allows the radiometer temperature scale to be determined.

The black-body source and image load would be made from a machinable or castable microwave absorber, such as Ecosorb-110, in an aluminium frame or tray. The surface of the absorber would be machined into pyramids to decrease the reflectivity. The calibration sources would have to be maintained at a stable and even temperature of about 100 K by suitable heaters and equipped with accurate temperature sensors. The image load would be mounted directly on the 20 K plate.

It is usually necessary to perform phase switched detection of weak astronomical signals by chopping the telescope beam between two positions on the sky, thus cancelling out the effects of slow gain drifts in the receiver. This could be accomplished by rocking e.g. M5 back and forth. If M5 is tilted $\pm 1^\circ$ it results in a beam throw on the sky of $2.4'$.

Actuators will be required to tune the diplexers and perform the beam-switching, these must operate at cryogenic temperatures in a vacuum. An actuator design for the *Odin* satellite based on an electromagnet is being constructed by ACR Electronic and has a mass of about 250 g.

The total mass of the optics components and actuators, not including the mixers and LO units, is 12.8 kg including 50 % for mechanical supports and contingency.

4.3.4 The mixer array

The mixer array consists of 9 waveguide SIS mixers. Each mixer can be constructed by machining the feedhorn, waveguide and channel for the SIS element in two halves of a copper block. The array would then be assembled from 9 mixer blocks. Alternatively, the array may be constructed as an array of open SIS mixers with integrated antennas on a dielectric substrate. However, the waveguide approach appears to offer the highest sensitivity and is the one adopted for this model payload.

SIS mixers generally require a magnetic field to suppress undesirable noise mechanisms in the junctions and the mixer blocks would include provision for superconducting electromagnets to this end. A possible configuration for the mixer array is shown in Figure 7. The overall size of the array would be about $30 \times 50 \times 50$ mm and would have a mass of about 700 g. The mixer array

component	x/mm	y/mm	z/mm	beam size/mm	mass/kg
HET focal plane (M3)	0	0	0	55 × 94	0.22
calibration unit	0	−160	0	75 × 114	0.25
polarising grid 1	0	−200	0	82 × 121	0.53
SSB diplexer (M 4)	0	−400	0	120 × 159	0.62
M 5 (f=540mm)	0	−301	99	147 × 187	0.89
polarising grid 2	0	−301	−161	128 × 148	0.93
LO diplexer	0	−301	−351	114 × 120	0.44
M 6 (f=165mm)	−181	−301	−170	119 × 131	0.50
mixer array	−181	−301	−335	–	–
M 7 (f=571mm)	−170	−471	−161	146 × 184	0.87
LO window	330	−471	−161	59 × 97	0.34
M 8 (flat)	599	−471	−161	79 × 117	0.39
M 9 (f=457mm)	599	−262	−161	120 × 158	0.61
M 10 (f=300mm)	599	−797	−696	106 × 131	0.45
LO array	599	−497	−696	–	–
image load	−144	−368	0	64 × 112	0.22

Table 1: The HET optics system

The coordinates and beam sizes at the various optical elements are indicated above together with estimated masses.

would be mounted on the 20 K plate using thermally insulating supports and cooled to 2 – 4.5 K by a thermal strap to the liquid helium tank or by a connection to the 4 K cooling bus (possibly augmented by a dedicated 2 K cooler) depending on spacecraft configuration.

4.3.5 The local oscillator (LO) system

Each mixer is supplied by its own local oscillator chain. Each LO will consist of a Gunn oscillator operating at a frequency of about 100 GHz followed by a cascade of two varactor frequency multipliers. The 9 LO sources are grouped together to form the LO unit. The signals from the LO unit are coupled to the mixer array through the quasi-optic system. The LO unit is mounted between the telescope and the payload module.

The frequency of each Gunn oscillator must be adjustable over a 5 – 10 % band and controlled to an accuracy of better than 0.2 ppm. This is achieved by phase locking the Gunn oscillator to a fixed low frequency reference oscillator by a system of microwave synthesisers, the phase-lock loop (PLL) unit. The PLL unit, located in the service module, must be mounted within 5 m of the LO unit. The estimated characteristics of the LO control system are listed in Table 2.

4.3.6 The intermediate frequency (IF) system

The intermediate frequency (IF) system accepts the IF signal from the mixer(s) in operation, and amplifies and filters the signal(s) in several steps. The first amplification stage is the most critical with regard to overall system performance. These pre-amplifiers are therefore located immediately next to the mixers and are cooled to minimise noise contribution. The specifications

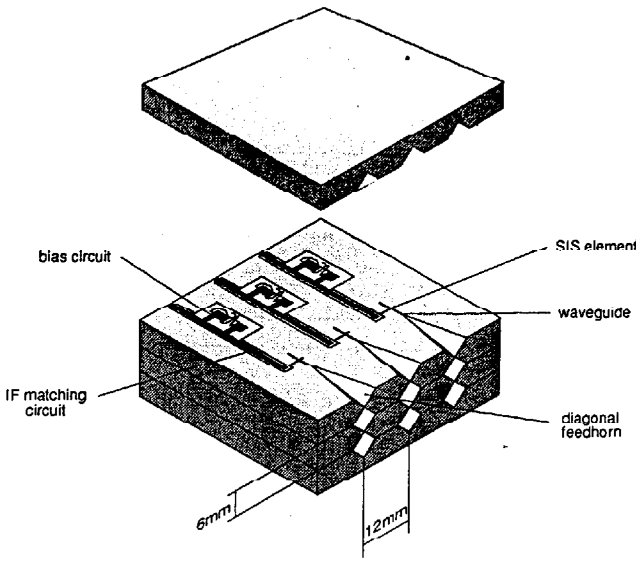

Figure 7: The mixer array

Perspective view of the proposed 3×3 mixer array showing a possible construction technique. The diagonal feedhorns, waveguides, and channels for the SIS mixer element, IF matching circuit and mixer bias circuit are machined in the upper and lower mating surfaces of four copper plates.

and characteristics of the IF system of the *FIRST* heterodyne receivers are listed in Tables 3, 4, and 5.

The above could be achieved with a cooled pre-amplifier (IF1) at ≤ 23 K followed by a second amplifier (IF2) at a temperature of $80 - 313$ K within 2 m of the pre-amplifier. An IF unit operating at ambient temperature in the service module would distribute the IF signal to the spectrometers after further amplification and conditioning. A 10 GHz cooled HEMT IF pre-amplifier with specifications similar to those required for *FIRST* has been built (B. Albinsson, Chalmers) in the ESA TRP programme. It has a size of about $45 \times 24 \times 14$ mm and an isolator of $19 \times 19 \times 14$ mm. The amplifier has a mass of < 50 g and the isolator weighs about 25 g so the mass is 75 g per IF channel giving a total mass of 700 g for the 9 cooled amplifiers, cf. Table 6.

The second stage amplifier (IF2) could be similar to the pre-amplifier (IF1) although the noise performance and power dissipation (40 mW per channel) are not so critical here. The ambient temperature IF unit (IF3, located in the SVM) would be constructed from two commercial components. The specifications are summarised in Table 7.

One non-trivial problem not considered here is that of multiplexing the IF signals from the 9 mixer channels between the four spectrometers in a redundant fashion. However, it is probably unnecessary to cover all possible combinations in which case the complexity could be reduced considerably.

Frequency accuracy	< 0.2 ppm
Frequency adjustment range	> 10 %
LO unit	
Volume	240 × 120 × 140 mm
Mass	5 kg
Power (4 channels operating)	8 W
PLL unit	
Volume	450 × 150 × 100 mm
Mass	5 kg
Power (4 channels operating)	28 W

Table 2: LO control system characteristics

Minimum bandwidth	2 GHz (goal 4 GHz)
Passband gain variation	< 3 dB
Stability (Allan variance turnover time)	> 100 s
Linearity (gain compression)	< 1 %
Spurious response suppression	–30 dB
Internal spurious-to-signal ratio	–30 dB

Table 3: Science requirements on the IF system

4.3.7 Spectrometers

The spectrometer accepts the suitably conditioned signal from the IF system, and performs spectral analysis of the down-converted signal frequency passband over an instantaneous bandwidth and with a frequency resolution appropriate to the particular observation being carried out. Different observations will have different requirements regarding both bandwidth and resolution, therefore the spectrometer needs to be reconfigurable, or a number of different spectrometers would be necessary. Additionally, for redundancy reasons, backup spectrometers are included.

Below the basic scientifically driven specifications of the *FIRST* spectrometer are listed in Table 8.

At the moment it is not obvious what spectrometer technology is the most suitable for the *FIRST* payload requirements. The two most likely candidates are the (hybrid) digital autocorrelator

IF centre frequency	10 GHz
IF system noise temperature	< 20 K
Input match	–14 dB return loss
Output signal level	–25 dBm/GHz
Output matching	–14 dB return loss

Table 4: Interface requirements on the IF system

Operating temperature of cooled pre-amplifier	≤ 23 K
Operating temperature of second-stage amplifier	80 – 313 K
Operating temperature of ambient stages	0 – +40°C
Vibrations	TBD

Table 5: Environmental requirements on the IF system

Bandwidth	2 GHz
Noise temperature, at 6 K physical temperature	20 K
Gain	24 dB
Size	45 × 24 × 14 mm
Size of isolator	19 × 19 × 14 mm
Mass of amplifier	50 g
Mass of isolator	25 g
Power dissipation	10 mW

Table 6: Cooled HEMT IF pre-amplifier (IF1) specifications for a single channel

spectrometer (DACS) and the acousto-optical spectrometer (AOS). Both are being developed for space missions other than *FIRST*; the DACS for the Swedish/International *Odin* and the AOS for the NASA *SWAS* spacecraft. *SWAS* is scheduled to be launched in 1995, and *Odin* in 1997. Although their spectrometer requirements are less demanding than those for *FIRST*, their hardware illustrates well what will be needed onboard *FIRST*.

The hybrid DACS design intended for the *Odin* mission is currently being prototyped (Omnisys/Edge). It is a 1 GHz bandwidth, 1000 channel design, with size 150 × 130 × 50 mm, mass 1 kg and a power consumption of 15 W. This type of spectrometer is inherently flexible and can be reconfigured under software control to fulfil the high resolution requirements. It could also be configured to accept multiple IF inputs simultaneously, which then would have to share the available number of channels between them.

The AOS under construction for *SWAS* has a bandwidth of 1 GHz with 1000 channels, a size of 400 × 130 × 130 mm, mass 8 kg, and power consumption 7 W (not including IF power amplifier). A separate, perhaps similar, spectrometer would be required to satisfy the high resolution spectrometer requirements.

The baseline chosen for the *FIRST* model payload is to have a complement of both a prime and a backup DACS and a prime and backup AOS; the prime and backups are identical. The DACS will

Volume	78 × 46 × 21 mm
Mass	200 g
Power dissipation	400 mW

Table 7: Ambient IF amplifier specifications for a single channel

Maximum instantaneous processed bandwidth	2 GHz (goal 4 GHz)
Number of frequency resolution channels	2000 (goal 4000)
Maximum resolution	250 kHz

Table 8: Spectrometer specifications
Spectrometer science driven requirements. In addition, obvious spacecraft driven considerations are mass, size, power and thermal (stability) requirements.

have 2000 (goal 4000) spectral resolution channels, and a spectral resolution which is selectable in the range 250 kHz to 1 MHz. The AOS will have a bandwidth of 4 GHz with 1500 channels. The specifications are given in Table 9.

DACS with 2000 (goal 4000) × 1 MHz/250 kHz reconfigurable	
Volume	150 × 130 × 100 mm
Mass	2 kg
Power	30 W
AOS with 1500 channels with 4 GHz bandwidth	
Volume	150 × 130 × 50 mm
Mass	2 kg
Power	10 W

Table 9: DACS and AOS specifications for *FIRST* requirements

4.3.8 Miscellaneous control electronics

Electronics are required for the control and monitoring of a number of functions in the receiver. The mechanical actuators require electronics to read the position sensors and drive the motor to the desired position. The SIS mixers and cooled IF amplifiers require special bias supplies for their correct operation. Additional electronics will be required to monitor the IF signal levels and control the IF multiplexer to direct the IF signals to the active spectrometer. Also it will be desirable to monitor the temperature of various components such as the calibration unit.

These electronics could be combined into a single unit together with a processing unit to facilitate communication with the spacecraft telemetry system. The estimated size, mass and power consumption are detailed in Table 10.

Volume	160 × 150 × 100 mm
Mass	3 kg
Power	3 W

Table 10: Miscellaneous control electronics characteristics

4.4 Mechanical and thermal design

The dimensions and masses (including contingencies) of the instrument units are given in Table 11.

Unit	# of	Dimensions (mm)	Mass (kg)
Focal plane unit	1	740 × 400 × 400	19
LO unit	1	240 × 120 × 140	5
PLL control unit	1	450 × 150 × 100	5
IF2 unit	1	150 × 150 × 30	1
IF3 (ambient) unit	1	150 × 100 × 100	3
DACS spectrometer	2	150 × 130 × 100	2
AOS spectrometer	2	150 × 130 × 50	2
Control electronics	1	160 × 150 × 100	3
Cable harness			1
Total			45

Table 11: Heterodyne instrument dimensions and masses
Heterodyne instrument dimensions and masses per unit as listed in section 4.3.2. The focal plane unit incorporates the cold IF (IF1). These masses and dimensions include necessary margins. This table, and the tables that follow, assume no dedicated 2 K cooler for the HET.

The dissipation, allowed operating temperature ranges, their stability, and allowed non-operating temperature ranges are given in Table 12, and the spacecraft interface temperature and temperature stability requirements are given in Table 13.

4.5 Alignment requirements

The required alignment tolerances for the focal plane unit, including all cold optics and M3, are given below:

Absolute:	Δx:	±6 mm
	Δy, Δz:	±1 mm
	$\Delta\theta_x$:	±1°
	$\Delta\theta_y$, $\Delta\theta_z$:	±0.2°

The rotations are about the centre of mirror M3, i.e. position (0, 0, 0) as defined in Table 1. The required stability is one order of magnitude better for all parameters over a timescale of 1 hour.

The required alignment tolerances for the complete local oscillator unit, including mirrors M8, M9, and M10, relative to the focal plane unit, are as follows:

Absolute:	Δx:	±10 mm
	Δy, Δz:	±0.3 mm
	$\Delta\theta_x$:	±0.4°
	$\Delta\theta_y$, $\Delta\theta_z$:	±0.5°

Subsystem	Power dissipation	Operating temperature	Non-operating temperature
Mixer array	10 μW	$\leq$ 4.5 K	$\leq$ 360 K
Electromagnets	2 mW	$\leq$ 6 K	$\leq$ 360 K
IF1 (cold)	40 mW	$\leq$ 23 K	$\leq$ 360 K
Cold optics	2 mW	$\leq$ 50 K	$\leq$ 360 K
LO unit	8 W	80 – 313 K	80 – 313 K
PLL control	28 W	0 – +40 °C	–50 – +85 °C
IF2	0.2 W	80 – 313 K	$\leq$ 360 K
IF3 (ambient)	1.6 W	0 – +40 °C	–50 – +85 °C
Spectrometers	30 W	0 – +40 °C	–50 – +85 °C
Control electronics	3 W	–10 – +50 °C	–50 – +85 °C

Table 12: Heterodyne instrument dissipation and temperature requirements
The dissipation and temperature requirements for the various units of the HET instrument. The dissipation of the mixer array assumes that all 9 channels are operating; in the cryostat spacecraft option the mixer array should be strapped to the superfluid helium cryogen tank. The dissipation of the cold optics is the total contribution of the chopper, hot load and diplexer. The IF1, IF2, IF3, LO unit and PLL control dissipation values assume 4 operating channels; the spectrometer value refers to 1 operating DACS.

The rotations are about coordinate (351, –471, –161). The required stability is one order of magnitude better for all parameters over a timescale of 1 hour. Note that the alignment for the LO unit with respect to the focal plane unit must also be satisfied for ground tests of e.g. the coupling of the LO power to the mixers.

Although the mirrors M8, M9, and M10 are considered part of the LO unit assembly and will be mounted on the LO unit support structure with no articulation requirements, for reference their required alignment tolerances are (for M8, M9, M10, respectively):

Translation normal to mirror surface:	±0.2, 0.4, 0.2 mm
Translation parallell to mirror surface:	±2, 0.3, 0.2 mm
Rotation about axis in plane of mirror:	±0.03, 0.02, 0.02°
Rotation about normal to mirror:	±0.4, 0.4, 0.4°

4.6 Harness

There are 9 co-axial cables required going from the mixers at 2 – 4.5 K via the cold IF amplifiers at 15 – 20 K to the ambient. These will carry microwave signals at 10 GHz to the ambient electronics. Power dissipation within the cables themselves is insignificant.

The co-axial cables are Micro-Coax UT-085 with outer/inner/dielectric areas of $1.6 \times 10^{-6}/7.0 \times 10^{-8}/2.0 \times 10^{-6}$ m^2, respectively. The proposed cable has stainless steel outer shell, a foam PTFE dielectric, and a BeCu inner conductor. Cable attenuation between mixer and cold IF amplifier < 0.5 dB, between cold IF amplifier and outside of cryostat < 3 dB is required. The co-axial cables could be arranged in a single unscreened bundle, cross-talk will not be a problem.

Subsystem	Interface temperature	Temperature stability timescales			
		1 s	10 s	100 s	1000 s
4 K cooling bus	≤ 4.3 K	0.6 mK	0.6 mK	6 mK	60 mK
20 K cooling bus/IF1	$<$ 23 K	15 mK	15 mK	150 mK	1500 mK
IF2		15 mK	15 mK	150 mK	1500 mK
IF3 (SVM)		10 mK	10 mK	100 mK	1000 mK
Spectrometers (SVM)		3 mK	3 mK	30 mK	300 mK

Table 13: HET/spacecraft interface temperature and temperature stability requirements
The temperature and temperature stability requirements for various HET/spacecraft interface points and units. In the cryostat spacecraft option the mixer array should be strapped to the superfluid helium cryogen tank.

There are 9 pairs of high current wires going from the electromagnets in the 4 K area to ambient required. These wires have an area of 2.0×10^{-7} m^2 and will carry a dc current of up to 50 mA, voltages will be less than 10 V. Wire resistance is irrelevant from the electrical point of view, but crucial as regards dissipation. The wires should be run as twisted pairs to minimise stray magnetic fields, shielding is not required.

The low current bias and sensor wires are AWG-36 with area of 1.3×10^{-8} m^2, the maximum allowable resistance per wire is 5 ohm. The dc current per wire will be less than 10 mA and voltages will be less than 10 V. The wires be can single-strand with insulation, so-called enamelled. The wires could be arranged as twisted pairs or as a single unscreened bundle, cross-talk is not a problem, and shielding is not required.

Finally, the optics actuator wires are also AWG-36 but they do carry currents of up to 100 mA, however, with very low duty cycles, making the internal dissipation very small. Screening is not important but they should be grouped to minimise stray magnetic fields and routed to reduce the coupling to other sensors and bias wiring to avoid disturbing other equipment.

Item	2 – 4 K	4 – "20 K"	"20 K" – ambient	Type
Cable harness length (cm)	0.15	0.2		
# of IF co-axial cables	9	9	9	co-ax
# of mixer wires	18	18	18	2
# of sensor wires	4	4	16	2
# of electromagnet wires		9	9	1
# of optics actuator wires			32	1.9
# of optics sensor wires			24	2
# of heater wires			4	2
# of IF amplifier bias wires			45	2

Table 14: Cabling harness for the HET instrument
There are three different kinds of cables, co-ax, type 1 and 2, type 2 having a smaller cross-section than type 1. Type 1.9 cables are physically type 2, but do carry a higher current with a low duty cycle.

4.7 Overall power/dissipation budget

The heat loading on the various cold stages is summarised in Table 15. The calculations assume the harness given in Table 14.

4.8 Data rate

To calculate the maximum data rate to be expected we assume that two spectrometers of 2000 channels each are operating and that each channel results in 4 bytes of data per integration. The maximum integration time is dependant on the spacecraft orbit, the observing frequency and the resolution in use, due to the Doppler effect and spacecraft acceleration. The highest resolution and frequency correspond to a velocity resolution of 68 $m\,s^{-1}$ so an integration time of up to 10 s is allowed if the orbital acceleration is no more than 6.8 $m\,s^{-2}$.

Thus, the data rate is 24 kbps, allowing 80 % for header and housekeeping information.

4.9 Instrument performance

Currently SIS mixer operation has been demonstrated with high sensitivity at frequencies up to about 700 GHz (cf. Figure 8). The sensitivity achieved is between 5 to 10 times the quantum limit of $h\nu/k$ – this is shown in the figure for comparison. The sensitivity of SIS mixers at frequencies significantly in excess of 700 GHz will probably be dependant on the progress in development of new SIS junction technologies based on superconducting alloys, such as niobium nitride, and insulators such as magnesium oxide. How rapid progress will be made is hard to estimate – a conservative estimate for the DSB mixer sensitivity might be $20 \times h\nu/k$ at 1 THz.

In estimating the performance of the HET as a whole, allowance must be made for the effect of the SSB filter, the losses in the quasi-optics, and the beam-switching techniques used. The SSB filter will approximately double the receiver noise temperature. A conservative estimate of the quasi-optic losses is less than 2 dB at 4 K, a factor of 1.6. For beamswitched observations with equal time on the source and reference positions and 10 % of time lost while moving between the positions, the system sensitivity is reduced by a factor of 2.1. So the effective SSB system noise temperature is increased by a factor of 6.7 over that of the DSB mixer.

Item	2 K	4 K	"20 K"
Mixer dissipation	0.01		
Structure	0.04	2.0	
Mixer bias wire conduction		0.11	
Sensor wire conduction		0.02	
Cold HEMTs dissipation			40
IF cable conduction	0.05	1.73	
Cold optics dissipation			2.0
Magnet bias dissipation		2.0	5.5
Magnet wire conduction		2.0	
Total dissipation	0.01	2.0	47.5
Total net conduction ×1.1	0.11	6.45	
Radiation	~ 0	~ 0	
Net heat load	0.12	8.45	47.5

Table 15: HET thermal loading calculations in units of mW

Total heat loads in the focal plane for the HET 2 K and 4 K areas, and dissipation only for the "20 K" stage, which will have a temperature in the 15 – 23 K range. The internal radiative loads on the 2/4 K stages are negligible, the heat load from the focal plane is not included. The total 4 K heat load will be delivered to the instrument/spacecraft interface on the 4 K bus bar. For the cryo-cooler HET (without a dedicated 2 K-cooler) the mixer dissipation should be added to the total 4 K figure given.

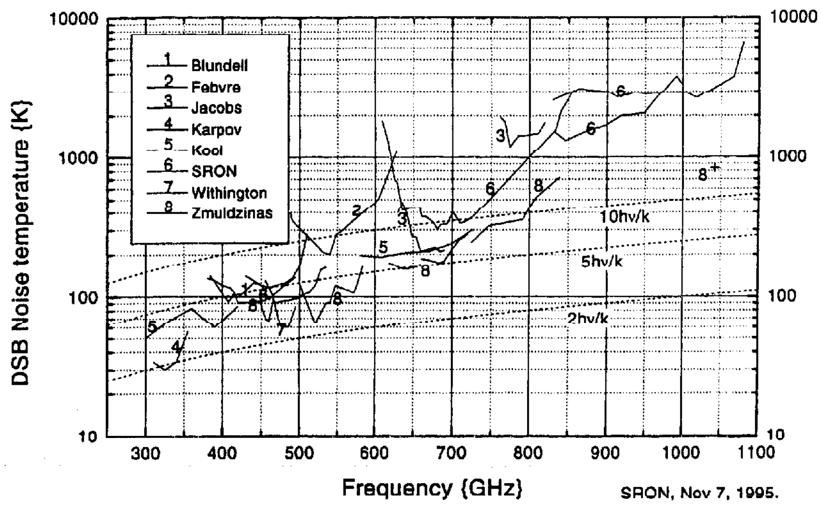

Figure 8: SIS double sideband system temperatures achieved

Currently achieved receiver sensitivities in the submillimetre region. The plot shows the DSB noise temperature of SIS mixers in the submillimetre region. For comparison lines are drawn at 2, 5, and 10 times the quantum noise limit $h\nu/k$.

5 The photoconductor instrument (PHOC)

5.1 Introduction

Direct detection with a photoconductor is a process where the incoming photons excite charge carriers into the conduction or valence band. A bias voltage across the photoconductor then causes a current to flow which is proportional to the input photon rate, i.e. power. The sensitivity is limited by detector thermal noise, detector shot noise, noise in the signal source and telescope thermal emission. With current detector technology the main limiting factor for direct detection with FIRST would be the telescope thermal background and its fluctuations.

In the foreseen FIRST environment the direct detection method is more efficient than heterodyne detection approximately for spectral resolving powers R ($= \nu/\delta\nu = \lambda/\delta\lambda$) less than 3×10^4 for wavelengths shorter than 300 μm. Arrays of detectors are more easily implemented using these types of detectors. An exact comparison with heterodyne spectrometers is impossible because the spatial vs. spectral multiplex advantage depends on the individual astronomical source, but the main strength of direct detection instruments is imaging at low to medium spectral resolution.

Grating spectrometers provide the highest transmission which can be twice that of Fabry-Pérot (F-P) interferometer systems. In connection with a detector array they also allow for spectral multiplexing. No further information is obtained, however, when a spectral line is over-resolved by a large factor. This naturally limits the spectral multiplex advantage. For extended objects, the spectral multiplex advantage of a grating spectrometer over a F-P spectrometer can easily be overcome by the spatial multiplex advantage of an imaging F-P system with a sufficiently large two-dimensional detector array. A two-dimensional spatial array has the additional advantage of absolute registry between pixels in a map. This feature facilitates significantly improved registry between the far infrared maps and those obtained with other telescopes in other spectral lines. Furthermore, very high (≤ 10 km s^{-1}) and selectable spectral resolution can only be obtained with a F-P system. Easy tuning between different spectral lines and different redshifts is a further requirement. Imaging F-P spectrometers have already been used for airborne observations.

We will describe an instrument to perform spectroscopy and continuum measurements (photometry) over the 85 – 210 μm range, using Fabry-Pérot interferometers and photoconductive detector arrays.

5.2 Scientific rationale

The far infrared wavelength region contains a large number of spectral lines from abundant atoms, ions and molecules. These lines probe a wide range of excitation and ionization stages. They provide detailed information on density, temperature, velocities and abundances of ionized and neutral components of interstellar and circumstellar gas. High angular and spectral resolution measurements and accurate spatial mapping of these lines are necessary for determining the spatial distribution and kinematics. The astronomical objects for far infrared line spectroscopy range from nearby molecular clouds and star formation regions to active galactic nuclei and quasars. As a consequence, the line widths will vary from a few km s^{-1} to several hundred km s^{-1}; therefore a suitable instrument has to be able to adapt for high resolution and/or large bandwidth. In addition, for most of the mentioned objects their continuum emission is also of high scientific value and interest in the whole of the submillimetre and far infrared region.

5.3 The photoconductor instrument description

5.3.1 Overall capabilities

The PHOC receiver is designed to provide imaging and spectroscopy in the region $85 - 210\ \mu m$. A 16×16 array of stressed Ge:Ga photoconductive detectors, nominally operating at 1.7 K is used.

The PHOC can operate in four modes, which are characterised by the spectral resolution, R:

1. High resolution spectroscopy : $R = 1 - 3 \times 10^4$
2. Medium resolution spectroscopy: $R = 1 - 3 \times 10^3$
3. Narrow-band photometry: $R \approx 5$
4. Broad-band photometry: $R \approx 2.3$

5.3.2 Instrument description

The PHOC instrument consists of:

1. A cold focal-plane unit, containing optics at nominally 20 K (this temperature will be in the $15 - 23$ K range depending on spacecraft concept) and 4 K and a detector array at 1.7 K with cryogenic readout electronics. Cooling at 20 K and 4 K is provided by the spacecraft, and the 1.7 K temperature is provided by an internal dedicated cooler or a direct strap to the superfluid helium cryogen tank, depending on the satellite concept.

2. Helium storage tanks and tubing for the internal cooler (only with the cryo-cooler option).

3. Four (three) warm electronics boxes located in the service module at 300 K (nominal temperature):

(i) Two analogue electronics boxes for the science data and control of the focal plane moving mechanisms.

(ii) A digital electronics box for data processing, instrument control and telemetry interface to the spacecraft.

(iii) A control box for the 1.7 K cooler (only with the cryo-cooler option).

4. A cryo-harness connecting the warm and cold parts of the instrument.

5.3.3 Optical chain

The focal-plane unit is shown schematically in Figure 9. A Fabry-Pérot (F-P) interferometer requires a parallel beam. The input optics define the instrument field of view and collimate the telescope beam. The chopping mirror M4 provides sky modulation. Three interchange wheels, similar in design to the *ISO* Long Wavelength Spectrometer F-P interchange wheel, allow filters and F-P interferometers (optimised for different wavelength ranges) to be selected. The first F-P wheel contains two high-resolution and two medium-resolution F-Ps and an open position. The second F-P wheel contains two low-resolution F-P interferometers, two broad-band photometric filters and an open position.

The function of the low-resolution F-Ps is to order-sort the high- or medium-resolution F-Ps. A filter wheel is mounted between the two F-P units, and contains a set of five bandpass filters and an open position. The filters serve to order-sort the low-resolution F-P, and, when both F-P wheels are in the open positions, they can be used for narrow-band photometry (R $\approx$ 5). Broad-band photometry (R $\approx$ 2.3) is also available by using the two photometric filters contained in the low-resolution F-P wheel. A compilation of the available F-Ps and filters is given in Table 16.

Having passed through the F-P and filter wheels, the beam is condensed onto the detector array with an f-ratio of f/35. The photoconductor array operates nominally at 1.7 K and is contained in a 2 K enclosure for optimum stray light baffling.

High-resolution F-P	Filter Wheel	Low-resolution F-P / Filter
85 – 135 μm (H)	85 – 105 μm	85 – 135 μm (filter)
85 – 135 μm (M)	105 – 126 μm	85 – 135 μm (F-P, n=5)
135 – 210 μm (H)	126 – 151 μm	135 – 210 μm (filter)
135 – 210 μm (M)	151 – 181 μm	135 – 210 μm (F-P, n=5)
open	181 – 210 μm	open
	open	

Table 16: Available Fabry-Pérots and filters

Available Fabry-Pérots (F-Ps) and filters. Both high-resolution ($R = 1 - 3 \times 10^4$; H) and medium-resolution ($R = 1 - 3 \times 10^3$; M) F-Ps are available. The filters on the filter wheel are used either for narrow-band photometry or in combination with the F-Ps. The filters on the low-resolution F-P wheel are used for broad-band photometry.

5.3.4 Detector and signal readout

As a baseline for the photoconductive detector array the Ge:Ga FIRSA (Far-Infrared Stressed Array) is adopted which is presently under development as a demonstration model for FIRST. The 16 × 16 element array (Figure 10) consists of 16 identical linear modules (Figure 11). Mechanical stress is applied within each module to the whole stack of 16 detector elements with a spring-lever mechanism which allows precise adjustment of the stress.

To minimise microphonics, electrical crosstalk, and electromagnetic interference the cryogenic readout electronics (CRE) is integrated into each linear detector module. While the CRE modules are mechanically mounted to the detector modules they are thermally connected to the 4 K stage. In this way, the heat load to the 1.7 K stage ($\sim$ 0.2 mW) is only a small fraction of the total power dissipated by the CRE ($\sim$ 1.2 mW). By switching feedback capacitors and the readout rate the CRE is capable of handling the full dynamic range in signal of both the photometric and spectroscopic observing modes.

5.3.5 Joule-Thomson cooler

Since the detector array needs to operate at lower temperatures than can be provided by the cryo-cooler spacecraft, the PHOC instrument has its own internal refrigerator. It is an open-cycle Joule-Thomson (J-T) expansion cooler, and it will be responsible for providing cooling from the 4 K stage to the nominal operating temperature of the photoconductor array of 1.7 K. The refrigerator is a slightly simplified version of the one used with the BOL instrument in that it does not involve a

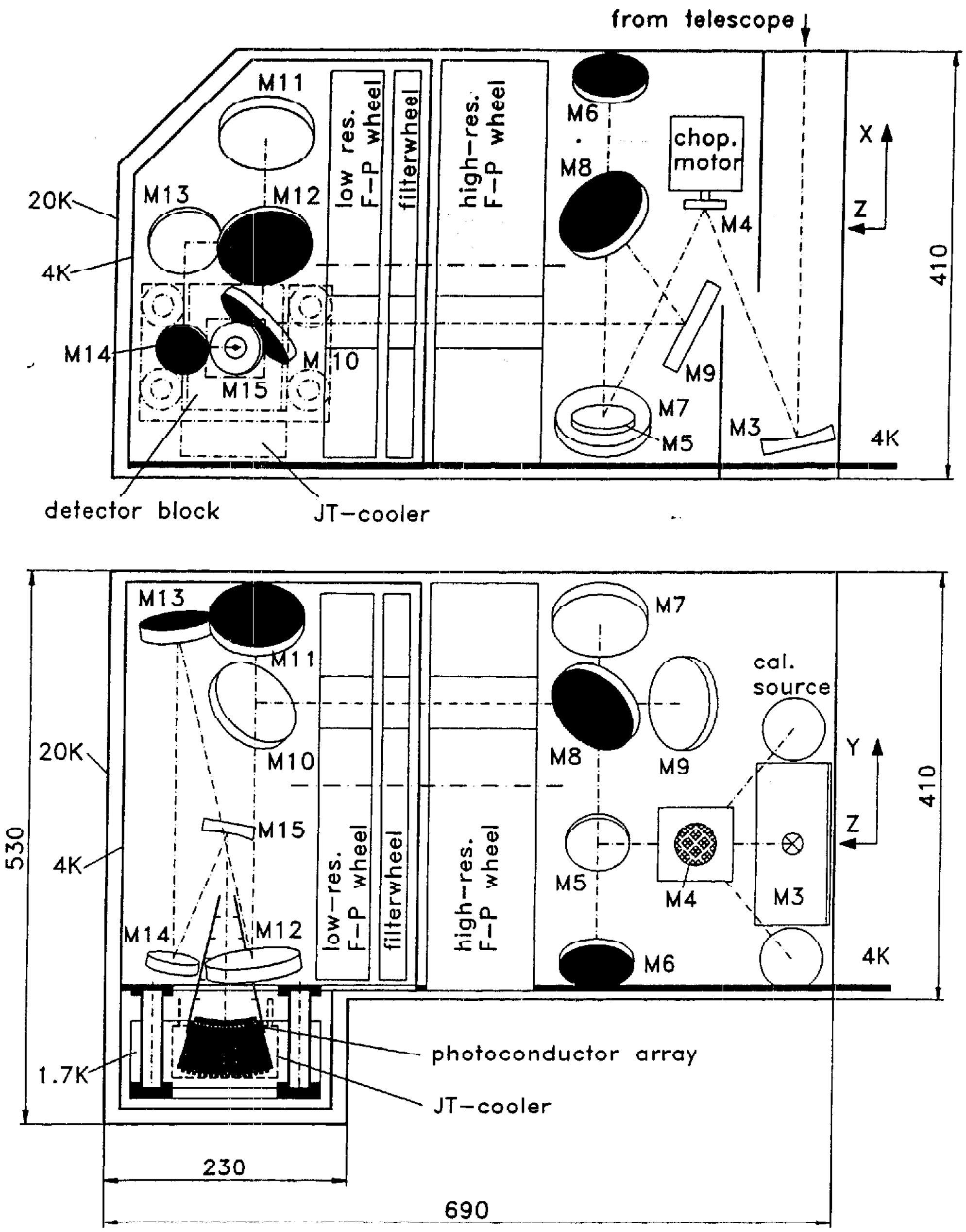

Figure 9: Schematic figure of the PHOC.

Schematic figure of the PHOC instrument. The f/10 beam from the telescope secondary is incident on M3. Sky chopping is effected by the wobbling flat mirror M4. The beam is collimated, passed through the Fabry-Pérot and filter wheels, and re-imaged onto the detector array with a final focal ratio of f/35. The detector array is contained in a 2 K enclosure, and maintained at the operating temperature of 1.7 K by an open-cycle J-T expansion cooler or a strap to the superfluid cryogen, depending on the cooling concept of the satellite.

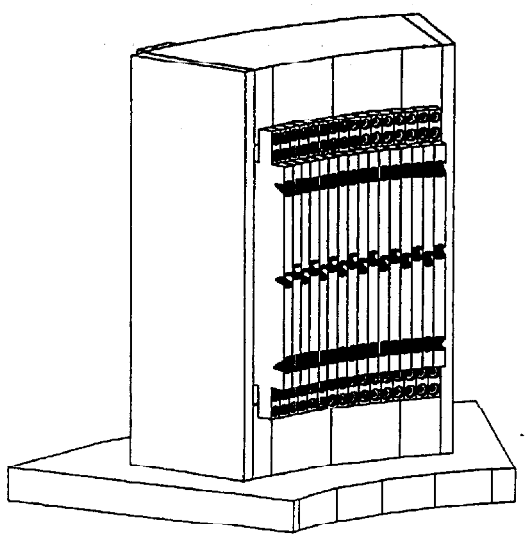

Figure 10: Front view of the assembled detector array
Schematic view of the 16 × 16 element FIRSA photoconductor array (drawing courtesy ANTEC). The array consists of 16 identical linear modules of stressed detectors and light cones which act as area-filling feed optics for the integrating cavities around each individual detector element. Only the top, bottom, and centre rows of light cones are indicated here.

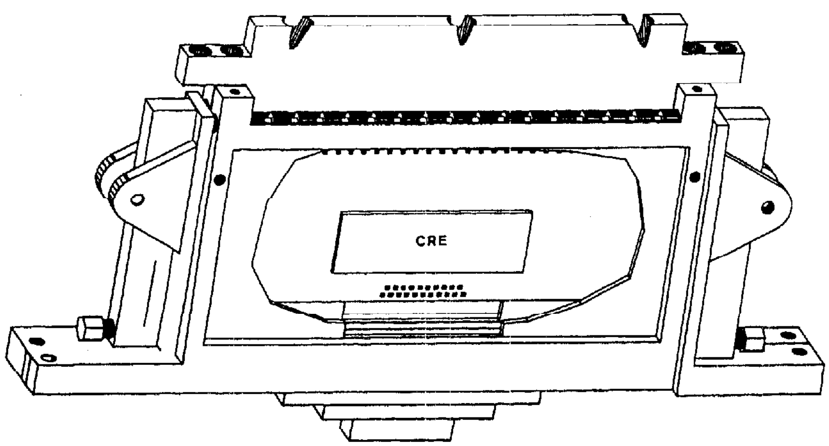

Figure 11: 16-element linear detector module
Cut-away drawing of one linear module of 16 stressed detectors (drawing courtesy ANTEC). The cryogenic readout electronics (CRE) is thermally isolated from the detector block and heat-sunk to the 4 K stage. Mechanical stress is applied by a screw and a spring-lever.

$^3He/^4He$ dilution stage. It consists of helium gas storage tanks with flow rate control valves located on the outside of the payload module, and two separate fully redundant helium supply systems:

1. Three helium gas storage tanks (35.5 l at 265 bar) with flow rate control valves and control electronics mounted on the outside of the payload module.

Items 2. to 7. below are duplicated, thus comprising two completely redundant helium tubing and heat exchanger systems.

2. Helium piping, two CuNi tubes with 0.6 mm outer and 0.3 mm inner diameter from 300 K to 1.7 K.

3. Cold trap and heat exchanger at 65 K, size $1.5 \times 3 \times 5$ cm^3, made of copper. Minimum length of tubing from ambient temperature is 50 cm.

4. A similar heat exchanger at 20 K, minimum length of tubing from 65 K heat exchanger is 25 cm.

5. Another similar heat exchanger at 4 K, minimum length of tubing from 20 K heat exchanger is 100 cm.

6. Heat exchanger and J-T expansion stage at 1.7 K, minimum length of tubing from 4 K heat exchanger is 15 cm.

5.4 Mechanical and thermal design

The PHOC instrument is designed to provide the necessary low operating temperatures for its various components while keeping the power loading on the cryo-coolers or cryogen to within strict limits. The main thermal-mechanical interface to the spacecraft is at the 20 K baseplate / radiation shield.

For instrument alignment and rigidity during launch, it is essential that the 4 K and 1.7 K boxes be securely fixed with respect to the 20 K baseplate. This must be achieved while at the same time not exceeding the thermal loading limits. The design concept to meet these requirements foresees a rigid baseplate for the 4 K box which is suspended on tensioned Kevlar threads while the 1.7 K structure inside the 4 K box is supported by CFRP tubes. The temperature requirements are given in Table 17.

Subsystem	Interface temperature	Temperature stability timescales 1 s	10 s	100 s
Ge:Ga detectors	≤ 1.7 K	will be maintained by instrument		
2 K shield	≤ 2 K	will be maintained by instrument		
4 K cooling bus	≤ 4.3 K	0.1 mK	1 mK	10 mK
20 K cooling bus	≤ 23 K	0.3 mK	3 mK	30 mK

Table 17: PHOC/spacecraft interface temperature and temperature stability requirements
The temperature and temperature stability requirements for various PHOC/spacecraft interface points and units. In the cryostat spacecraft option the stressed Ge:Ga detector array should be strapped to the superfluid helium cryogen tank, in the cryocooler spacecraft the 4.3 K interface is the lowest temperature instrument/spacecraft interface.

The dimensions and masses of the principal instrument units are given in Table 18.

Unit	# of	Dimensions (mm)	Mass (kg)
Focal plane instrument unit	1	cf. Fig. 9	22
He tanks incl. gas(*)	3	diameter 432	9
Valves, piping, etc.(*)			6
Warm analogue electronics	2	200 × 200 × 150	4
Warm digital electronics	1	200 × 200 × 200	5
Warm J-T cooler control box(*)	1	200 × 200 × 150	4
Cable harness			1
Total			73 (36)

Table 18: Photoconductor instrument dimensions and masses
Dimensions and masses for the PHOC units, the values given include margins. (*)The J-T cooler components are only needed with the cryo-cooler version of the spacecraft.

The "warm" electronics boxes are all located in the service module and have an operating temperature range of −15 – +45 °C, and an allowed non-operating temperature range of −30 – +60 °C.

5.5 Alignment requirements

There are absolute alignment requirements, and requirements of stability as follows:

Absolute:	Δx, Δy, Δz:	±1 mm
	$\Delta\theta_x$:	±5′
	$\Delta\theta_{yz}$:	±3′ (combined)
Stability:	Δx, Δy, Δz:	±0.1 mm over 1 hour
	$\Delta\theta_x$:	±3′ over 1 hour
	$\Delta\theta_{yz}$:	±1′ (combined) over 1 hour

5.6 Harness

Electrical leads to the cold focal plane unit are needed to provide power to the cold electronics, read out the detector signals, control the instrument mechanisms and monitor various housekeeping parameters. For the preliminary instrument design, the minimum numbers of wires between the various temperature stages are given in Table 19.

Route	wires	# of wires	# of shields	length
1.7 – 4 K	detector signal	16 × 16	0	2 × 2 cm + 3 cm
	bias	16	0	2 × 2 cm + 3 cm
	1.7K–thermoms	16 × 4	0	3 cm
4 – 20 K	bias and checkout	19	1	30 cm
	supplies and T-sens	2 × 11	2 × 1	30 cm
	Clock/Synch/Out	20 × 1	20 × 1	30 cm
	1.7K–thermoms	16 × 4	0	30 cm
	LR F-P cap pads out	12	12	30 cm
	LR F-P cap pads drive	12	4	30 cm
	LR F-P drive coils	24	0	30 cm
	LR wheel posn sens	4	2	30 cm
	LR wheel motor coils	8	0	30 cm
	Filter–wheel motor coils	8	0	30 cm
	Filter–wheel posn sens	4	2	30 cm
	4K–thermoms	8	0	30 cm
20 – 300 K	bias and checkout	19	1	400 cm
	supplies and T-sens	2 × 11	2 × 1	400 cm
	Clock/Synch/Out	20 × 1	20 × 1	400 cm
	1.7K–thermoms	16 × 4	0	400 cm
	HR + LR F-P cap pads out	2 × 12	2 × 12	400 cm
	HR + LR F-P cap pads drive	2 × 12	2 × 4	400 cm
	HR + LR F-P drive coils	2 × 24	0	400 cm
	HR + LR wheel posn sens	2 × 4	2 × 2	400 cm
	HR + LR wheel motor coils	2 × 8	0	400 cm
	Filter–wheel motor coils	8	0	400 cm
	Filter–wheel posn sens	4	2	400 cm
	4K–thermoms	8	0	400 cm
	calibration sources (2)	2 × 8	0	400 cm
	chopper	12	0	400 cm

Table 19: Photoconductor instrument electrical connections

A listing of photoconductor instrument electrical connections. Critical connections have been made redundant, and are included in the numbers given.

Route	wires	cross section [$\times 10^{-5}$ cm^2]	Heatload [μW]	Total Heatload
1.7 – 4 K	detector signal	503	65.9	74.2 μW
	bias	31	4.1	
	1.7K–thermoms	126	4.2	
4 – 20 K	bias and checkout	286	15.3	262.3 μW
	+ insulation	2145	10.3	
	supplies and T-sens	2 × 198	21.1	
	+ insulation	2 × 1603	15.4	
	Clock/Synch/Out	20 × 28	29.9	
	+ insulation	20 × 309	29.7	
	1.7K–thermoms	126	6.7	
	HR + LR F-P cap pads out	2 × 236	12.6	
	LR F-P cap pads drive	2 × 236	12.6	
	LR F-P drive coils	2 × 189	10.1	
	LR wheel posn sens	2 × 79	4.2	
	LR wheel motor coils	2 × 63	3.4	
	Filter–wheel motor coils	63	3.4	
	Filter–wheel posn sens	79	4.2	
	4K–thermoms	63	3.4	
	+ insulation		≈ 80	
20 – 300 K	bias and checkout	286	218	3 mW
	+ insulation	2145	30	
	supplies and T-sens	2 × 198	302	
	+ insulation	2 × 1603	45	
	Clock/Synch/Out	20 × 28	427	
	+ insulation	20 × 309	87	
	1.7K–thermoms	126	96	
	HR + LR F-P cap pads out	2 × 236	360	
	HR + LR F-P cap pads drive	2 × 236	360	
	HR + LR F-P drive coils	2 × 189	288	
	HR + LR wheel posn sens	2 × 79	121	
	HR + LR wheel motor coils	2 × 63	96	
	Filter–wheel motor coils	63	48	
	Filter–wheel posn sens	79	60	
	4K–thermoms	63	48	
	calibration sources (2)	126	96	
	chopper	94	72	
	+ insulation		≈ 220	

Table 20: Heatloads of the wires of the photoconductor instrument

For the thermal calculations involving the harness it is assumed that the wires are stainless steel with diameters of 50 μm, 100 μm, and 100 μm, for the 1.7–4, 4–20, and 20–300 K ranges, respectively. For shielded cables the total cross section is taken to be 2.5 × of the the total cross section of the inner conductor. The insulation is assumed to be P.T.F.E.

5.7 Overall power budget

5.7.1 Cold instrument

The heatload of the wires of the photocondutor instrument is given in Table 20. The average power loading on the various cold stages is summarised in Table 21.

Temperature	Internal dissipation	Conduction by structure	Conduction by wires and tubing	Radiation	Total	
					operation	standby
1.7 K	0.15 mW	0.07 mW	0.08 mW	$\leq$ 0.5 μW	~ 0.3 mW	~ 0.15 mW
4 K	2.9 mW	3.0 mW	0.3 mW	0.5 mW	6.7 mW	3.8 mW
"20 K"	3.5 mW				3.5 mW	

Table 21: Heatloads on the photoconductor instrument

Total heat loads in the focal plane for the PHOC 1.7 and 4 K areas; the radiative load on the 4 K stage does not include the heat load from the focal plane. The total 4 K load can be assumed to be delivered to the instrument/spacecraft interface on the 4 K bus bar. It is assumed that the instrument is mounted on a nominally 20 K cold plate, the dissipation only at this level is given. For information, calculations by the PWG indicate that conduction by wires and tubing put an additional load on the 20 K stage of 4 mW, and radiation of typically 10 mW.

The CRE is thermally decoupled from the 1.7 K stage. By that means the total power load of the CRE to the 1.7 K stage can be reduced to 150 μW. The remaining heatload of the CRE, 1.2 mW, is dissipated to the 4 K level. By connecting the detector block with 4 CFRP-tubes to the 4 K stage the power transfer of this structure to the 1.7 K stage is only 70 μW. A peak power dissipation of 150 mW is produced by operation of one of the F-P or filter wheels. A duty cycle of 1 % is assumed, giving an average dissipated power of 1.5 mW. The curing of the detectors will dissipate 10 mW with an assumed duty cycle of 2 %. This adds up to an average internal dissipation at the 4 K level of 2.9 mW. The chopping mirror, similar in design to the device built for the ISOPHOT instrument, dissipates 1.5 mW (assumed continuous). The calibration sources are assumed to dissipate 10 mW with a duty cycle of 5 %. Together with the second F-P wheel this leads to an average internal dissipation at the 20 K stage of 3.5 mW.

5.7.2 Warm instrument

The time averaged, as well as the peak, dissipation of each of the four (three) warm electronics boxes is estimated at 10 W giving a total of 40 (30) W. This applies, thus, to the analogue boxes (cooler control, mainly mechanism drives and mainly detector signals, respectively) and to the digital electronics box.

5.8 Data rate

The overall data rate will be less than 25 kbps. Assuming that each of the 256 pixels of the detctor array is sampled at 30 Hz (twice the maximum chopping frequency) with 16-bit resolution, a "raw" data rate of 123 kbps is generated. Realistic integration times per scan or sky position, however, will be > 0.2 s. On-board digital signal processing will, therefore, easily allow a reduction of this data rate to 20 kbps. Allowing 2 kbps for housekeeping data still keeps the total rate well within 25 kbps.

5.9 Instrument performance

5.9.1 Optical parameters

The plate scale at the detector array is chosen such that the telescope beam is fully sampled at 200 μm, i.e. $7''$/pixel. The field of view is, therefore, $112'' \times 112''$. The physical pixel size at the light cone array is 3.6 mm. The re-imaging optics illuminates the detector array with a focal ratio of f/35.

The internal chopper mirror allows the position on the sky to be switched by up to $\pm 5'$ at frequencies between 0.1 and 15 Hz.

5.9.2 Spectral resolution

The maximum resolving power of the high resolution Fabry-Pérot is a function of the collimated beam diameter and of the field of view. For a 60 mm diameter beam, a resolving power 3×10^4 (10 $\mathrm{km\,s^{-1}}$) is obtainable over a $70''$ diameter field of view, i.e. over half the array. Medium-resolution spectroscopy will be possible over the full array without any degradation.

5.9.3 Modes of operation

The instrument will provide four basic modes of operation: high-resolution spectroscopy, medium-resolution spectroscopy, narrow-band photometry and broad-band photometry. These modes will involve a total of 18 different combinations of F-P and filter wheel positions.

5.9.4 Sensitivity

The PHOC detectors will provide telescope-background limited performance for both the photometric and spectroscopic modes. Table 22 gives an overview of the NEPs for the different modes of operation, both referred to the detector and referred to the sky including all losses in the system. Note that the table does not include the overhead for scanning several resolution elements which will be necessary for most observations.

λ (μm)	R	Telescope efficiency	$\eta_{pixel}^{(a)}$	BLIP NEP$^{(b)}$ (W Hz$^{-1/2}$)	Det. NEP$^{(c)}$ (W Hz$^{-1/2}$)	Coupling$^{(d)}$ correction	System NEP (W Hz$^{-1/2}$)
100	3×10^4	0.5	0.81	12×10^{-18}	5×10^{-18}	49	6.3×10^{-16}
150	3×10^4	0.7	0.36	8×10^{-18}	5×10^{-18}	53	5.0×10^{-16}
200	3×10^4	0.7	0.20	6×10^{-18}	5×10^{-18}	71	5.5×10^{-16}
85 – 135	3	0.6	0.75	2.5×10^{-16}	5×10^{-18}	14	3.0×10^{-15}
135 – 200	3	0.7	0.3	1.3×10^{-16}	5×10^{-18}	19	1.4×10^{-15}

Table 22: Sensitivity of the PHOC instrument in different modes of operation

(a) The plate scale for the photoconductive array was chosen to achieve approximately full beam sampling. The light from a point source is therefore distributed over several pixels.

(b) The BLIP NEP is defined as the optical power incident onto the detector that produces a signal equal to the r.m.s. noise measured under the quoted background conditions. The quantum efficiency and generation/recombination noise are taken into account, but otherwise the detector is assumed to be noise free. The following assumptions have been made to calculate the BLIP NEP: The telescope has an emissivity of 4% at a temperature of 150 K; the transmission of the cold optics, τ_{cold}, was assumed to be 10% for spectroscopy and 30% for photometry, respectively. The detector quantum efficiency was assumed to be 30%. In the high-resolution mode, leakage from incomplete order sorting of the F-Ps has also been taken into account.

(c) The detector NEP is defined as the optical power equivalent to the intrinsic noise of the combination of detector and readout electronics under dark condition.

(d) The coupling factor is defined as $(\tau_{cold} \times \eta_{chop} \times \eta_{tel} \times \eta_{pixel}^{1/2})^{-1}$ where τ_{cold} is the transmission of the instrument as quoted above, η_{chop} is the chopping efficiency (0.45), and η_{tel} is the telescope efficiency as listed in the table. The factor $\eta_{pixel}^{1/2}$ takes into account that, for the photoconductive array, several pixels have to be coadded to recover the light from a point source. The system NEP is obtained by multiplying the geometric sum of the NEPs (background and detector) with the coupling factor.

6 The bolometer (BOL) instrument

6.1 Introduction

There are currently no photoconductors available for use as sensitive astronomical detectors for wavelengths longward of around 200 μm; bolometric detectors, which require much a lower operating temperature, must be used.

The FIRST bolometer (BOL) instrument is designed to perform spectroscopy over the 200 – 400 μm range, and continuum measurements (photometry) over a the 200 – 900 μm range, using Fabry-Pérot interferometers and bolometer detector arrays.

6.2 Scientific rationale

Cf. section 6.2. The wavelength region 200 – 400 μm is largely unexplored, and will not have been observed by *ISO* at all. Wavelengths between 200 and 350 μm are completely blocked by the Earth's atmosphere. There is a low-transparency window at 350 μm through which observations can be made from the ground, but only with great difficulty. The thermal emission of many astronomical sources peaks in this part of the spectrum (e.g., planets, star-forming cloud cores, star-burst galaxies). The short submillimetre region is also rich in atomic and molecular transitions which can be used to probe the physics and chemistry of these objects.

6.3 The bolometer instrument description

6.3.1 Overall capabilities

The BOL receiver will provide medium resolution imaging spectroscopy in the region 200 – 400 μm and imaging photometry in the region 200 – 900 μm. Two bolometer arrays are employed; the short wavelength (< 400 μm) array has 61 pixels, 25 of which are optimised for low background (spectroscopy) and the remaining 36 for high background (photometry), while the long wavelength array has 8 pixels. The nominal operating temperature of the bolometer arrays is 0.1 K.

The BOL can operate in two modes, which are characterised by the spectral resolution, R:

1. Medium resolution spectroscopy: $R = 1 - 3 \times 10^3$, in the wavelength range 200 – 400 μm.

2. Photometry: $R \approx 3$ in the wavelength range 200 – 900 μm.

6.3.2 Instrument description

The BOL instrument consists of:

1. A cold focal-plane unit, containing optics, Fabry-Pérots and filters. This unit will be mounted on the mechanical interface to the spacecraft, an optical bench at a temperature in the range 15 – 23 K depending on whether the cryostat or cryo-cooler option is chosen, and on the details of the spacecraft thermal design. Within the focal plane unit, cooling to lower temperatures (2 K and 0.1 K) is provided by the dilution refrigerator, which is part of the instrument.

The focal plane unit contains a 4 K enclosure which is connected via a heat strap either to the 4 K "thermal bus-bar" (cryo-cooler version) or to a 4 K shield (cryostat version).

2. A JFET module mechanically connected to the focal plane unit by rigid but thermally isolating supports. There ia a thermal connection to a higher temperature shield (15 – 120 K) to which the dissipated power is conducted.

3. A continuous flow expansion/dilution refrigerator system, comprising ^{3}He and ^{4}He gas storage tanks mounted on the outside of the payload module, and piping at intermediate temperatures down to 0.1 K.

4. Four warm electronics boxes located in the service module at 300 K (nominal temperature):

(i) Two analogue electronics boxes for the science data and control of the focal plane moving mechanisms.

(ii) A digital electronics box for data processing, instrument control and telemetry interface to the spacecraft.

(iii) An electronics box for the control of the dilution refrigerator system.

5. A cryo-harness connecting the warm and cold parts of the instrument.

6.3.3 Optical chain

The instrument is very similar to the PHOC and the focal-plane unit is shown schematically in Figure 12. A Fabry-Pérot (F-P) interferometer requires a parallel beam. The input optics define the instrument field of view and collimate the telescope beam. The chopping mirror M4 provides sky modulation. Three interchange wheels, similar in design to the *ISO* Long Wavelength Spectrometer F-P interchange wheel, allow filters and F-P interferometers (optimised for different wavelength ranges) to be selected. The first F-P wheel contains two medium-resolution F-Ps and an openposition. The second F-P wheel, contains two low-resolution F-P interferometers and an open position, while the filter wheel contains four broad-band photometric filters and an open position.

The function of the low-resolution F-Ps is to order sort the medium-resolution F-Ps. The filter wheel is mounted between the two F-P units, the filters serve to order-sort the low-resolution F-P. When both F-P wheels are in the open positions, photometry ($R \approx 3$) is available in a total of three bands by using the photometric filters and both bolometer arrays.

Having passed through the F-P and filter wheels, the beam is divided onto the two bolometer arrays by means of a dichroic. The two arrays operate nominally at 0.1 K. The short wavelength array has 61 hexagonally close-packed pixels, 25 of which have read-out electronics optimised for spectroscopy (low background), and the remaining for high background (photometry). The long wavelength array, which is used for photometry only, has 8 pixels. Each array also contains a reference bolometer which is blanked off from all incident radiation. The signals from these will be used to enable measurements of the total power on the detectors, and to monitor and compenste for temperature fluctuations of the 0.1 K stage.

6.3.4 Detector signal readout

Bolometric detectors require low-noise FET preamplifiers, and silicon JFETS are currently the best available transistors for the first stage. These do not operate below about 40 K, and have best noise performance at temperatures of 100 – 150 K. To minimise electrical pick-up and potential microphonic effects, it is essential to have the first stage JFETs as close to the detector elements as possible. The thermal budget for the low temperature stages does not permit the JFETs to

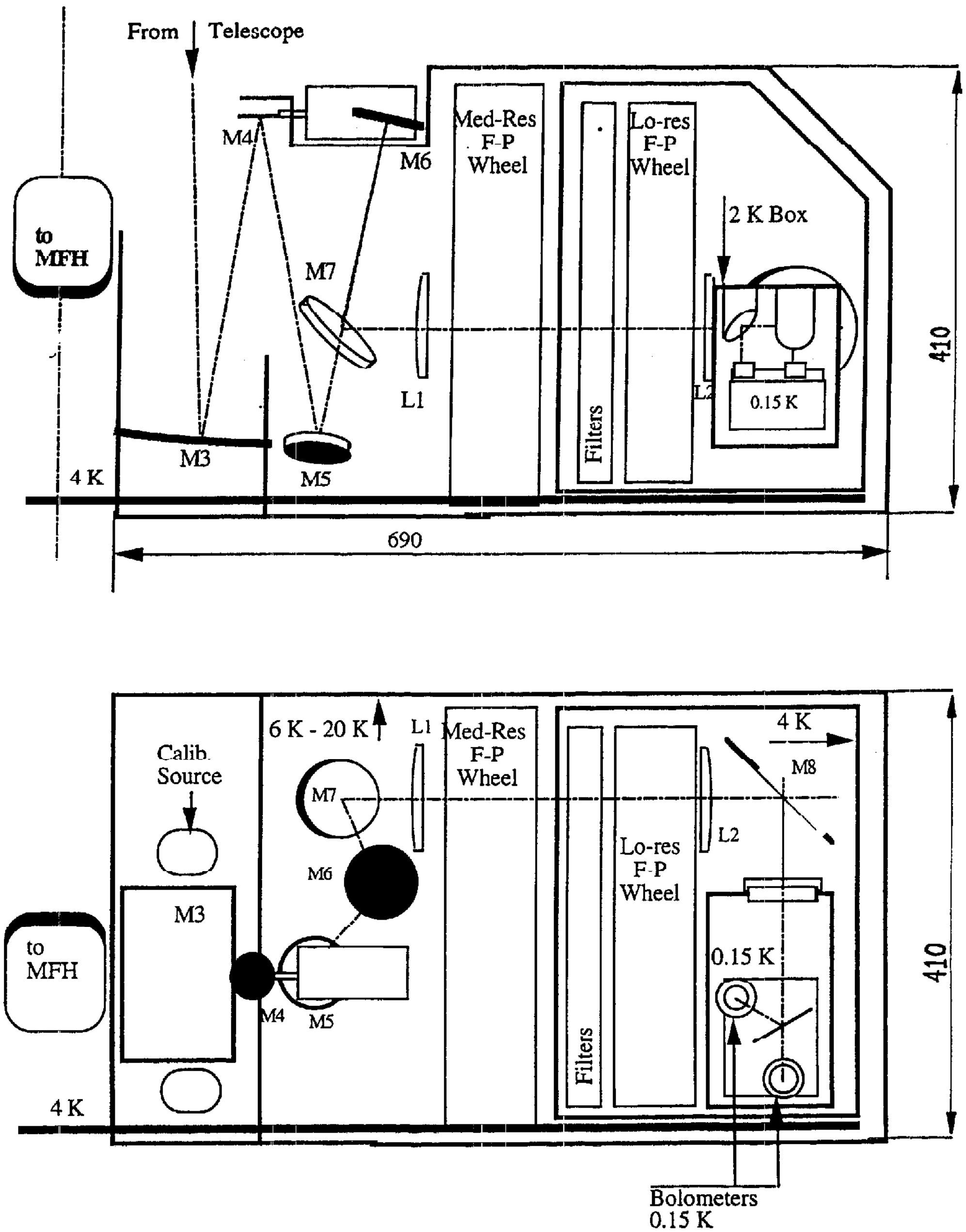

Figure 12: Optical scheme of the bolometer instrument

Schematic figure of the BOL instrument. The f/10 beam from the telescope secondary is incident on M3. Sky chopping is effected by the wobbling mirror M4. The beam is collimated, passed through the Fabry-Pérot and filter wheels, and re-imaged onto the detector arrays with a final focal ratio of f/4.5. The detector arrays are contained in a 2 K enclosure, and maintained at 0.1 K by the dilution refrigerator.

be located on any of these. A JFET module will therefore be thermally connected to a shield at temperatue of $\leq$ 100 K but mechanically mounted on the outside the focal-plane unit 4 K box by rigid but thermally insulating supports.

Inside this module, the JFETs themselves will be mounted on a thermally isolated stage and heated to their optimum operating temperature of about 120 K. The stability of this stage will be maintained by the instrument. Heating of the JFETs will dissipate 6 mW, which together with their operating dissipation of 25 mW will be a load on the shield to which they are thermally connected. The estimated load on the 4 K stage due to the JFET module is 1 mW.

6.3.5 Dilution cooler

Since the detector arrays need to operate at lower temperatures than can be provided by the spacecraft, the BOL instrument has its own internal refrigerator. The principle of operation is an open cycle ^{3}He/^{4}He expansion/dilution effect which is independent of gravity, and the dilution refrigerator will be responsible for providing cooling from the 2-K stage (cryostat option) or 4 K stage (cryo-cooler option) to the nominal operating temperature of the bolometer arrrays of 0.1 K.

The dilution effect, which has been demonstrated for liquid cryogen pre-cooling, in an open cycle for ± 1 g conditions at the CRTBT Grenoble, stems from the fact that the enthalpy of ^{3}He in a dilute phase of a ^{3}He/^{4}He mixture is larger than in the concentrated phase. Thus, when ^{3}He atoms are transferred from a concentrated phase into a dilute phase cooling will result according to the enthalpy difference of the two phases. Such a separation of phases, into a ^{3}He rich (concentrated) and a ^{3}He poor (dilute), occurs automatically for ^{3}He/^{4}He mixtures below 0.8 K, and a finite percentage of ^{3}He in the dilute phase down to absolute zero allows cooling to continue even at mK temperatures where the saturated vapour pressure of even ^{3}He is negligible.

The open cycle dilution refrigerator is extremely simple. It consists of helium gas storage tanks with flow rate control valves mounted on the outside of the payload module, and two separate fully redundant helium supply systems:

1. Four gas storage tanks (two for ^{4}He (35.5 l at 265 bar) and two for ^{3}He (18.3 l at 110 bar)) with flow rate control valves and control electronics mounted on the outside of the payload module.

Items 2. to 7. below are duplicated, thus, comprising two completely redundant helium tubing and heat exchanger systems.

2. Helium piping, three CuNi tubes with 0.6 mm outer and 0.3 mm inner diameter all the way from 300 K to 2 K.

3. Cold trap and heat exchanger at 50 − 70 K, size $1.5 \times 3 \times 5$ cm^3, made of copper. Minimum length of tubing from ambient is 50 cm.

4. A similar heat exchanger at $\sim$ 20 K, minimum length of tubing from 50 − 70 K heat exchanger is 25 cm.

5. Another similar heat exchanger at 4 K, minimum length of tubing from $\sim$ 20 K heat exchanger is 100 cm.

6. Heat exchanger and J-T expansion at 2 K (not needed for the cryostat option), minimum length of tubing from 4 K heat exchanger is 10 cm.

7. 2 K to 0.1 K heat exchanger internal to the instrument and thermally linked with the electrical wiring.

6.4 Mechanical and thermal design

The BOL instrument is designed to provide the necessary low operating temperatures for its various components while keeping the power loading on the liquid helium bath or the 4 K thermal bus-bar to within strict limits.

The cooling requirement of the filter wheel stage (the box that contains the filter wheel and the last Fabry-Pérot wheel) results from photon noise considerations. The photon noise produced by this thermal stage in the different bands must be less than that produced by other unavoidable sources (self-emission from the telescope and the M3–M7 mirrors). Table 23 shows the photon noise produced on the detectors of the two arrays by the "filter wheel stage" compared to that produced by the "unavoidable" sources only.

It is clear from this table that, for a temperature of 6 K, the filter wheel stage would be the dominant source of photon noise; this is not acceptable. Any temperature higher than 4.5 K is unacceptable for the filter wheel stage. It is assumed that filters at 2 K are used in front of the detector arrays. In the cryostat option, these filters and the 2 K box will be cooled by a thermal strap to the liquid helium bath. In the cryo-cooler option, cooling to 2 K is provided by the dilution refrigerator.

Mode	Photon noise T=4 K $W\,Hz^{-1/2}$	Photon noise T=6 K $W\,Hz^{-1/2}$	Photon noise (unavoidable) $W\,Hz^{-1/2}$
280 – 400 μm (spectroscopy)	4.1×10^{-18}	2.5×10^{-17}	6×10^{-18}
600 – 900 μm (photometry)	3.0×10^{-17}	8.4×10^{-17}	7.5×10^{-17}

Table 23: Photon noises
Photon noise originating from the filter wheel stage assumed at 4 K and at 6 K, compared with the "unavoidable" noise originating from the self-emission of the telescope and the internal mirrors in front of the filter wheel stage, for a spectroscopic and a photometric mode.

The temperature requirements are given in Table 24, and the dimensions and masses of the principal instrument units are given in Table 25.

Subsystem	Interface temperature	Temperature stability timescales		
		1 s	10 s	100 s
Bolometer arrays	≤ 0.1 K	will be maintained by instrument		
2 K shield	$\leq$ 2 K	will be maintained by instrument		
4 K cooling bus	≤ 4.3 K	0.1 mK	1 mK	10 mK
20 K cooling bus	$\leq$ 23 K	0.3 mK	3 mK	30 mK

Table 24: BOL/spacecraft interface temperature and temperature stability requirements
The temperature and temperature stability requirements for various BOL/spacecraf interface points and units. These numbers assume a damping of at least a factor of 10 between the the 4 K interface and filter, and a factor of at least 4 between the 20 K interface and mirrors.

Unit	# of	Dimensions (mm)	Mass (kg)
Focal plane instrument unit	1	cf. Fig. 12	23
JFET box	1	100 × 100 × 100	(*)
^{4}He tanks including gas	2	diameter 432	9
^{3}He tanks including gas	2	diameter 352	5
Valves, piping, etc.			6
Warm analogue electronics	2	200 × 200 × 100	3
Warm digital electronics	1	200 × 200 × 100	4
Warm dilution cooler control box	1	200 × 200 × 160	4
Cable harness			1
Total			72

Table 25: Bolometer instrument dimensions and masses

Dimensions and masses for the BOL subunits, the values given include margins. (*)The JFET box has a mass of approximately 700 g, it is mechanically but not thermally connected to the focal-plane unit and therefore included in its mass.

6.5 Alignment requirements

There are absolute alignment requirements, and requirements of stability as follows:

Absolute:	Δx, Δy, Δz:	±1 mm
	$\Delta\theta_x$:	±5′
	$\Delta\theta_{yz}$:	±3′ (combined)
Stability:	Δx, Δy, Δz:	±0.1 mm over 1 hour
	$\Delta\theta_x$:	±3′ over 1 hour
	$\Delta\theta_{yz}$:	±1′ (combined) over 1 hour

6.6 Harness

Electrical leads to the cold focal plane unit are needed to provide power to the cold electronics, read out the detector signals, control the instrument mechanisms and monitor various housekeeping parameters. For the preliminary instrument design, the numbers of wires between the various temperature stages are given in Table 26. For a more detailed description, cf. Appendix 1.

6.7 Overall power budget

6.7.1 Cold instrument

As for the PHOC a peak power dissipation of 150 mW is produced by operation of one of the F-P or filter wheels. A duty cycle of 1 % is assumed, giving an average dissipated power of 1.5 mW. The chopping mirror, similar in design to the device built for the ISOPHOT instrument, dissipates 1.5 mW (assumed continuous). The calibration source is assumed to dissipate 10 mW with a duty

Route	# of wires	# of shields
0.1 – 4 K	308	31
4 – "20 K"	472	73
"20 K" – ambient	562	89

Table 26: Bolometer instrument electrical connections

For the thermal calculations involving the harness it is assumed that the wires are 40 μm constantan, 30 mm long; 40 μm stainless steel, 30 mm long; and 100 μm stainless steel, 50 mm long; for the 2–4, 4–"20", and "20"– (assumed) 50 K ranges, respectively. For shielded cables the total cross section is taken to be 2.5 × cross section of the inner conductor. It is believed that these lengths are underestimates, thus making the computed power loads pessimistic.

Temp.	Internal dissipation	Cond. by structure	Conduction by wires & tubing	FET box	Radiation	Total (operating)	(standby)
0.1 K	3 nW	81 nW	5 nW		0.3 nW	< 0.1 mW	< 0.1 mW
2 K	< 0.1 mW	2 mW	< 0.1 mW		0.1 mW	2.3 mW	2.3 mW
4 K	3.7 mW	2.2 mW	0.6 mW	1 mW	0.3 mW	7.8 mW	4.1 mW
"20 K"				31 mW		31 mW	31 mW

Table 27: Heatloads on the bolometer instrument

Total heat loads in the focal plane for the BOL 0.1, 2, and 4 K areas; the radiative load on the 4 K stage does not include the heat load from the focal plane. The total load on the 4 K stage will be delivered to the instrument/spacecraft interface on the 4 K bus bar. It is assumed that the instrument is mounted on a nominally 20 K plate, only the dissipative load on this stage is given. For information, the conductive load by wires and tubing on the 20 K stage was calculated by the PWG to be 32 mW. Note that for the cryo-cooler version, the cooling at 2 K is provided by the instrument itself.

cycle of 5 %. Taken together this adds up to an average internal dissipation at the 4 K level of 3.7 mW.

The first stage of the preamplifiers dissipate a total of 31 mW. Should their load on the "20 K" stage be unacceptably high, it would be acceptable, but not preferable, to mount the JFETs on the next higher temperature shield.

6.7.2 Warm instrument

Both the time-averaged and peak dissipation of each the four warm electronics boxes are estimated at 10 W. This is true for the analogue boxes (mainly mechanism drives and detector signals, respectively), the dilution control electronics box, and the the digital electronics box, thus giving a total dissipation of 40 W.

6.8 Data rate

The overall data rate will be less than 15 kbps. Calculating for a mode in which all 69 pixels are used simultaneously, and assuming that each detector is sampled at 10 Hz with 16-bit resolution, 11040 bits/s are generated. Allowing 2 kbps for housekeeping data, the total adds up to well within 15 kbps.

6.9 Instrument performance

6.9.1 Optical parameters

The plate scale for the short wavelength bolometer array ($200 - 400\ \mu$m) is $25''$/pixel resulting in a hexagonal field of view of diameter $225''$. The plate scale for the long wavelength array ($400 - 900$ μm) is $56''$/pixel with a field of view of diameter $200''$.

The internal chopper mirror allows the position on the sky to be switched by up to $3'$ at frequencies between 0.1 and 15 Hz.

6.9.2 Spectral resolution

The maximum resolving power of the high resolution Fabry-Pérot is a function of the collimated beam diameter and of the field of view. For a 60 mm diameter beam, a resolving power 3×10^3 ($100\ \mathrm{km\,s^{-1}}$) is obtainable over all pixels of the short wavelength bolometer array.

6.9.3 Modes of operation

The instrument will provide two basic modes of operation: medium-resolution spectroscopy and photometry. There are two sub-modes for spectroscopy and three sub-modes for photometry. They are listed in Table 28. One submode uses both bolometer arrays to cover the wavelength ranges $280 - 350\ \mu$m and $350 - 600\ \mu$m simultaneously.

Filter bands	Wavelength range	Mode$^{(a)}$	Detector$^{(b)}$
1	$210 - 280\ \mu$m	medium-resolution spectroscopy	SWB
1	$280 - 400\ \mu$m	medium-resolution spectroscopy	SWB
1	$210 - 280\ \mu$m	photometry	SWB
1	$280 - 600\ \mu$m	photometry	LWB+SWB
1	$600 - 900\ \mu$m	photometry	LWB

Table 28: Modes of operation

Modes of operation. $^{(a)}$*Medium-resolution spectroscopy has* $R = 1 - 3 \times 10^3$, *and photometry has* $R \approx 3$. $^{(b)}$*SWB: short-wavelength bolometer; LWB: long-wavelength bolometer.*

6.9.4 Sensitivity

With currently available bolometer technology, BLIP operation will only be possible in the photometry mode, while the spectroscopy mode will be limited by detector noise. Table 29 gives an overview of the NEPs for the different modes of operation, both referred to the detector and referred to the sky including all losses in the system.

λ (μm)	R	Telescope efficiency	η_{pixel}	BLIP NEP[(a)] (W Hz$^{-1/2}$)	Det. NEP[(b)] (W Hz$^{-1/2}$)	Coupling[(c)] correction	System NEP (W Hz$^{-1/2}$)
250	3×10^3	0.7	1	4.2×10^{-18}	2×10^{-17}	32	6.4×10^{-16}
210 – 280	3	0.7	1	2.4×10^{-16}	2×10^{-17}	11	2.6×10^{-15}
280 – 380	3	0.7	1	1.4×10^{-16}	2×10^{-17}	11	1.5×10^{-15}
380 – 600	3	0.7	1	1.8×10^{-16}	2×10^{-17}	11	2.0×10^{-15}
600 – 900	3	0.7	1	7.5×10^{-17}	2×10^{-17}	11	0.8×10^{-15}

Table 29: Sensitivity of the BOL in different modes of operation

(a) The BLIP NEP is defined as the optical power incident onto the detector that produces a signal equal to the r.m.s. noise measured under the quoted background conditions. The quantum efficiency is taken into account, but otherwise the detector is assumed to be noise free. The following assumptions have been made to calculate the BLIP NEP: The telescope has an emissivity of 4% at a temperature of 150 K; the emissivity of the 65 K optics is 1% and that of the 23 K optics is 10%. The transmission of the cold optics, τ_{cold}, was assumed to be 10% for spectroscopy and 30% for photometry, respectively. The detector quantum efficiency was assumed to be 80%.

(b) The detector NEP is defined as the optical power equivalent to the intrinsic noise of the combination of detector and readout electronics under dark condition.

(c) The coupling factor is defined as $(\tau_{cold} \times \eta_{chop} \times \eta_{tel} \times \eta_{pixel}^{1/2})^{-1}$ where τ_{cold} is the transmission of the instrument as quoted above, η_{chop} is the chopping efficiency (0.45), and η_{tel} is the telescope efficiency as listed in the table. The system NEP is obtained by multiplying the dominant NEP (either background or detector) with the coupling factor.

JML Report11

From: J-M Lamarre
To: FIRST PWG

January 26, 1995

Wires routing:

0.1 K to 4K **Detectors, thermometers, Dilution**

	Nb of Wires	Nb of Shields
69 bolometers	276	27
2 Blanked bolometers	8	1
4 Thermometers (0.1 K, 1.6 K)	16	2
Dilution control	8	1
Total	308 wires	31 shields

4 K to 20 K **Detectors, thermometers and Fabry-Perots**

	Nb of Wires	Nb of Shields
69 bolometers	276	27
2 Blanked bolometers	8	1
4 Thermometers (0.1 K, 1.6 K)	16	2
Dilution control	8	1
2 Fabry-Perots (LR and HR)	96	32
3 Fliter Wheels	36	6
8 Thermometers	32	4
Totals	472 wires	73 shields

20 K to Warm electronicsThe same plus J-FETs temperature control

	Nb of Wires	Nb of Shields
69 bolometers bias -grounds	207	27
2 Blanked bolometers	6	1
J-FET supply	11	1
JFET sources	71	14
JFET grounds	71	0
JFET Temperature control	8	1
4 Thermometers (0.1 K, 1.6 K)	16	2
Dilution control	8	1
2 Fabry-Perots (LR and HR)	96	32
3 Fliter Wheels	36	6
8 Thermometers	32	4
Totals	562 wires	89 shields