

HARP-B

Project Overview

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Notes on this document

The document FDR02 was itself an edited version of a paper presented at the SPIE conference on 'Astronomical Telescopes & Instrumentation' Waikoloa, HI, USA, August 2002. The author list on that paper was as follows:

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Many other people have contributed to the design and development of HARP-B since the date of that paper, including Graham Bell, Jane Buckle, and Rob d'Allesandro at MRAO, and Craig Walther at the JAC.

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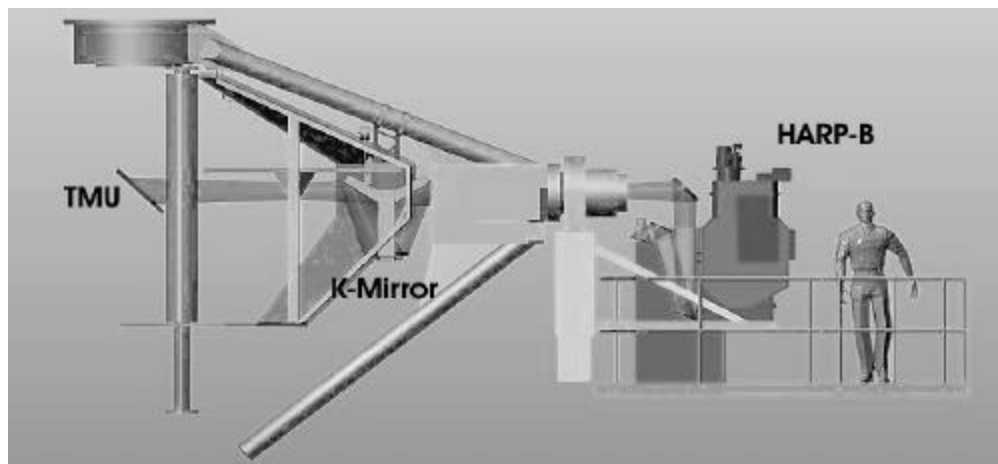
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INTRODUCTION

1.1 Project history

In late 1998 a proposal was submitted to the JCMT board for the funding of a programme to provide the JCMT with two heterodyne focal plane imaging arrays working at ‘B’ and ‘D’ bands – the ‘Heterodyne Array Receivers Programme’ (HARP). It was envisaged that each array would occupy its own cryostat (this unit being referred to as a ‘camera’), and be positioned on the right hand Nasmyth platform of the JCMT. The cameras would share a common set of fore optics bringing the beam out of the telescope via an image de-rotator and through the RHS bearing/encoder unit. The image de-rotator (now termed the ‘HARP K-Mirror’), fore-optics and the ‘B’ camera came to be known as ‘HARP-B’. A collaborative group led by the MRAO (part of the Astrophysics Group of the Cavendish Laboratory), in conjunction with the UK-Astronomy Technology Centre (UK-ATC), the Herzberg Institute of Astrophysics (HIA) and the Joint Astronomy Center (JAC) then produced a conceptual design for HARP-B, the funding for which was secured in late 1999. An image of the configuration on the JCMT is shown in Figure 1.



1.2 Scientific drivers

HARP-B offers a front-rank heterodyne observing facility at the world’s largest sub-mm telescope. Working in conjunction with the new ‘ACSIS’ correlator & imaging system^[1,2], HARP-B provides spectral-line imaging capability with high sensitivity at 325 to 375GHz. This is the first sub-mm spectral imaging system on JCMT - complementing the continuum imaging capability of SCUBA-2 – and affording significantly improved productivity in terms of speed of mapping. It offers the opportunity for a wide-ranging scientific programme including:

- ? Large-scale unbiased surveys of star formation and outflows in molecular clouds
- ? Large-scale studies of hierarchical structure and clumping in molecular clouds
- ? The dynamics and excitation of the molecular gas in the Galactic Centre
- ? The distribution and properties of molecular clouds in face-on and edge-on galactic disks, starburst and Seyfert galaxies, and interacting galaxy systems
- ? Studies of the chemical processing of molecular clouds by shocks and turbulence
- ? The chemical and physical state of comets near perihelion

1.3 Core Specification

The following list gives the core specification for HARP-B:

- ? A 16-element array in a 4x4 configuration, where the combination of the receiver noise temperature and beam efficiency, (T_{rx}/η_{beam}), averaged across the array is better than 330 K SSB for the central 20 GHz of the tuning range, including the CO (3-2) line.
- ? A frequency tuning range of 325 – 375 GHz.
- ? IF centre frequency (5GHz) and bandwidth (>1.6GHz) compatible with the ACSIS backend system
- ? A calibration system and optics that have load temperatures and efficiencies stable and uniform enough to make 5% inter-pixel calibration possible.
- ? Beam positions known to accuracy better than 1/10 of the beam width.
- ? Hardware image de-rotation.

A control system and associated hardware that can tune and make the array ready for operation within 5 minutes.

2 MANAGEMENT & ORGANISATION

The HARP-B project is a significant undertaking across 5 sites in 4 countries. The project was therefore set up with formal project management and the appropriate requirements for planning and reviews. The structure adopted was that of a collaborative consortium composed of MRAO, UK-ATC, HIA and JAC, with the SIS junctions fabricated by DIMES under contract to JAC. Under this arrangement, MRAO performed the project management and took the scientific lead. MRAO therefore specified the technical details and interfaces for the entire project, and held overall responsibility for the final delivery and commissioning. UK-ATC, HIA and JAC had responsibility for several key areas within the overall project, which for management purposes was broken down as far as possible into individual workpackages with clean interfaces that could proceed independently. The main workpackages and responsibilities are shown in Figure 2.

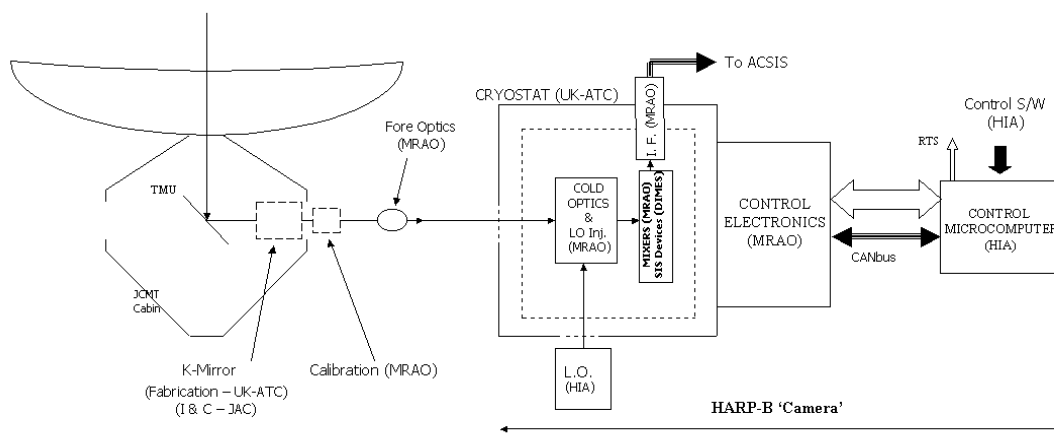


Figure 2 - Diagram showing responsibilities for the HARP-B workpackages

3 TECHNICAL OVERVIEW

3.1 K-Mirror

The unit consists of three mirrors mounted close to the right-hand stub-axle of the telescope. The mirrors are labeled M1, M2 and M3 in the order in which they are encountered by the beam from the sky. The K-mirror performs two functions: it forms an image of the secondary mirror at a point near the elevation encoder; and it acts as an image (and polarization) rotator. The minimum requirement is to provide for the needs of the HARP-B receiver, but the K-mirror may be used for other future instruments. These may have rather different requirements, especially with regard to the surface finish of the mirrors and the field of view. The mirror surfaces have therefore been specified to a finish which makes them compatible with the highest operational frequencies of the JCMT. The K-mirror rotates as a unit about the elevation axis (y-axis) of the telescope. Movements are defined in terms of the angle of rotation of the unit (θ_K) around this axis (note that the effective rotation of the image and polarization is twice this angle). The K-mirror is shown in Figure 3.

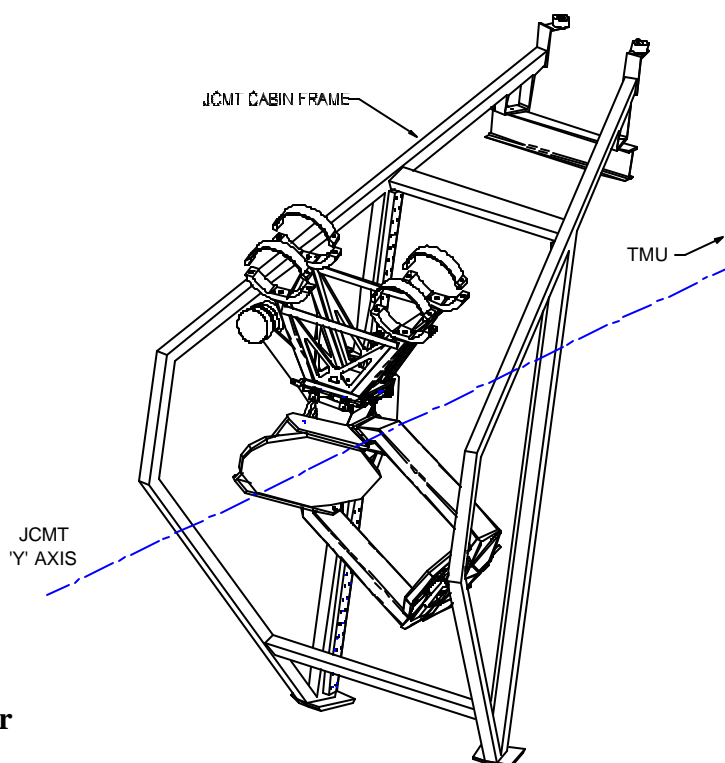


Figure 3 - The HARP K-Mirror

The K-mirror was completed at UK-ATC in June 2002 and installed in the JCMT cabin in July 2002. Its key specifications are as follows:

? Accuracy of θ_K	+/- 0.1 deg
? Range of rotation	± 58 deg
? Speed of rotation	5 deg/sec
? Acceleration in θ_K	5 deg/sec ²

3.2 Optics and Calibrator

A schematic of the HARP-B optics & calibrator system are shown in Figure 4. There are four powered mirrors between the encoder and the array and these are optimized together to take advantage of aberration balancing and deliver the best possible images at the array consistent with other requirements. A two-mirror relay system (M4 & M5) forms an image of the focal plane just behind the cryostat window and a pupil on the cold stop, which is well inside the cryostat. The cold stop is reflective (i.e. a mirror surrounded by cold absorber) and slightly curved. This curvature and that of the mirrors in the Mach-Zehnder interferometer form an image of the sky with low aberrations at the detector array.

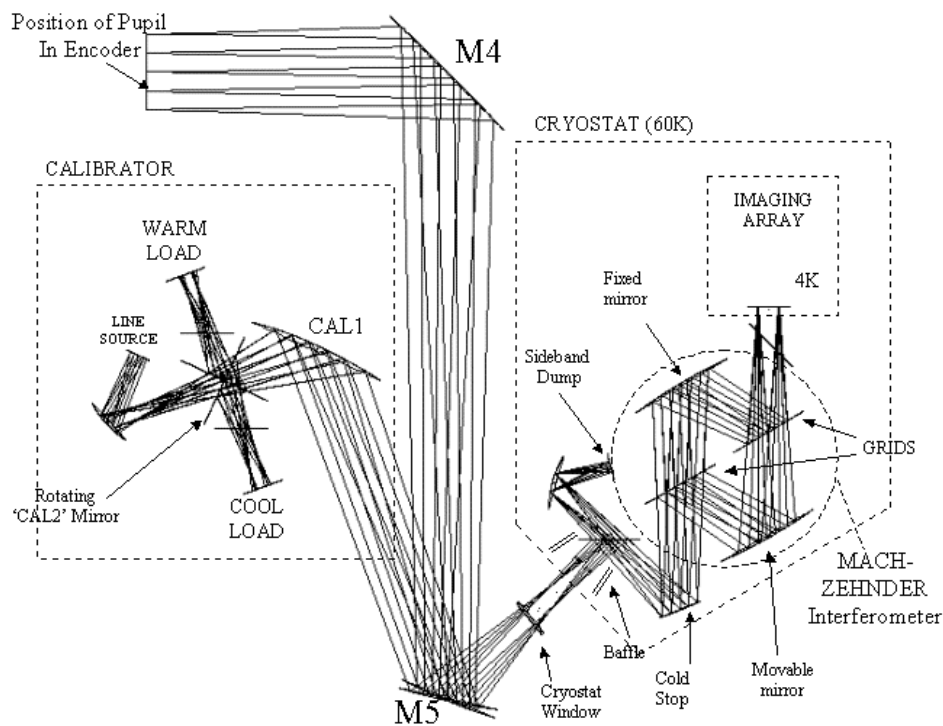


Figure 4 - The HARP-B Optics & Calibrator System

Note that the line source is shown as above for clarity. In the real system it is injected from a point perpendicular to the plane of the paper above the centre of CAL2

3.2.1 Cold Optics

To obtain the best sensitivity it is necessary for the instrument to operate in a single-sideband mode and for the image sideband to be terminated in a load that is as cold as possible. Because the optics required to achieve sideband separation inevitably have some losses and because there are also losses involved in going into and out of a cold vacuum space, there is a substantial sensitivity advantage in placing the single-sideband filter inside the cryostat. The SSB filter takes the form of a polarizing Mach-Zehnder Interferometer with two fixed wire grids and two curved mirrors, one of which is moved to achieve the desired path difference such that the desired signal is transmitted and the image frequency rejected. In addition to the SSB filtering other factors which were taken into account in arriving at this scheme were the blocking of IR radiation, the cold "stop" to reduce side-lobes, the injection of the Local Oscillator signal and the provision of low-loss vacuum windows. The large through-put of the

instrument means that it is necessary to make these optics quite large, and they are therefore the dominant factor in determining the size of the cryostat and the layout of the optics. The bulk of the cold optics operate at $\sim 70\text{K}$ and the termination for the image sideband and the cold stop are at about 12K .

3.2.2 Calibrator

To perform calibration measurements or for optimizing the instrument, the lower relay mirror (M5) is mechanically tilted so that the receiver “looks” into the Calibrator unit. A mirror (CAL1) collects the beams and focuses them onto the calibration loads via the flat switching mirror CAL2. There are two loads: “cold” and “hot”. The cold load operates at a temperature which is close to that of the absorbing material in the atmosphere (typically $\sim 10\text{K}$ below the ambient temperature at ground level), while the hot load is at about 40K above ambient. For a calibration during normal observing, CAL2 is set pointing at the cold load and M5 is flipped rapidly to its ‘calibrate’ position where a total power and/or spectrum measurement is made. It is then flipped back to the Sky. This two-load calibration takes only a few seconds and should be sufficient to give the system temperature to an accuracy of a few percent. To obtain a value for the receiver temperature, and also for tasks that require separate knowledge of sky brightness (e.g. sky dips) CAL2 is also switched to the hot load and a second measurement is made. The three-load calibration takes a few more seconds.

In addition, a low-power narrow-band coherent signal can be injected into the receiver from the calibration unit by switching CAL2 to a third position. This signal is used for tuning and optimization procedures and can also serve as a more general test signal. It is produced by a broad-band multiplier and YIG oscillator, the frequency of which is adjustable to anywhere in the band of the receiver within a few seconds (with moderate resolution and high accuracy). The optical arrangement is such that the signal is distributed to all the mixers, although a high degree of uniformity is not required. To avoid linearity issues, the power in this signal is only a modest fraction of the total power signal across the full IF band, but it can be detected with high signal-to-noise ratio on a spectrum analyzer or with ACSIS. The signal is narrow band and can therefore be used to set up and calibrate the Mach-Zehnder SSB filter. It is also possible to modulate it rapidly, by purely electronic means, so that a continuous read-out of the signal-to-noise ratio can be obtained while adjustments are being made. The calibrator is a self-contained unit, mounted directly onto the telescope framework. All of its functions are controlled or monitored electronically via the CANbus.

3.3 Imaging Array Unit

The HARP-B ‘imaging array’ unit consists of an array of mylar beam splitters for LO injection, two decks of 8 horn-reflector antennas holding 16 radial-probe mixers, with air-cored coils for Josephson current suppression, and 16 HEMT cold IF amplifiers with isolators and bias tees. The overall assembly is shown in Figure 5. This unit is physically independent of the cold optics, so that maintenance and upgrades can be carried out easily.

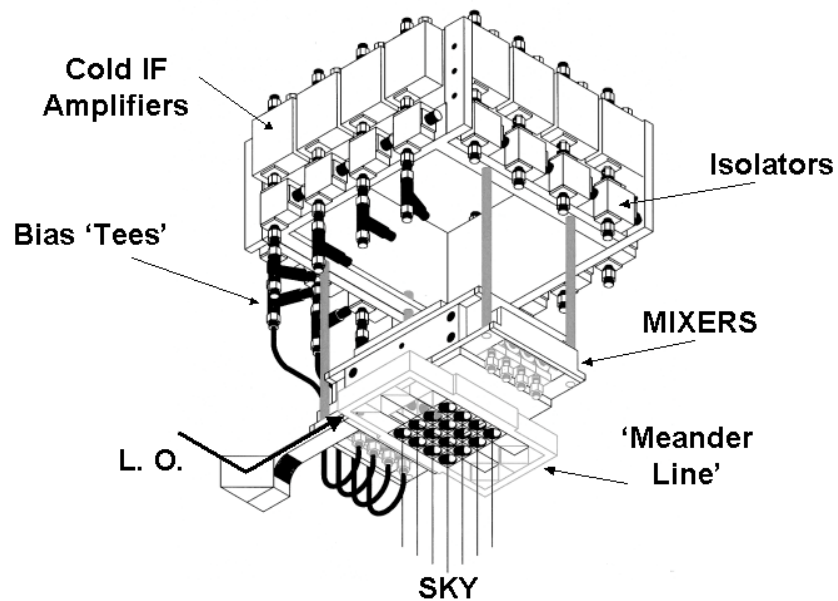


Figure 5 - HARP-B Imaging Array

3.3.1 SIS Mixer Design

Work at MRAO on designing & developing SIS devices for HARP-B has concentrated entirely on the radial-probe design (see Figure 6).

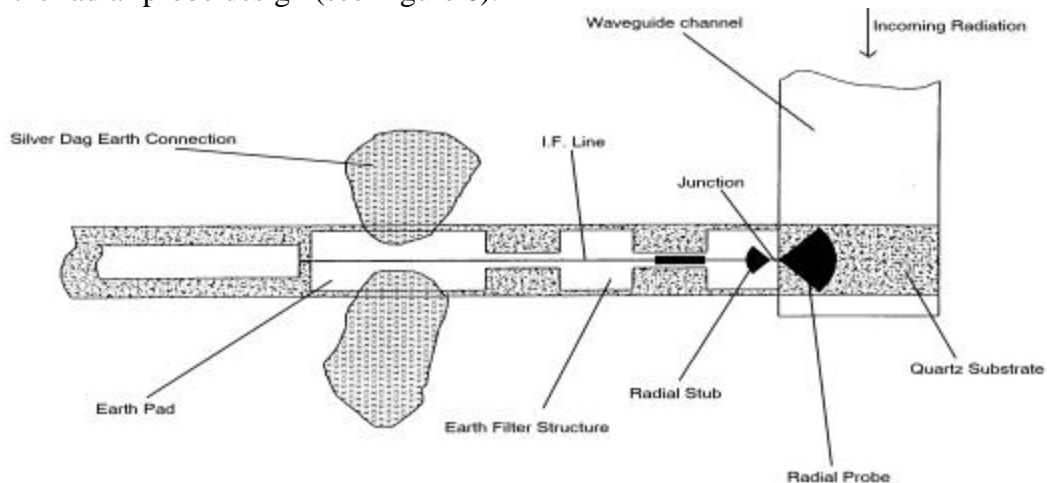


Figure 6 - Radial probe SIS mixer device

These mixers give broadband operation without the need to reduce the height of the waveguide. In the radial-probe mixer, a single-sided radial probe extracts power from a rectangular waveguide. Radial probes are able to match tunnel junctions to full-height waveguide, with a return loss of better than -25dB , over the whole of the waveguide band. One of the other advantages of the radial-probe mixer is that many devices are fabricated during a single device processing run, and these devices should have similar characteristics.

The basic imaging 'pixel' is based on the horn-reflector antenna. That is to say each mixer consists of a corrugated waveguide horn with a reflector mirror at its aperture. This

arrangement produces well-collimated beams with a high degree of efficiency. The reflectors are designed to produce a focal plane slightly in front of the array, commensurate with the requirements of the LO injection system. For HARP-B, the feed-horn, waveguide, device and IF slots forming a ‘mixer’ are manufactured as split aluminium blocks, which are gold sputtered as a finishing process. The blocks are light-weight, low thermal mass, free from waveguide flanges and straight-forward to machine. The corrugated feed-horns are machined directly into the split blocks. The horn design has been refined to make the manufacturing process as fast and reliable as possible, using a design that has fewer corrugations per wavelength and constant depth slots along the whole of the length, compared to a classical design. Air-cored superconducting coils are used at the back of the blocks to suppress Josephson currents.

3.3.2 LO Injection Unit

An array of small Mylar beam splitters was adopted for reasons of bandwidth and ease of fabrication. The LO beam is folded back and forth across the array, passing through the Mylar beam splitters as it goes. This unit is termed the ‘meander line’. The horn-reflector antennas produce quite well-collimated beams and the beam splitters are as close as possible to their projected apertures. This arrangement has a large RF bandwidth, and injects LO power in a highly efficient manner. A major problem when designing any LO injection scheme is ensuring that LO power is injected reasonably uniformly across the array, although the performance of SIS mixers is relatively insensitive to LO power. We have taken a range of $\pm 15\%$ variation in the LO coupling as the goal. As we cannot control the LO power into each mixer individually, it is important to ensure that all of the SIS devices behave in a similar way.

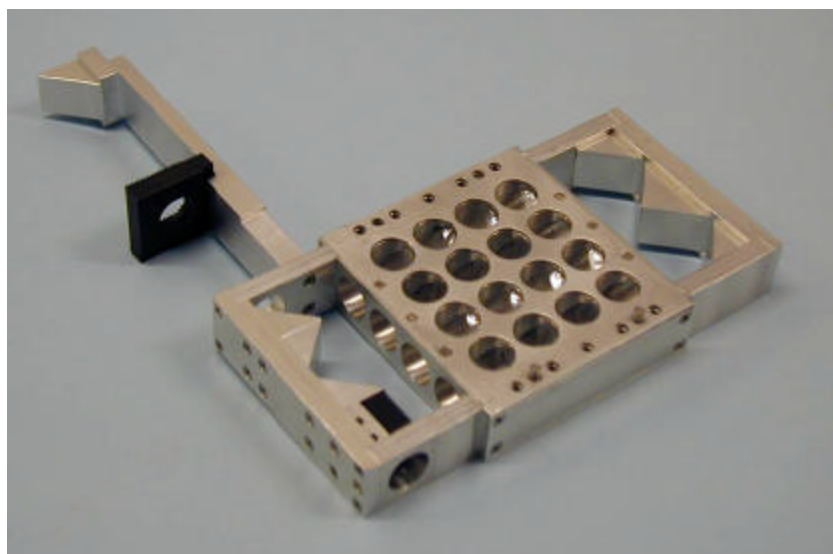


Figure 7 – The LO Injection Unit

The LO meander line is easy to understand in principle, but was quite difficult to design in practice. However, the final unit is compact and reasonably straightforward to manufacture. It was found necessary to pretension the Mylar in the beam-splitters to ensure that it remains tight when cooled. It is bonded to the aluminium frames that make up the unit.

3.4 I.F. System

Each pixel of the IF system consists of five units: a bias tee/isolator/cold and IF amplifier connected to the 4K stage, plus two warm IF amplifiers separated by a bandpass filter and a fixed level setting attenuator. The warm sections are mounted externally on the top of the cryostat. The co-axial interconnecting cable from the 4K stage to the wall of the cryostat has both inner and outer made of stainless steel to minimize heat load on the 4K stage. The IF signal loss between the output connectors of the cold IF amplifiers and the vacuum vessel wall is less than 5dB. A centre frequency of 5GHz has been chosen and the 3dB IF bandwidth is ~2GHz. The overall mid-band gain is a minimum of 75dB and the noise temperature at the input to the IF chain is ~7K. The final warm IF amplifier has a simple total power detector built in, to allow setting-up and performance optimization without the need for the ACSIS system to be connected.

3.5 Local Oscillator

The primary function of the LO system is to generate a signal in the range from 330-370 GHz with a minimum power level of 1 mW, with a high resolution in frequency (<30 KHz) and with a switching time of less than 1ms, compatible with observing requirements. It is an automated system capable of tuning the frequency and varying the power level of the LO signal by up to 15dB under computer control without any operator intervention.

The system comprises three major subsystems, the LO Chain, motorized micrometer control system, and a micro-controller performing control functions. The LO Chain is the RF system that generates the local oscillator signal. A Gunn Oscillator is used to generate a signal between 109-124 GHz. A portion of the signal is mixed down to a lower frequency and fed into the all-digital phase-lock system. The PLL compares this with a ~350 MHz reference frequency from a PTS frequency synthesizer and produces a servo bias voltage to phase-lock the Gunn output. A frequency tripler is used to convert the microwave RF signal to a B-band LO signal to be fed to the LO injection system of the mixer array through a feedhorn. Two micrometers are available to tune the frequency and the coupling efficiency of the Gunn output. The frequency multiplier is also equipped with two micrometers to adjust the coupling efficiency of its input and output. A motorized control system based on the Galil DMC2140 controller is used to control the four tuning micrometers. The micrometer positioning commands are issued to the motor controller from the HARP-B micro via Ethernet and a RS232 terminal server. The LO controller is an embedded micro-controller based on the Siemens C164 architecture. LO control and status monitoring commands are sent from the HARP-B micro to the LO microcontroller via the CANbus. The LO micro-controller interprets the CANbus messages and provides the necessary control and monitoring signals to the hardware components in the LO chain.

3.6 Cryostat

The cryogenic systems design for HARP-B was intimately connected with the overall instrument layout. The optical scheme leads to a straight-forward cryostat design in that the HARP-B optics are all in one plane. This allows the cryostat to be constructed as a lower 60K cold optical bench with optics on one side and the cryo-cooler on the other (with a removable side panel and thermal shields to allow easy access) and a 4K unit on top to house the array.

The cryostat has therefore been designed so as to create two separable units for efficient assembly and maintenance. The upper part of the cryostat holds the 4K cooling equipment and hence the imaging array unit. The mixer, LO injection and super-conducting coil unit must be within 0.25K of 4K and the temperature stability must be better than $\pm 0.1K$ in 30min. The periodic temperature fluctuation at the mixer blocks associated with the 4K cooling cycle is no greater than $\pm 0.05K$.) This part of the cryostat is designated the 'Main Array Package' (MAP). The lower part of the cryostat holds the cold optics and their associated 60K cooling equipment. It is designated the 'Cold Optics Package (COP)'. The cryostat can be pre-cooled with liquid nitrogen and uses both a two-stage CTI cooler and a three-stage Daikin cooler to maintain the operating temperature of the array at $4 \pm 0.25K$ and the optics package at $60K \pm 5K$. It is possible to go from all parts at ambient temperature & pressure to all parts at their working temperature and pressure in ~ 48 hours.

Suitable internal wiring is connected to a number of hermetically sealed connectors on the vacuum vessel under the attached controller units. The design of the cryostat internal 'dc' wiring makes use of woven ribbon cable wire assemblies. These have advantages in that the wires can be neatly routed, readily heat strapped and the Nomex weave protects the wire from damage. The outer (room temperature) connectors are hermetic circular military-style connectors. At the cold end, the Nanonics duallobe type of connectors are used, plugged into mating connectors on the array assembly. This provides modularity to aid assembly and dismantling of the instrument. The cable assemblies are thermally anchored at different temperature stages. The co-axial cables carrying the IF signal are heat strapped to the various temperature stages.

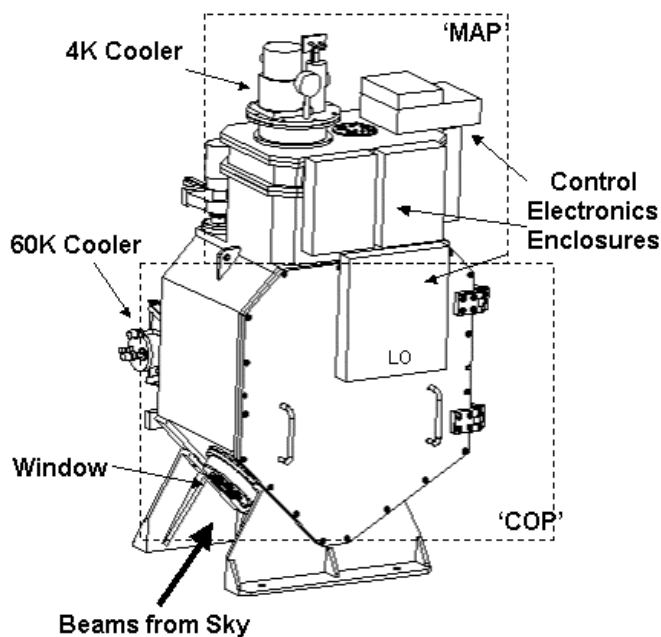


Figure 7 - HARP-B Cryostat

The cryostat internal temperatures are monitored at eight points in the MAP and eight points in the COP. There are separate input connectors and cable harnessing for the temperature monitoring of the cold optics (CTI-cooled) hardware and the array package (cooled by the

Daikin). This allows each unit to be run separately in the event that the units are commissioned individually. Vacuum monitoring is via a single combined Pirani/AIM (inverted magnetron) gauge head. Temperature and vacuum data can be accessed by the HARP-B control computer. An image of the HARP-B cryostat is shown in Figure 7.

3.7 Control and Monitoring

HARP-B is a slightly unusual instrument from an electronics point of view. On the one hand, in order to control and monitor the 16 mixer systems we needed to overcome the problem of many large and unreliable wiring harnesses with associated connectors. On the other hand, many of the ‘one off’ control requirements can be accomplished via simple, cheap, off the shelf modules. This however leads to a multiplicity of different standard interfaces (e.g. GPIB, RS232, Ethernet, ‘TTL’, analogue, etc.) for the control computer to deal with. For the multiple ‘16-off’ control requirements solutions exist to solve reliability problems with large wiring harnesses by using a fast serial bus with robust protocols to distribute commands to many small individual controllers located near the centres of operation. HARP-B uses this approach. We identified the Controller Area Network (CAN) bus as particularly suitable for HARP-B. CAN is a fast, well-established protocol which is very widely used in small micro-controllers and other devices. The CAN protocol deals with all the necessary bus negotiations, to ensure that message packets are delivered across the bus without supervision from high level software. In HARP-B a common CAN bus connects several electronic modules together in a daisy-chain configuration, each particular module performing one aspect of the control of 16 devices. The HARP-B control electronics is built around this central CANbus backbone, which is driven by the HARP-B microcomputer. Bought-in items such as motor controllers for the SSB filter (Mach-Zehnder interferometer) and autotuning of the LO are controlled via Ethernet to a terminal server or simple parallel TTL bits in order to minimize the number of types of interface. Figure 8 shows an overall view of the system.

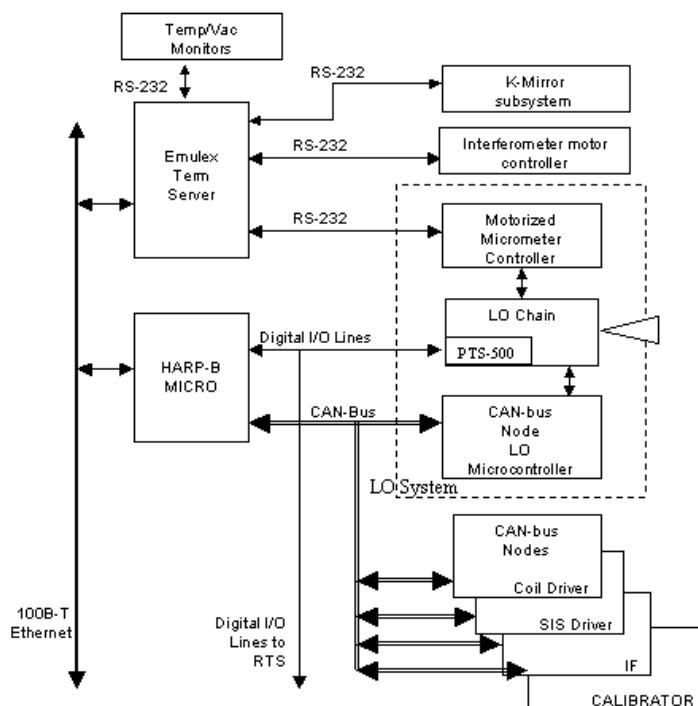


Figure 8 - HARP-B control electronics

3.8 Microcomputer & Control software

The HARP-B control computer is a Power-PC based embedded system running the VxWorks real-time operating system. It receives high-level software commands from the JCMT Observatory Control System (OCS) and other telescope subsystems through the DRAMA messaging facility over a standard Ethernet connection. It communicates with the low-level control electronics via the Controller Area Network (CAN) bus.

The control system for the HARP-B receiver is implemented in several pieces running on different CPU's. The highest levels of the HARP-B control system overlap with the rest of the observatory control system (OCS), and in particular with ACSIS, and is run in the central control computer. The mid-level software to tune the receiver is run in the dedicated HARP microcomputer detailed above. The HARP microcomputer does not interact directly with the hardware but communicates with a set of dedicated microcontrollers, some commercial motor controllers and specialized sensors, and some custom boards accessible over a CAN bus. The latter can be put into a sleep mode during observing to keep the electrical environment near the detectors quiet.

The OCS controls HARP-B through a set of DRAMA actions that have been standardized for all frontends at the JCMT. For four key commands are INITIALISE, CONFIGURE, SETUP_SEQUENCE, and SEQUENCE. The INITIALIZE action is used primarily at the start of an observing session to bring the receiver into a known passive state. The CONFIGURE action tunes the receiver to a new frequency. The SETUP_SEQUENCE prepares the receiver to start an integration, setting the optics to direct the beam to the sky or to a particular thermal load, and selecting an RTS state table to control frequency switching during a following SEQUENCE command. The SEQUENCE command locks out mechanical changes to the receiver while the backed is taking data, and passes control to the RTS for frequency switching.

Status

The instrument completed its acceptance tests at MRAO in September 2005 and was shipped to Hawaii. It has been installed on the JCMT and integrated with the telescope system and the ACSIS backend. A first spectrum was obtained on 11th December 2005. It is expected that scientific commissioning will be completed early 2006.

Acknowledgement

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