# A CRYOGENICALLY COOLED, THIRTEEN BEAM, 21CM RECEIVER FRONT END

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## ABSTRACT

An extensive Southern Hemisphere extragalactic radio astronomy survey of the λ21 cm emission line of neutral hydrogen (HI) is about to begin on the 64-m Parkes radio telescope in NSW, Australia. To do this a 13-beam receiver, using a cryogenically cooled front end for maximum sensitivity, has been developed by the ATNF. This paper highlights various design and construction details of the front end, and reports the results of laboratory and telescope testing of the front end cryogenic and electronic systems.

## I. INTRODUCTION

The primary scientific rationale for a 21-cm multibeam receiver on the Parkes 64-m telescope is to conduct sensitive large-area surveys of the Southern Hemisphere sky for neutral hydrogen emission from external galaxies. A detailed description of the key scientific objectives of this project has been given by Staveley-Smith et al[1] [2]. These include: a survey for optically obscured galaxies behind the Southern Galactic Plane, a Southern Hemisphere HI survey for faint optical galaxies, a deep HI survey aimed at high-latitude fields, and a piggy-back Galactic Plane pulsar search which uses the sensitivity of the system, whilst taking advantage of the survey observation mode.

To achieve this, a collaborative venture between ATNF, the University of Melbourne, the Australian National University's Mount Stromlo and Siding Spring observatories, the University of Western Sydney, the Nuffield Radio Astronomy Laboratories, and the University of Wales, Cardiff, was set up to mobilise the scientific and engineering expertise required for a project of this size. Accordingly, the ATNF undertook the design and construction of a major receiver system which includes a large 26-channel cryogenic front end system, with a system temperature target of 25K (the subject of this work), a 26-channel down-conversion system, and the development of a high-resolution (1024 channels) 2-bit digitised, 64-MHz bandwidth spectral-line correlator for all 26-channels of the multibeam receiver output.

## II. THE 13 BEAM RECEIVER SYSTEM

### Receiver Electronics

The receiver has the basic form of a low-noise 26-channel dual conversion hetrodyne system with a high-resolution spectrometer back end. Outputs from a 13-element feed-horn array couple via circular waveguides into a cryogenic dewar where 26 low-noise preamplifiers, 1 for each polarization, and cooled to 16 K, provide an initial 40-db of gain across a 1200-1800 MHz band with an excess noise contribution of about 5K.

The 26 preamplifier outputs are passed through the dewar walls via a hermetic coaxial connector bulkhead, whereupon further amplification and filtering outside the dewar limits the received band to 1230-1530 MHz. These signals are then fed to a 26-channel down-conversion system which amplifies, filters and mixes the incoming signal to an intermediate frequency band covering the frequency range 50-350 MHz.

The receiver thus far is housed in the telescope focus cabin, from which the 26 separate IF channels are then passed to the telescope control room via low-loss coaxial cables. Here the passbands are corrected by cable-equalisation filters and then accurately filtered in precise band-determining filters to a bandwidth of 64 MHz which defines an instantaneous accessible Doppler velocity range of 14,000 $kms^{-1}$.

At this point the IF signals are digitised to 2-bit, 4-level digital data at a sample rate of 128 Msamples $s^{-1}$ from the 64-MHz band (128-192 MHz). The sampler units automatically control sampler decision levels to reduce zero-level offsets and to maintain magnitude levels at the point which gives optimum signal-to-noise ratios. They also include total power detectors and synchronous demodulators which are used in conjunction with a switched noise source injected into the input waveguides to measure the operating system temperature.

The digitised data is then autocorrelated using a NASA SERC high-performance correlator chip [3] to form a 1024-channel autocorrelation spectrum for each of the 26 sampled data streams, the resultant channel spacing corresponding to 13 km $s^{-1}$.

### The Feed Horn Array

This consists of 13 stepped circular horns arranged in a hexagonal pattern, the apertures of which are located on the telescope prime focus plane, and couple directly into the cryogenic dewar interface through circular waveguide vacuum windows. A plan view of the feed horn aperture plane is shown in Fig. [1].

Stepped circular horns were chosen because of their excellent pattern symmetry, low spillover and good cross polarization properties [3]. They are also convenient to manufacture, as are the following circular waveguide components in the cryogenic dewar.

The horn aperture diameter is close to one wavelength which, for the Parkes reflector, maximises the forward antenna gain and gives a FWHP beamwidth of 14.4 arcmin, whilst the horn spacing of $1.2\lambda$ gives a beam spacing of two FWHP bandwidths (~29 arcmin) on the sky.

Figure 1: Plan view of the 13-beam feed-horn array aperture plane. Note the overall diameter of 1290 mm and horn aperture diameter of 240 mm ($\lambda$ = 21cm)

Predicted performance for the array feeds and reflector indicates an efficiency of 69.3% for the central beam relative to an ideal uniformly illuminated aperture, and 59.8% for the most extreme beam on the hexagon. The coma sidelobe level for the extreme beams is 14 db below the peak value.

An interesting feature of this hexagonal array is, if it is rotated by $15^{\circ}$, it can be tracked across the sky with the beams overlapping at the half-power points, giving a Nyquist-sampled strip approximately $1.7^{\circ}$ wide.

## III. THE CRYOGENIC FRONT END

The cryogenic front end (Fig. 2), is situated right at the focal plane area of the telescope optics. It has been constructed as a removable entity (for repairs and maintenance) and can be translated and rotated across the focal plane by the telescope's receiver positioning system.

Figure 2: Cross-section view of the assembled front end. Note the input waveguide path through vacuum window, gapped waveguide and orthomode transition.

The complete front end consists of the feed-horn array, the cryogenics dewar containing cooled orthomode transducers and high electron mobility transistor (HEMT) preamplifiers, the ambient temperature amplifier-filter module, and a multipurpose electronics module which contains support electronics, HEMT amplifier bias supplies and a comprehensive monitoring system. The monitoring system indicates the bias states of all transistors in these 26 cooled HEMT amplifiers, as well as temperature and vacuum information on the cryogenic system performance.

## The Input Signal Path

To achieve the maximum receiver sensitivity, it is essential to keep the attenuation in the signal path between the feed horn and the HEMT preamplifiers to an absolute minimum. For this reason a great deal of care was taken in designing the components in this waveguide and coaxial cable path.

Figure 3 shows that the first of these is the vacuum barrier interface where the microwave signals enter the cryogenic dewar. This must maintain a high-quality vacuum seal to prevent the ingress of atmospheric contaminants whilst providing a low-loss microwave path. The use of Kapthon film 0.125 mm thick, edge clamped, and sealed with Armstrong A-12 epoxy, provides a suitable vacuum barrier, with a 100-mm-thick expanded polystyrene plug epoxied in place underneath the Kapthon film, giving mechanical support against atmospheric pressure.

The next component in the input signal path is the gapped waveguide structure. The primary task of this device is to stop heat flowing from the room-temperature vacuum window region (at ~300 K) to the orthomode transition (OMT) waveguide cooled to ~ 130 K. The gap separation in the waveguide wall-end faces is 1.0 mm and this separation is maintained by four G-10 fibreglass straps fixed securely to each side of the waveguide gap region. (Each strap is 36 mm wide, an insulation length of 32 mm and 1.5 mm thick, giving a total heat load between 0.6 W for each waveguide gap and 7.6 W for the full waveguide gap array).

The conventional design for a gapped waveguide junction such as this would require a choke joint with a stub-like, quarter-wavelength groove, spaced one quarter wavelength from the waveguide walls, and incorporated into the waveguide flange faces. For this system, however, because of the close proximity of the neighbouring waveguides, and also because of weight considerations, a simpler gap structure was adopted. The choke groove was eliminated, the gap spacing closed down to 1 mm and the flange face width set at 17.5 mm, making the series gap reactance less than 5Ω at the operating frequency. When tested in the finished input-waveguide assembly, the gap effect on the overall match and insertion loss of the structure was so small as to be indeterminate.

The final component in the input signal path is the waveguide-to-coaxial orthomode transition (OMT).

This device uses a simple orthogonal probe into waveguide structure to couple incoming signals from the input waveguide-to-coaxial connectors on the outer waveguide walls. Short stainless-steel coaxial lines then connect these to the HEMT preamplifiers. It is important to note that the OMT is at a physical temperature of ~130 K, whilst the HEMT preamplifiers are operating at 16 K, and so a substantial temperature differential exists between the two, making it necessary to use stainless-steel coax lines for these connections. This form of OMT design was chosen because of its simplicity, ease of manufacture, and low insertion loss (~0.02 db for each probe). Isolation between the orthogonal probes was achieved by separating the probes by about 0.1 guide wavelengths along the length of the guide. A septum is then used to tune the front probe; the rear probe is tuned by the waveguide backshort. The resultant return loss for each probe was $\geq$ 24 db right across the 300-MHz operating band whilst the probe-to-probe isolation was $\geq$ 22 db.

Final testing of the fully assembled horn-window-gap-OMT structure yielded an overall return loss of -20 db across the operating band with probe-to-probe isolation of $\geq$22db.

So that calibration signals can be injected into the receiver input, a small directional loop coupler is incorporated in the input waveguide just down-stream from the feed horn. Positioned at $45^{\circ}$ to the orthomode transition output, a modulated noise source can be coupled equally into each polarization for the purpose of continuously monitoring each RF channel's system noise temperature and gain.

## The High Electron Mobility Transistor (HEMT) Preamplifier

These amplifiers were manufactured by the Nuffield Radio Astronomy Laboratories (NRAL) at Jodrell Bank as part of their contribution to the overall multibeam project. The design has been described in great detail by Gallego and Pospieszalski [5] and a view of the interior of one of these amplifiers is shown in Fig. 3.

The design uses a hybrid MIC approach, with commercially available HEMT chip (FHR02X) from Fujitsu, and is wire-bonded into microstrip matching and coupling networks realised in Duroid 6010.5, .”050-inch-thick substrate material.

The result is an amplifier with high gain (~40 db), an input noise temperature of 5K across the operating band (1395 $\pm$ 32 MHz), low input and output reflection coefficients, and unconditional stability at any physical temperature in the range 5K to 300K.

Figure 3: An interior view of the 1200-1800 MHz HEMT preamplifiers

## The Post Amplifier-Filter Module

The post amplifier - filter module provides 28 db of overall gain after the low-noise cooled preamps (provided by two Mini-Circuits VNA 25 Series amplifiers), sufficient to raise the incoming signals in the 1230-1530 MHz observing band to an appropriate level for down conversion to the 50-350 MHz intermediate frequency band. It also provides image-rejection filtering required before the first conversion mixer by means of a 6-pole microstrip bandpass filter constructed on Rogers RT Duroid R03010 substrate material. This filter is tuned to the 1230-1530 MHz signal band, and provides ≥ 20 db of attenuation in the 1640-1940 MHz image band.

A troublesome 1168-MHz, air-navigation beacon, situated at a nearby airport, is also removed from the outcoming signal spectrum by incorporating a narrowband notch filter at the input to this module. This filter provides ≥ -35 db of attenuation at the beacon frequency and eliminates the possibility of intermodulation effects caused by this strong interfering signal further down the amplifier chain.

A close-up view of several channels in this module is given in Fig. 4.

Figure 4: An interior view of the post amplifier-filter module. The input at the bottom of the picture and the output at the top

## IV. THE CRYOGENIC SYSTEM

### The Vacuum Dewar

Because of the diameter of the feed-horn array and the length of the cooled waveguide components contained within, the vacuum dewar is required to have physical dimensions of 1.2 m diameter and 0.6 m long. This would not be a difficult vacuum tank to construct if conventional stainless steel materials and techniques were used, but a strict weight limit for the front end system imposed by the telescope receiver positioning system precluded using stainless steel and so aluminium was used instead. Even then, the allowable weight of the dewar and end plates required the use of relatively thin (6 mm) dewar walls on the cylindrical section with stiffening bars welded on the outside to resist the hoop tension forces. The end plates also required a set of six 25-mm-diameter support rods spaced evenly around a 313-mm-diameter bolt circle around the centre of the tank to prevent the central region from deflecting excessively.

This is an important requirement because the feed-horn must be kept correctly in axial alignment when coupled to the dewar input waveguide.

To keep the gas pressure thermal load for this system well below 1 W requires the ultimate vacuum pressure within the dewar, when operating at cryogenic temperatures, to be much less than $10^{-5}$ torr (preferably $10^{-6}$ torr). To do this, large activated charcoal traps have been installed on both the 20-K and 100-K platforms to augment the cold metal surfaces in cryopumping leakage products. These provide some 440-$cm^2$ area of activated charcoal granules attached to the 20-K platform, along with 895-$cm^2$ attached to the 100-K system. We expect that these will have to be regenerated at regular six-monthly intervals.

The largest leakage component met so far comes from the foam support plugs in the waveguide vacuum windows; this is because the gas used to generate the foam escapes to the low vacuum side. The speed of this process has been greatly increased (~50x) by drilling a matrix of holes in the foam so that the longest diffusion path for the escaping gas is now 2.5 mm.

To date, the lowest leak rate measured for the complete dewar with all O-rings, windows and connectors installed, has been 2 x $10^{-3}$ torr litre $s^{-1}$. We believe that this will improve when all gas-emitting products are removed from the foam support plugs.

## Cryogenic Refrigerators

The cryogenic cooling for this system is provided by a pair of Cryogenic Technologies Inc (CTI) 1020 CP cryocoolers, operating in parallel and sharing the thermal load and both operating from separate helium compressors. The total capacity of this dual system should thus be 20 W on the 20-K platform and approximately 100 W on the 100-K platform.

As is usual with these systems the 20-K platform is reserved for low-noise amplifier cooling whilst the 100-K platform is used to cool the radiation shields and, in this case, the 13 orthomode transitions. This arrangement can be seen clearly in Fig. 2. The calculated total-equilibrium heat loads for all radiation, conduction and gas loads on both platforms are 98 W for the 100-K platform and 6 W for the 20-K platform. This agrees well with the CTI load-capacity curves, which indicate loads of 100 and 10 W for the observed platform temperatures.

Extensive use of super insulation was made between the radiation shields and the outer walls of the dewar. Some 20 layers of this material were used to cover the 4 square metres of radiation shield with an estimated factor of 4 reduction in the radiation load.

The mass of metal attached to each platform amounts to 13 kg of copper at 20 K and 12 kg of copper with 44 kg of aluminium at 100 K. The cooldown times for these enthalpy loads is 16 h for the 20-K system and 42 h for the 100-K system.

## V. SYSTEM PERFORMANCE SUMMARY

The completed multibeam receiver was recently installed on the Parkes 64-metre telescope. The microwave and cryogenic performance of the front end is summarised in Table 1.

**Table 1**

| | | | |
|---|---|---|---|
| Operating frequency: | | 1230 - 1530 MHz | |
| Overall front end RF gain: | | 60db | {40 db cryogenic }<br>{20 db ambient } |
| Output spectral power density: | | -50 dbm/MHz (cold sky) | |
| Receiver noise temperature: | | 6 K (measured at dewar window) | |
| Overall system noise temperature: | | 24 K | {average of 26 receivers}<br>{measured on telescope } |
| 20-K platform temperature (HEMT amp): | | 16 K | |
| 100-K platform temperature: | | 95 K (close proximity to refrigerator)<br>130 K (outer edge of rad shield) | |
| Cooldown time: | HEMT amplifiers: | 16 h | |
| Cooldown time: | Radiation shields: | 44 h | |
| Mass cooled: | 20 K platform: | 13 kg | |
| Mass cooled: | 70 K platform: | 56 kg | |

Thus far the 26 receiver channels have operated with good stability and with a sensitivity consistent with the measured overall system noise temperature.

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