Cryogenically Cooled Millimetre-Wave Front Ends for the Australia Telescope

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Abstract — **Cryogenically cooled receiver systems covering three millimetre-wave observing bands have been installed on the Australia Telescope National Facility Compact Array (ATCA), situated near Narrabri in northern New South Wales, Australia. The ATCA consists of six 22-metre dish antennas capable of operating at frequencies in excess of 115 GHz. Millimetre-wave receiver systems covering the frequency ranges 16 to 26 GHz and 85 to 105 GHz have been upgraded with the installation of a receiver system covering the 30 to 50 GHz band. We will describe the final receiver system and present the results of tests on these receiver systems.**

I. INTRODUCTION

The Australia Telescope National Facility (ATNF) comprises a 64m-diameter dish at Parkes, NSW, six 22m diameter dish antennas of the Australia Telescope Compact Array (ATCA), situated near Narrabri, NSW, and a single 22m diameter dish antenna situated at Mopra, near Coonabarabran, NSW. Five of the Compact Array antennas are moveable on an east-west rail track three kilometres in length, while the sixth dish is fixed at a position three kilometres further to the west. The Australia Telescope 22m diameter antennas use cassegrain optics and are capable of operating at frequencies in excess of 115 GHz.

In April 2007 five of the ATCA antennas already equipped with 3 mm (85 to 105 GHz) and 12 mm band (16 to 26 GHz) receiver systems were outfitted with components to add a 7 mm band (30 to 50 GHz) to the receiver's capability. The sixth ATCA antenna, which was equipped with a 12 mm band receiver system, was also outfitted with a 7 mm band capability.

The receiver bands exploit "windows" between frequencies of strong atmospheric absorption due to atmospheric oxygen at around 50 and 120 GHz. The resonance frequencies of many molecules of astronomical interest are covered by the receiver bands. The 12 mm band includes the water vapour (H_2O) line at 22 GHz and the silicon monoxide (SiO) lines at 43 and 86 GHz are included in the 7 mm and 3 mm bands respectively.

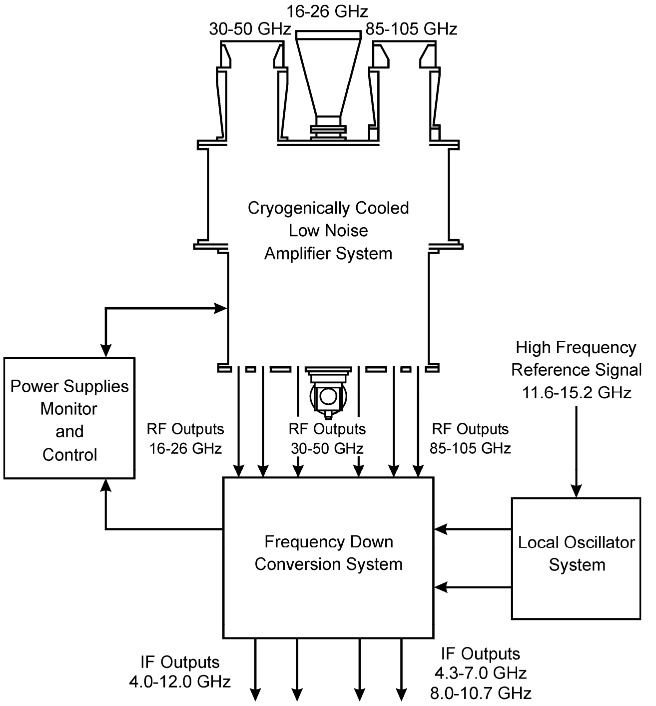

Fig. 1 Block diagram of the front end containing three millimetre wave receiver systems

The 7mm band receiver upgrade was carried out by the ATNF and partially funded by NASA. This capability allows NASA missions to be tracked at Ka band (32 GHz) by the arrayed antennas at Narrabri.

The three bands are not available simultaneously. The front end package has separate feed horns for each band and the position of the receiver package is controlled through a combination of turret rotation and package translation so that the relevant feed horn is positioned at the focus of the antenna.

II. RECEIVER SYSTEM DESCRIPTION

The receiver system architecture is broadly similar to that of the other receiver systems installed in the ATCA antennas which have already been described [1]. The system block diagram, Fig. 1, illustrates the main sub-systems of the new receiver.

The front end dewar contains all the cryogenically cooled RF components to obtain dual linear orthogonal polarisation channels for the 3 mm, 7 mm and 12 mm bands. Careful design is required to minimise signal loss and added noise at the input to the low noise amplifier (LNA) systems.

After amplification, separate mixer and local oscillator (LO) systems down-convert the signal from each polarization to an intermediate frequency (IF) band of 4 to 12 GHz providing 8 GHz of instantaneous bandwidth. The IF signals are further down-converted in the existing, antenna-based, electronics [1].

III. THE CRYOGENIC LOW NOISE AMPLIFIER SYSTEM

The critical components in the cryogenic LNA system, shown in Fig. 2, include the feed horns, the wide band orthomode transducers (OMT), calibration injection couplers, the broadband, monolithic microwave integrated circuit (MMIC) LNAs and isolators. To achieve the lowest possible receiver noise temperature, all of these RF input components, except for the 12 mm band feed horn, are cooled to less than 15 Kelvin by a closed cycle helium refrigerator system.

The feed horns are wideband compact corrugated horns [2], with variable slot depth mode converters, designed to fully illuminate the 22 metre diameter telescope surface. The feed horns for the 3 mm and 7 mm bands, which are scaled versions of the feed for the 12 mm band, are enclosed in extensions of the main vacuum dewar and cooled to 15 Kelvin.

The ortho-mode transducer for the 12 mm band, described in [3], consists of two orthogonal, stepped, double ridged waveguide sections. The OMT has an insertion loss of less than 0.3 dB, a return loss better than 25 dB and isolation of better than 50 dB over the 16 – 25 GHz band at room temperature.

The ortho-mode transducer for the 3 mm band, described in [4], was based on the OMT designed for the 12 mm band and is similar to that described by Bofiot [5]. The OMT consists of a square to double ridged waveguide transition followed by a junction with two side arms and a continuing rectangular waveguide. The polarisation in the continuing rectangular waveguide goes through a stepped transition and a bend allowing it to exit through the top of the OMT. The other polarisation is split equally in the two side ports and is ultimately recombined at the rear of the OMT. At room temperature the OMT has an insertion loss of less than 0.16 dB for both polarisations and port to port isolation, with the square port terminated, better than 45 dB.

The ortho-mode transducer for the 7 mm band is similar in structure to the OMT for the 3 mm band, described above. It has an average insertion loss at room temperature of 0.09 dB for both polarisations and port to port isolation better than 50 dB.

Fig. 2 The cryogenic LNA assembly with the vacuum dewar removed. The 7 mm band horn and low noise amplifiers are on the left, the 12 mm band horn and low noise amplifiers in the centre and the 3 mm band horn and low noise amplifiers on the right

InP HEMT MMIC low-noise amplifiers were designed by CSIRO for each of the receiver bands and fabricated using an advanced, 0.1 micron, InP HEMT process [6]. Each transistor in the MMIC amplifiers is individually biased, with the bias voltages supplied to the transistors through on-chip decoupling networks. To achieve the optimal performance of the receivers, the bias of each MMIC LNA amplification stage can be independently adjusted locally and the bias continually monitored. The first transistors are biased for minimum noise while the subsequent transistors are biased for maximum gain.

A gain of greater than 30 dB is required in the LNA system so that the noise contribution from the room-temperature microwave components in the down-conversion system is negligible. In the 12 mm band a gain of 30 dB can be obtained from a single MMIC amplifier with 3 transistor gain stages. The 7 mm band has 50 dB of cooled gain, provided by two four stage MMIC amplifiers. For the 3 mm band, where a four stage amplifier has a gain of only 15 – 17 dB, two packaged MMIC amplifiers, each having an isolator at its input, are used in each polarization.

The MMIC chip for the 12 mm band is mounted in a cryogenically coolable package that has coaxial input and output connectors. The MMIC chips for the 7 mm and 3 mm bands are mounted in cryogenically coolable packages that have waveguide inputs and outputs. In the 7 mm band package, waveguide probes and short lengths of microstrip transmission line on alumina substrate are used to couple the input and output signals from the WR-22 waveguide to the MMIC chip. In the 3 mm band package, WR-10 waveguide is used and the waveguide probes and transmission lines are on GaAs substrates.

IV. DOWN-CONVERTER ELECTRONICS

After amplification by the cryogenic LNA system, RF signals from all three frequency bands are down-converted to a common 4.0 to 12.0 GHz IF band. This IF band is subsequently limited to two sub-bands 4.3 to 7.0 GHz and 8.0 to 10.7 GHz for use with the existing ATCA second stage IF system [1].

The conversion system uses conventional double balanced mixers for the 12 mm observing band and InP HEMT MMIC mixers for the 7 mm and 3 mm wavelength bands. For the 12 mm band a conventional lower sideband conversion is used while the 7 mm and 3 mm bands utilise sideband separating mixers [7]. This scheme ensures full frequency coverage of the wide RF bands while minimising the LO tuning range.

Where possible, commercial MMICs are integrated into sub-assemblies along with ATNF developed waveguide and microwave printed circuit filters, power dividers and couplers. CSIRO designed GaAs MMIC amplifiers, doublers and triplers are used in the system where commercial devices are not available.

The LO is generated at each antenna by multiplying a reference signal provided by a photonic, high frequency reference distribution system [8]. This system provides a variable, 11.6 to 15.2 GHz, reference tone which is doubled to provide an LO in the range 26.7 to 30.4 GHz for the 12 mm band conversion, tripled to provide an LO in the range 36.0 to 45.6 GHz for the 7 mm band conversion and multiplied 8 times to provide an LO in the range 92.8 to 104.0 GHz for the 3 mm band conversion.

The primary LO for the 12 mm band conversion is generated from the common reference in a single sub-assembly. This sub-assembly integrates commercial MMIC GaAs power amplifiers, a doubler, microstrip devices and bias electronics into a single assembly [9]. The LO for the 7 mm band conversion is generated using CSIRO designed triplers, fabricated using the NGST 0.15 micron GaAs pHEMT process [10], whilst commercial GaAs amplifiers provide amplification for the final LO drive to the mixers. For the 3 mm band conversion, a combination of commercial GaAs devices, CSIRO designed InP doublers and GaAs power amplifiers are used to generate the fundamental LO signal used in the mixers [11].

The high RF frequencies from the receiver front-end require that the first frequency conversion be located on the receiver package, as close as possible to the vacuum dewar.

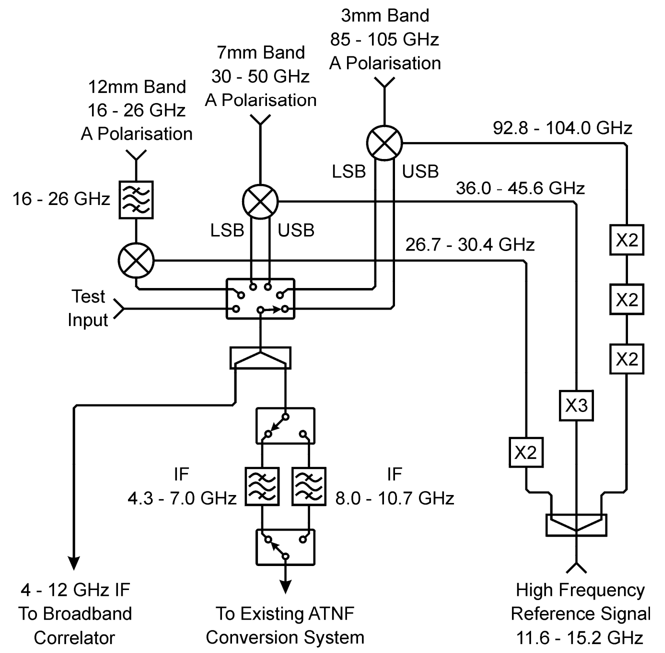

Fig. 3 Block diagram of the down converter module for one polarisation

Where possible the system has been designed to keep the LO reference signal and its harmonics out of the astronomical observing bands. To further minimise interference all of the conversion and LO chain components have been integrated into a single, RF shielded enclosure.

Fig. 3 is a block diagram of the down converter system. The entire conversion system is required to have a high degree of gain and phase stability. To achieve this stability, the down converter system has been realised using extensive integration of microstrip and waveguide components, MMIC devices such as amplifiers, mixers and switches. This minimised the use of connectors also reducing the size and cost.

All of the functions of the conversion system are remotely controllable. To simplify system operation and assist in fault diagnosis the interface also allows the remote monitoring of MMIC mixer bias parameters, reference and LO signal levels.

V. MONITORING AND CONTROL ELECTRONICS

The monitoring and control sub-system provides extensive and comprehensive local (Receiver Front Panel) and remote (Array Control Building) monitoring and control of the critical and sensitive parameters associated with the front-end package. Analog and digital information is collected via a Dataset, digitized and sent through optical fibre to the Control Building.

Monitoring of the cryogenic system measures temperature, dewar vacuum and refrigerator helium supply and return pressures. The status of all DC power supply systems is also continuously monitored.

Throughout the Front-end, LO and Conversion systems there is control and monitoring of the signal path, signal level and RF switches directing the IF output. The receiver calibration systems can also be locally or remotely controlled and their status monitored.

VI. RESULTS

In April 2007, the new 7 mm band components were integrated into the existing millimetre-wave front end packages which were already equipped to cover the 12 mm and 3 mm bands. Fig. 4 shows the measured noise performance of the cryogenically cooled millimetre-wave low noise receiver systems.

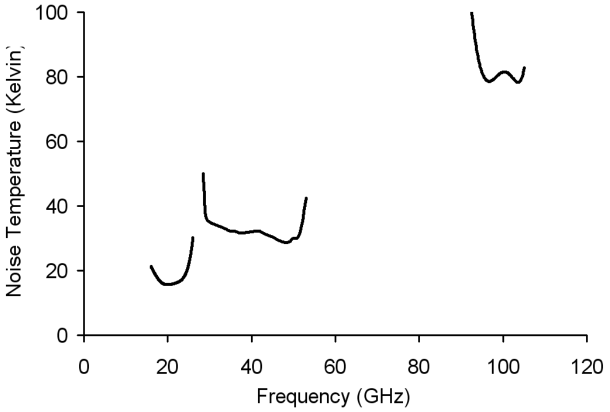

Fig. 4 Noise Temperature of the millimetre-wave receiver systems

The spectrum shown in Fig. 5 [12] was obtained from a spectral scan of the Kleinmann-Low (KL) nebula in the Orion Molecular Cloud 1 (OMC1). The scan took 96 separate receiver tunings to cover the 42.5 to 45 GHz frequency range. The spectrum is dominated by strong silicon monoxide (SiO) and methanol (CH_3OH) lines with thermal transitions of ethylcyanide (CH_3CH_2CN) also identifiable. In addition there are three unidentified spectral lines at around 43.0167, 43.477, and 44.0532 GHz.

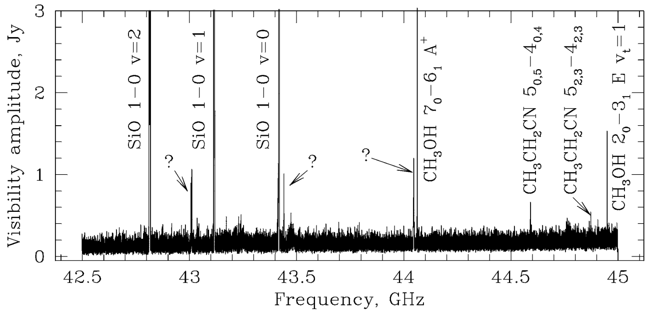

Fig. 5 Spectrum of the Kleinmann-Low nebula in the Orion Molecular Cloud 1 showing emission from SiO, CH_3OH and CH_3CH_2CN [12]

VII. CONCLUSION

In April 2007, the receiver systems of the ATCA antennas were upgraded with the inclusion of a new band covering 30 to 50 GHz. As a result five ATCA antennas have been equipped with receiver systems which cover three “millimetre-wave” observing bands in the range 16 to 105 GHz.

It should be noted that the millimetre-wave receiver system recently installed on the Mopra antenna has improved low noise amplifiers and local oscillator system [4], [9] and operates over an extended 3 mm band from 77 to 117 GHz. It is possible that in the future the receivers of the Compact Array will be upgraded to cover this extended 3 mm band.

ACKNOWLEDGMENT

The authors wish to acknowledge the valuable assistance of P. Axtens, D. Gain, E. Hakvoort, P. Sykes and J. McFee for work on the cryogenics system and assembly of the receiver systems. The staff at the Narrabri observatory contributed to the success of this project by assisting with the installation and commissioning of these receiver systems. The authors also wish to acknowledge the contributions of P. Bonvino, M. Bourne, G. Cook, P. Cooper, M. Death, M. Huynh, O. Iannello and R. Moncay who machined, with precision, the MMIC sub-assembly packages and many other parts for the receiver systems.

REFERENCES

[1] M. W. Sinclair, G. R. Graves, R. G. Gough, and G. G. Moorey, “The receiver system,” *Journal of Electrical and Electronics Engineering, Australia, IE Aust. and IREE Aust.* vol. 12, no. 2, pp. 147-160, June 1992.

[2] G. L. James, “Design of wide-band compact corrugated horns”, *IEEE Trans. Antennas and Propagation*, vol 32, no. 10, pp. 1134-1138, October 1984.

[3] A. Dunning, “Double ridged orthogonal mode transducer for the 16-25 GHz microwave band”, in *Proc. Workshop on the Applications of Radio Science* February 20–22, 2002.

[4] G. Moorey, R. Bolton, A. Dunning, R. Gough, H. Kanoniuk and L. Reilly, “A 77 – 117 GHz cryogenically cooled receiver system for radioastronomy,” in *Proc. Workshop on the Applications of Radio Science,* February 15–17, 2006.

[5] A. Bofiot, E. Lier and T. Schaug-Pettersen, “Simple and broadband orthomode transducer,” *IEE Proceedings*, vol. 137, Part H, No. 6, December 1990.

[6] R. Lai, M. Barsky, R. Grundbacher, L. Tran, T. Block, T. P. Chin, V. Medvedev, E. Sabin, H. Rogers, P. H. Liu, Y. C. Chen, R. Tsai and D. Streit, “0.1 μm InGaAs/InAlAs/ InP HEMT production process for high performance and high volume mm-wave applications,” *Proc. GaAs Mantech*, 1999.

[7] J. Archer, M. W. Sinclair, A. Dadello, S. Giugni, R. G. Gough, G. Hincelin, S. Mahon, P. Roberts, O. Sevimli and X. Wang, “Millimetre-wave integrated circuits for radio astronomy and telecommunications”, in *Proc. Workshop on Applications of Radio Science 2000*, April 27-29, 2000, Beechworth, Australia, pp. 198-203.

[8] M. R. Leach, “Upgrade of the Australia telescope compact array local oscillator reference system”, in *Proc. Workshop on the Applications of Radio Science 2000* , April 27-29, 2000, Beechworth, Australia, pp. 193-197.

[9] G. Moorey, P. Axtens, M. Bowen, A. Dunning, R. Gough, G. Graves and H. Kanoniuk, “A 77 – 117 GHz radioastronomy receiver frequency conversion and local oscillator system,” in *Proc. Workshop on the Applications of Radio Science,* February 15–17, 2006.

[10] R. Lai, M. Biedenbender, J. Lee, K. Tan, D. Streit, P. H. Liu, M Hoppe and B. Allen, “0.15 μm InGaAs/AlGaAs/ GaAs HEMT production process for high performance V-band power MMICs,” in *IEEE GaAs IC Symposium*, San Diego, CA., pp 105-108, October 1995.

[11] G. Moorey, J. Archer, R. Gough, G. Graves, P. Roberts, M. Bowen and H. Kanoniuk, “MMICs for the Australia Telescope millimetre-wave receiver system,” in *Proc. 12th European Gallium Arsenide and other Compound Semiconductors Application Symposium,* October 11–12, 2006, Amsterdam, The Netherlands, pp. 359-362.

[12] I. Feain, and M. Voronkov, “First light at 7 millimetres,” *ATNF News, Australia*, CSIRO Australia Telescope National Facility. issue. 62, pp. 16-17, June 2007.