A cryogenically cooled millimetre-wave receiver system was recently installed in an antenna located at Mopra near Coonabarabran as part of the Major National Research Facility (MNRF) funded project to extend the frequency coverage of the Australia Telescope National Facility receiver systems. The frequency down-conversion and local oscillator systems for the new dual-band, 16 – 26 GHz (12mm band) and 77 – 117 GHz (3mm band), receiver will be described. The system design and active components required to down-convert the very wide, 77 – 117 GHz, frequency range will be highlighted.

INTRODUCTION

The Australia Telescope National Facility (ATNF) comprises the 64-metre dish at Parkes, NSW, the array of six 22-metre dish antennas of the Australia Telescope Compact Array (ATCA), situated near Narrabri, NSW, and a single 22-metre dish antenna located at Mopra near Coonabarabran, NSW. The 22-metre, cassegrain, dish antennas of the ATCA and Mopra are capable of operating up to 115 GHz. The maximum frequency at which these antennas can operate is limited by site atmospheric conditions and the surface accuracy of the main reflector. Five of the ATCA antennas have been equipped with receiver systems covering two observing bands: 16 to 26 GHz, which is referred to as the 12 mm band, and 85 to 105 GHz, which is referred to as the 3 mm band [1].

Since 1994 the ATNF has operated an 86 to 115 GHz Superconductor Insulator Superconductor (SIS) mixer based receiver system on its 22 metre antenna at Mopra. A cryogenically cooled Monolithic Microwave Integrated Circuit (MMIC) amplifier based receiver system was recently installed to replace the SIS receiver. This new receiver system covers the 12 mm band and an extended 3 mm band: 77 – 117 GHz. Provision has also been made to accommodate a third receiving band covering 30 to 50 GHz, designated as the 7mm band, as a future expansion.

The SIS receiver system produced an IF output in the range 1.2 – 1.8 GHz and utilised a mechanically tuned Gunn-oscillator based Local Oscillator (LO) system. The broader frequency coverage of the extended 3 mm band and the 4 – 12 GHz intermediate frequency (IF) necessitated the re-design of the existing ATCA 3 mm frequency conversion system and associated local oscillator chain. This paper describes the frequency conversion and LO systems in detail with particular emphasis on the design of the new 3mm conversion and LO components. It also includes a description of the 12mm conversion and 4 -12 GHz IF systems. The cryogenically cooled receiver system for this band is the subject of a companion paper [2].
THE RECEIVER SYSTEM

The receiver system block diagram, Fig. 1, illustrates the main sub-systems of the new receivers. Astronomical signals in the 3mm and 12mm bands are first amplified in the cryogenically cooled, low noise amplifier (LNA) system. The broadband LNAs, for both receiver bands, use Indium Phosphide (InP) High Electron Mobility Transistor (HEMT) MMICs as the amplifying elements. The LNAs operate at 15 Kelvin in a common vacuum dewar and are cooled by a closed cycle helium refrigerator.

After amplification, the frequency conversion and local oscillator systems down convert astronomical signals from each polarization to an intermediate frequency. The frequency conversion and LO systems are integrated into a single RF screened enclosure located adjacent to the cryogenics package. The conversion system generates two dual polarisation IF output signals: a 4 - 12GHz band IF suitable for input to new broad-band systems currently being developed and a selectable, 4.3 - 7.0GHz or 8.0 - 10.7GHz, IF for further down-conversion in the existing, ATCA antenna-based electronics [3].

All of the critical system parameters and major system functions can be remotely monitored and controlled via a dataset interface. The necessary power supplies, MMIC bias, control and monitor functions are provided on the receiver package.

LOCAL OSCILLATOR AND FREQUENCY CONVERSION SYSTEM

The simplified block diagram, Fig. 2, illustrates the scheme used for frequency down conversion and generation of the required LO signals from a 10.9 – 15.2GHz reference signal. The 12mm band uses a single lower-sideband conversion where an LO signal, in the range 26.7 – 30.4 GHz, is generated by doubling the reference signal. For the 3mm band the same reference signal is doubled three times to generate an LO in the range 87.2 – 106.7 GHz. The conversion is accomplished using side-band separating, resistive HEMT mixers [4], where both sidebands are available. This enables full frequency coverage of the wide RF bands while minimising the LO tuning range [1].

The high RF frequencies require that the down conversion and LO components of the receiver system be located on the receiver package as close as practicable to the vacuum dewar. A single RF shielded enclosure is used to minimise the leakage of harmonics of the reference and LO signals into the observing bands. Figure. 3 shows the conversion module installed on the receiver package. The 3mm conversion assembly occupies the cavity at the extreme left of the module. The assembly includes all of the components that make up the frequency conversion and LO systems. The vacant cavity immediately to the right of the 3mm conversion is for the future 7mm conversion assembly. The 12mm conversion assembly (not fitted) and the two IF assemblies that complete the conversion system are located in the two cavities on the right of the module. To minimise losses, the waveguide and coaxial inputs to the module are located on the bottom face of the module adjacent to the vacuum dewar RF outputs.

All of the functions of the conversion module are remotely controllable via a dataset interface. To simplify system operation and assist in fault diagnosis all of the LO power levels...
and important MMIC bias parameters are monitored as analogue voltages using the common dataset interface.

The conversion system makes extensive use of both commercially available and purpose designed MMIC amplifiers, microstrip components and waveguide devices. Where possible, components have been packaged as multi-chip modules which are integrated into specific conversion assemblies for each band. To simplify maintenance the module and the individual conversion assemblies have been designed so that they are easily replaceable in the field.

3MM CONVERSION

The simplified block diagram of the 3mm conversion and LO multiplier chain, Fig. 4, illustrates the architecture of the multiplier chain including the integrated doubler/power amplifier assemblies. The first doubler sub-assembly uses commercially available MMIC devices and is designed as a self contained component that integrates all of the RF components, bias electronics and LO output power monitoring into a single enclosure. The assembly also includes a microstrip filter and gain equaliser fabricated on 0.010” Rogers RT6002 Duriod [5]. The MMIC power amplifiers and bias decoupling components are attached using conductive epoxy to separate Silvar [6] chip carriers that provide a matched Coefficient of Thermal Expansion (CTE) to the GaAs devices. The output of the first doubler is split using a Wilkinson power divider providing a 21.8 – 26.7 GHz output to drive separate multiplier chains for each polarisation. The second doubler sub-assembly consists of a 50GHz GaAs doubler chip directly wire bonded to a 50GHz power amplifier. The assembly has a coaxial input and a WR-19 waveguide output [7]. The final LO signal is produced by doubling the input reference a third time in a 100 GHz doubler/power amplifier sub-assembly, which has a WR-19 waveguide input and WR-10 waveguide output [7].

Fig. 4. Block diagram of the LO multiplier chain and frequency conversion for the 3mm band.

Fig. 5 shows the completed 3mm conversion assembly which integrates: five individual multi-chip sub-assemblies; mixer sub-assemblies; filters; waveguide equalisers, couplers and isolators; IF amplifiers; MMIC bias supplies and a regulated power supply into a single self contained unit. The WR-10 waveguides visible at the bottom right of the image are the RF inputs. All DC power supply voltages, control and monitor signals are connected to the assembly via a single interface located below the two waveguide inputs. The coaxial 10.9 – 13.3 GHz reference input and IF outputs are located at the rear and top of the assembly respectively. To simplify system maintenance the assembly is designed as an integrated dual polarisation conversion unit that can be replaced as a complete assembly in the field. The assembly includes the facility to remotely monitor the LO power at each step in the multiplier chain. To reduce the potential for LO harmonics to interfere with adjacent observing bands when the 3mm conversion is not in use, the regulated supply to the first LO doubler assembly can be shut down remotely.
3mm Frequency Conversion

To minimise the contribution made by the conversion system to the overall receiver temperature, a minimum of 30dB of cooled gain is required. The dual chip MMIC amplifiers designed for use in the receiver had less than 30dB gain at 115GHz. To increase the cooled gain without compromising the image rejection of the system an additional single chip MMIC amplifier and waveguide equaliser were integrated into the vacuum dewar. As a consequence the total cooled gain of the receiver over the range 75 – 115 GHz band is approximately 40dB [2].

The 3mm frequency conversion was designed around the existing wideband resistive HEMT mixers [4] developed for the ATCA 85 – 115GHz conversion system, previously described [1, 7]. The mixers fabricated by Northrup Grumman Space Technologies1 (NGST) using a 0.1 micron InP process [8], have a minimum conversion loss of approximately 12dB which increases to 15dB at the upper end of the frequency band. The image rejection, using an 8.0 – 10.7 GHz IF band, is generally greater than 20dB with a minimum of 15dB. The LO power required was nominally +5dBm [4].

Fig. 6, shows the conversion loss of the HEMT mixers, measured on wafer, using a gate bias of 0V, with three different levels of LO input power. The conversion loss does not alter significantly with an LO power as low as 0dBm. In addition the image rejection remains consistent across the full range of LO input power tested. The acceptable mixer performance with reduced LO power and a cooled gain of 40dB meant that only one 100GHz power amplifier was required in the LO multiplier chain.

3mm LO Multiplier Chain

The existing ATCA, 85 – 115GHz conversion system [7] was used as the starting point for the LO system for the 77-117 GHz Mopra receiver. The principal goal of the re-design of the LO multiplier chain was to reduce the noise added by the LO signal to the conversion while simultaneously increasing the operating bandwidth. The design process was further constrained by the desire to use as many elements of the existing LO chain as possible and the necessity to use those MMIC devices already in hand or commercially available.

The Mopra antenna is used primarily in a single dish mode, but Very Long Baseline Interferometry (VLBI) observations have been carried out at 3mm. When used as a correlation telescope noise on the LO may show up as phase jitter which may reduce correlation of the astronomical signals. Even if the phase jitter is acceptably small there may be another significant problem. Even what appears to be a low level of noise, in the range 4 - 12 GHz on either side of the LO signal, will be converted in the mixer and appear on the IF output. This additional noise may significantly increase the noise figure of the conversion system and consequently the overall system temperature. To minimise this effect, noise sidebands between 4 GHz and 12 GHz either side of the LO signal need to be suppressed to lower than -145dBm/Hz.

1 Space Technology division of Northrop Grumman Corporation was formerly known as TRW.
The operating frequency of the LO multiplier chain necessitated the use of broad-band MMIC power amplifiers. The doubler/amplifiers, described previously [7], have significant gain outside the nominal operating bandwidth of the multiplier chain. This results in the addition of out-of-band noise and spurious harmonic products generated as part of the multiplication process to the IF output of the conversion. The unwanted noise on the LO signal was minimised by optimising the operating point of the frequency doublers and amplifiers, removing the 100 GHz power amplifier prior to the mixer and adding filters at each stage in the multiplier chain. The filters before and after the first doubler/amplifier sub-assembly, at 12.5GHz and 25GHz, use a modified evanescent waveguide design with coaxial input and output.

Due to the accumulated gain variation of the local oscillator components equalisation was required to reduce variation in the LO output power over the LO operating frequency range. The nonlinear response of the doublers and the 1dB compression point of the LO MMIC power amplifiers [7] dictated that equalisation must occur at 50GHz.

3mm Local Oscillator Equaliser

The use of a reflective equaliser would have resulted in large ripple in the frequency response of the LO chain as a result of multiple reflections. To avoid this ripple an equaliser was developed based on the circuit of Fig. 7a. Two branch line couplers are connected to lengths of waveguide terminated in a short circuit. This structure may be reduced to that of Fig. 7b. By keeping the waveguide stubs equal and terminating the unused ports it is possible to achieve the desired equalisation curve whilst still maintaining matched input and output ports. Using this structure attenuated frequencies are absorbed rather than reflected.

A waveguide model of this circuit was constructed and optimised in Microwave Office [9] before being optimised in HFSS [10] using 3D finite element analysis. A reduced width waveguide section was incorporated after the equaliser to act as a high pass filter removing unwanted noise from outside the band. An image of one half of the final design is shown in Fig. 8. Prior to assembly two absorbing spears are inserted in the terminated waveguides. Fig. 9 shows the simulated performance of the 3mm LO equaliser.

![Fig. 7. Equaliser schematic representation](image)

- **a.** Dual branch line hybrid structure.
- **b.** Simplified structure of (a).

![Fig. 8. Lower half, 3mm LO equaliser.](image)

![Fig. 9. 3mm LO equaliser simulated response, using HFSS [10].](image)
3mm Local Oscillator Performance

Fig. 10 shows the output power of the final LO multiplier chain, measured at the input to the mixer, over the full LO tuning range. The ripple in the output power is primarily caused by mismatches between the various components of the multiplier chain. The level at which the final 100 GHz power amplifier enters gain compression decreases as the frequency increases. The LO chain gain equalisation was designed so that at lower LO frequencies, where the final power amplifier has a higher compression point, the output power delivered by the multiplier chain is greater. Over the full tuning range of the LO system the power amplifiers were not driven into gain compression, but sufficient LO power is provided to the mixers to ensure their conversion loss is acceptable.

12MM CONVERSION

The 12mm frequency conversion assembly, shown in Fig. 11, consists of three main multi-chip modules, associated microwave isolators and a common local power supply regulator card. To simplify system maintenance the assembly is designed as an integrated dual polarisation conversion unit that can be readily replaced as a complete assembly in the field. The assembly includes the facility to remotely monitor the LO power delivered to each of two conversion sub-assemblies separately. To reduce the potential for LO harmonics to interfere with adjacent observing bands when the 12mm conversion is not in use, the regulated supply to the LO doubler assembly can also be shut down remotely.

The conversion assembly converts input RF signals from the 16 – 26GHz observing band down to a 4 -12 GHz IF. The conversion assembly utilises a separate conversion sub-assembly for each linear polarisation. Fig. 12 shows a conversion sub-assembly that integrates the RF amplifiers, image filter, double balanced mixer, IF diplexer/filter, IF amplifiers, along with their MMIC bias supplies into a single multi-chip module [11]. The filters and diplexer are fabricated separately on 0.005” Rogers RT6002 Duriod [5] and eutectically bonded into the body. The MMIC devices and bias decoupling components are attached directly to the body using conductive epoxy and ribbon bonded to the microstrip components as previously described [11].

The 26.7 - 30.4 GHz primary local oscillator signal used in the 12mm conversion sub-assemblies is generated from the common 10.9 – 15.2 GHz reference by the LO doubler sub-assembly. The sub-assembly is designed as a self contained component that integrates all of the necessary RF components, bias electronics and LO output power monitoring into a single enclosure. To minimise duplication of design effort the assembly uses the same MMIC devices and architecture as the first frequency doubler in the 3mm LO multiplier chain. The output LO signal is generated from the reference using a passive Heterojunction Bipolar Transistor (HBT) frequency multiplier, and commercial GaAs MMIC power amplifiers used to provide the required input drive for the frequency multiplier and LO output power for the conversion sub-assembly.
IF SECTION

To ensure compatibility with the existing ATCA systems while providing for the new wide-band correlator systems under development, the conversion module generates two different IF output signals for each linear polarisation. The simplified block diagram, Fig. 13, shows the major components in the sub-system. The broad-band IF output from the desired RF band is selected using a PIN diode switch. An unlevelled 4 - 12GHz IF and a selectable, 4.3 - 7.0GHz or 8.0 - 10.7GHz IF, which can be adjusted over a 15dB range in 1dB increments, is then produced for each polarisation. A separate narrow-band monitor port designed for use in fault diagnosis is also provided.

![Fig. 13. Block diagram of the 4 – 12GHz IF section.](image)

The IF section of the conversion module is made up of two self-contained units, the RF band select and IF assemblies, designed so that each can be replaced as a complete assembly in the field. The RF band select assembly, visible in the centre of Fig. 3, consists primarily of two non-reflective PIN diode switches used to select the IF output from the desired RF conversion assembly. The IF assembly, visible on the far right of Fig. 3, is made up of three different RF sub-assemblies for each polarisation, co-axial isolators and a regulated power supply.

Two of these assemblies, the step attenuator sub-assembly, shown in Fig. 14, and the 4 – 12GHz IF splitter were designed to have as many components in common as possible. The major mechanical component of each assembly is an ATNF designed microwave circuit board. The circuit board includes all of the microstrip components and is fabricated commercially using on 0.010” Rogers RT6002 Duriod [5] on a 0.25” copper substrate. The substrate is machined to accept chip carriers on which the MMIC amplifiers and step attenuator dies are directly attached. The attenuator drive electronics and amplifier bias supplies are on a separate circuit board mounted on the reverse side of the copper substrate.

The IF filter sub-assembly is manufactured using the same methods and materials as the other assemblies. The significant difference is that manufacture of the latter sub-assembly is simplified by the use of commercially packaged microwave devices throughout.

ASTRONOMICAL RESULTS

The new 77 – 117 GHz receiver system was installed on the Mopra antenna in September 2005. The extended frequency coverage of the receiver has allowed astronomical observations to be successfully carried out between 80.6 GHz and 115.3 GHz. The spectra for the source M17-SW [12], shown in Fig. 15, were obtained using the 3mm receiver and the new Mopra Spectrometer (MOPS). The lines, observed simultaneously, are C$^{14}$S, at 96.4 GHz, and CS, at 97.97 GHz.

![Fig. 14. The step-attenuator sub-assembly](image)

Fig. 16 shows the system temperature for the complete receiver system measured above atmosphere with an antenna elevation of 60° [13]. The new 77 – 117 GHz receiver has significantly increased the frequency range of the 3mm observing band and removed the delay associated with the mechanically tuned Gunn oscillators used on the SIS receiver. When the receiver is used in conjunction with MOPS simultaneous observation of broadly spaced spectral lines is now possible.
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REFERENCES