32nd URSI GASS, Montreal, 19–26 August 2017

Design and Laboratory Testing of the Five hundred meter Aperture Spherical Telescope (FAST) 19 Beam L-band Receiver

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Abstract

We describe a multibeam receiver for the FAST radiotelescope. The receiver provides 19 dual polarised beams over a band of 1050–1450 MHz with an expected receiver noise temperature under 7 K and aperture efficiency of greater than 62%. The feed is currently undergoing final assembly and testing.

1 Introduction

The observing efficiency of large-reflector radiotelescopes can be increased by an order of magnitude or more using multibeam feeds [1]. This has motivated the National Astronomical Observatories, Chinese Academy of Sciences (NAOC) to contract CSIRO to deliver a 19 beam feed for the Five-hundred-meter Aperture Spherical Radio Telescope (FAST). The design is similar to those built for the Parkes 64 m and the Arecibo 300 m radiotelescopes [2, 3].

FAST is sited in the province of Guizhou in China [4, 5] and was opened in September 2016. It has an active surface where a 300 m diameter section of the 500 m diameter surface is shaped to form a paraboloid. It uses prime focus optics and the focus cabin is suspended on cables above the reflector.

The receiver comprises 19 closely spaced horns (Figure 1) in a hexagonal array. The receiver equivalent noise temperature is expected to be under 7 K based on measurements of a single pixel system (one array element in isolation) and the aperture efficiency is predicted to range from 62.6% to 74.6% based on electromagnetic modelling.

2 Mechanical Challenges

The cryostat Dewar is maintained at a high vacuum to prevent condensation and convective heat losses. Three Gifford-McMahon cryo-coolers are mounted to the rear plate of the cryostat to provide the cooling for, nominally,

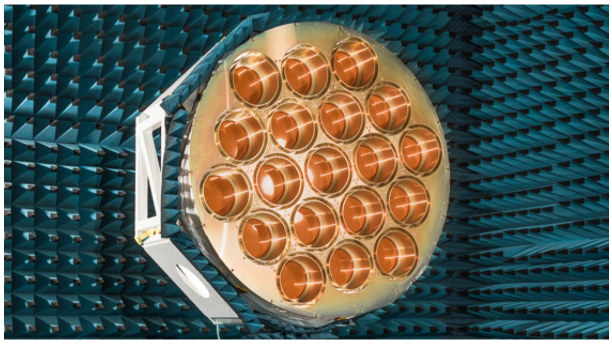

Figure 1. The feed array undergoing radiation pattern measurements.

20 K and 70 K thermal stages. The thermal stage conduction plates are further mechanically divided into sectors corresponding to the three cryo-coolers to allow for the thermal contraction of these plates. The components are connected to these plates via spring linkages also to allow for thermal contraction as the feeds are rigidly mounted to the front plate of the cryostat. The low noise amplifiers (LNAs) are connected to the 20 K stage and ortho-mode transducers (OMTs) are connected to the 70 K stage (Figure 2).

The ambient temperature electronics are mounted in three cabinets fixed to the back plate of the cryostat. A cable wrap carrying power, helium lines, the RF signals and monitor and control signals is mounted on top of the three cabinets. The entire structure weighs over 1.2 t and is about 2 m high and 1.6 m in diameter (Figure 3).

3 Feeds

Multibeam feed arrays typically have two competing constraints: the feed horn spacing must be small enough to effectively sample the focal fields and feed horn apertures must be large enough to efficiently illuminate the reflector. In order to efficiently image the sky the beam spacing was constrained to two full width half maximum (FWHM)

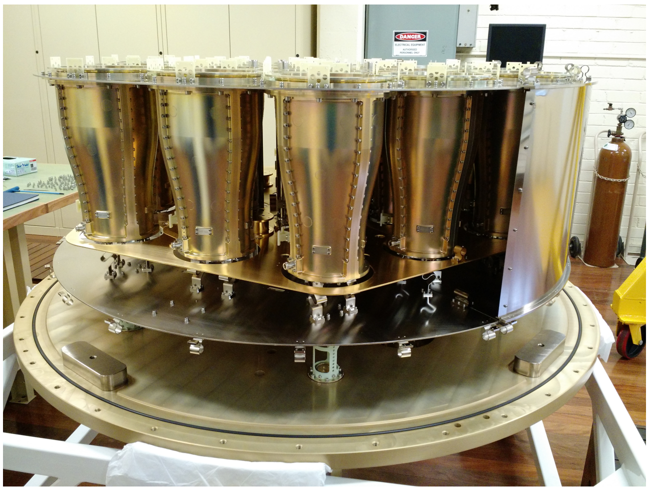

Figure 2. The array during a trial assembly showing the nickel plated 70 K plate and the gold plated 20 K plate. The thermal gap, pressure windows and feeds are yet to be mounted on top of the OMTs.

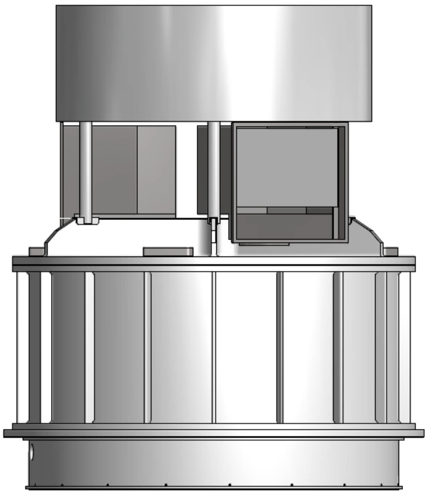

Figure 3. Side view of the feed package. The cable wrap drum is shown on top with the equipment cabinets in the middle and cryostat at the bottom.

beamwidths at the maximum frequency of operation. This constraint resulted in a feed separation of 270 mm. The extent of the array is limited by scan loss and distortion in the offset beams. The maximum scan loss of the 19 beam hexagonal configuration (0.66 dB) is within the 1 dB specification. An increase in the number of beams over the 13 beams of the Parkes multibeam is possible due to the slightly larger f/D: 0.466 as compared with the 0.410 f/D of Parkes [4].

A preliminary design was conducted during the feasibility stage [6] and revised before production. In this revision, a single choke ring was added to the feed design to improve pattern symmetry, reduce sidelobes and to reduce feed to feed coupling. The choke ring's effectiveness is limited

Table 1. The calculated half power beamwidth (HPBW) and aperture efficiency of the central element and worst case edge element of the array.

Freq.	HPBW (°)		Efficiency (%)	
(GHz)	Central	Edge	Central	Edge
1.05	0.064	0.065	72.1	66.7
1.25	0.053	0.056	73.4	66.1
1.40	0.051	0.052	71.6	63.5
1.45	0.048	0.051	72.5	62.6

by the available space and comes at the cost of a slightly increased beamwidth, however, the overall performance is improved. The calculated half power beamwidth aperture efficiency [7] of the feed-dish model is shown in Table 1 for the central and worst case edge beams. Their radiation patterns are shown in Figures 4 and 5. The radiation patterns of the feed/OMT combination have been measured and exhibit good agreement with the electromagnetic model [8].

4 OMTs

The OMT design is limited by the weight and height constraints of the overall system. The preliminary design was a stepped quad-ridged structure whereas the revised design uses an optimised smooth spline shape for the walls and the ridges. The coaxial feeding section contains matching components that reduce the overall length of the OMT. A gap and pressure window come between the OMT and the horn section of the feed. The gap is to provide thermal isolation between the 70 K OMT and the ambient temperature window. As a further measure to reduce the overall length of the system, the noise injection couplers are placed in the pressure window. The reflection coefficients of the fully assembled OMTs and feeds are shown in Figure 6.

5 Low Noise Amplifiers

The LNAs have a two stage design targeting a low input reflection coefficient as well as a low noise figure. The former is important for minimising ripple in the system gain and noise – both important parameters for radio astronomy. Commercial bare-die GaAs-HEMTs (gallium arsenide high electron mobility transistors) are bonded onto a printed circuit board containing the lumped element matching networks. The biases are supplied from ambient temperature electronics. The full complement of 44 LNAs (38 plus six spares) have been tested and show excellent repeatability with a cryogenic gain of 32 dB and a typical equivalent noise temperature of 3 K. The noise performance of the LNA and feed-LNA combination is shown in Figure 7. The LNA scattering parameters are shown in Figure 8.

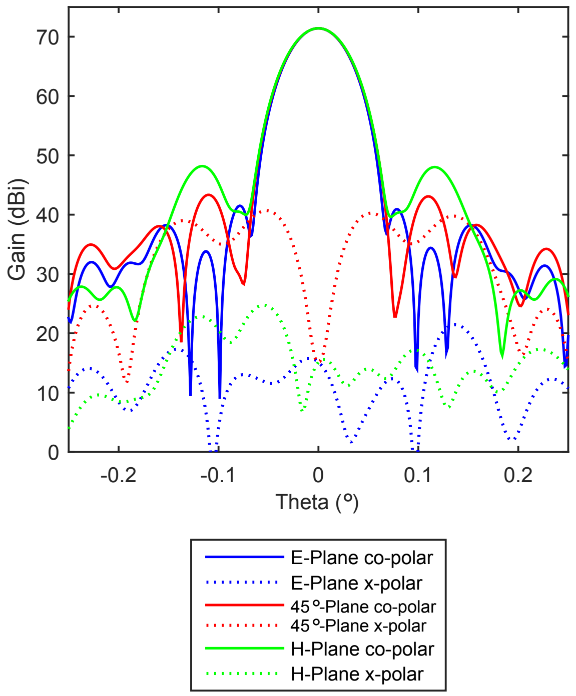

Figure 4. Calculated co- and cross-polar radiation patterns of one polarisation of the central beam (with reflector).

6 Receiver Signal Chain

The OMTs (at 70 K) are connected via short cables to the LNAs (at 20 K). Cables run from the LNAs to the 70 K plate and then to the bulkhead on the cryostat rear plate. Additional filtering and amplification is provided before the signals pass to the RF over Fibre (RFoF) link that runs from the focus cabin to the control building on the ground where it passes through an anti-aliasing filter before digitisation. The inevitable presence of radio frequency interference (RFI) dictates the need for careful control of levels, particularly at the input to the RFoF link and the digitisers.

7 Control and Monitor and Noise Systems

The receiver is provided with a comprehensive control and monitor system accessible via an Ethernet over optical fibre connection. A noise injection system for gain calibration is mounted outside the Dewar on the front face. The noise diode itself and a single gain stage are temperature stabilised to remove thermal level variations and the noise is distributed via splitters to all 19 feeds via equal length cables. A coupled copy of the noise signal is passed back through the ambient RF signal path to the control building so it is available for sophisticated calibration schemes such as correlating it against the receiver signals.

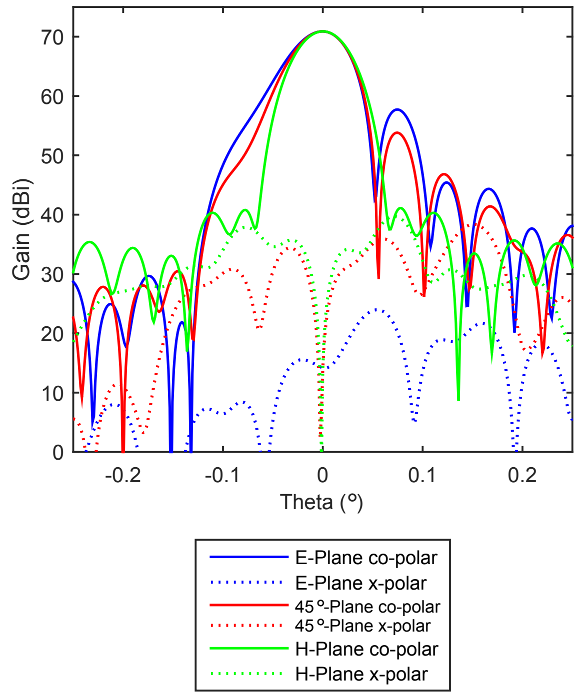

Figure 5. Calculated co- and cross-polar radiation patterns of one polarisation of an edge beam (with reflector). The pattern is centred on the maximum, corresponding to an offset in the H-Plane of 0.1925°.

8 Conclusion

We present the simulated and measured performance of components of a 19 beam multibeam receiver for the FAST radiotelescope. The receiver promises excellent on-dish performance with lower than 7 K receiver noise temperature and greater than 62% predicted aperture efficiency. There have been many refinements on previous designs including shortened OMTs, choked feeds, superior LNAs and other improvements making construction and maintenance more practical. We look forward to the installation and the commissioning results and a long life for the receiver in the service of radio astronomy.

9 Acknowledgements

The authors acknowledge the National Astronomical Observatories, Chinese Academy of Sciences (NAOC) for funding this project, Jin Chengjin of NAOC for fruitful discussions on the details of the receiver and the workshop staff at CSIRO who built most of the components and were very responsive in meeting our mechanical needs.

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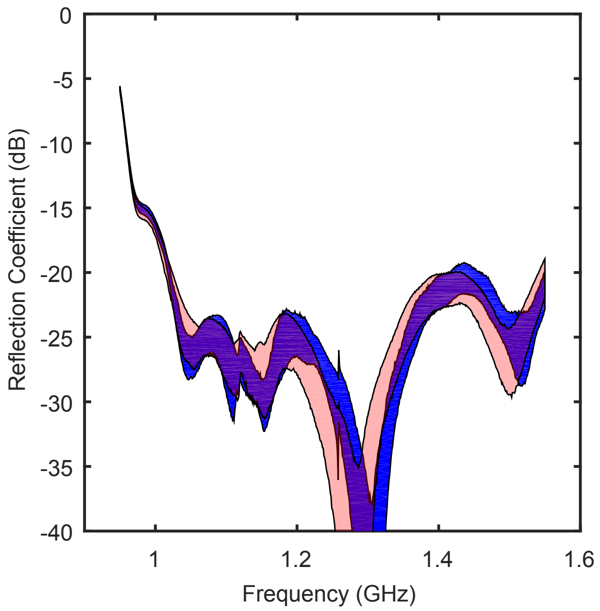

Figure 6. Measured reflection coefficient (dB) of the coaxial ports for the two polarisations – shown in blue (Polarisation A) and pink (Polarisation B) – for all 19 elements of the multibeam feed. Asymmetries in the coaxial probes of the OMT result in different reflection coefficients for the two polarisations.

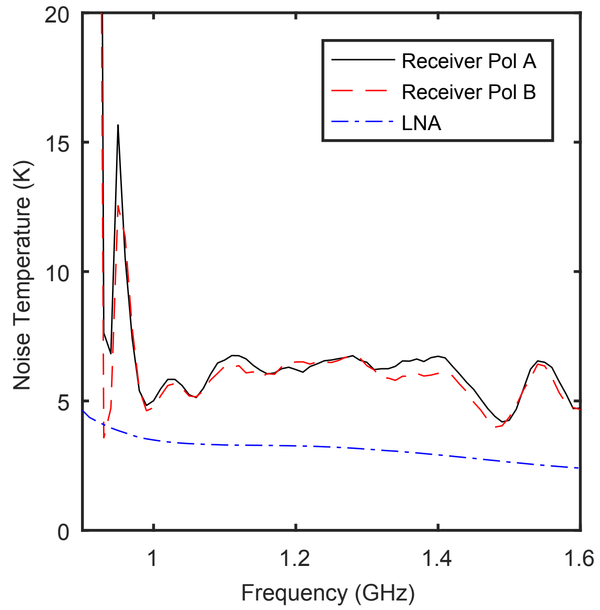

Figure 7. Measured LNA and receiver equivalent noise temperature for one of the elements.

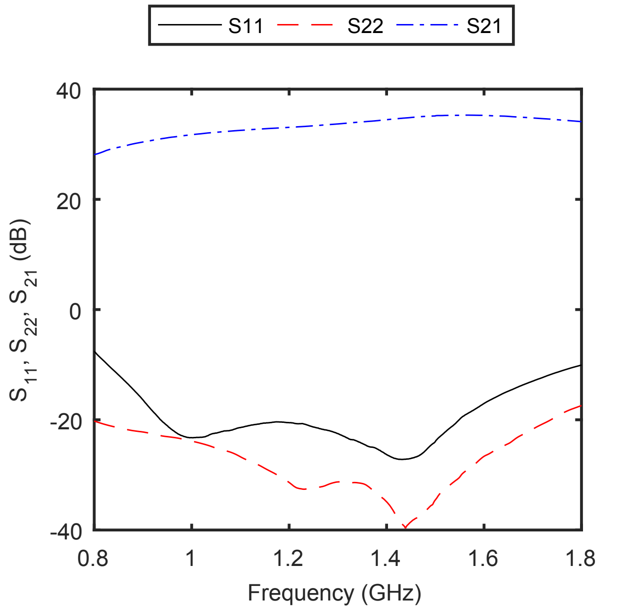

Figure 8. Averages of the scattering parameters of the 44 LNAs.

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