Abstract — This paper presents the measured sensitivity of CSIRO’s first Mk. II phased array feed (PAF) on an ASKAP antenna. The Mk. II achieves a minimum system-temperature-over-efficiency $\frac{T_{\text{sys}}}{\eta}$ of 78 K at 1.23 GHz and is 95 K or better from 835 MHz to 1.8 GHz. This PAF was designed for the Australian SKA Pathfinder telescope to demonstrate fast astronomical surveys with a wide field of view for the Square Kilometre Array (SKA).

1 INTRODUCTION

We present preliminary measurements of the sensitivity of CSIRO’s first Mk. II phased array feed (PAF) [1] on an ASKAP antenna as shown in Figure 1. Over the next two years, Mk. II PAFs will be installed on thirty 12 m parabolic reflectors of the Australian SKA Pathfinder telescope (ASKAP) [2] to demonstrate fast astronomical surveys with a wide field of view for the Square Kilometre Array (SKA). The SKA is an international project to build the world’s largest radio telescope with a square kilometre of collecting area [3].

Figure 2 shows that the Mk. II achieves a minimum system-temperature-over-efficiency $\frac{T_{\text{sys}}}{\eta}$ of 78 K at 1.23 GHz and is 95 K or better from 835 MHz to 1.8 GHz with the receiver near room temperature. By comparison, the CSIRO Mk. I PAF is 95 K or better only from 735 MHz to 1.2 GHz [4]. This significant improvement was achieved via enhanced antenna array and low-noise amplifier (LNA) designs [5]. Both Mk. I and Mk. II ASKAP PAFs are based on a connected-element “chequerboard” array [6] that is dual-polarized, low-profile, and inherently wide-band.

The only other PAF being built in comparable numbers to the ASKAP PAFs is ASTRON’s APERTIF PAF for 12 antennas of the Westerbork Synthesis Radio Telescope. It is specified for $\frac{T_{\text{sys}}}{\eta} = 93$ K over 1.13 GHz to 1.75 GHz [7].

Next steps to improve PAF sensitivity include the adoption of lower-noise transistors [8] and cryogenically cooling PAFs as recently demonstrated on the Green Bank Telescope [9].

2 MEASUREMENT SYSTEM

Figure 1 shows the prototype Mk. II PAF installed on ASKAP antenna 29 at the Murchison Radio-astronomy Observatory (MRO) in Western Australia. Antenna 29 is cabled so a receiver can be tested as a PAF at the antenna’s focus or as an aperture array on the ground nearby.

Radio-frequency (RF) signals from each of the 188 “chequerboard” ports are modulated onto optical fibre links within the PAF package. The RF signals then travel over 1.4 km of optical fibre to the digital receiver in the ASKAP control building. The ASKAP digital receiver [10] directly samples 192 signals (188 from the PAF and 4 spare) and then uses an oversampled poly-phase filter bank [11] to divide these signals into 1 MHz channels. Each directly-sampled band has approximately 600 MHz RF bandwidth, but only 384 MHz are passed to the beamformer in the current configuration. A particular contiguous 384 MHz sub-band is selected for beamforming via a software command to set the centre frequency.

The ASKAP’s beamformer [12] includes a firmware Array Covariance Matrix (ACM) module to calcul-
The ratio of system temperature $T_{\text{sys}}$ to antenna efficiency $\eta$ is then given by [13]

$$\frac{T_{\text{sys}}}{\eta} = \frac{AS}{2k_B(Y - 1)}$$

(4)

where $A$ is the geometric antenna (reflector) area, $S$ is the known flux of the reference source and $k_B$ is Boltzmann’s constant. Antenna efficiency is defined by $\eta = \eta_{ap}\eta_{rad}$, the product of aperture efficiency and radiation efficiency. The efficiencies and system noise temperature of receiving arrays are more fully defined in [15]. They both depend on the beamformer weights as can be implied from equations (3) and (4).

Equation (4) shows that $T_{\text{sys}}/\eta$ is minimised by maximising $Y$. Rearranging (5) reveals an eigenvalue problem

$$R_{\text{off}}^{-1}R_{\text{on}}w = Yw.$$  

(5)

Maximum beamformed Y-factor corresponds to the dominant eigenvalue of $R_{\text{off}}^{-1}R_{\text{on}}$ and is achieved with beamformer weights set to the dominant eigenvector [14]. In this work we included all ports of both polarizations in the beamformer weight solution by using the full $188 \times 188$ matrix $R$ when solving equation (5). Figure 2 shows the resulting sensitivity for the beam corresponding to the strongest of two dominant eigenvalues. This should be the overall best-case maximum sensitivity beam, but its polarization will be biased by any polarization in the signal field (calibrator) or noise fields (e.g. spillover and receiver noise).
Table 1 summarises the measurements made for this work. On and off-source measurements were made in three of ASKAP’s RF bands over two days in September 2014. The off-source position was a +7° offset in right ascension. We used Taurus A as the flux reference assuming the flux model of [16]. Tau A is 0.5% and 3.5% polarized at wavelengths of 20 cm and 30 cm respectively [17].

Care should be taken when comparing our measurements to those from the northern hemisphere using Cas A as the flux reference. The strength of Cas A is evolving non-uniformly with time [18]. This necessitates ongoing monitoring of flux calibration sources concurrent with their use to measure the sensitivity of new telescope receivers [19].

Single-dish beamforming with a PAF on a 12 m reflector antenna in the southern hemisphere is challenging as Tau A, the strongest available unresolved source, has a flux of 980 Jy at 1.25 GHz. This is weaker than the system equivalent flux density of 2,000 Jy at the same frequency. Most single-dish beamforming for the Mk. I BETA PAFs has been performed using the Sun, which although slightly resolved by a 12 m reflector antenna, provides a much higher signal-to-noise ratio (S/N) of order 100 to 1,000 [4]. In this work we have for the first time successfully beamformed on a single 12 m ASKAP antenna with an instantaneous S/N less than unity. This is important for commissioning, but we expect the full ASKAP to make high S/N beamforming solutions via interferometry [13, 20].

We also measured aperture-array sensitivity via the method of [21] and found a beam equivalent system noise temperature referenced to the sky of $T_{sys} < 50$ K from 800 MHz to 1.7 GHz. Beamformer weights and spillover differ between aperture array measurement of $T_{sys} = T_{sys}/\eta_{rad}$ and on-dish measurement of $T_{sys}/\eta$. Measuring efficiency is not as simple as dividing one by the other.

4 CONCLUSION

Our $T_{sys}/\eta$ measurement for the first Mk. II PAF shows a doubling of low-noise bandwidth over the Mk. I PAF results in [4]. Above 1.4 GHz, sensitivity has been doubled and survey speed should be quadrupled. The Mk. II PAF has operated reliably at the MRO and near continuously since it was installed on antenna 29 in September 2014. This has included numerous summer weeks with maximum daily site temperatures regularly exceeding 40°C.

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