One square metre of a million

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One Square Metre of a Million

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Abstract — The One Square Metre Array (OSMA) is the second of three stages leading to the Square Kilometre Array (SKA). The SKA telescope will be sought after by astronomers around the globe, as its sensitivity to astronomical sources will be greater than two orders of magnitude better than current telescopes.

The OSMA system consists of two beamforming stages - RF and Digital. In this paper the RF beamformer is discussed in detail and recent findings presented. One of the major features of the RF beamformer is its large instantaneous bandwidth which is due to the fact that time delays are used to form beams.

I. OSMA - THE ONE SQUARE METRE ARRAY

As a lead up to the astronomical telescope SKA [1], several developments have been devised to prove technology, algorithms and feasibility of such a large telescope. These developments include the Adaptive Antenna Demonstrator (AAD) [2, 3], the current development of OSMA, and finally the Thousand Element Array (THEA) [4] to be completed in the year 2000.

The OSMA system, which is pictured in Figure 1(a), is a phased-array receive-only antenna with a mixed RF and digital adaptive beamforming architecture operating in the frequency range of 1.5 GHz to 3.5 GHz. The linearly polarized antenna consists of an 8 by 8 element active centre region surrounded by two rows of passive elements (totalling 80 elements). The array is built up of broadband bow-tie antenna elements with an integrated balun [5] and the distance between adjacent elements is 75mm in both directions. The array is backed by a ground plane which is rounded at the array edges to reduce diffraction effects.

The beamforming hierarchy is illustrated in Figure 1(b) where the active elements are connected to 16 RF beamformer units (RFBF I). Each RFBF I unit receives signals from four bow-tie elements, producing two identical beam outputs. The outputs of the RFBF I units can be connected to both a 16-channel adaptive digital beamforming (ADBFS) unit or to a second stage 16-channel RF beamformer unit (RFBF II). The receivers perform frequency down conversion to an intermediate frequency of 70 MHz. OSMA will be used in two different modes; a RF beamforming mode, or a mixed RF/digital adaptive beamforming mode.

(a) OSMA Bow-tie Array

(b) OSMA Beamforming Hierarchy

Fig. 1: (a) The OSMA array inside the NFRA test facility. (b) The beamforming hierarchy of OSMA is divided into several stages - allowing many different beamforming configurations.

The OSMA system is connected to Matlab using an experimental measurement system [6], from which all system devices can be controlled. Matlab provides a powerful interface to control and analyse data from the OSMA system. Graphical-User-Interfaces (GUI) provide real-time control and visualisation of beamforming experiments.

Part of the system specification of SKA is its ability to reject Radio Frequency Interference (RFI), a major problem for astronomical telescopes. Typically, RFI signals are significantly stronger than astronomical sources, resulting in saturation of the receivers and thus making the resulting images void. Using four stages of processing OSMA rejects RFI by:

1. The antenna elements are only receptive to energy originating from a conic angle of less than 50° , rejecting terrestrial based interference.
2. The RF beamformer narrows the observed region (4 element beamformer module) and suppresses RFI originating from extra-terrestrial sources through low sidelobes.
3. The frequency down conversion process selects only the frequency band of interest, reducing the bandwidth and the possible number of interfering sources.
4. The adaptive digital beamforming can remove the remaining RFI through optimal weighting of the 16 RF beams.

II. TIME DELAY BEAMFORMING

Beamforming at the RF stage can be implemented in many ways [7], including phase shifters and time delays. For each technique, there exists a number of advantages and disadvantages. A radio astronomical application requires a large instantaneous bandwidth and for this reason OSMA uses a system of switched delay lines, or Time Delay Units (TDU), to *steer* the RF beam. Additional advantages for this type of implementation include low power consumption and resistance to temperature fluctuations. A major disadvantage though is its large size, as at the centre frequency of the design, 2GHz, the corresponding wavelength is 15cm. The longest time delay possible in the RFBF 1&2 beamformers corresponds to a look direction of $\pm 40^\circ$. The half power point of the bow-tie antennas occurs at $\pm 50^\circ$.

Figure 2(a) illustrates a scale drawing of the RF beamformer circuit, where a four stage microstrip TDU is used. The 4-bit quantisation of the TDU is rather coarse, however as the total number of elements is large, the phase errors average out making it possible to finely steer a beam with low side-lobes. The final resolution is provided in the digital beamformer, where 12-bit phase shifts are possible. The magnitude of the errors that occur in the RF-beamformer have been measured to be smaller than one quantisation step. Since the digital beamformer has far greater phase resolution, calibration of the array is implemented digitally [8].

(a) RF-Beamformer Microstrip Circuit

(b) RF Beamformer Performance

Fig. 2: (a) Microstrip circuit board layout of the RF Beamformer. The antenna outputs enter from the bottom of the layout and are immediately amplified by a LNA, weighted in amplitude with an 8-bit variable attenuator (VAT) and then delayed with the 4-bit TDU. A Wilkinson combiner adds the four delayed signals into one. The combined output is split into two: one is used for further RF combination and the other for the digital beamformer. The RF Beamformer module digital controller is located in the top left corner on a separate PCB. The entire module is encased in an aluminium housing. (b) The phase shifting performance of the RF beamformer module relative to the first TDU setting.

Figure 2(b) illustrates the measured phase for each of the sixteen (2^4) TDU settings, in agreement with the expected linear relationship of phase with frequency. This phase relationship makes it possible to steer the main beam of the array without squinting over a large frequency range.

To account for phase and gain variations in the RF Beamformers, each unit is calibrated on the bench using a Network Analyzer for each of the TDU and VAT settings. Once this data is obtained, the unit is installed in the array where a phase toggling technique [9] is used to determine each antenna's gain and phase offsets. After such a calibration method it is possible to steer the RF beamformer in *any* desired direction. Alternatively, it is possible to treat the time delays in the RF beamformer as phase shifts (given a particular steering frequency) so that look directions greater than 40° are possible. However, the system has bandwidth limitations.

III. OSMA DIGITAL BEAMFORMING

The sixteen outputs of the RFBF 1 units are used as default inputs to the digital beamforming system. However, it is also possible to use different combinations of antenna elements (such as 4×4 elements) to feed the digital beamformer. Each RFBF 1 signal undergoes two frequency down conversions, firstly to 70 MHz and secondly to base band. The analogue-to-digital converter (ADC) sampling frequency is 8 Mhz, providing a narrow band signal of bandwidth 4 MHz.

There exists two digital beamformers, providing two simultaneous digital beams. The idea of having multiple beams is advantageous in astronomy since observations typically exist for long periods of time. Having

more than one beam [10] increases the observation efficiency of the telescope, as well as making other astronomical experiments possible.

The resolution of the digital beamformer is dependent on how many signals are combined and the location of the antennas. Since the resolution of the RFBF 1 is relatively larger than the digital beam, it is possible to move the digital beams around inside the RF beam. Both beams can have adaptive weights, but their directions will be constrained within the half power contour of the RF beam. Results from the digital beamformer can be found in [11].

IV. OSMA RF BEAMFORMING RESULTS

Figure 3(a) illustrates the combination of frequency and spatial responses of an RF beamforming module. In this experiment a positioner holding the RFBF 1 module is rotated through an angle θ and the response measured using a Network Analyzer. Over the 2 GHz frequency band shown the beam pattern is relatively stable achieving the desired large instantaneous bandwidth. The tapering of the main lobe is due to the nature of higher frequencies producing greater spatial resolution. For some frequencies (for example 3.1 GHz) the beamformer output is corrupted by resonances.

Figure 3(b) illustrates a fully RF beam steered to broadside for an 8×8 antenna array configuration. Rectangular weighting has been applied and it can be observed that it is still possible to form nulls of large depths (greater than 80dB) with such large quantisation errors in the RF beamformer. OSMA represents approximately one sixteenth the area of the next demonstrator THEA.

(a) RF Beamformer Module Pattern

(b) 8×4 Antenna Array Beamforming Pattern

Fig. 3: (a) The large bandwidth of the RF beamformer is illustrated here for a single module steered to broadside. (b) A fully RF Beam steered to broadside for an 8×8 element configuration. θ and ϕ represent the positioners elevation and azimuth direction respectively.

V. CONCLUSIONS

A short description of the OSMA system has been given, including details of how RFI suppression can be achieved. An important component of this is the RF beamformer, of which detailed implementation details were given. One of the features of the RF beamformer is the 4-bit time delay unit which provides a large instantaneous bandwidth up to an octave. The beamforming results from OSMA indicate promising results for the next demonstrator, THEA.

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