D-PAD: A sparse aperture array for radio astronomy and testbed for Square Kilometre Array technologies

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Abstract

The D-PAD sparse aperture array is a pathfinder for the SKA Phase 1 Aperture Array. Here, we give an overview of the D-PAD system then discuss the deployment of the first D-PAD tile. D-PAD is designed as a test-bed for novel radio astronomy techniques, such as next-generator correlator architectures, RFI excision algorithms, and calibration schemes. D-PAD aims to investigate the dynamic range achievable using sparse arrays. Proving that high dynamic ranges can be achieved with sparse arrays is an important step towards the phase 1 SKA aperture array design.

1 Introduction

The Square Kilometre Array (SKA) is one of the most ambitious projects to date in radio astronomy. The SKA will be an array of connected antennas spread over an area about 3000 km, with an aggregate antenna collecting area of approximately one square kilometre, between centimeter and meter wavelengths [1]. The low frequency aperture array component is set to be built first, at a remote, radio quiet site in either Western Australia or South Africa.

D-PAD is an aperture array based radio telescope designed as a test-bed for SKA technologies. D-PAD has been designed to be the simplest instrument possible that replicates most key aspects of an SKA aperture array. All hardware has been chosen to be both flexible and reconfigurable, and the digital backend is designed to be compatible with SKA AA low- and mid-frequency frontends. This will allow the rapid prototyping of antennas, low noise amplifiers, filters and signal transport methods. The backend also provides the signal processing power necessary to investigate new correlator and direct imaging implementations.

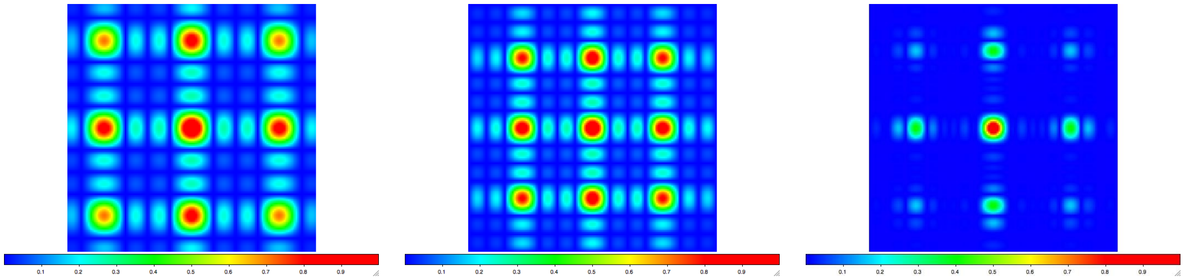
In this paper, we report on the design of the D-PAD system and the deployment of the first D-PAD tile. We begin by briefly discussing how D-PAD will overcome the grating lobe response found in sparse arrays. We then introduce the D-PAD system, and discuss various analogue components; this is followed by explication of the D-PAD digital architecture. We conclude with discussion of the future use of D-PAD and its role in the SKA related research.

2 Product beam grating lobe mitigation

The side lobes and grating lobes of an aperture array cause it to be sensitive to radiation from undesired directions, which can potentially poison our sought after signal with unwanted noise. Grating lobes are a major problem for radio astronomy as they cause source confusion, due to ambiguity of the location of the source. For a single aperture array, this poses a problem; however, if we correlate the output of multiple arrays the affect of side and grating lobes can be somewhat mitigated. For a pair of receiver antennas separated by a distance d with voltage outputs $V_1(t)$ and $V_2(t)$, a correlator adds a time delay τ_g then computes the time average :

$$\langle V_1(t)V_2^*(t-\tau_g)\rangle_t = \frac{1}{T}\int_0^T V_1(t)V_2^*(t-\tau_g)dt. \tag{1}$$

These data are mapped into Fourier space and then inverted to form an image of the radio source's intensity distribution [2]. Each correlation product contains the product of each antenna's radiation power pattern,



(a) 2λ element spacing (b) $\frac{5\lambda}{2}$ element spacing (c) Product beam

Figure 1: An example of attenuation of grating lobes in the product beam of two arrays. In a) and b), we have the radiation power patterns at $300MHz$ for a 4×4 gridded array with spacing 2λ and $5\lambda/2$, respectively. Sub-figure c) shows the product beam, in which the grating lobe response is attenuated.

$A_1 A_2$, known as the *product beam*. In D-PAD, we intend to use this to our advantage to suppress the affect of grating lobes. If we ensure the grating lobes occur in different positions, then they will be suppressed in the product beam, mitigating their effect. A simple example of this is shown in Figure 1, for two regularly gridded arrays with different inter-element spacings.

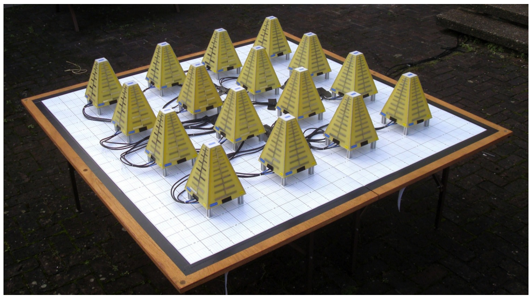
3 The D-PAD system

D-PAD is a sparse aperture-array based interferometric synthesis telescope, consisting of eight analogue beamformed aperture array "stations", which are connected to a central correlator. Each station consists of 16 dual polarisation antennas, yielding a total of 128 antennas. The correlator computes the time averaged product for each of the $(8 \times 7/2 = 28)$ baselines between stations; these data are then used to form synthesis images. D-PAD operates over the frequency range 1000-1500MHz, digitizing and processing the full 500MHz bandwidth.

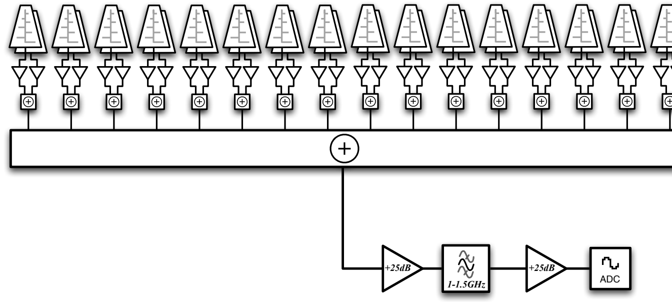
The first fully functional D-PAD station is shown in Figure 2a. The array is currently arranged into a 4×4 square, spaced at 2λ at 1500MHz. We will shortly begin work on measuring the radiation power pattern of this array configuration at a test range. The analogue systems are shown diagramatically in Figure 2b, and discussed below.

3.1 Antenna design

We have designed a bespoke dual polarisation log-periodic dipole array (LPDA) high gain antenna for use in the D-PAD system. The antenna blade is based on a design by Pantoja [3], in which the antenna structure is printed onto a dielectric substrate. Each "antenna element" consists of four separate LPDA "blades", which are arranged into a pyramidal structure, as shown in Figure 2a; each blade is a fully functional single polarisation antenna in its own right. By arranging the blades into a pyramidal structure, we have two perpendicular pairs of antenna blades, one for each polarisation. The output of each blade pair is amplified then power combined, resulting in one output signal per polarisation. Antenna performance has been simulated in FEKO and verified in an anechoic chamber, see Figure 3. Initial results suggest that the antenna, low noise amplifiers and power combiner have an overall system temperature of between $90 - 140K$.



(a)



(b)

Figure 2: a) first station of the D-PAD system. b) diagram of the D-PAD analogue systems, shown for a single polarisation of one station.

3.2 Analogue components

A diagram of the D-PAD analogue systems is shown in Figure 2b. The output of each antenna blade will be directly connected to a low noise amplifier; we have selected the Avago MGA-633P8, which has a noise temperature of under $30K$ over the D-PAD operational range. After this, the signal from each antenna pair is combined using a Mini-Circuits GP2S+ power combiner then amplified further, before being sent via coaxial cable to two separate analogue beamformers, one per polarisation. Initially, we will use Mini-Circuits ZC16PD-24 16 way power combiners. A bespoke Wilkinson power combiner based beamformer module is currently under development.

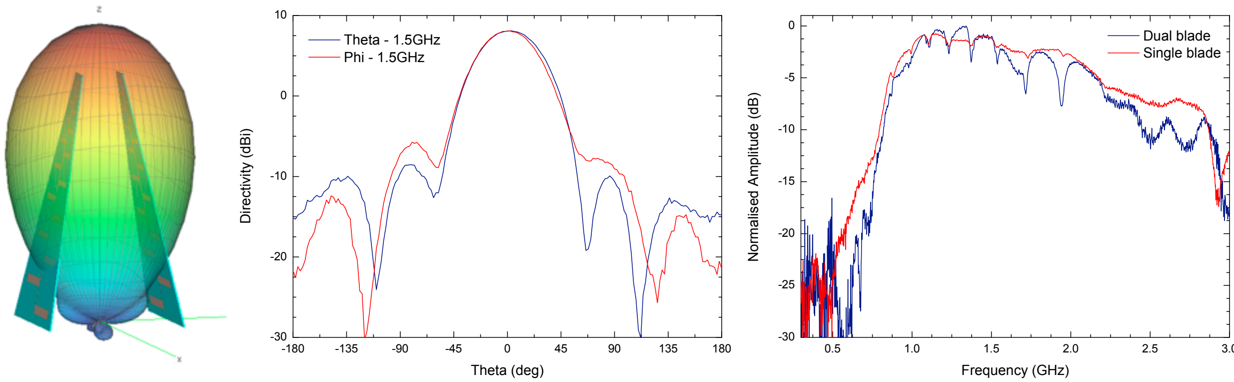
After beamforming, the signal from each beamformer is amplified, then bandpass filtered to select the 1000–1500MHz band. The bandpass filter has been made in-house, using an edge coupled bandpass filter design [4]. The initial station uses Mini-Circuits ZRL-2150+ to provide extra amplification, although this will also be made in-house if we can fabricate a comparable amplifier with significant cost saving.

3.3 Digital backend architecture

Once the signals from each station are amplified and filtered, they will be digitised for correlation. D-PAD, is based upon hardware designed by the Collaboration for Astronomical Signal Processing and Electronics Research (CASPER), who provide open source, FPGA based hardware designed for radio astronomy [5].

In D-PAD, we will be utilising CASPER iADC analogue to digital converters and ROACH boards for signal processing. The ROACH, or Reconfigurable Open Architecture Computing Hardware board, is a Xilinx Virtex-5 FPGA based signal processing board, designed to be interconnected with other devices via 10 gigabit ethernet.

To compute the necessary correlations, we will use the CASPER Packetised Signal Processing Architecture provided by the CASPER collaboration. In this architecture, each signal is first put through a polyphase filter bank, then the correlation operation is conducted in the frequency domain. The architecture allows the correlation to be spread over multiple ROACH boards, interconnected via a 10 gigabit switch. Due to the complexity that arises with interconnected boards, we will first design gateware to perform the digitsation, fourier transform and correlation operations on one ROACH. A ROACH based spectrometer has already been tested on the first D-PAD station, and the bright sourceCygnus A and the HI spectrum of the Milky Way were successfully detected.



(a) (b) (c)

Figure 3: a) Simulation of far-field radiation pattern for an angled pair of D-PAD antenna blades b) Radiation power pattern for D-PAD antenna, as measured in an anechoic chamber. c) Measured gain magnitude of D-PAD antenna over 500-3000MHz

4 Conclusions

Quantifying the dynamic range limits of sparse arrays on small systems such as D-PAD is an important step toward ensuring large, more complex systems such as the SKA can meet its dynamic range requirements. The first task of the full D-PAD system will be to undertake a drift scan survey of an annulus of the Northern sky over a three month period. The data produced will then be calibrated to produce a map of the sky. We will then correlate our map with other surveys to deduce the dynamic range and effect of grating lobes. Once this has been demonstrated, the system will be available for use as a more general test-bed for SKA technologies and correlator architectures. This will allow the rapid prototyping of antennas, low noise amplifiers, filters and signal transport methods, making D-PAD a useful tool that should be exploited in the SKA aperture array design process.

References

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