A PHASED-ARRAY FEED DEMONSTRATOR FOR RADIO TELESCOPES

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ABSTRACT

Future centimetre-wavelength radio telescopes will use low-noise phased arrays as feed antennas. Two key advantages of this technology over conventional horn feeds are that it will enable the radio telescope to have many simultaneous beams on the sky, increasing the speed of the instrument, and it will also allow the properties of the feed to be optimised. However, phased-array feeds are not in use yet because technology has only recently advanced towards the high sensitivity and bandwidth required for astronomy. We describe the early stages of development of an engineering demonstrator that will explore the capabilities of phased-array feeds.

INTRODUCTION

Most centimetre-wavelength radio telescopes use single horn antennas as feeds and thus have a single beam on the sky. If phased arrays are used as feeds then multiple beams can be synthesized, increasing the instantaneous field-of-view and speed of the telescope significantly. The pattern of the feed array could also be optimized to match the optical configuration of the telescope, reducing the effects of aberrations [1]. With a versatile beamformer additional capabilities will be available, including correction of surface errors [2], compensation of polarization errors, interference mitigation, and suppression of near-field scattering by feed struts [3]. Although several experiments have been performed using simple phased-array feeds (Rick Fisher and Richard Bradley in the US [4], and Mariana Ivashina and others in the Netherlands [5]), phased-array feeds have not been deployed on telescopes because the underlying technologies were unable to provide the high-sensitivity and large-bandwidth requirements of radio astronomy. However, technology has now advanced to the point where phased-array feeds can begin to be considered seriously. Those technologies are densely-packed phased array elements (such as Vivaldi antennas [6, 7]), low-cost low-noise amplifiers, integrated-circuit receiver systems, low-cost high-speed digitizers, and high-speed digital signal processors.

We have commenced construction of a phased-array feed demonstrator system (PHAD). PHAD will be an *engineering* demonstrator as it will lack the sensitivity and bandwidth for scientific observations, but will be a early step in the development of systems that can be truly competitive scientific instruments. The structure of PHAD will be highly modular, permitting easy modification and upgrade of subsystems. For example, the antenna array will be composed of many four-element subarrays, each of which can be easily removed. This will make it possible to test experimental element designs (such as elements with integrated low-noise amplifiers) without having to replace the entire array. PHAD will be used to demonstrate many capabilities of phased-array feeds, including: wide-field imaging, optimal beamforming, polarimetry, ground-radiation cancellation, suppression of ground noise coupled by feed struts, compensation of non-operating elements, and interference mitigation. PHAD will be temporarily installed on the Dominion Radio Astrophysical Observatory (DRAO) 26-m telescope ($f/D = 0.3$) for testing.

EXPERIMENTS

PHAD will be capable of a large number of experiments that will aid in understanding of phased-array feeds as well as demonstrating the capabilities of these systems. Table 1 lists a campaign of experiments, progressing from pre-installation testing through to the exploration of advanced features on a telescope. Understanding these experiments will help define the system specifications for PHAD. For example, although only a small number of antenna elements are needed to feed a dish, much larger numbers are required to obtain high efficiency or to correct off-axis aberrations.

Table 1: PHAD Experiments

Off telescope	
	Detect transmitter
	Calibration
	Detect astronomical sources
On telescope	
	Simple beamforming using satellites
	Simple beamforming using astronomical sources
	Calibration
	Measure aperture efficiency
	Deep integration of weak sources
	Optimal beamforming
	Cancellation of spillover noise
	Multi-pixel imaging
	Correct off-axis aberrations
	Measure instrumental polarization
	Correct instrumental polarization
	Correct for non-functioning element(s)
	Interference mitigation
	Null feed-strut scattering

IMPLEMENTATION

Design philosophy

The goal of the PHAD project is to develop an engineering demonstrator that is similar as possible to what a science-capable array would look like. To do so, we attempt to follow a development path that is as direct as possible and that avoids technological solutions that would be discarded. For example, while it might be quicker to implement a beamforming network with analog hardware, that effort would be wasted since we ultimately want a digital beamformer. Another design goal is to build as much flexibility into the system as possible. This is achieved by making the system extremely modular and by storing the data streams from *every* array element for off-line beamforming. Data storage is a very powerful feature for diagnostics and experimentation.

In designing PHAD we must make compromises due to both cost and time constraints. Some compromises we consider to be acceptable, such as limiting the bandwidth and sensitivity (by using commercially-available integrated devices thereby speeding development) while others are not, such as using single-polarization Vivaldi elements, which may either obscure real problems or introduce spurious problems that would not be present in a dual-polarization array. Indeed, some compromises are desirable, such as beamforming in software instead of hardware because don't simply reduce cost and development time but also add tremendous flexibility to the system.

Specifications

Table 2 lists the key specifications for PHAD. The frequency range is chosen to include important radio astronomy bands as well as wireless communication bands. Using this frequency band enables us to use inexpensive yet high-performance integrated circuits developed for personal communications. This band is also chosen since the DRAO 26-metre dish has good performance in that range [8]. The system temperature specified is both achievable with available ICs and will provide PHAD with sufficient sensitivity ($\Delta T_{min} \sim 0.1$K, $\Delta S_{min} \sim 1$ Jy) to perform the experiments listed in Table 1 [9]. The bandwidth was also selected as being attainable with RF ICs but without compromising the experimental goals of the project. The array will have about 200 elements as this is sufficient to sample the focal spot (Airy disk plus first sidelobe as shown in Fig. 1b). The array will be composed of Vivaldi elements [6, 7] as they have a wide bandwidth (at least an octave) and have a high packing density (element spacing of $\lambda/2$ at the highest operating frequency) to prevent the formation of grating lobes [10]. The array will be composed of elements for each sense of linear polarization because the exploration of polarimetry capabilities is an important part of the PHAD project.

Table 2: PHAD Specifications

frequency	1–2 GHz
system temperature	$\sim$70K
bandwidth	$\sim$1 MHz
number of elements	$\sim$200
element type	Vivaldi
element spacing	$\lambda_{min}/2$
polarizations	2 linear

Signal Chain

The focal-plane radiation will be sampled by a Vivaldi antenna array, similar to the one shown in Fig. 1a and scaled to a lower operating frequency. Note that this array is composed of 4-element subarrays and thus is highly modular and adaptable. Integral to each element is a wideband slotline-to-coplanar-waveguide transition.

Each array element will feed a low-noise amplifier (LNA). We are currently evaluating LNA ICs that are specified to have a noise figure of $\sim$1 dB or $\sim$70K. Although a design with discrete components would have lower noise, we are compromising a slight loss of sensitivity for reduced development time.

The receiver will be implemented using a highly-integrated receiver IC. For example, receiver ICs for consumer direct-broadcast satellite receivers have a very low-cost and provide a mixer, gain-controlled amplification, output filtering, and a synthesized local oscillator in a single package. We are currently proposing to use a direct-conversion (double-sideband) receiver architecture which incurs a slight loss of sensitivity from sideband folding but is very simple to implement.

The baseband signals will be sampled and recorded by commercial data recording system (Lyrtech, Quebec City, Canada, `www.lyrtech.com`). This system has a high capacity (16 channels per card for a total of 192 inputs), high sampling rate (105 megasamples per second) and high resolution (14-bits). Each card also has a field-programmable gate array (Xilinx Virtex II XC2V3000) for hardware implementation of signal processing algorithms. This system also has enough solid-state memory to store $\sim$4 seconds of data. This data will then be downloaded to a general-purpose computer where beamforming algorithms will be implemented using a matrix-manipulation language such as OCTAVE [11] or MATLAB. Simple beamforming experiments using synthetic data have shown that data will be processed at $\sim 1/10$ the rate at which the data is acquired [9].

Radio Frequency Interference Considerations

The original concept for PHAD has the digital recording system placed adjacent to the array of antennas and receivers at the focus of the telescope. Since digital systems generate broadband interference, very effective shielding will be required to minimize self-generated interference so that the theoretical sensitivity can be achieved. An alternate configuration under investigation is to locate the digital recording system some distance away from the feed and to link it with the receiver array with an analog optical-fibre transmission system [12]. These systems are commercially available for applications known as “RF over fibre.”

CONCLUSIONS

We have described an engineering demonstrator for phased-array feeds on reflector antennas. This system will be very flexible, both in the ways that it can be configured and upgraded due to its modular structure. This versatility will enable us to thoroughly explore the design and implementation issues involved with phased-array feeds and to demonstrate the unique capabilities of this type of feed. An extensive set of experiments has been proposed, the results from which will lead directly to the development of scientifically-useful phased-array feeds.

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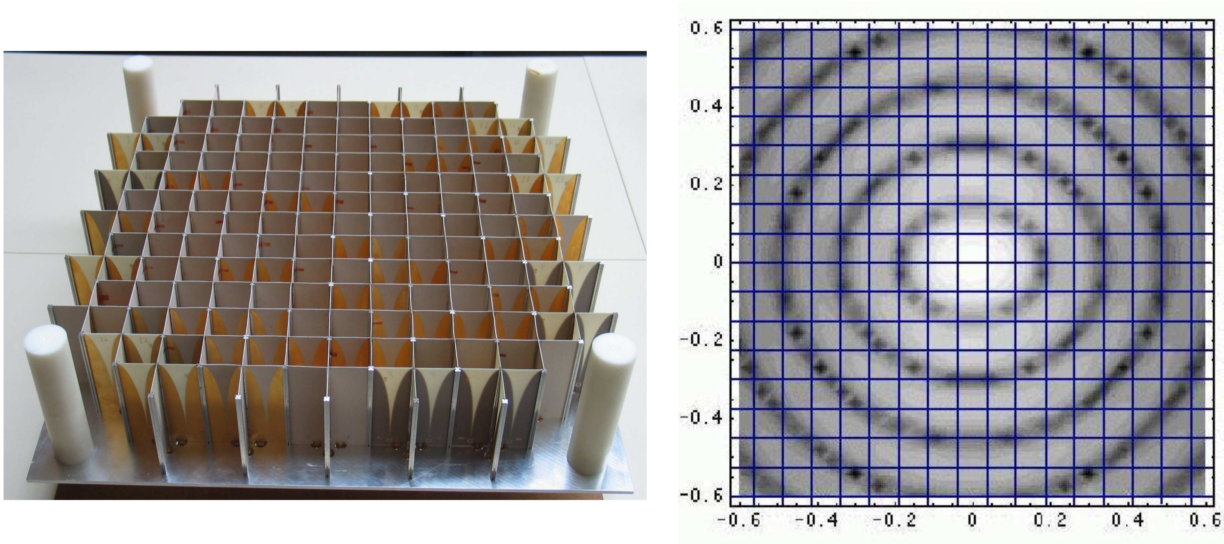

a) b)

Figure 1: A prototype of a Vivaldi array similar to what will be used for PHAD is shown in a). This array operates from 1.8–6 GHz and the element spacing is 5 cm or $\lambda/2$ at 3 GHz. In b) the array grid ($\lambda/4$ spacing) is superimposed on the focal field distribution for the DRAO 26-m antenna (calculated using GRASP9 [13]).

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