Development of a Low-Noise Wide-Band Phased-Array Feed

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Abstract

Low-noise phased-array feeds are a new way to expand the field of view of radio telescopes at centimetre wavelengths. First generation engineering demonstrators of this technology have been constructed and tested by several institutes worldwide. The development of second-generation phased-array feeds is now underway. We describe one effort to design and build an astronomy-capable phased-array feed using techniques to reduce front-end noise and increase system bandwidth.

1 Introduction

One key design requirement for future centimetre-wave radio telescopes is a wide instantaneous field of view (FoV) to enable deep surveys of the early universe [1]. One way to achieve a large FoV is by deploying a large number of small reflector antennas [2]. An even larger FoV is possible if a phased array is mounted at the focal plane of a reflector antenna and multiple parallel beamformers form a set of adjacent beams on the sky [3]. Such phased-array feeds (PAFs) have been under intense interest and analysis over the last decade and technology demonstrators have been constructed and tested in the USA [4], Australia [5, 6], the Netherlands [7, 8], and Canada [9]. The success of these demonstrators has stimulated plans for PAF upgrades to existing telescopes [10] and for new telescopes using PAFs [1, 11].

All early demonstrators for PAF technology were technology demonstrators. They were designed to answer questions concerning calibration and beamforming, efficiency, and system noise, not for astronomical research. This focus allowed designers to make compromises on system design. In particular, PAF demonstrators did not have state-of-the-art system temperature, used off-line beamforming instead of a dedicated real-time hardware beamformer, and processed narrow bandwidths. The next step in the evolution of this technology is to make PAF systems with very low noise temperatures ($\sim$ 20K), wide instantaneous bandwidth ($\geqq$ 500 MHz) and with real-time beamforming.

This paper will describe the work underway in the PAF group within the National Research Council of Canada to develop a new PAF with sensitivity and bandwidth specifications suitable for radio astronomy. This new system is called the Advanced Focal Array Demonstrator (AFAD) and is based upon experience gained from an earlier demonstrator called the PHased-Array feed Demonstrator (PHAD) [9].

2 System Architecture

Specifications for AFAD are given in Table 1 and are expanded upon here. The frequency range is chosen to cover the neutral hydrogen line at 1.42 GHz at the high end and to extend downward to observe doppler-shifted hydrogen. An element spacing of 10 cm is chosen to prevent the appearance of grating lobes over the receiving band [12]. Polarimetry is an important application of PAFs so this demonstrator will be fully capable of polarimetric observations. The array size is sufficient for multibeam operation and is readily adaptable to available reflector antennas for testing. Only a portion of the digitized input signal band is transmitted to the beamformer, limited by the available data rate of common 10G optical fibre links.

Table 1: Specifications for the Advanced Focal Array Demonstrator

Frequency range	0.7–1.5 GHz
Element spacing	10 cm ($\lambda/2$ @ 1.5 GHz)
Polarization	Dual
Array size	< 1 m $\times$ 1 m
Processed bandwidth	0.5 GHz

2.1 Vivaldi Array

AFAD will continue to use Vivaldi elements similar to those used in its predecessor [9] which were fabricated as printed circuit boards using a loss-loss substrate. PHAD was highly modular and had low-noise amplifiers located many centimetres from the feed point of the array elements. Since PHAD operated at room temperature, the loss in the transmission lines from the LNAs to subsequent receiver stages led to a significant increase in system temperature. AFAD will reduce transmission line loss by placing the LNA as close as possible to the array element feed point [13]. Slotline loss can also be reduced by increasing the thickness of the Vivaldi element, thereby increasing the surface area over which currents flow. This increased thickness permits the LNA to be embedded within the element and will provide excellent electromagnetic shielding. Although thick Vivaldi elements have been described elsewhere [14, 15, 16], this is the first known attempt to integrate an LNA inside an element.

2.2 Receiver Chain

In contrast to other PAF systems, the AFAD receiver chain will not perform any analog frequency conversions. Instead, this operation will be performed in the digital domain. Functions that will be performed in the analog domain include amplification, filtering, equalization, and level control.

2.3 Analog-to-Digital Conversion

Each element will have a dedicated analog-to-digital converter (ADC) which will sample at 3 Gs/s with 8-bit precision. The ADC will drive a field-programmable gate array (FPGA) which will downconvert and filter the signal to baseband (0–0.5 GHz). The baseband signal is then transmitted to the beamformer over 10 Gb/s fibre-optic cable.

It is envisaged that the receiver analog and digital components be housed together in well-shielded modules, one per array element. Because there will be $\sim$60 dB of analog gain, and also because of the proximity of analog and digital subsystems, particular care will have to be taken in designing the shielding for this module. Figure 1 shows a sketch of array elements and receiver modules for AFAD.

2.4 Beamformer

The AFAD beamformer will be located at the base of the radio telescope. It will be based upon custom FPGA boards currently under development at our institute. Each board will have eight interconnected Xilinx Virtex-6 FPGAs for a total processing capacity of 8 TMAC. With this processing power 8 boards will be required to form 32 beams from 128 elements. Each board accepts 10-Gb/s streams from 16 elements. Each stream will be first divided into 512 frequency channels. These channelized signals are then distributed to other boards via Zone 2 ATCA backplane interconnect. Once each board has data from all elements beams will be formed.

Besides beamforming, other modes will be required. A beamformer calibration mode (essentially cross-correlation

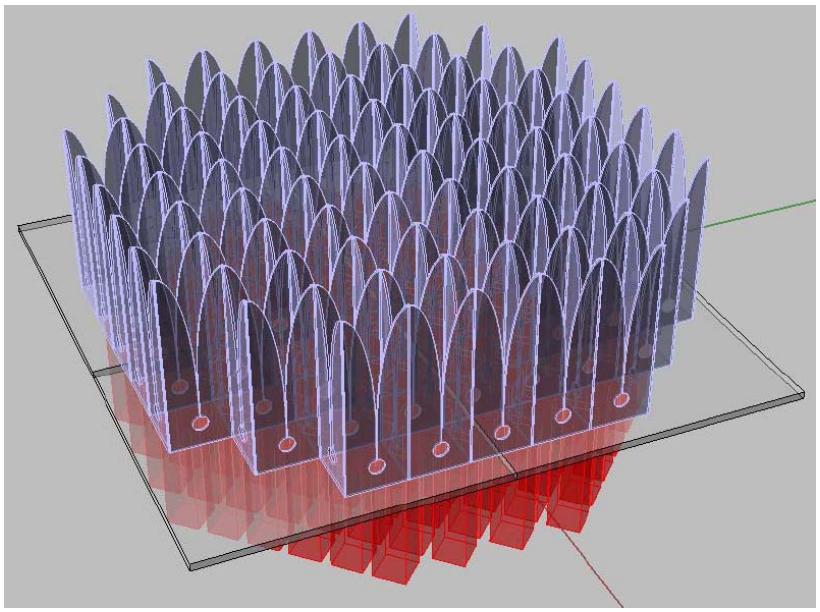

Figure 1: Sketch of the AFAD dual-polarized antenna array and receiver modules. Vivaldi elements are shown above the ground plane (rendered translucent here). Receiver modules (below the ground plane) will plug directly into the outputs of the active Vivaldi elements.

between elements) is required to determine weights. A gain/phase tracking facility is required to measure and compensate for gain and phase variations in receiver chains by monitoring a calibration tone transmitted from near the reflector surface. Another possible mode is to capture and store data snapshots for diagnostics or special experiments.

3 Conclusion

We have described a second-generation phased-array feed demonstrator for radio astronomy. This system will have specifications suitable for radio astronomy observations, namely high sensitivity and wide bandwidth. This demonstrator will employ Vivaldi elements with embedded LNAs to reduce loss and achieve high sensitivity, a direct-sampling high-speed ADC to achieve wide bandwidth, and a high-performance FPGA-based beamformer to form multiple wide-band beams.

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