Phased Array Feeds for the Square Kilometre Array

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Abstract

A novel method to form multiple instantaneous beams on the sky with a reflector antenna is to employ a dense Phased Array Feed (PAF). This technology is currently being developed to greatly increase the survey speed of existing and future radio telescopes. This paper reviews the current state of PAF development projects for radio astronomy, the particular challenges and the potential for incorporation of PAFs into the ultimate radio survey instrument – the Square Kilometre Array.

1. Introduction

Modern astronomy relies on obtaining increasingly sensitive and large surveys of the sky to untangle major questions, such as the evolution and complex interactions of galaxies and their precursors. Phased Array Feed (PAF) systems can provide the desired field of view and increased survey speed to existing and future reflector telescopes. PAFs operate as radio cameras, forming multiple instantaneous beams on the sky by a weighted combination of their element responses. This beam forming process provides many degrees of freedom, for example to control the beam pattern and its sidelobes, to optimize the aperture efficiency and to perform RFI mitigation. The increased complexity of PAF systems with respect to conventional horn-based systems comes with a number of technological challenges, mainly in the areas of low-noise amplifier design, signal transport, digital signal processing and system calibration. In the following sections, a number of PAF systems which are currently under development for both existing and new telescopes are introduced. Apart from being state-of-the-art science-capable instruments themselves, these first-generation PAF instruments also serve as pathfinders for the Square Kilometre Array (SKA, www.skatelescope.org) by demonstrating the feasibility and competitiveness of PAF technology.

2. APERTIF

APERTIF ("APERture Tile In Focus") is the ASTRON SKA Pathfinder aiming to increase the survey speed of the Westerbork Synthesis Radio Telescope (WSRT) with a factor 20 by installing PAFs [1]. APERTIF will operate from 1000 to 1750 MHz using an array of 121 Vivaldi elements (Figure 1, left) with room-temperature LNA's (T_{sys}= 55K). APERTIF prototype measurements have successfully demonstrated the key advantages of PAFs: 37 instantaneous beams forming an 8 deg^2 field of view over the entire frequency range, 65 K system temperature with room-temperature LNA's, 75% illumination efficiency, synthesis imaging, a significant reduction of the reflector – feed interaction and a dual-beam observation of two pulsars separated by 3.8 degrees on the sky (i.e. more than seven beamwidths of the 25-m dishes). The call for Expressions of Interest (EoI) for APERTIF Surveys has been very successful. Eighteen research groups have submitted an EoI; if all proposed surveys were performed, it would keep APERTIF busy for more than 20 years. However, the large field of view, and 300 MHz bandwidth of APERTIF make it possible to do surveys with different scientific aims commensally.

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Figure 1. An 121-element APERTIF PAF installed in the WSRT (left) and the first ASKAP dishes (right)

3. ASKAP

The Australian SKA Pathfinder (ASKAP) is a new 36-dish array radio telescope, fully-funded by the Australian and WA Governments and CSIRO, under construction at the Australian SKA candidate host site in remote WA. ASKAP is designed to maximize PAF performance and provide wide field-of-view imaging across the frequency band 800 MHz – 1.8 GHz. More details on the system design are given in DeBoer et al [2]. ASKAP will focus on ten major sky surveys. These are supported by international teams who are currently undertaking detailed design and feasibility studies (www.atnf.csiro.au/projects/askap/science.html). The primary challenge is the necessity for real-time manipulation of raw telescope data due to the data volumes generated by the ASKAP PAFs. The ASKAP dish antennas have been designed as 12-m symmetric prime focus (f/D=0.5) with a 3-axis mount and have a natural field-of-view at 1.4 GHz of 1 square degree. The chequerboard-type PAF [3] is designed to multiplex this to yield an instantaneous field of view of 30 deg^2. In addition to the usual azimuth and elevation mounts, the third axis provides a 'sky-mount' system which keeps the PAF at a constant parallactic angle during each observation. The third axis can also facilitate polarization calibration as well as keeping the side-lobes from the dish structure (e.g. feed legs) stationary in the field. In this way the third axis allows the az-el telescope to mimic a true equatorial mount. Note that in future it is anticipated that the third axis could be redundant with sky de-rotation and side-lobe subtraction possible to high precision within software processing. During 2011 the first six ASKAP antennas will be equipped with PAF systems, integrated and tested. The first science data should flow in early 2012.

4. AFAD

The Canadian PAF group has constructed a first generation demonstrator (the PHased-Array feed Demonstrator or PHAD) [4] and have commenced development of a second generation system called the Advanced Focal Array Demonstrator (AFAD). While PHAD was purely an engineering demonstrator, AFAD will have the sensitivity and instantaneous bandwidth necessary for astronomical research. AFAD is also being designed to use architectures and technologies that may not be the most economic solution today, but are representative of what will be commonplace at the end of this decade when this technology will be required for the SKA. AFAD will use an array of Vivaldi elements operating between 0.7 and 1.5 GHz. To reduce receiver noise LNAs will be placed at the feed point of the elements to reduce transmission line loss. After direct sampling at 3 GS/s, the digitized signal will be filtered, down-converted to baseband (0 to 0.5 GHz) and transmitted to a real-time beamformer over 10 Gb/s optical fibres, one per element. The beamformer will be based upon FPGA boards currently under development. Each board will have 8 interconnected Xilinx Virtex-6 FPGAs for a total processing power of 8 TMAC. With this processing power, 8 boards will be required to form 32 beams from 128 elements.

5. BYU/NRAO L-band PAF

In June, 2010 an active impedance matched dipole L-band PAF design was fabricated and tested with ambient temperature LNAs. Single- and dual-polarization versions of the PAF prototype were mounted on the Arecibo telescope in June and August as part of the AO40 phased array feed feasibility study conducted by the National Astronomy and Ionosphere Center (NAIC) at Cornell University. In late 2010, the ambient temperature PAF (Figure 2) was moved to the NRAO Green Bank Outdoor Test Facility for characterization. It is currently mounted on the Green Bank 20-Meter telescope and tests of sensitivity, calibration stability, and imaging are currently underway. Most recently, redesigned dipole PAF elements that mate to a cryostat built by R. Norrod at

NRAO Green Bank were fabricated and completed in February, 2011. First light with the cryogenic system on the 20-Meter Telescope is expected in early 2011. Back end signal processing hardware and algorithms for PAFs are also a major emphasis at BYU. Studies of long term calibration stability, dish-rim external reference calibration, polarimetric beamforming algorithms, controlled-pattern beamformers, and interference mitigation algorithms are ongoing. A 64 input, 50 MS/s data acquisition and real time signal processing back end based on CASPER ROACH hardware is currently in development and gateware for a spectrometer has been completed. High-rate streaming over 10 Gb/s ethernet and a correlator/beamformer engine are in development. The long term goals include PAFs for Arecibo and other large reflectors, technology development for future instruments such as the SKA, and a permanent instrument on the Green Bank Telescope, the Focal L-band Array for the GBT (FLAG).

Figure 2. BYU/NRAO L-band 19 element single-polarization phased array feed.

6. PAFs for the SKA

In the SKA, PAFs will likely share the reflector with other feed types. In principle, PAFs are flexible in the sense that they can adapt to many types of optics and focal lengths. ASKAP has traded-off several optics designs (symmetric, offset, prime, secondary) and mount types against the size of the PAF (which is a dominant driver of the system costs), attainable efficiency and the practical need to construct a new antenna array on a rapid timescale. The latter condition constrained them to source a near-commercial reflector antenna 'product' given that any unusual optics solution would have added increased risk, cost and delay to the project. For the SKA, dual reflector Gregorian optics is considered to optimize the high-frequency horn performance. It is currently being investigated how both feed types can be optimally accommodated.

As the survey speed of a wide-field instrument is inversely proportional to the squared system temperature, efforts to reduce system noise in PAF systems are critical. One key problem is the influence of mutual coupling between densely packed array elements on receiver noise and sensitivity. The effect of mutual coupling on PAF performance is now fully understood from a theoretical point of view [5,6] and efforts are underway to optimize phased array element designs to minimize the noise increase due to mutual coupling [7]. Other important efforts are LNA designs with reduced noise figure at U. Calgary [8] and ASTRON [9], and progress at CSIRO on differential LNAs that eliminate the need for a balun. As mentioned in Section 5, early steps taken at NRAO and BYU towards a cryogenic phased array feed for the GBT should lead to PAFs with still lower system noise temperature.

Current calibration and beamforming schemes for PAF systems follow a bi-scalar scheme in which the signals from both sets of receiving elements for the two polarizations are treated independently. However, electromagnetic coupling between the receiving elements in a PAF makes the two polarizations mutually dependent, which begs the question whether a bi-scalar approach can fully recover the polarimetric properties of the incoming signals. The polarimetric performance of PAF systems is being studied by researchers at ASTRON, BYU and Chalmers. They have developed a generic framework to describe polarimetric phased arrays and assess their polarimetric performance. This framework is used to compare different polarimetric calibration schemes including the bi-scalar approach [10]. Some initial conclusions are that PAF systems can be polarimetrically calibrated without loss in sensitivity, that a bi-scalar beamformer can emulate a full-polarimetric beamformer by sacrificing half the bandwidth and that the sensitivity loss in bi-scalar calibration depends on the polarimetric orthogonality of the receiving elements.

On SKA timescales and at SKA scales, alternative technologies will further reduce the costs and increase the competitiveness of PAF systems, such as RF over fibre for transporting the RF signals from the focus to the pedestal and dedicated digital signal processing.

7. PAFSKA

PAFSKA coordinates all PAF development activities relevant to the SKA. An international group of radio astronomy institutes share their PAF R&D results and cooperate to design PAF systems appropriate for the SKA. The PAFSKA group is promoting the inclusion of PAFs as 'mid-band' SKA receivers in the range ~600 MHz – 1.5 GHz. Whilst the focus is currently on an L-band PAF for SKA, there is potential for SKA to adopt PAFs at higher frequencies, particularly if digital signal processing costs are significantly reduced. SKA is currently in its Concept design stage with elements of the SKA PAF system to be reviewed as part of the Dish Array sub-system CoDR planned for later in 2011. The preliminary design for the SKA PAF will continue through to 2014 via an 'SKA Advanced Instrumentation Program' and draw on the expertise of this PAFSKA group.

8. Conclusion

Significant steps have been made in the development and demonstration of PAF technology for radio astronomy. In the next few years, several science-capable PAF systems will come into operation, followed by the SKA. Whilst the challenges of dynamic range, calibration and real-time data handling currently remain, we are confident that these novel receivers will be successful and enable new leading-edge astronomy.

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