Advances in Phased Array Systems for Radio Astronomy

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***Abstract*—Phased array antenna systems are a defining technology in many current and planned radio astronomical instruments. Phased array technology enables new observing modes due to their large field-of-view, multi-beaming capability and rapid response. The radio astronomical application provides interesting challenges such as stringent requirements on system temperature and system calibration. In this paper, we discuss the motivation for using phased array systems in radio astronomy and provide an overview of recent advances and results in this area.**

I. Introduction

Traditionally, radio astronomical instrumentation consists of a large parabolic reflector with a receiver in its focus. Phased array technology provides a number of attractive features compared to the traditional dish with single receiver:

- As an aperture array, phased array systems can provide a much larger field-of-view, that potentially spans a full hemisphere. This allows all-sky transient monitoring as demonstrated by the Amsterdam-ASTRON Radio Transient Facility And Analysis Centre (AARTFAAC) [1].
- As phased array feed (PAF) in the primary or secondary focus of a reflector antenna, phased array systems can significantly increase the field-of-view of the reflector dish by forming multiple beams simultaneously, thereby making the telescope a much more capable instrument for doing surveys of large fractions of the radio sky. PAFs are currently being developed for the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands (the Aperture Tile-in-Focus (APERTIF) project) [2] and the Australian SKA Pathfinder (ASKAP) [3]. This multi-beaming capability can also be used in an aperture array (or directly radiating phased array) to enlarge their instantaneous field-of-view or track multiple sources simultaneously.
- Since phased arrays are steered electronically, the response time of the telescope is not limited by mechanical repositioning. This is particularly attractive in aperture arrays, which are not limited by the field-of-view of the reflector dish.

These abilities make phased arrays an instrument defining technology in current and planned radio astronomy facilities. A consortium will be formed to enhance aperture array developments in the pre-construction phase of the Square Kilometre Array (SKA) [4], a future radio telescope envisaged to be at least an order of magnitude more sensitive than current instruments. The Netherlands Institute for Radio Astronomy (ASTRON) is also developing a PAF system to enhance the capabilities of the WSRT. In this paper, we present the current status of these development efforts starting with the aperture arrays and continuing with the PAF system.

II. Aperture array developments for SKA

Aperture array (AA) systems are envisaged to play a major role in the SKA in the 70 MHz to 1.4 GHz frequency range. This range will be covered by a low frequency AA (LFAA) system for the 70 – 450 MHz range and a mid frequency AA (MFAA) for the 450 – 1500 MHz range. Each system will consist of an array of order 200 stations with on-site digital processing for initial data reduction and connected by high-capacity data links to a central processing facility.

The feasibility of this system concept is demonstrated by the Low Frequency Array (LOFAR), an AA radio telescope covering the 10 – 250 MHz range built in The Netherlands with extensions throughout Europe [5]. LOFAR has been instrumental to drive development of calibration and imaging software that can deal with time-varying direction dependent effects (TDDEs). Dealing with TDDEs is a necessity at these low frequencies due to ionospheric distortions of the incoming radio waves.

The development of this calibration and imaging software was enabled by a proper mathematical description of the data, the data model or measurement equation, and extensive use of array signal processing techniques to find optimal solutions for calibration [6][7][8] and imaging problems [9][10][11]. The rigorous mathematical framework also allows rigorous error analysis, which can provide valuable input for instrument requirement specification. Mathematical analysis of the developed calibration and imaging software also improved our understanding of the practical and fundamental limits of calibration and imaging. An important conclusion from these studies is, that future instruments need to be designed for calibratability [12] to ensure that they operate up to their abilities and keep the required processing power and data transport capacity manageable.

Current design studies on the antenna and analog electronics for both LFAA and MFAA concentrate on low-cost designs with low system noise and good polarimetric behavior over the specified scan range. The most promising candidate for the LFAA system is a station consisting of individual log-periodic antennas [13] while design studies for the MFAA system tend towards station arrays of electronically connected tiles. Each of these tiles is an array of Vivaldi elements whose signals are combined in an analog tile beamformer before digitization [14].

III. PHASED ARRAY FEED DEVELOPMENTS

The goal of the Aperture Tile-in-Focus (APERTIF) [2] project is to develop a phased array feed (PAF) system for the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands operating in the 1130 – 1750 MHz frequency band. The WSRT consists of 14 parabolic reflector dishes with 25 m diameter and f/D = 0.35. The APERTIF system will have a system temperature of 70 K and an aperture efficiency of 75% and will provide 37 beams on the sky for an effective field-of-view of 8 square degrees over the entire frequency range. The current cryogenically cooled horn feeds have a system temperature of 30 K and an aperture efficiency of 55%. The APERTIF system provides a net gain in survey speed compared to the current WSRT system of about a factor 17.

A prototype PAF system has been installed in one of the WSRT dishes. It consists of 121 Vivaldi elements arranged in a rectangular grid along two orthogonal orientations to sample the focal field in two polarizations. Holographic measurements have been done to validate the design of the system. It was also used to demonstrate the ability of a PAF system to do the same polarimetric observations as a regular horn feed [15].

Much effort was invested in developing optimal beamforming and calibration methods for polarimetric observations [16][17]. This resulted in a practical polarimetric calibration strategy for PAF systems that works on unpolarized sources by relying on the intrinsic polarimetric quality of the receiving elements [18]. The intrinsic polarimetric performance of the antennas does not only facilitate the calibration, but also allows to beamform the two sets of antennas (one for each polarization) separately without much sensitivity loss. This greatly simplifies the design of the beamforming system.

IV. CONCLUSIONS

In this paper we presented an overview of some current development efforts in the area of phased arrays for radio astronomy. Phased array technology offers exciting new possibilities making it an instrument defining technology. These efforts do not only focus on antenna and electronic design, but also involve fundamental studies on the design and calibration of such systems and development of appropriate calibration and imaging techniques. An important conclusion for the SKA is, that a proper instrument design should consist of a hardware design and a corresponding data processing pipeline design and that the instrument should be designed for calibratability.

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