Wideband Array Developments for Planned and Future Radio Astronomy Antennas

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***Abstract*— The radio astronomy community is engaged in the development of the Square Kilometre Array (SKA). The SKA will have 10-100 times improved sensitivity and 10^5 times improved survey speed compared to existing radio telescopes. Besides dishes, Aperture Arrays (AA) are a promising concept: they potentially offer a very large field of view in theory only limited by the computing power and they hold promise for multi-octave frequency coverage. Provided that e.g. polarimetric and calibration issues can be solved, this approach is the preferred solution for low frequency astronomy, with the SKA AA-low system, specified to run from 70 to 450MHz, and the AA-mid system designed for 400-1420MHz. This contribution will address some key issues to be solved using input from demonstrators.**

***Index Terms*—radio astronomy, aperture arrays, focal plane array, wide frequency band, widefield, SKA, calibration, polarization, interferometry, redundancy**

I. Introduction

With the recent establishment of a legal framework and the site selection in 2012, the radio-astronomical community, involving universities and industry, made important steps toward the Square Kilometre Array (SKA, www.skatelescope.org) as the next generation low frequency radio telescope [1]. Its large collecting area will be realized by a distributed network of radio telescope stations spiraling outward from the core along three to five arms out to 3000km to enable high resolution observing. All stations operate in concert based on the principles of interferometric aperture synthesis imaging. Each station is either realized as multiple receiving elements, so called aperture array ("AA") stations, or as one reflector dish at higher operating frequencies. Developments performed in European framework programs demonstrated that an SKA using phased AA's, operating from 70MHz up to 1.4GHz with a dish based array covering ~1.2GHz to 10GHz represents one design approach for the projected SKA science cases [2]. The large field of view is determined by the element beampattern and the installed computational power allows for multiple simultaneous beams (Fig.1). As the final system is still being discussed, another implementation includes phased array feeds on dishes as field of view expansion technique allowing simultaneous beams for wide field high efficiency observations. Also wideband feed studies are ongoing possibly combined with focal plane array feeds.

SKA's large collecting area, (distributed) among stations is to be produced at "low cost" while enabling use in relatively harsh, desert like conditions in South Africa with partnering African countries and in Australia with New Zealand. Both sites are suitably located: they have, e.g., favorable atmospheric and ionospheric conditions and have a low radio interference level. Prior knowledge on performance is to be gained from demonstrator projects. Dish projects are progressing in South Africa (MeerKAT,[3]) as well as in Westerm Australia (ASKAP,[4]). These projects are using offset and symmetric dishes respectively, the latter making use of a rotating subreflector to "freeze" the observing beam on the sky to assist high dynamic range (ratio of strong to low brightness sources) imaging. The large AA programs are LOFAR at low frequencies and EMBRACE from 500-1500MHz.

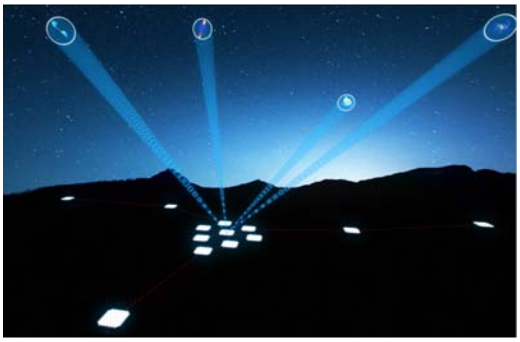

Figure 1. Artist impression of Aperture Array simultaneous multi-beam observation (courtesy Swinburne Univ. Australia)

Phased Focal Plane Arrays or Phased Arrays Feeds (PAF's) are being demonstrated by the APERTIF system in the Netherlands and as feed approach for ASKAP.

We will address key results obtained with Pathfinder systems, particularly with LOFAR, APERTIF and EMBRACE., We also address the required next steps and specific issues that result from the wide field of view capability over the wide frequency range with these new instruments and that are essential for the intended high dynamic range imaging use for the SKA and other applications [5].

II. Present Arrays as Demonstrators

A. LOFAR and EMBRACE

The Low Frequency Array (LOFAR) consists of an array of Low Band Antennas (LBA's) form 30-90MHz and an array of High Band Antennas (HBA's) operating from 110-250MHz

[6]. It extends form the central core in the Netherlands to stations in Germany, Poland, France, Sweden and the UK. At these frequencies the ionosphere is of particular relevance its effect being most pronounced for the LBA. The particular arrangement of LBA stations consisting of thousands of short electrical dipoles is such that the ionosphere can effectively be calibrated out by first removing a "tomographic image" of it before an astronomically useful image is made. Other effects are related to the rotating sky with a continuously changing response through time variable sidelobes and beamshape. Novel calibration techniques based on radio astronomical sources were developed to cope with the effects. LOFAR is capable of polarimetric imaging already delivering astro-physical science and is a powerful learning machine for SKA. Figure 2 shows the lay-out of a typical LOFAR station depicting so-called LBA (droopy dipoles) in sparse configuration and HBA "tiles" each consisting of Bowtie-shaped dipoles in a denser configuration. "Dense "refers to an element distance equal or less then the wavelength at the frequency of operation.

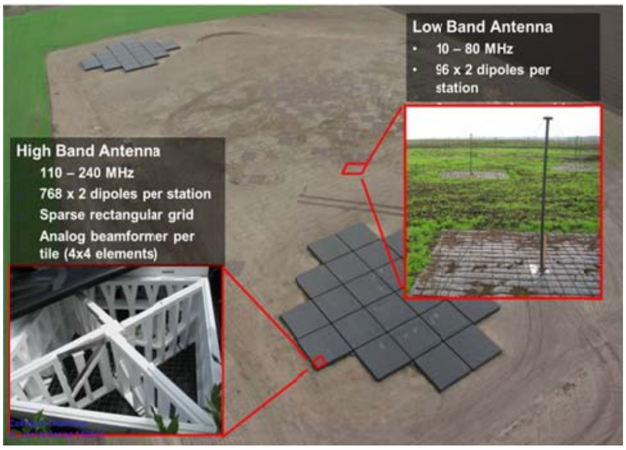

Figure 2. Lay-out of typical Dutch LOFAR station depicting LBA and HBA antennas. Each station has 96 dual polarization LBA dipoles and 48 tiles each with 16 dual polarization bowtie-shaped dipoles. The LOFAR "core"is about 10x larger while stations in other European countries have double the amount of tiles i.e. 96.

The potential of simultaneous multibeam observations from Fig 1. is nicely demonstrated in LOFAR in Fig. 3.

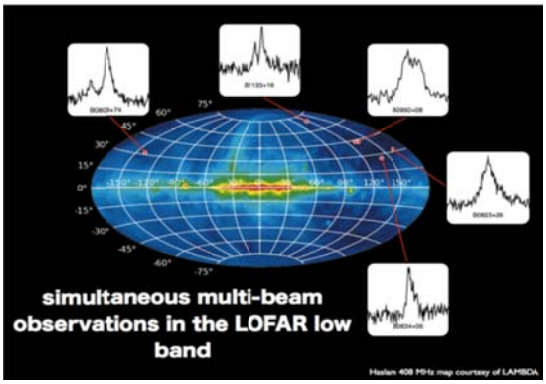

Figure 3. Real simultaneous observation of 5 Pulsars ("pulsating stars") widely distributed across the sky. The bright horizontal central "line" depicts radiation from our galaxy.

For the 500-1500MHz range, a densely packed arrangement of (in this case Vivaldi) elements has been designed and implemented in a first demonstrator system called EMBRACE. It consists of 150m^2 aperture array near the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands and a smaller version of 80m^2 at the Nancay Radio Observatory in France [7]. Its potential is illustrated by the dual beam experiment in Fig. 4.

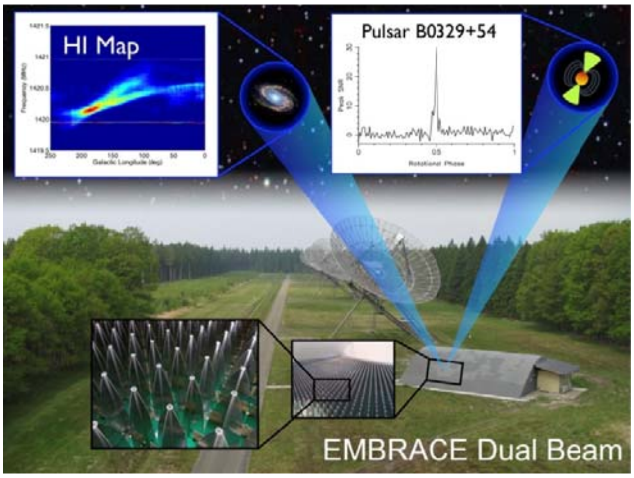

Figure 4. Real simultaneous observation of two widely distributed radiosources (i.e. a pulsar and an image of our Milky Way in the radio) The inserts show EMBRACE as it is located at the WSRT site and a "sea"of 10.000 densily packed elements. A similar smaller staion has been build in Nancay, France.

As with LOFAR, multiple simultaneous beams can be formed on the sky with changing shape as the earth rotates. Hence it is required to have accurate knowledge through modeling to be compared with calibrated data. While the effect of the ionosphere is much smaller, the number of available radio sources is also smaller and additional calibration techniques are required. Further developments of Aperture Arrays specifically for the SKA pre-construction phase is the design, construction and evaluation of Aperture Array Verification Systems (AAVS) for both AA-low ("LOFAR-like") and AA-mid ("EMBRACE-like") for which an international consortium is being set-up.

B. APERTIF

Radio astronomical signals are very weak compared to telecommunication signals. A radio astronomical observation therefore typically takes a number of hours for each observed field. This makes survey observations, in which a significant fraction of the sky is mapped out, very costly in terms of telescope time. The use of (dense) focal plane array feed ("PAF") systems can significantly increase the field-of-view, and hence the survey speed, of reflector-based radio telescopes. These systems offer a continuous highly efficient field expansion of about 50 times the normal single feed element beam. The goal of the Aperture Tile-in-Focus (APERTIF) project is to upgrade the WSRT with PAF's [8]

The current WSRT system consists of 14 dishes with 25 m diameter and f/D = 0.35. At 1.4 GHz, the current cryogenically cooled horn feeds provide a system temperature of 30 K, an aperture efficiency of 55% and 160 MHz observing bandwidth.

The APERTIF system is designed to operate between 1.13 GHz and 1.75 GHz with the frequency band being limited by radio interference conditions and not by principle. The PAF system will operate at the environmental temperature leading to a system temperature of 70 K. It will provide an aperture efficiency of 75%, full instantaneous frequency coverage and 37 beams on the sky for an effective field-of-view of 8 square degrees. Despite the higher system temperature of the PAF system, it still provides a factor 15-20 increase in survey speed compared to the current WSRT system.

The polarimetric properties of the beams formed on the sky do not only depend on the feed response and telescope optics, but also on the applied beamforming scheme. The polarimetric calibration of the PAF beamformer has therefore received considerable attention over the last years, as will be discussed in more detail in the next section. One APERTIF prototype system has been installed in one of the WSRT dishes (see Fig. 5) and used in conjunction with two neighboring telescopes for experimental validation of the proposed beamforming techniques. With this system, we were able to do a full polarimetric characterization of the individual feeds in the PAF system as well as of the response of the complete PAF system [9][10]. This led to the first successful polarimetric measurement on an astronomical source with a PAF system by reconstructing the rotation measure of BL Lac over the frequency range from 1190 MHz to 1390 MHz [10].

Figure 5. APERTIF PAF prototype system mounted in the prime focus of one of the WSRT dishes as seen from the reflector.

A similar system to APERTIF using a different antenna face, is being developed in Australia in the Australian SKA Pathfinder (ASKAP) project [4]. This SKA precursor project is planned to be part of a survey telescope in the first SKA phase. Building from Aperture Arrays and other dish based telescopes, like a further evolution of the MeerKAT project[3] mentioned earlier, this SKA phase is planned to deliver about 10% of the SKA performance. Together with the projects to be addressed in the last section, these will therefore provide crucial insights for further development of the SKA for the next phases.

III. COMMON ISSUES

Phased array systems provide large spatial and spectral coverage, but the response of the system to impinging radio waves varies with polarization, frequency and direction due to varying instrumental response and varying propagation conditions over the large spectral and spatial operating range. Calibration and imaging methods for these instruments therefore need to be able to deal with direction dependent effects that may vary with time and frequency. In turn, these developments led to a new perspective on quantifying the polarimetric performance of an antenna system.

Radio astronomical phased array systems typically consist of stations whose beamformed output signals are then combined using aperture synthesis principles. In this context, stations can either be aperture array stations or a dish with a phased array feed. Such systems require calibration at station level as well as synthesis array level. Recently, much progress has been made in both areas. These developments were enabled by a combination of a proper mathematical description of the received signals, the data model or measurement equation [11][12][13], and extensive use of array signals processing techniques to find optimal solutions to the calibration challenges.

The AA-low stations will probably consist of sparse irregular antenna arrays. Such arrays can be calibrated using an all-sky source model [13]. This method has been used for LOFAR station calibration. In dense regular arrays, like EMBRACE and AA-mid, the regularity in the array can be exploited by using redundancy calibration [14]. Recently, redundancy calibration was reformulated using array signal processing techniques leading to a new algorithm that provides statistically efficient performance [15]. This means that the algorithm produces unbiased results with minimal variance.

In recent years, the calibration of PAF systems was developed from scratch by a collaboration between ASTRON, Chalmers University and Brigham Young University. This led to a theoretically optimal beamforming strategy that optimizes sensitivity while providing a perfect polarimetric response in the beam center [16]. This result was used to validate a practical calibration approach that relies on the intrinsic polarimetric performance of the antennas to calibrate the PAF beamformer using an unpolarized source [17]. Despite the development of all these new algorithms, both PAF and AA systems still have a direction dependent response that needs to be dealt with at synthesis array level. This can be done by an algorithm based on space alternating expectation maximization [18]. If cross-talk and mutual coupling between stations can be ignored, this method produces statistically efficient results while being computationally efficient as well.

To make these advanced algorithms working, the phased array system should be sensitive enough to detect sources in a sufficient number of directions on appropriate time scales to handle the time-varying direction dependent effect. This realization has led to the calibratability requirement [19] i..e. any radio telescope system should be designed in such a way that it is calibratable. A more detailed analysis [19] has shown that the calibratability requirement can be translated into requirements on, for example, aperture efficiency, beam size and side lobe level. This implies that calibratability could prove to be a powerful consideration to constrain the design space of the SKA.

The data model or measurement equation provides a rigorous mathematical foundation for system analysis including error propagation analysis. We can now make rigorous prediction of the impact of, e.g., electronic drift or station calibration errors on the station beam shapes. This is illustrated in Fig. 6, which shows the result from an error propagation analysis on the calibration errors for the on-axis beam of the APERTIF PAF prototype system. The error pattern indicates a preferred direction for the most significant beam errors due to the covariance between the gain calibration errors on the individual PAF elements.

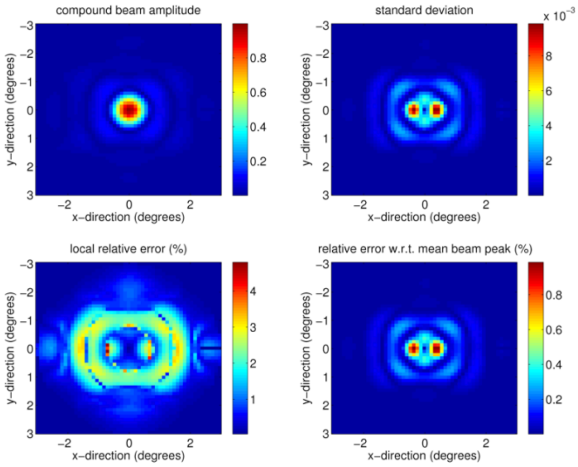

Figure 6. APERTIF PAF prototype system calibrated on an unpolarized point source with SNR = 200 after integration showing the on-axis compound beam pattern (top left), the error pattern (standard deviation, top right), the local relative error (bottom left) and the error relative to the main beam peak gain (bottom right). prototype system mounted in the prime focus of one of the WSRT dishes.

Since imaging and calibration impose requirements on the allowed variability of the station beam pattern on specific time scales, this implies that we can rigorously derive requirements on, e.g., stability of electronic components, thus providing valuable input for system designers.

Another important consequence of the wide field-of-view provided by phased array systems, is that characterization of their polarimetric performance by a single requirement on the bore sight response is insufficient. What matters for radio astronomical systems is their ability to reconstruct the polarization state of the received signal, all over the provided field-of-view. This led to a new figure-of-merit for the polarimetric performance of radio telescope systems, the intrinsic cross-polarization ration (IXR) [20]. The IXR provides a measure of the reconstructability of the polarization state of the incoming signal. This reconstructability can be quantified as an upper limit on the increase in system noise caused by reconstruction of the polarization state of the incoming signal.

The accurate measurements of the polarization state of an observed source represent a critical point to achieve the desired science goals and the study of AA's and PAF's as polarimetric instruments is ongoing [10][16][17]. Evaluation of this accuracy is, however, not straightforward when accounting for polarimeter calibration correction at the post-processing stage, but is feasible by using the IXR. This will be discussed in detail elsewhere in this conference [21]. The approach is promising and it has been applied in both single element and array analysis [22], primarily aiming at a deeper understanding of polarization calibratability and antenna array performances. Recent work suggest that calibratability requirements can be actually included in polarization requirements defined by means of IXR[17][23].

IV. AA Verification systems for the SKA

SKA is now entering the Pre-construction phase in which detailed design should lead to a design for SKA1, the first construction phase which is approx. 10% in size of the full SKA. For the AA's an international consortium is being formed to execute this work. Partners in this consortium are likely to include, but not limited to, ASTRON, ICRAR (Australia), University of Cambridge, University of Manchester, University of Oxford, INAF (Italy), RRI (India), Observatoire de Paris and institutes from Portugal, Spain and South Africa. An important element in the pre-construction phase is the design, construction and evaluation of Aperture Array Verification Systems (AAVS) for both AA-low and AA-mid. These verification systems, when realized at the SKA site, will take into account local harsh conditions but also enjoying low Radio Frequency Interference levels. A sequence of verification systems should lead to a pre-production model and full detailed design documentation for the production of SKA-AA-Low

A. *AA-Low*

The SKA specification for AA-low is significantly different from the pathfinders and precursors, not only in terms of performance, but also in terms of cost. The large frequency coverage, 70-450MHz, requires a different antenna and front-end design, higher data rates require a new signal processing back-end and the local SKA site environment needs to be taken into account in the mechanical design. The sensitivity specification of SKA1 requires a collecting area in the order of 10 times LOFAR: with the expected budget significant cost saving needs to be realized.

The first verification system, AAVS-0, has largely been realized. A 16-element log-periodic antenna, realized by Cambridge University [24] is under evaluation. And initial tests have started with a Vivaldi array realized by INAF, Italy [25]. After a selection process, evaluating electro-magnetic performance and costs it is expected that either the log-periodic or the Vivaldi will be used for the design of AAVS-1 (~256 antenna elements) and AAVS-2 (a couple of stations).

B. *AA-Mid*

The approach for AA-mid is slightly different from AA-low since the AA-mid is currently seen as an essential concept for realization of the SKA phase 2 science case. At the start of SKA1 construction (scheduled 2016) a decision will be taken on SKA2 technology. By that time the AA-mid technology has to demonstrate improvements on aspects as system noise temperature, power consumption and costs. Furthermore system stability and calibratability, discussed in section III of this paper, will need to be demonstrated in order to meet SKA2 dynamic range requirements. AAVS-2 will be a few small stations. An interesting option is to expand AAVS-2 into a larger number of small stations, e.g. 14, creating a collecting area of ~2000m^2 which will not only prove the capabilities of the AA-mid technology but could also serve as a survey demonstration instrument [26]. The latter is currently planned as part of the Advanced Instrumentation Program of SKA1.

V. CONCLUSIONS

Wideband-widefield developments based on phased arrays primary intended for use in radio astronomy, are maturing from ideas to real implementations. New windows on the universe have been opened through LOFAR as low frequency AA. For use as focal plane arrays very high efficiency in simple prime focus dishes has been demonstrated while for all concepts the prime characteristics, including the polarization properties, are now well understood. These studies and projects have provided insights for further and larger developments. AA Verification systems are therefore planned toward the SKA as the natural next step with potential applications outside the field of radio astronomy.

VI. ACKOWLEDGEMENTS

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