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Aperture Array Development for Future Large Radio Telescopes

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Abstract—**We present the design of a phased array system for future radio telescopes. This includes a system overview and recent results of the designed and implemented system, the Electronic Multi-Beam Radio Astronomy Concept (EMBRACE). Furthermore, simulations with a full-EM antenna simulator, combined with measurements on actual hardware, will provide information for the next design step, the Aperture Array Verification System (AAVS). With AAVS, we will prove design readiness of this novel array technology.**

Index Terms—**phased arrays, antenna arrays, array design, mutual coupling, radio astronomy, array signal processing.**

I. INTRODUCTION

Since the early 1990s, the global radio astronomy community has been contemplating the design and development of a radio telescope with nearly two orders of magnitude higher sensitivity than current instruments. This radio telescope is now known as the Square Kilometre Array (SKA) [1]. A key figure of merit for the SKA is the survey speed, a measure how fast a given fraction of the sky can be mapped out with a given sensitivity. The survey speed is proportional to the product of the square of the instantaneous telescope sensitivity and the instantaneous field-of-view (FoV) [2].

The cost per unit survey speed for a given system concept depends strongly on the operating frequency. For frequencies below 1.5 GHz, the aperture array concept seems very attractive [3]. A consortium of European research institutes led by ASTRON in the Netherlands has therefore launched the aperture array verification program (AAVP) to demonstrate that astronomical aperture arrays are sufficiently mature to be a viable concept for SKA over the frequency range between 500 and 1500 MHz. The aim is to show this point by building the aperture array verification system (AAVS) and show that it adheres to the SKA specifications.

The design of the AAVS will greatly benefit from the experience gained from its precursor, the Electronic Multi-Beam Radio Astronomy Concept (EMBRACE). EMBRACE is a single polarization phased array demonstrator with two stations, one in Westerbork, The Netherlands and the other in Nançay, France. Figure 1 shows a photograph of one of these stations. In the next section, we will describe the EMBRACE antenna system in more detail, including recent results. The antenna array simulations and measurements of the current design will be presented next. In the last section, we will outline the next steps towards the AAVS and SKA based design on the experience gained from EMBRACE.

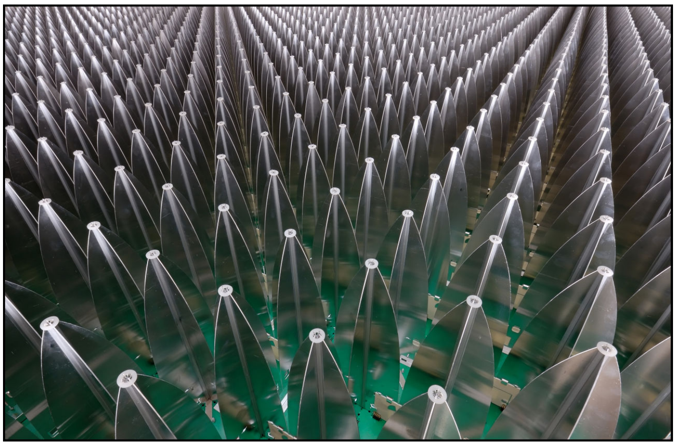

Fig. 1. Photograph of the Vivaldi elements of one of the EMBRACE stations.

TABLE I
EMBRACE DEMONSTRATOR MAIN REQUIREMENTS.

Requirement	Remark	Value
Number of stations	In France and the Netherlands	2
Total physical collecting area	Both stations	300 m^2
Aperture efficiency		≥ 0.8
Frequency range		0.5 – 1.5 GHz
System temperature	@ 1 GHz	≤ 100 K
Instantaneous array bandwidth	RF beams	100 MHz
Number of analog beams		2
Polarization	Single linear	1
Half power beam width	RF beam @ 1 GHz	> 15 deg
Scan range θ		≥ 45 deg
Side lobe levels	w.r.t. main beam. No grating lobes	≤ -13.2 dB
Signal dynamic range	@ output A/D converter	≥ 60 dB

II. EMBRACE

Table I summarizes the main requirements for the EMBRACE antenna system. The system provides two independent analog beams of approximately 16° beam width at 1 GHz.

A. Architecture

In the development phase towards SKA, it is imperative to demonstrate the low cost potential of sufficiently large designs like EMBRACE. Therefore, costs have been a key design driver throughout the design process.

An EMBRACE station can be divided roughly into two parts: a front-end and a back-end. The front-end consists of the antenna array including the radome, the supporting mechanics for the array and the signal distribution between the tiles and the back-end. A large phased array system is inherently distributed over a large area. Since active Low Noise Amplifiers (LNAs) have to be integrated close to the elements, the distribution of DC power already forms an important cost driver. In EMBRACE the number of required cables is reduced by multiplexing DC power, control signal and an analog RF beam signal on one coaxial cable.

To achieve electrical continuity between tiles, the radiating elements on the final tile design were oriented at 45 degree angles with the tile edges. The final tile design contains 2×72 Vivaldi elements and has an area of 1.125 m^2. The mechanical design has evolved to a dual polarization arrangement of Vivaldi radiators, in which each radiator is laser cut out of a solid thin aluminum sheet and the individual radiators are connected by extruded profiles.

The design of the phased array started with the scanning requirement at the highest frequency of operation. This provided the element separation, producing a radiation pattern free of grating lobes within the visible range. Each tile produces two independent analog RF beam, which follow from the combination of all the elements. Bot beams can be electronically steered to the horizon using a combination of phase shifters and time delay lines, ignoring the grating lobes at the highest operating frequencies. The FoV of one of the resulting RF beams is inversely proportional to the size of the tile. It follows that with an element separation of 12.5 cm, the array element array can meet the scanning requirement up to 45 degrees from zenith at 1.4 GHz in combination with the FoV requirement.

More detailed information concerning the EMBRACE system can be found in [4]

B. Recent Results

1) Pulsar First Light: EMBRACE has achieved the first ever pulsar detection with an L-Band Aperture Array during the night of 1-2 December 2010. This is an exciting and important result, as the detection of such a weak astronomical signal, especially considering the limited available collecting area of EMBRACE, places high demands on the pointing precision of the beam and the dynamical behavior of the EMBRACE array at WSRT.

This first light measurement was carried out over 13 hours at a central frequency of 1207 MHz, using a total bandwidth of 12 MHz. The detected pulsar, PSR B0329+54, has a rotational period of 714 milliseconds, and a phase-averaged flux density of 203 mJy. For this observation, the EMBRACE configuration consisted of 24 tiles, resulting in a total effective collecting area of 27 m^2. The system temperature is approximately 100 K.

Figure 2 shows the pulsar signal as a function of time and rotational phase, with the cumulative pulse profile, i.e. the sum of all pulses, shown at the top (and repeated twice for clarity). Only a 2-hour section of the data is shown because the signal varies strongly in brightness due to scintillation.

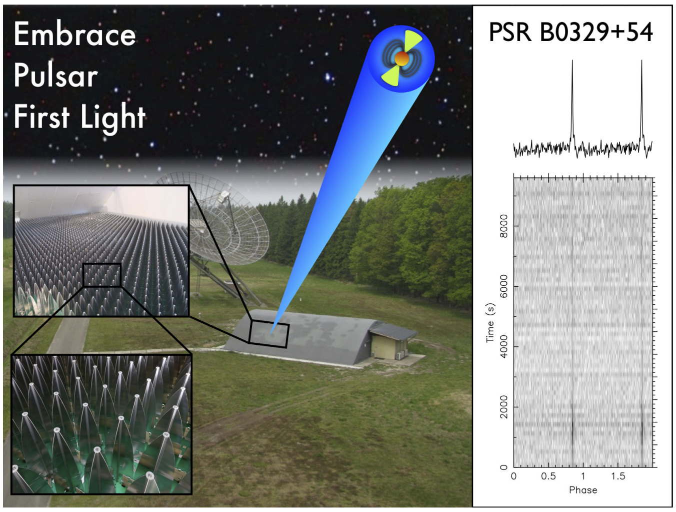

Fig. 2. EMBRACE Pulsar First Light.

2) First HI Map: After the pulsar first light, EMBRACE continued producing excellent results. On January 7, 2011 a 24 hours survey was held to detect HI. For this experiment an 4x4 tile configuration was used, resulting in a collecting area of 18 m^2. An integration time of 14 seconds per pointing was used. The available bandwidth of 12 MHz was processed, resulting in sufficient frequency redundancy to correct for gain variations and removal of sub-band selection filter effects, located on the Remote Station Processing (RSP) boards. Figure 3 shows the measured HI map with EMBRACE in Equatorial coordinates.

For this experiment we adapted the post-processing pipeline to perform real-time FFT, correlation and integration off all samples.

C. Antenna Array

The precursor of EMBRACE within ASTRON's R&D program on wide band aperture array technology, was the Thousand Element Array (ThEA), which successfully demonstrated a wide band phased array based on Vivaldi elements [5]. Therefore, the Vivaldi radiator was chosen as the appropriate radiator to produce a scanning array covering a factor 3 in frequency. The dimensions of a single antenna element, including feed geometry, are shown in table II, III, Fig. 4 and Fig. 5.

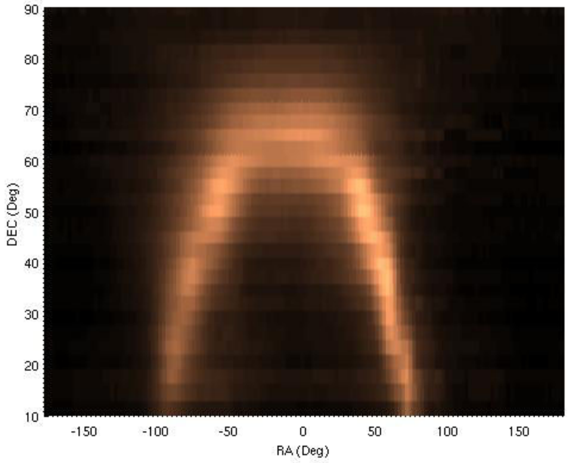

Fig. 3. H1 detection with EMBRACE.

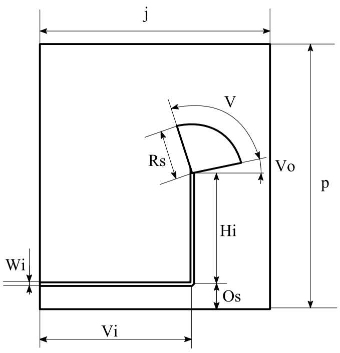

Fig. 4. Final feed geometry.

TABLE III
FINAL FEED BOARD DIMENSIONS.

Feed Dimensions	**Value**
Stripline Width (Wl)	1 mm
Stub Radius (Rs)	15 mm
Stub Opening Angle (V)	96°
Stub Outer Angle (Vo)	12°
Board Width (p)	82 mm
Board Length (j)	70 mm

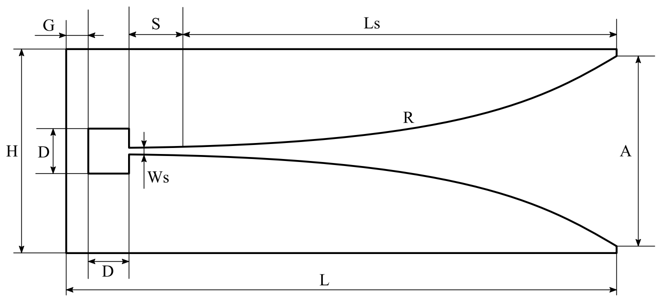

Fig. 5. Final antenna geometry.

TABLE II
FINAL ANTENNA DIMENSIONS.

Antenna dimensions	**Value**
Element Separation (H)	124 mm
Aperture Height (A)	118 mm
Tapered Slot Length (Ls)	294 mm
Rate of Exponential Slotline (R)	0.01 mm^{-1}
Cavity Length (D)	26 mm
Slotline Width (Ws)	2 mm
Constant Slotline Length (S)	15 mm
Cavity Ground Distance (G)	15 mm
Total Antenna Length (L)	350 mm

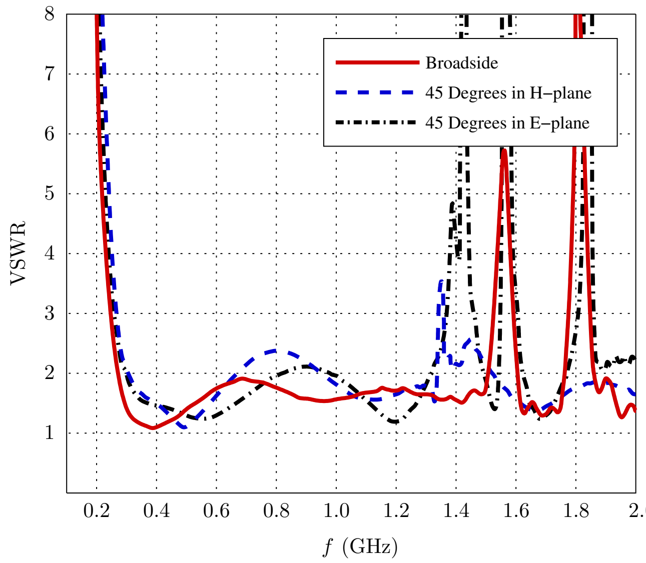

Fig. 6. Simulated active VSWR for an infinite array of EMBRACE-elements.

As the demonstrator stations are large phased arrays ($20\lambda \times 20\lambda$), the array can be modeled using the infinite array approach. We used a periodic boundary finite difference time domain (PB-FDTD) code developed in [6]. The simulated active VSWR for broadside scan, 45-degrees E-plane scan and 45-degrees H-plane scan is shown in figure 6.

For broadside scan the active VSWR is better than 2 between 0.3 and 1.5 GHz. Around 1.6 and 1.8 GHz two blind scan angles occur. If the array is scanned 45 degrees in the E-plane an additional scan blindness will occur around 1.4 GHz. Furthermore scanning the array 45 degrees in the E- and H-plane degrades the performance between 0.7 and 1.1 GHz.

Verification measurements of the scattering parameters were done with a single tile. Because a single tile can not be considered as an infinite array, a (finite) tile is simulated using an in-house developed full-EM antenna simulator (CAESAR [7]).

To validate this simulator a small tile of 16 elements was built, simulated and measured. A picture of this small tile is shown in Fig. 7. Only one polarization of this tile (8 elements)

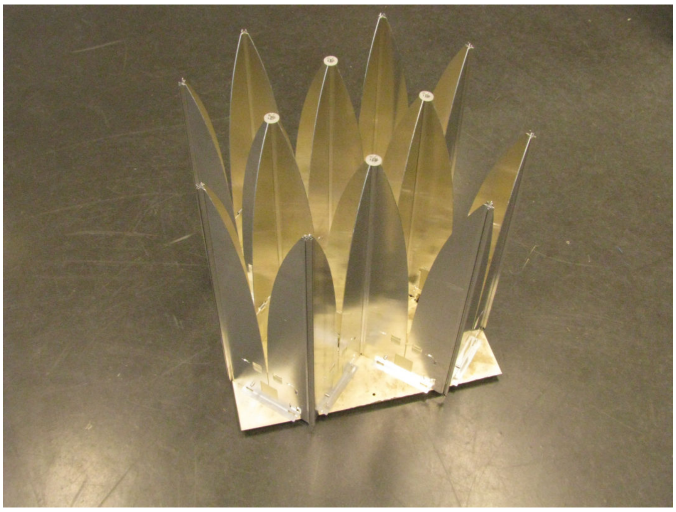

Fig. 7. Small test array.

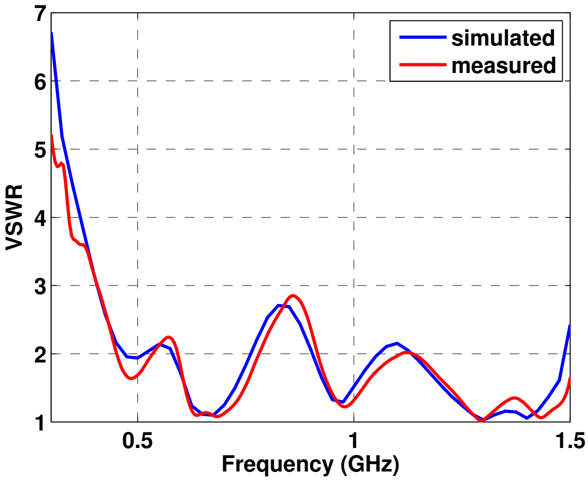

Fig. 8. Active VSWR for center element of small array.

is used and equipped with feed boards.

The active VSWR of one of the two center elements is shown in Fig. 8. The phase of the active reflection coefficient is shown in Fig. 9. One can see that the correspondence between measurement and simulation resembles very well. The active VSWR of a single tile is shown in Fig. 10. The corresponding phase active reflection coefficient is shown in Fig. 11.

III. Next Steps

We are now verifying the results obtained from a full system simulator (combination of full-EM antenna simulator and circuit simulator) [7] with measurements on the actual hardware. This is an important step, because one of the main challenges for the AAVS will be to demonstrate that aperture arrays can meet the SKA requirements within specified cost envelop. This requires further improvement of the mechanical design to allow efficient production and assembly of the antenna system. Several routes have already been explored

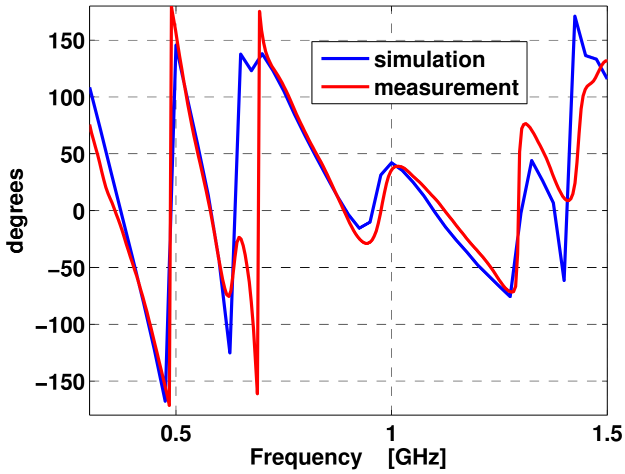

Fig. 9. Phase of active reflection coefficient for center element of small array.

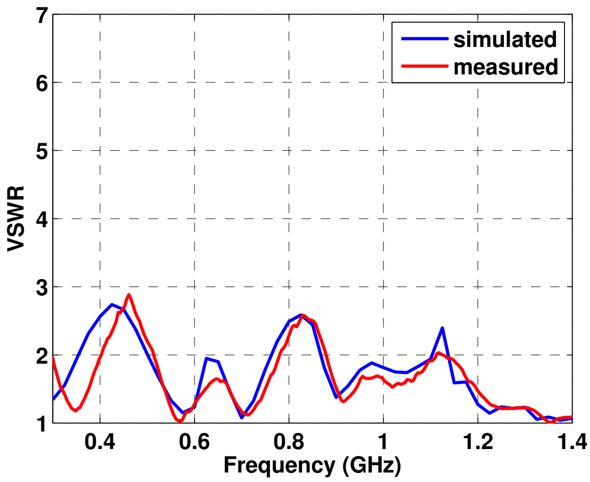

Fig. 10. Active VSWR for center element of a single tile.

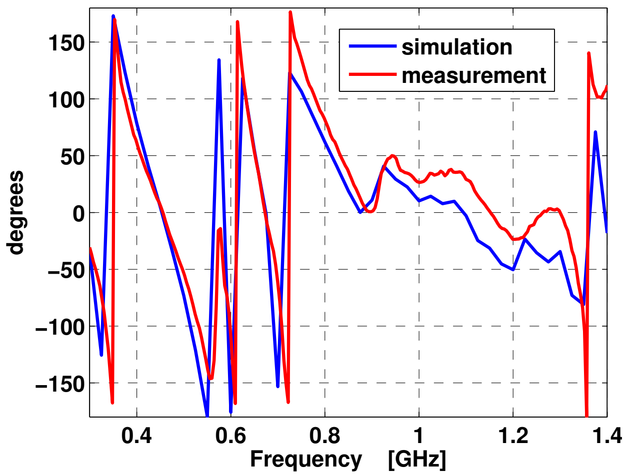

Fig. 11. Phase of active reflection coefficient for center element of a single tile.

including copper Vivaldi profiles printed on a thin foil. We need accurate performance simulations to assess new ideas quickly.

Early experience with the EMBRACE stations in Westerbork and Nançay also showed, that to demonstrate aperture arrays can meet the SKA requirements within power and cost envelopes, a site is required with RFI levels similar to the envisaged SKA sites. Therefore, AAVS will be built on the SKA site, which will be known after the decision on the final SKA site has been made around 2013.

The AAVS will consist of about 15 stations with a total collecting area in the order of 2000 m^2. The individual components of the system are currently being designed and reviewed. The array configuration of the AAVS stations is still being discussed, but will be chosen such that it will not only be a technological demonstrator, but will also fill the astronomical niche of instruments with good short baseline coverage.

IV. Conclusions

In this paper we presented the design of a phased array system for future radio telescopes. We also presented recent results of EMBRACE, proving the system capabilities in an early stage of evaluation. Full-EM simulation and measurement results assure a well functioning next step design, ready for scientific measurements, when placed on the correct site.

Acknowledgment

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References

[1] P. E. Dewdney, P. J. Hall, R. T. Schilizzi, and T. J. L. W. Lazio, "The Square Kilometre Array," *Proceedings of the IEEE*, , no. 8, pp. 1482–1496, Aug. 2009.

[2] J. D. Bunton and S. G. Hay, "SKA cost model for wide field-of-view options," *Experimental Astronomy*, vol. 17, no. 1-3, pp. 381–405, 2004.

[3] A. van Ardenne, J. D. Bregman, W. A. van Cappellen, G. W. Kant, and J. G. bij de Vaate, "Extending the Field of View With Phased Array Techniques: Results of European SKA Research," *Proceedings of the IEEE*, vol. 97, no. 8, pp. 1531–1542, Aug. 2009.

[4] G.W Kant, M. Ruiter, E. van der Wal, and P. Benthem, "The building of EMBRACE," *Widefields Science and Technologies for the SKA - SKADS Conference 2009*, 2009.

[5] S. J. Wijnholds, A. G. de Bruyn, Bregman J. D., and J. G. bij de Vaate, "Hemispheric Imaging of Galactic Neutral Hydrogen with a Phased Array Antenna System," *Experimental Astronomy*, vol. 17, no. 1-3, pp. 59–64, 2004.

[6] H. Holter and H. Steyskal, "Some experiences from FDTD analysis of infinite and finite multi-octave phased arrays," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 12, pp. 1725–1731, Dec. 2002.

[7] R. Maaskant, *Analysis of Large Antenna Systems*, Ph.D. thesis, Eindhoven University of Technology, Eindhoven (The Netherlands), June 2010.