SKA Mid Frequency Aperture Arrays: Technology for the Ultimate Survey Machine

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Abstract

Higher frequency Aperture Array technology, up to 1.5GHz, is being prepared for large scale deployment in radio astronomy. Novel approaches in order to increase performance and lower the production costs are a key element of the success as well as scientific demonstration. This paper describes the current status, technology innovations and planned demonstrators.

1. Introduction

The Square Kilometre Array, SKA [1], the next generation radio telescope, is currently under development. The full SKA will be 100x more sensitive and will survey the sky a million times faster than any present radio telescope. The SKA will be built in Australia and in Southern Africa.

2. Aperture Arrays in SKA

Aperture Arrays (AA) are the enabling technology that will fulfil the promise of the SKA: As a transformational survey machine. The Mid Frequency Aperture Array (MFAA) is particularly well suited to perform the “billion galaxy survey”. This will advance our understanding of galaxy formation and evolution, and help determine the nature of dark energy. In addition, MFAA will accommodate a range of survey related science projects profiting from the wide field-of-view, large bandwidth, and the unique capability of aperture arrays to observe multiple fields-of-view simultaneously.

Figure 1. Artist Impression of the AA-mid SKA

The Field of View (FoV) of AAs, in principle, only depends on the availability of computing power: a large survey speed can be reached with a large array and modest signal processing or with a modest sized array and a substantial signal processing back-end. The survey speed of an instrument is here defined as:

$$\text{Survey Speed} = \left(\frac{A_{eff}}{T_{sys}}\right)^2 . \text{ FoV}$$

wherein A_{eff} is the effective area and T_{sys} the system temperature.

Fig. 2 compares these two options in two different designs; both designs generate nearly identical survey speeds. Design 2 is a smaller array, smaller than suggested in the SKA Design Reference Mission (DRM), nevertheless due to a very large FoV it fully complies with the survey requirement. These simulations are based on an array with a half-lambda pitch of 0.2m, determining the dense to sparse transition frequency at 750MHz. The antenna spacing, the size of the array and the back-end computing are crucial optimization parameters of this AA system.

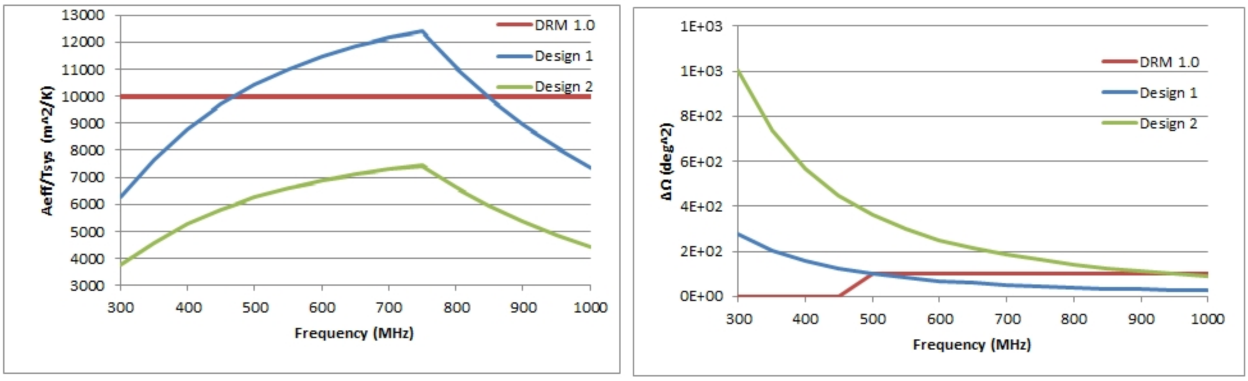

Figure 2. Effective Area divided by T_{sys} (left) and field-of-view (right) function of frequency for two designs

3. AA Test System

EMBRACE [2,3,4] is an MFAA SKA Pathfinder. Two EMBRACE stations were built, largely financed by the European Commission Framework Program 6 project SKADS [5]. The EMBRACE system at Westerbork, The Netherlands, is composed of 9504 close-packed Vivaldi antenna elements. A smaller system is installed at Nançay, France, and is composed of 4608 Vivaldi antenna elements. EMBRACE is the first large-scale demonstrator of the dense aperture array technology for radio astronomy.

EMBRACE has been operational since 2011. After an initial period of engineering testing and preliminary astronomical observing including the testing of multi-beam capabilities EMBRACE has moved into an operational phase with regularly scheduled astronomical observations such as pulsar observations and extragalactic spectral line observing. EMBRACE system characteristics such as beam main lobe shape and system temperature are behaving as expected. EMBRACE has shown long-term stability, and after three years operation continues to prove itself as a robust and reliable system capable of sophisticated radio astronomy observations, see Fig. 3 with an example observation.

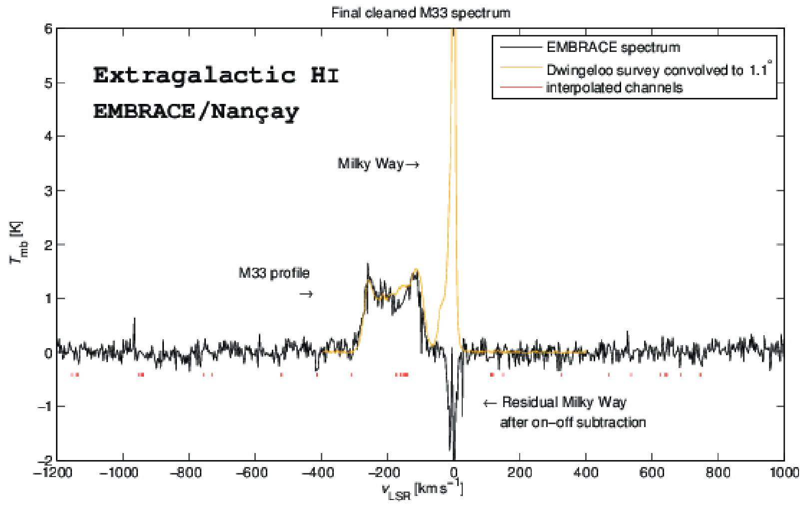

Figure 3. The spectrum of the galaxy M33 after a half hour integration using the Nançay EMBRACE station [6]

4. Technology

There have been considerable front-end developments undertaken to construct a cost effective AA system. Due to the large total number of elements (10-40 million) for the SKA, high volume production techniques and technology is essential.

4.1 Antenna Technology

Two main front-end antennas have been designed. One is a tapered slot Vivaldi antenna developed by ASTRON and deployed in EMBRACE. The other is the Octagonal Rings Antenna (ORA) [6], which is a relatively new design invented by the University of Manchester. ORA uses a different electromagnetic concept which enables forming the antenna array as a planar structure. This has major advantages in a mass production environment, suitable for MFAA.

The Vivaldi Tapered Slot Antenna (TSA) has been widely used in various applications for its broadband and wide scan angle capabilities. The TSA developments for SKA have focused on designs that could deliver low-cost manufacturing and low antenna noise temperature.

Figure 3. The candidate antenna technologies for MFAA, Vivaldi (left) and ORA (right)

The ORA antenna is dual polarized and operates at wide scan angles. The patented planar antenna array[1] structure can be fabricated by etching, ink-jet or screen printing, ideal for large scale implementation with a low cost. The main characteristics of the ORA array have been verified with field measurements. The ORA's properties include: 1) A simple planar structure based on low cost manufacturing techniques; 2) Low, stable cross polarization over a broad bandwidth and wide scan angle; 3) Wide scan angle with a stable scan pattern.

4.2 Receiver Integration

Current micro-electronic development for a future dense aperture array system is focused on the realization of an integrated receiver system. This work is done in a collaboration by Observatoire de Paris and Université de Bordeaux. Integrated systems are essential to improve performance as well as reducing power consumption and cost.

An optimized Application Specific Integrated Circuit (ASIC) for analog beamforming [7] will be designed and fabricated following on from previous work done for the EMBRACE demonstrator. An important innovation is the use of time delay via self-inductance. This permits large instantaneous bandwidth operation and is an improvement to the phase adjustment method currently used for the EMBRACE demonstrator. This technology, together with fast digitization is the best solution for maximizing performance and minimizing cost and power consumption.

4.3 Environmental prototypes

During the development of instruments like EMBRACE it turned out that many design drivers are difficult to determine, nevertheless they have a large effect on the requirements. Environmental aspects such as dust, dirt, vegetation, water, bugs, rodents and other wildlife are requirements that will play a major part in the success of the design. Combining this with further cost reduction for mass production; it is crucial to start gathering on-site measurements results as soon as possible. Four prototypes will be deployed on the South African SKA Karoo site for a sustained period of time (3+ years). The goal is to learn which concept or sub concept performs best and which environmental aspects are the most important.

Figure 4. An example, the realization of prototype 4.

[1] Wide Band Antenna, GB2469075A and WO2010/112857A1

5. SKA MFAA Pathfinder

In the path towards an MFAA system for the full SKA, building and testing a pathfinder system which is science capable is a crucial step. The pathfinder will serve as a verification system, and in addition it will illustrate the unique capabilities and science potential of MFAA. The pathfinder under consideration is called the African European Radio Astronomy Aperture Array ($AERA^3$). $AERA^3$ will verify interferometric imaging capabilities, spectral line detection, transient signal detection and polarization performance over very wide fields-of-view.

In the preliminary specifications, $AERA^3$ is planned to have a sensitivity (A/T) ~ 40 m^2/K at 1GHz, distributed over 10-20 stations. The configuration will be core concentrated, with 50% of the collecting area within a100m circle, and maximum baselines ranging from 300m to 1000m. The unique capability of $AERA^3$ is the multiple independent fields-of-view.

The science cases that are of interest to this pathfinder include:

- HI intensity mapping from redshift 0.5 to 2.5 (300-1000MHz) to detect baryonic acoustic oscillations (cosmology)
- HI mapping of the local Universe (1200-1450MHz) to detect large scale, low density gas in the Milky Way
- Fast transient searches over the whole sky, with positional accuracy within a few arcminutes
- Slow (~days or more) transient searches over the whole sky (to explore unknown parameter space)
- Pulsar timing when using multiple independent fields-of-view (gravitational wave detection)
- Polarization mapping of the Galaxy to refine the grid of Rotation Measure measurements (study Galactic magnetic field)

Each of these cases provides new science. The intensity mapping experiment relies on large, instantaneous fields-of-view, rather than mosaicking, as they require the noise to be uniform over the field. Similarly, the pulsar timing will benefit enormously from the multiple fields-of-view, enabling timing of pulsars in different directions simultaneously, with identical systematics due to the instrument. These unique capabilities can only be provided by MFAA technology.

6. Conclusion

From the costing work undertaken it has become clear that the cost balance between the analog part of the system (including electronics and mechanics) and the digital part changes significantly over time. A much greater field-of-view can be processed at the same cost over time. This was and still is the strongest aspect of aperture array technologies. Although the cost of aperture array technology per square meter is similar if not lower than alternative technologies, in terms of field-of-view it is unmatched. The MFAA technology will be developed in such a way that the design is scalable, to meet the cost and technical requirements of the SKA.

7. References

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