

The SKA New Instrumentation: Aperture Arrays

A. van Ardenne, A.J. Faulkner, and J.G. bij de Vaate

Abstract The radio frequency window of the Square Kilometre Array is planned to cover the wavelength regime from cm up to a few meters. For this range to be optimally covered, different antenna concepts are considered enabling many science cases. At the lowest frequency range, up to a few GHz, it is expected that multi-beam techniques will be used, increasing the effective field-of-view to a level that allows very efficient detailed and sensitive exploration of the complete sky. Although sparse narrow band phased arrays are as old as radio astronomy, multi-octave sparse and dense arrays now being considered for the SKA, requiring new low noise design, signal processing and calibration techniques. These new array techniques have already been successfully introduced as phased array feeds upgrading existing reflecting telescopes and for new telescopes to enhance the aperture efficiency as well as greatly increasing their field-of-view (van Ardenne et al., Proc IEEE 97(8):2009) by [1]. Aperture arrays use phased arrays without any additional reflectors; the phased array elements are small enough to see most of the sky intrinsically offering a large field of view.

The implementation requirements of high frequency, astronomically capable phased arrays are severe in terms of power and cost due to the large numbers of channels and the amount of digital processing required. However, technological roadmapping shows that a cost effective large scale implementation for the SKA is achievable soon. An aperture array covering this frequency range is the only instrument able to perform some of the most challenging science experiments planned for the SKA and is likely to make some transformational discoveries. In the context of defining and developing the next SKA phase the international Aperture Array Verification Program, is working on both the sparse low frequency array from 70 to 450 MHz and a dense array from 400 to 1,450 MHz as the low frequency system for the SKA.

A. van Ardenne (✉)
ASTRON, P.O. Box 2, 7990 AA Dwingeloo, The Netherlands
e-mail: ardenne@astron.nl

The work aims to provide insight into the status of enabling technologies and technical research on polarization, calibration and side lobe control required to fully realise the potential of phased arrays for the SKA aperture synthesis array.

2.1 Introduction

The Square Kilometre Array, SKA is the next generation low frequency radio telescope with preliminary specifications described by Dewdney et al. [2]. The work performed in the European funded FP6 programme, SKA Design Studies, SKADS [3, 4], showed that an implementation of the SKA using phased aperture arrays, AAs, operating from 70 MHz up to 1.4 GHz with a dish based array covering $\sim 1.2\text{--}10$ GHz represents the most capable design for the agreed SKA Phase 2 science case [5]. Here we discuss the scientific benefits of AA and the need for the proposed frequency range; the development and trade-offs of a suitable array; and the system implications including central processing load.

The deployment of the SKA, starts with an $\sim 10\%$ instrument, Phase 1, in 2016 includes a low frequency sparse AA covering 70–450 MHz, the details are described in SKA memo 125 [6]. The development of the technically and astronomically less mature dense AA system will continue in parallel preparing for deployment in SKA Phase 2 commencing in 2018. This schedule enables SKA Phase 1 to benefit from the experience gained with current low frequency AAs, LOFAR [7] and MWA [8] systems, followed by the more challenging dense AA in Phase 2. These developments are core to the Aperture Array Verification Program [4, 9] advancing AA's for the SKA.

2.2 Scientific Benefits

An AA is a very different receiver concept from conventional dishes; it has multi-beaming capabilities, with very fast changes in observation direction. If we consider the benefits to the SKA Design Reference Mission [5], Figure shows the sensitivity and survey speed requirements of the various science experiments. Most of the major surveys are performed below the neutral hydrogen line at 1.4 GHz; this sets the highest frequency required of the AA system.

Remote galaxies are receding progressively faster due to the expansion of the Universe, this Doppler shifts the hydrogen line to lower frequencies, which enables measuring three dimensional structure, however, the signal also gets progressively weaker and increasing the survey speed requirement at lower frequencies, it was shown e.g. in Alexander [5] that the FoV needs to increase as λ^3 for an optimum survey time. An AA can adjust survey speed as a function of frequency by varying the number of beams across the bandwidth.

The requirement for high dynamic range, particularly for continuum experiments, exceeding $10^7 : 1$ will be very difficult to achieve. AA's have the characteristics necessary to achieve excellent dynamic range: physical stability, unblocked

aperture, small individual beams due to large diameter of the array, ability for exquisite calibration of the “surface” over frequency. There is substantial research ongoing into optimizing the appropriate calibration techniques.

Pulsar and transient detections require a large number of beams for fast surveys and timing of multiple pulsars concurrently; AAs also have the ability to buffer data which enables a “look back” to find the pre-cursor of a transient event.

A subset of Fig. 2.1 could similarly be produced for the first SKA phase using the detailed science Design Reference Mission has been produced [10].

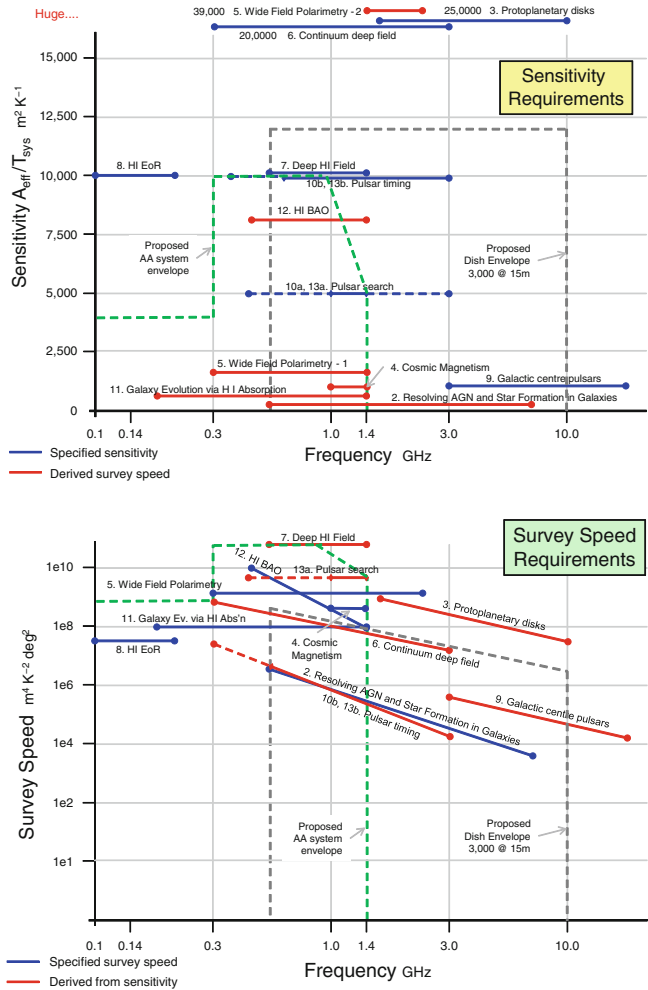


Fig. 2.1 The sensitivity and survey speed requirements for the SKA science case. The sensitivity specifications are shown in the left hand panel with the survey speed's on the right. Note that high survey speeds are typically needed below 1.4 GHz

2.3 Designing for Aperture Arrays

The production of SKA₁ will start in 2016. In order to have a production-ready design of SKA-low, a series of Aperture Array Verification Systems (AAVS) will be built, starting with a relatively open exploration phase and subsequently focusing on the final design. Three phases have been identified, starting with AAVS0, a modest antenna test system of approximately ten antennas, AAVS1 with 250 m² collecting area, similar in size to the first LOFAR initial test stations or the MWA 32 Tile system, and AAVS2. AAVS1 will demonstrate electromagnetic and front-end performance with sufficient collecting area in order to make astronomical verification possible, and should establish the antenna tile and station configuration. AAVS1 will be commissioned by the end of 2012 or early 2013. AAVS2 is the SKA₁ pre-production array, built with production tooling and sufficiently large area (1–2% SKA₁). The AAVS1 and AAVS2 will be built at the chosen SKA site or at a site, similar in terms of RFI and climate conditions i.e. in Portugal near Moura.

For AA-low, several antenna element types are being evaluated including options of splitting the frequency band in two. This might be useful to limit the required bandwidth of each antenna but, importantly a single antenna array with e.g. an $\lambda/2$ frequency of 130 MHz will be very sparse at the top-end of the band, resulting in a low filling factor and many grating lobes. A split into two arrays, sharing the back-end, reduces these artifacts significantly and possibly increases noise and antenna performance e.g. by reducing sky noise at the highest frequency.

Various types of antenna elements are being investigated emphasizing the potential for excellent cost-performance ratios. For example, bow-tie and log-periodic antenna elements and array prototypes are being developed because of their potential capabilities to cover the entire AA-low band and a 5 times frequency scaled (350–2,250 MHz) model of the conical log spiral antenna is being simulated and prototyped as an example of a wideband antenna for array development all offering potentially very low cost.

In the final SKA₁, a system consisting of 50 stations, each 180 m diameter and 11,200 antennas, can fulfill the above sensitivity requirement by creating a total physical collecting area of 1.3 km².

The required bandwidth for AA-low implies an instantaneous bandwidth of 380 MHz, but it is preferable due to RF-effects (such as band-pass roll-off) to over-sample the incoming signal at 1 GS/s (500 MHz instantaneous B/W). Whilst the exact bit-depth of the Analogue-to-Digital Converter depends on many factors including the strength of interferers as well as the properties of the RF signal path, we take the conservative number of 8-bits, affording us about 48 dB dynamic range. After the signal has been suitably digitized, the signal processing functionality naturally falls into three main areas: Channelization, beamforming and correlation. Putting the correlation aside for the moment, it is expected that both the spectral and the spatial decomposition of the incoming bandwidth and the FoV will follow a hierarchical structure.

A dense AA station for the SKA has of the order of 75,000 dual polarization receiver chains. As for AA-low this implies a large amount of electronics which has severe cost and power implications. The dense array has effectively a fixed collecting area, so, is used where the Sky noise is relatively low and constant above ~ 400 MHz. Hence, the array sensitivity will be dominated by receiver noise giving the requirement for the lowest possible front-end noise performance for good sensitivity. The top frequency is limited by the number of elements that can be afforded; to stretch to 1.4 GHz we have allowed the system to become gradually sparse above 1 GHz.

An important decision for the array system design is how many elements in a cluster are beamformed using analogue techniques prior to using digital processing. Analogue beamforming is cheaper today than a digital system, but has some significant limitations: each beam that is formed requires another set of hardware; it is hard to have precise calibration, particularly to correct polarization issues; and analogue systems have potential drift issues. Digital signal processors, DSP, can implement high precision calibration and beamforming, and can provide a large number of beams just by using additional processing and communications capability. Analogue beamforming could use true time delays, TTDs, e.g. using circuit board tracks, but these are large; alternatively, phase shifters can be used, since they are easier to integrate, but they are relatively narrow band because low frequencies are delayed more than high frequencies, preventing a full bandwidth coherent beam. The ideal architecture is to digitize every element path and perform all the beamforming in the digital domain. This is very flexible; however, it is currently more expensive and higher power than an analogue system. The expectation is for a 2018 implementation to use TTD for small clusters of elements, probably four, and digitize the single, very large, beam that is produced. DSPs then form the very large number of beams from the array, within a field of view defined by the analogue beam.

The maximum instantaneous bandwidth of the system is the full frequency range that the array operates over. There may be some restrictions, discussed above; however the more important consideration is the total data rate from the array, which ultimately defines the performance of the system. With a flexible system, which is ideal for maximizing the science output, beams will not necessarily need to form conventional beams, but can be tailored over the observed sky as a function of frequency; for example to cover a relatively narrow frequency band over a larger observed sky area e.g. for transient event search; or create a constant field of view independent of frequency.

The sensitivity of the system is a function of frequency and is determined from: size and number of arrays, system temperature (T_{sys}), scan angle and the apodisation employed. A critical factor is the receiver noise, dominated by the front-end: element, first amplifier and their matching. Due to the number of receivers and the physical size of the array it is not practical to consider cooling the front-ends for improved noise figures. Consequently, the system will be running at ambient temperature. Progress in this area has been significant and the current best front-ends

have a T_{sys} of <60 K (including sky and receiver noise), with <50 K expected in 2011. The required <40 K is expected to be achieved before 2016.

Because an AA is essentially a major processing system with receiver inputs, the dynamic range and polarization purity requirements of the SKA are achievable, but will require sufficient analogue stability, and use an array of sufficient diameter to measure and counter the atmospheric effects. Only the required number of arrays for imaging quality will be deployed, the central processing requirements are thus reduced to a reasonable level considering the survey speeds and data rates that are achieved. In effect the processing in the arrays is mitigating the central processing load.

2.4 Technology Roadmap

The technologies required for the AAs are generally the focus of the ICT industry: faster and lower power processing, higher speed communications, lower cost, increased storage etc. Hence, AAs tend over time to get more practical, with better performance. At some time, dense AAs become affordable and indeed cheaper than traditional dishes. By carefully studying technology roadmaps for fabrication capabilities, discussion with major semiconductor and communication companies and review of markets that require similar components we anticipate that a dense AA system for the SKA meeting performance, cost and power constraints can be scheduled for 2018 construction.

The key components for the array itself, not currently available, are: an LNA with <15 K noise and an analogue system with <150 mW total power; a DSP, chip providing >20 TMACs and use ~ 25 watts integrated with up to 128 6-bit 3 GS/s digitizers each using <100 mW; a programmable DSP of >20 TMACS with 128 I/Os of >10 Gb/s each; and short-range ~ 50 m pluggable optical links of >120 Gb/s with >2.5 W power. There is a similar requirement list for the central processing systems. These are all projected and indeed will improve post 2018.

2.5 Conclusions

An outline of the required effort and initial developments have been discussed which should lead to a production-ready design of the low frequency aperture array component of SKA₁. Significant effort will be required but assessments indicate good possibilities for achieving the SKA₁ specifications. This will be supported by science simulations vis a vis the design parameters e.g. with respect to wide field polarimetric capabilities. If dense AAs can be implemented within the cost and power constraints in the timescale of the SKA they are the most capable technology available, representing almost the perfect collector system. The research performed in the SKADS program shows that technology evolution will be sufficient to enable substantial deployment in the second phase of the SKA starting in 2018.

Acknowledgements This paper is due to the work of many people in the SKADS project and continuing into the AAVP. The authors do not wish to list just a few participants, but to fully acknowledge the contributions made by everyone throughout these exciting developments.

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The Square Kilometre Array: Paving the way for the new
21st century radio astronomy paradigm

Proceedings of Symposium 7 of JENAM 2010

Barbosa, D.; Anton, S.; Gurvits, L.; Maia, D. (Eds.)

2012, X, 118 p., Hardcover

ISBN: 978-3-642-22794-3