Low Frequency Aperture Array Developments for Phase 1 SKA

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Abstract

Aperture Arrays (AA) mark a new era in radio astronomy combining high sensitivity with a large field-of-view, enabling very high survey and imaging speeds. This paper describes the development of low frequency aperture arrays leading up to SKA phase 1 within the Aperture Array Verification Program (AAVP) as part of the SKA program.

1. Introduction

The international radio astronomy community is currently pursuing the development of a new telescope with unprecedented sensitivity, resolution and survey speed: the Square Kilometre Array (SKA) [1]. In order to cover a frequency band of 70MHz to 10GHz, a frequency band dictated by the science case, several receptor technologies are considered. These include dishes for the high frequencies, phased array technology for the low frequencies and combinations of these in the form of phased array feeds. The realization of SKA as presently defined has two stages: Phase 1 (SKA_1) as the first construction phase is aimed to have unique science capabilities albeit at much lower investment levels and comprising a limited collecting area. SKA_1 focuses on a low frequency aperture array for 70-450MHz and a dish array for 400-3000MHz with single pixel feeds; higher frequency aperture arrays and phased array (dish) feeds are developed in an Advanced Technology Program (AIP). Phase 2 (SKA_2) comprises the full array. Experience from SKA low frequency pathfinders and precursors like LOFAR [2] and MWA [3] will be very relevant for the SKA_1 development.

2. Science requirements for the Low Frequency Band

The SKA_1 science case is outlined in the Design Reference Mission (DRM) [4]. A requirement summary is given in table 1.

Table 1. SKA_1 low frequency requirements summary

Parameter	Value
Frequency Range	70 – 450 MHz
A_{eff}/T_{sys}	1000 m^2 /K (@ z =10 (130MHz) sky noise ≈ 506 K)
Survey speed	10^7 $m^4K^{-2}deg^2$
Imaging dynamic range	10^6
Frequency resolution	0.2kHz

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Converting the science requirements in system requirements taking into account practical features and limitations of aperture arrays and sky noise (increasing for lower frequencies), an initial system design is given in [5]. A system consisting of 50 stations, each 180m diameter and 11,200 antennas, can fulfill the above sensitivity requirement by creating a total physical collecting area of 1.3 square kilometre.

3. Aperture Array Verification System

The production of SKA_1 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 realized, starting with a relatively open exploration phase and subsequently zooming in to the final design. Three phases have been identified, starting with AAVS0, a modest antenna test system of approximately 10 antennas, AAVS1 with 250 m^2 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. AAVS2 is the SKA_1 pre-production array, built with production tooling and sufficiently large area (1-2% SKA_1).Table 2 lists a summary of AAVS2 specifications. The AAVS1 and AAVS2 will be build at the chosen SKA site or at a site, similar in terms of RFI and climate conditions.

Table 2 Summary of AAVS2 specifications

Parameter	**Conditions**	**Value**
Sensitivity A_{eff}/T_{sys}	Broad sight, at 130MHz	20 m^2 / K
Number of stations		4
Frequency range	Instantaneous	70-450 MHz
Field-of-View (FoV)	@ 450 MHz	20 deg^2
Scan range		±45°

3.1 Station Layout Considerations

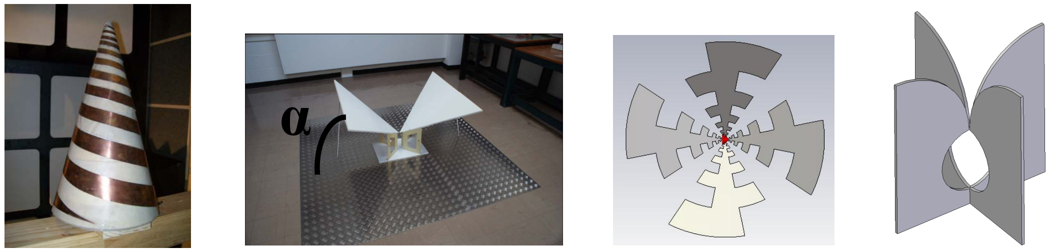
The AA-low array will be portioned into stations. The layout of an AA-low station is critical in achieving the optimal sidelobe profile as well as the desired sensitivity across the whole AA-low band. Various types of regular and irregular, both densely and sparsely sampled arrays have been studied for inclusion within the SKA_1 programme. Given the proposed AA-low scan range of ±45° from zenith, this implies a maximum element separation of ~0.6λ for a regular array if grating lobes are to be avoided. However, in this case the sheer number of elements required for the desired sensitivity at the top-end of the band is impractical from a cost perspective. For this reason sparse arrays, particularly arrays with randomized configurations, are more desirable since even at much larger separations, the power that would be present in the grating lobes is re-distributed into many smaller and "random" sidelobes; this in turn results in the array efficiency being smoother for the entire scan range. This is a useful feature of sparse random arrays and is the reason that they are of interest to the SKA community [6]. Furthermore, if each station has a different randomized design, the cross-correlation between stations in an interferometer would suppress the sidelobes in the cross-power beam. However, a more appropriate option may be to specifically tailor the antenna locations to a desired profile - that is, a deterministic approach to locating antennas in an under-sampled array.

3.2 Antenna prototype development

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 the antenna but more importantly a single antenna array with e.g. an λ/2 frequency of 130MHz will be very sparse at the top-end of the band, resulting in a low filling factor and many grating lobes. A split in two arrays, sharing the back-end, reduces these artifacts significantly.

Spiral antennas have many benign characteristics which remain fairly constant over frequency [7]. This includes features like constant beamwidth, high front-to-back ratio, consistent impedance behavior, low cross polarization and relatively low mutual coupling in an array configuration. A 5 times frequency scaled (350 – 2250 MHz) model of the conical log spiral antenna is being simulated and prototyped as an example of a wideband band antenna for array development (Fig. 1a). The simulated and measured results encourage further investigations. A dual polarized version of spiral antenna is also being investigated. In this design, a thin PCB substrate, 0.2~0.3 mm thick, has the spiral arms printed on both sides. When conformed to a conical former, the inner arm winds in opposite sense to the outer arms making it a ‘counter wound’ spiral antenna. This ‘counter-wound’ antenna is being simulated and prototyped for testing.

Bow-tie and log-periodic antenna elements and array prototypes (Fig. 1b) are being developed because of their potential capabilities to cover the entire AA-low band using one single element at very low cost. Design studies have indicated a good prospect for bow-tie antennas for the application [8]. In the BLU (Bow-tie Low-frequency Ultra-wideband) antenna the angle to the ground (α) provides an extra degree of freedom to improve the impedance and to control the beam-width (directivity up to 8 dBi). Toothed log-periodic antennas (Fig1c) are also being investigated for their improved pattern characteristics and impedance response with respect to the bow-tie antennas.



a b c d

Figure 1 Spiral antenna (a), BLU antenna (b), toothed log-periodic antenna(c), dual polarized Vivaldi (d)

A dual-polarized, metal-only Vivaldi antenna is shown in Fig. 1d. It is composed of a matching section with circular stub and a tapered slot radiating section. The single ended excitation is placed at the interface between these two sections [9]. The antenna provides a suitable matching level from 70 to 450 MHz. The cross polarization level at zenith is very low due to the symmetry of the antenna. The developed configuration does not require a ground plane. Therefore, the soil effect has been taken into account in the simulations. A new gridded version of the antenna is being developed in order to obtain an easy-deployable low-cost prototype.

3.4 Receiver prototype development

In the AA-low frame, some commercial LNAs are under evaluation which could represent a cost-effective solution, especially for the prototyping phase (AAVS0 and AAVS1), but also in the following industrialization for SKA_1. The measurements of an off-the-shelf LNA from RFMD are given in the Fig. 2.

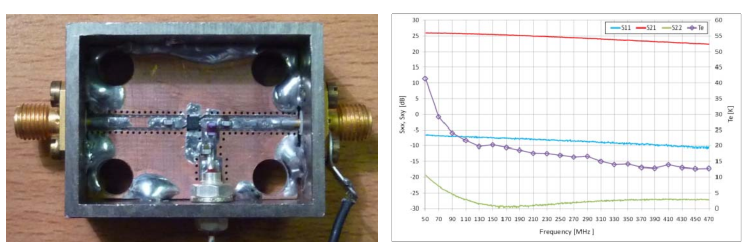


Figure 2 LNA based on SPF-5122Z: custom housing (left) and measurements (right).

3.3 Signal Processing

The required bandwidth for AAVS-low implies an instantaneous bandwidth of 380MHz, but it is preferable due to RF-effects (such as band-pass roll-off) to over-sample the incoming bandwidth at 1GS/s (500MHz 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 48dB 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 as shown in Fig. 3.

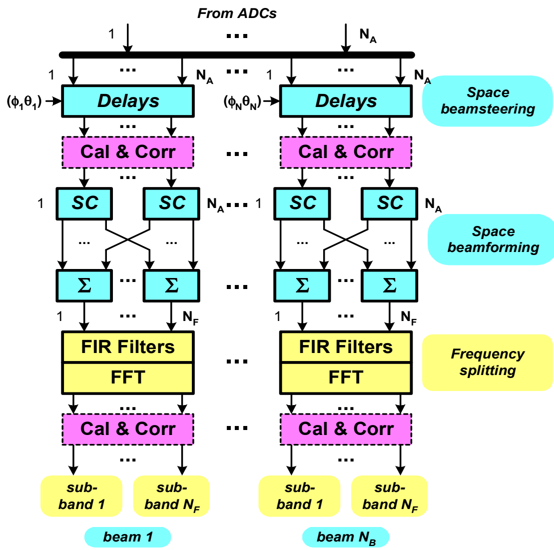


Figure 3 A schematic of a possible interleaved beamforming and channelization structure (adapted from Khlebnikov et al.). Depending on the science requirements the correct balance between FoV and spectral resolution can be selected.

Throughout AAVS it is expected that all the signal processing capabilities will be implemented on an FPGA based architecture, preferably on UNIBOARD or ROACH since much experience is already available on these platforms. Whilst the extent of AAVS has not yet converged, it is expected that the system will still be sufficiently small so that the correlator will be implemented in the same FPGA technology as the rest of the signal processing chain.

4. Conclusion

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 SKA_1. Significant effort will be required but assessments indicate good possibilities for achieving the SKA_1 specifications.

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