DESIGN CONSIDERATIONS FOR AN SKA QUALITY, COST EFFECTIVE APERTURE ARRAY

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Abstract: Use of an aperture array in the Square Kilometre Array, SKA, next generation radio telescope has many benefits: high survey speed, observing flexibility and the capability of whole sky monitoring for transient events. We discuss the engineering challenges to meet the performance needed for radio astronomy with acceptable cost and power requirements. These investigations are being undertaken within a European design study, SKADS. Initial results show that careful selection of the aperture array frequency range and integration with high frequency dish technologies creates a practical, affordable and high performance design for the SKA.

INTRODUCTION

A radio telescope with a square kilometre of collecting area to survey red-shifted hydrogen emission to the earliest cosmological epochs has long been an aspiration of radio astronomers, see e.g. Wilkinson[1]. The specification of the Square Kilometre Array, SKA, described by Jones[2] and ISPO[3], has been expanded in frequency coverage and angular resolution to cover many other scientific observation requirements, see Carelli et al.[4]. Such an instrument can be considered to be a physics instrument exploring fundamental scientific questions. The SKA performance is unaffordable built as a typical radio telescope, however, the progress of high performance data processing, wide bandwidth communications and low-noise, ambient temperature amplifiers makes the prospect of a telescope using IT a real possibility.

The European SKA Design Studies, SKADS[5], task is to produce a costed SKA design. Most of the technical work is the development of a mid-frequency, aperture array capable of meeting the cost and performance specifications for the SKA. While this work will evolve until the end of SKADS in June 2009, the first detailed design and costing model has been published, Alexander et al.[6]. This shows that by using the benefits of the aperture array at a low RFI, SKA site and fully integrated with high frequency dishes, it is possible to design a practical SKA.

SKA SYSTEM DESIGN

The current SKA frequency specification is from 0.1-25GHz, this range may be covered by multiple collectors, those proposed in the 'SKADS Benchmark Scenario' are shown in Table 1. The lowest frequencies, 100-300MHz are expected to be a dipole based, sparse aperture array. The highest frequencies have to use a dish, and with very wide-band feeds are expected to cover from <1GHz to >20GHz with a single receiver. The key red-shifted hydrogen frequencies of ~1GHz down to 300MHz requires high survey speeds, from a combination of sensitivity, bandwidth and field of view (FoV). This can be met with an aperture array.

Frequency Range	Collector type	Description
100-300 MHz	Dipole phased aperture array	LOFAR or MWA technology
<300-1000 MHz	Close packed aperture array	SKADS principal development
700 MHz->20 GHz	6.1m dish with wide-band feed	Allen Telescope Array technology

Table 1. SKADS proposed SKA collector technologies by frequency range

With aperture arrays covering the lowest frequencies, the dish and its feed can operate above 700-900MHz and hence may be small, with high frequency capability and low cost per unit area.

APERTURE ARRAY DESIGN

We only consider the mid-frequency, 300-1000MHz, aperture array here, which is the subject of the SKADS technical development. At this stage, we have used a close packed array with ~0.6λ spacing at the highest frequency to precisely sample the incoming signal; this decision will be reviewed in the course of SKADS. A critical decision for cost and power is the highest frequency of operation, f_{high}. The number of elements scales as f_{high}^2 plus the complexity of the components also increases with frequency. Scientifically acceptable cost optimization indicates using f_{high} of 1GHz to detect distant hydrogen, rather than the more obvious 1.4GHz of the hydrogen rest frequency. This results in an element spacing of ~18cm, and reduces the cost of the array by ~50%. To maximize survey speed we will use the full bandwidth of 700MHz, implying the use of direct RF conversion. This reduces complication for frequency shifting, but puts increased load on the processing systems. Digital electronics can cause self-induced RFI unless shielded, which is simplified by putting all of the digitization and processing inside a single screened bunker. Analogue links are used from the antenna elements to the processors, this is a substantial system cost and identifying low-cost links such as the forthcoming CAT-7 cable networking standard is critical. The lowest costs may be by using analogue phase shift systems to perform the initial beam-forming, particularly if they are mounted near the antenna elements; however, with the required bandwidth and precision this may not be possible.

The SKA specification requires a dynamic range of $\sim 10^7$:1 and cross-polarization purity of ~40dB, which is hard to achieve with any collector. The high-performance solution is to use an all-digital approach, whereby each incoming signal is equalized and immediately digitized with all the beam-forming performed digitally. This approach, shown in Figure 1, gives maximum control over the beam-forming in each spectral band. Clearly, the cost and power of many analogue-to-digital converters is a major factor, but due to the low external RFI at the SKA site and the high sample rate only relatively simple 4-bit digitization is required.

Digital Processing. The processing flow is illustrated in Figure 2. A lot of processing is required, ~20TMacs per 256 element tile, but is possible around 2011 using 45nm silicon technology on ASICS or multi-core processors. The first and largest processing requirement is to split the signal into spectral bands. This function could be performed on an ASIC, but is ideally kept on a programmable device for flexibility. The signal is corrected for physical time delay, phase and amplitude in each spectral channel. The polarization purity for each element in the observing direction is corrected by a matrix operation, followed by corrections for coupling and other array effects.The actual beam-forming for each spectral channel is performed by a computationally efficient 2-D Fast Fourier transform, FFT, over a block of 8 x 8 elements. This produces all 64 beams available, of which 8-16 will be used. The required beams on the sky are interpolated and tracked between adjacent beams produced by the FFT. These resultant sky beams are combined initially in groups of four making 'Tile' beams from 256 elements and subsequently with all the ~300 tiles in a Station. Appropriate station beams are transmitted to the central SKA correlator. The key to a high dynamic range system is to provide the many calibration coefficients to be used during the processing. Calculating and measuring these coefficients is a major task and techniques for doing so are being developed within SKADS .

CONCLUSIONS

With the technology projected over the next few years, the aperture array is a strong contender for providing collecting area with wide FoVs for the SKA and can meet the required stringent performance, cost and power requirements.

REFERENCES

[1] P.Wilkinson, *"The Hydrogen Array"* IAU Colloquium 131, ASP Conference Series, Vol. 19, 1991, T.J. Cornwell and R.A. Perley (eds.) , pages 428-432

[2] Jones D. L., *"SKA Memo 45"*, www.skatelescope.org

[3] ISPO, *"SKA Memo 69"* , www.skatelescope.org

[4] Carilli C. et al., *"Science with the Square Kilometre Array"*, New Astronomy Reviews, Vol.48, Elsevier, December 2004

[5] *"Square Kilometre Array Design Studies, SKADS"*, www.skads-eu.org

[6] Alexander P. et al., *"SKADS Benchmark Scenario Design and Costing"*, www.skads-eu.org

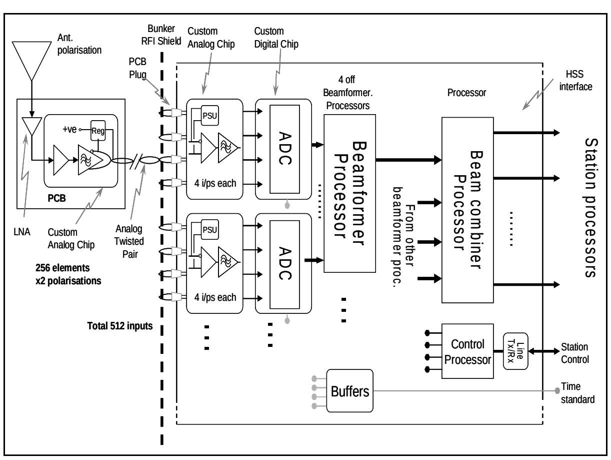

Figure 1. Signal flow in an all-digital system

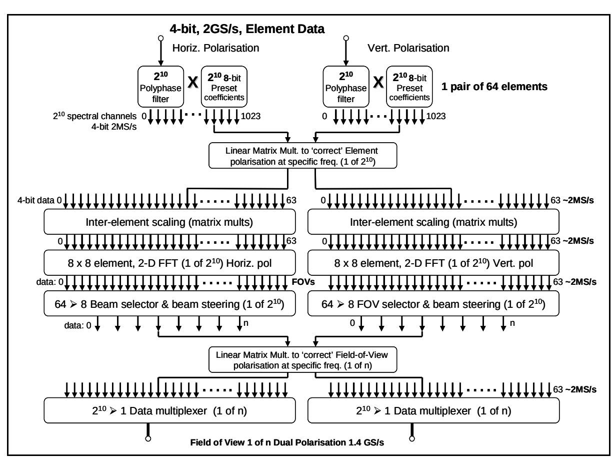

Figure 2. Processing for Beam-former Processor