Analysis of an Ultra Wideband Aperture Array Element for Low Frequency Radio Astronomy

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Introduction

The next generation of radio telescopes currently being designed will use so-called aperture arrays [1] as the core collector technology. These are phased arrays composed of several thousand antenna elements which are used to directly sample the incoming wavefront. The Square Kilometre Array (*SKA*) is the focus of this development work. This instrument will provide about two orders of magnitude improvement in sensitivity over existing facilities, but many thousand times improvement in the speed with which the sky can be imaged. This performance is required to deliver the scientific objectives of the experiment [2]. One part of the *SKA* design (*SKA AAlo*) calls for an ultra wideband antenna array able to operate from 70 to 450MHz. There are clear cost savings if this frequency range can be covered by a single antenna technology.

This document comprises of two sections. The first section summarizes the important aspects which should be considered in the analysis of elements for aperture array instruments, and the second section describes the design of an aperture array unit cell including an ultra wideband bow-tie element. We focus particularly on the analysis of the effective aperture, which is a key parameter for the *SKA* telescope.

Analysis of Aperture Array Elements for Radio Astronomy

The low frequency *SKA* requires ultra wideband array performance (up to bandwidth ratios of 7:1) with respect to impedance as well as radiation patterns (stable embedded element patterns with beam widths up to 90 degrees). When designing the front-end system, the primary figure of merit is the system sensitivity, which for arrays such as the *SKA* is given by the ratio of effective aperture to system temperature (A_{eff}/T_{sys}) [2]. The system temperature is dependent on both the impedance mismatch between the receiver electronics and the sky noise, which is dominant at the lower frequencies [3]. For these types of instruments, the effective aperture and system noise are therefore key parameters; the effect of mutual coupling between closely located elements may also bring about different undesired effects at the array level [4]. All these anomalies will propagate to the active reflection coefficient and the system noise.

It is important to recognize therefore that for the *SKA*, the array must be accurately characterized for every possible scan angle, mode and frequency in order to calibrate it, and it must provide a smooth and stable response along the desired scan angles. In order to simulate these very large arrays we make use of infinite array simulators in the design

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process. However, when the arrays are irregular in geometry, these packages only give a rough approximation to the EM solution. There are currently great efforts being made to develop codes capable of simulating full stations with sizes up to thousands of wavelengths [5],[6].

Furthermore, *RFI* (Radio Frequency Interference) is a major problem in low frequency radio astronomy, and practically invalidates some bands from being used. This must be taken into account when designing aperture arrays, as for example one may decide to realize a design where the aforementioned anomalies all fall in this region of exclusion.

Finally, the budget is also a very limiting factor in the realization of new generation radio telescopes such as the *SKA*. The presence of thousands and millions of elements requires the design of very low profile ultra wideband antennas which are cheap and easy to build and assemble.

Study of the Effective Aperture of a Bow-Tie Element

The selection of an antenna element for the *SKA AAlo*, should be based on the optimization of four parameters; the system noise, the effective aperture, the embedded element pattern and the cost per element. In this paper, we will analyze the performance in terms of effective aperture of an ultra wide band low profile bow-tie element as shown in Fig. 1. The parameters of the unit cell are “a”, where 2a is the size of the element along the E-plane; “b”, the size of the element along the H-plane; “A”, the size of the unit cell along the E-plane and “B”, the size of the unit cell along the H-plane.

An infinite regular phased array of the proposed elements has been simulated with the periodic boundaries approach of commercial software based on FD-TD [7]. The impact in the effective aperture of the unit cell with respect to both the inter-element spacing, *d*, (third column of Table 1) and the element size (fourth column of Table 1) was analyzed. We look at the results for a broadside scan, as the fields computed by the commercial software are meant to be the most accurate for this situation and also for a regular array, as already selected.

Figure 2 shows the results for a sweep of *d*. The unit cell is kept square and its size sweeps from 1m to 2.140m, meaning half wavelength spacing distances from 150MHz down to approximately 70MHz. We can distinguish two clear regions in this plot, the first ends at a frequency where the inter-element spacing is λ. In this lower frequency band the effective aperture is approximately constant with frequency and grows with *d*. However, the upper frequency band shows an effective aperture decreasing with increasing frequency at an approximate rate equal to half of the square of the wavelength for all *d*. This effect has already been reported before for an array of dipoles [8]. These regions represent the dense and sparse regimes of the array in terms of inter-element spacing. In actual fact for the present case it seems that in the sparse regime, the effective aperture is slightly better than $\lambda^2/2$. In Fig. 3 we look only at the two edge curves and the central one to see how for the dense regime, the effective aperture of the unit cell converges to its physical size, d^2, as expected. Furthermore, one can appreciate how the efficiency of the unit cell improves for more packed configurations. It is important to note that even with a relatively small bow-tie element, it is still possible to achieve a good effective aperture for the required frequencies.

For different element sizes, as shown in Fig. 4, the effective aperture of the unit cell reaches a maximum value equal to the physical area of the unit cell in the dense regime, almost independently of the size of the element.

Conclusion

This analytical study of an ultra wide band bow-tie element in an infinite regular array environment tries to give designers some useful hints on how to face a preliminary design of a radio astronomy instrument based on aperture arrays in terms of the effective aperture of the unit cell.

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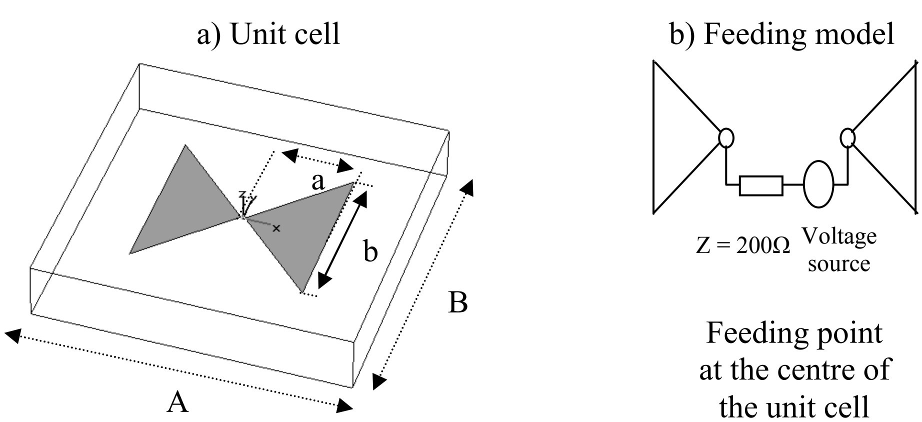

Fig. 1: Simulated unit cell of the regular array. a) Unit cell. The element type is a PEC made Bow-Tie element placed 166 mm on top of a ground plane. b) Feeding model.

Table 1: Unit cell dimensions for the parameter sweep				
	A	*B*	*a*	*b*
Variation of *d*	1m to 2.140m	1m to 2.140m	42.5cm	41.5cm
Variation of element size	1.5m	1.5m	31cm to 710cm	30cm to 70cm

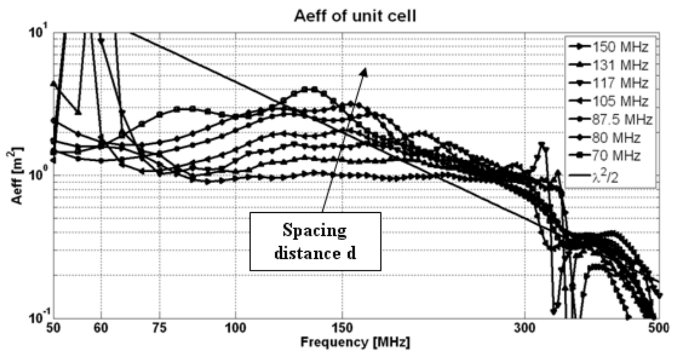

Fig. 2: Simulated unit cell effective aperture for an infinite regular array. The different curves are for different spacing distances between elements. In the legend is the frequency of the half wavelength spacing *d*. Also the $\lambda^2/2$ curve is plotted.

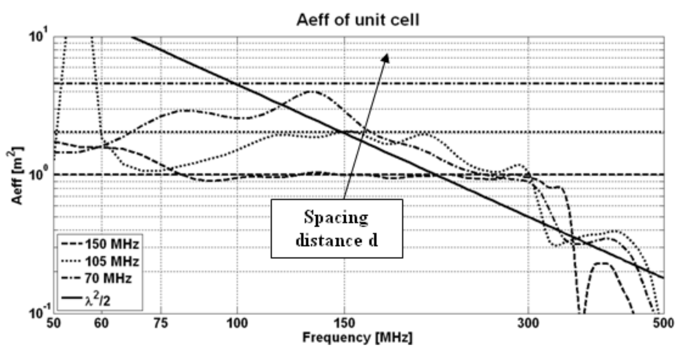

Fig. 3: Simulated unit cell effective aperture for an infinite regular array. The different curves are for different spacing distances between elements. In the legend is the frequency of the half wavelength spacing *d*. Also the $\lambda^2/2$ curve is plotted together with the physical areas for each spacing *d*.

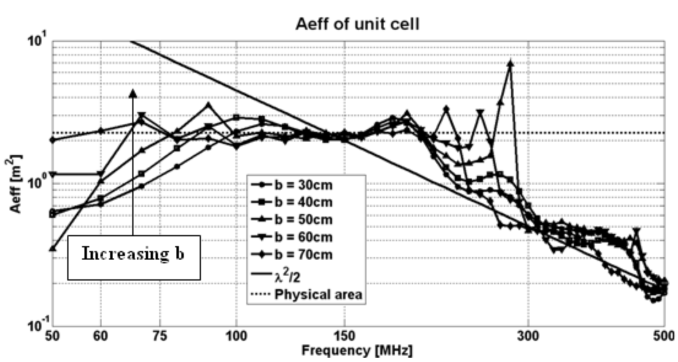

Fig. 4: Simulated unit cell effective aperture for an infinite regular array. The different curves are for different elements sizes. In the legend is the value of *b*. Also the $\lambda^2/2$ curve is plotted together with the physical area of the unit cell.