Analysis of the EMBRACE aperture array antenna by the characteristic Basis Function Method

Analysis of the EMBRACE Aperture Array Antenna by the Characteristic Basis Function Method

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Abstract — **This paper describes the use of the Characteristic Basis Function Method for the simulation of large phased array antennas for radio astronomy. It will be shown how the antenna effective area and the receiver noise temperature depend on array size. Also the receiving sensitivity A_{eff}/T_{sys} normalised with respect to the physical area of the array will be shown for different array sizes and scan angles.**

1 INTRODUCTION

In this paper we will describe the use of the Characteristic Basis Function Method (CBFM) for the analysis of a phased array antenna system known as EMBRACE (Electronic Multi-Beam Radio Astronomy ConcEpt) [1]. EMBRACE is a demonstrator of a receive only aperture array for a future generation radio telescope: the Square Kilometre Array (SKA). EMBRACE consists of two stations with a total collecting area of 300 m^2 in L-band. The purpose of the study described here is to investigate the sensitivity performance resulting from the use of non-contiguous tiles. Tiles with gaps between them could provide practical benefits and may be used for the next demonstrator: the Aperture Array Verification System (AAVS).

2 DESCRIPTION OF A SINGLE ANTENNA ELEMENT

Each EMBRACE station consists of separate subarray modules called tiles. Each tile consists of 144 elements (72 for each polarisation) and has a physical area of 1.125 m^2. All antenna elements are connected to each other. The border elements of each tile are connected to the corresponding elements of the neighbouring tile. Fig. 1 shows a part of the elements in one tile. Vivaldi elements are used as antenna elements (see Fig. 2). The elements are fed by a micro strip line. The PCB on the left contains the microstrip to slot line transition. We will refer to this PCB as the feed board.

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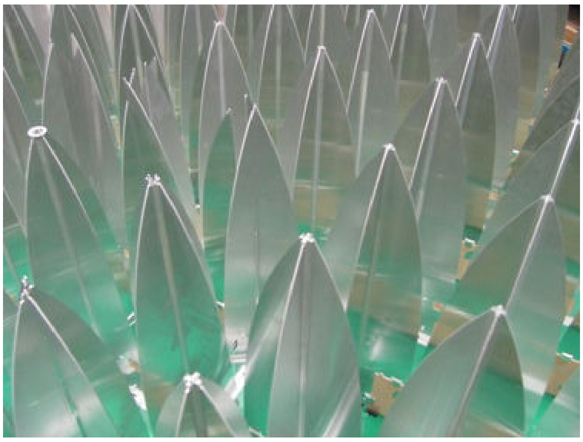

Figure 1: Part of a single antenna tile.

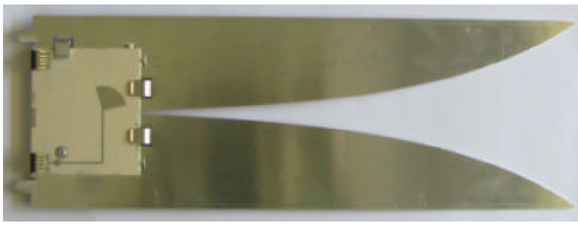

Figure 2: Single Vivaldi antenna element used in EMBRACE.

3 MODELLING

A combined circuit and electromagnetic approach is used to model the aperture array antenna.

The electromagnetic model of the antenna array is obtained through the Characteristic Basis Function Method [2]. The basic principle of CBFM is to subdivide the large antenna array into smaller subarrays. Sub-domain basis functions are employed to model the currents on these sub-arrays. The solutions for the currents on these sub-arrays are then used as a relatively small set of entire domain basis functions – also called Characteristic Basis Functions (CBFs) – to solve for the currents on the entire array. Since CBFs are constructed from sub-domain basis functions, the resulting method of moment (MoM) matrix will be reduced in size as compared to that of a direct MoM approach. This saves a significant amount of memory, which enables us to solve large antenna array problems.

The feed boards of the antenna elements are modelled through quasi-static field models, i.e., through transmission line models [3]. The coupling between the microstrip line and the slotline of each antenna element is modelled by a transformer. The parameters of this transformer are are determined empirically, but only once for a single antenna element.

The transmission-line model and the S-matrix of the array, as calculated by the CBF method, are combined using linear connection matrix theory [4].

4 VERIFICATION OF A SINGLE TILE

To verify the above-described combination of electrodynamic and quasi-static field models with measurements, the scattering parameters of a single EMBRACE-tile were simulated and measured. The simulated and measured S-parameters are then used to calculate the active reflection coefficient. Fig. 3 shows the active reflection coefficient of the centre element for broadside scan (only one polarisation is used). One can see that there is a fairly

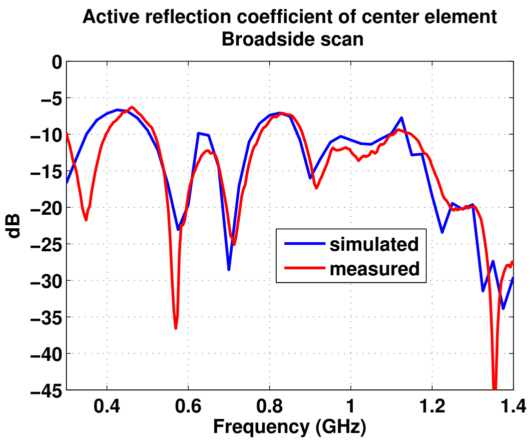

Figure 3: Calculated and simulated active reflection coefficient of a single EMBRACE tile (magnitude).

good correspondence between the active impedance calculated using the measured and simulated S-parameters. The phase of the active reflection coefficient is shown in Fig. 4.

5 EFFECT OF TILE SIZE ON RECEIVER NOISE TEMPERATURE AND EFFECTIVE AREA

The advantage of a large phased array over a small one is that the impedance and radiation characteristics of the antenna elements in a large array behave more uniformly, because the array approximates an infinite array. In this section we will show

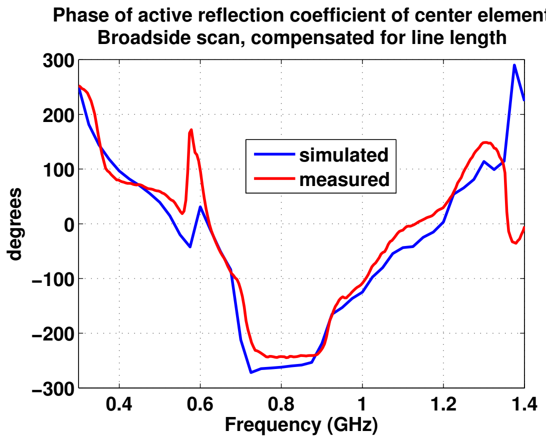

Figure 4: Calculated and simulated active reflection coefficient of a single EMBRACE tile (phase).

the receiver noise temperature and effective area as a function of the array size. As antenna elements we use the Vivaldi elements of the EMBRACE-tile.

In this paper, we refer to the effective area and receiver noise temperature at a reference plane in front of the antenna. These quantities can be found by dividing the corresponding quantities at a reference plane at the output (after the beam former) by a system gain. This system gain is determined by a simulation of the output noise temperature for the situation when all noise sources except the sky noise are turned off. The sky noise temperature is set to 1 K for all directions. The resulting output noise temperature is the system gain. By defining the system gain in this way the effect of losses and mismatch is included in this system gain. This means that the effective area for a large array approximates the value $A_{\mathrm{ph}} \cos\theta$, with A_{ph} the physical area of a unit cell and θ the angle of observation with respect to broadside.

The receiver system used in this section consists of the array elements, the feed boards, low noise amplifiers (LNAs), ideal phase shifters and an ideal power combiner. The LNAs have S-parameters $S_{11} = S_{22} = S_{12} = 0$, $S_{21} = 1$ in a 50 Ω-system. The noise parameters are T_{min}=30 K, r_{n}=0.05 and Γ_{opt}=0. Only one polarisation of the array is used. The other polarisation does not have feed boards.

Fig. 5 shows the receiver noise temperature for different array sizes if the array is scanned to broadside. The number of elements refers to the actual number of elements used, thus for one polarisation only. The receiver noise temperature does not change significantly if the array has 32 or more elements. Fig. 6 shows the receiver noise temperature if the array is scanned 60° in the H-plane. For frequencies below 0.4 GHz the receiver noise tempera-

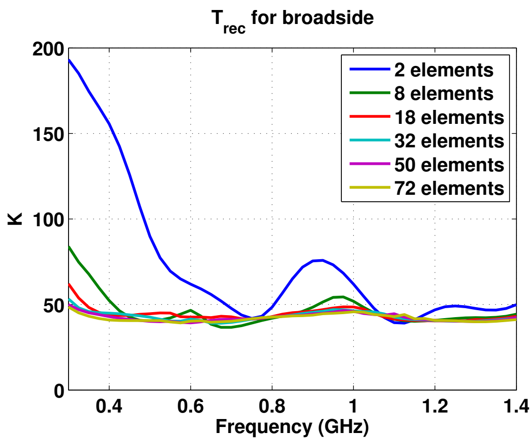

Figure 5: Receiver noise temperature for broadside scan for different array sizes.

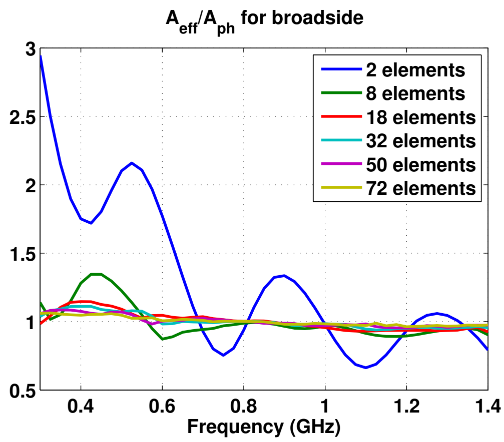

Figure 7: Normalised effective area for broadside for different array sizes.

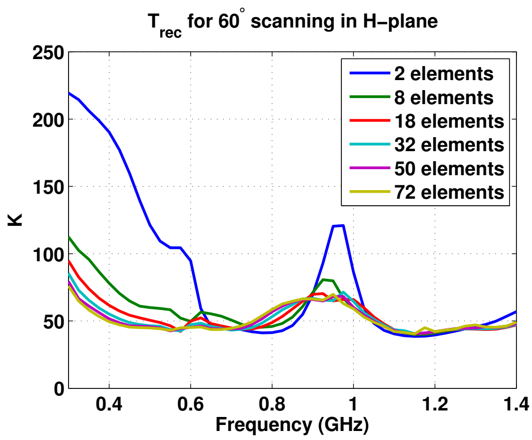

Figure 6: Receiver noise temperature for 60° H-plane scan for different array sizes.

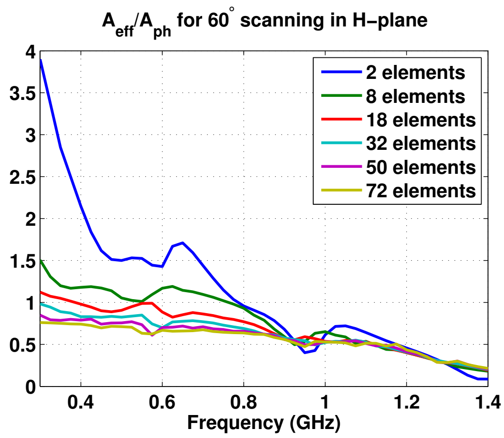

Figure 8: Normalised effective area for 60° for different array sizes.

ture is higher than for the case the array is scanned to broadside. The normalised (with respect to the physical area of a unit cell) effective area as a function of frequency for different tile sizes is shown in Fig. 7. For tiles larger than 18 elements, the normalised effective area approaches unity, which is the expected theoretical value for an infinitely large array. Fig. 8 shows the results for an array scanned 60° in the H-plane. For an array of 72 elements, the variation around the theoretical value for an infinitely large array (0.5) is larger than that of an array of the same size scanned to broadside.

To show the normalised (with respect to physical area) $A_{\rm eff}/T_{\rm rec}$-ratio as a function of frequency and scan angle, we can plot the x% percentile as a function of frequency. For the calculation of the x% percentile at a given frequency we consider the normalised $A_{\rm eff}/T_{\rm rec}$-ratio for all scan angles (within a grid) less than 60° with respect to broadside. An x% percentile of y means that the normalised $A_{\rm eff}/T_{\rm rec}$-ratio for x% of the considered scan angles is less than y. Fig. 9 shows the 50% percentile of the normalised $A_{\rm eff}/T_{\rm rec}$-ratio for scan angles less than 60°. One can see that for the 50%-percentile case, convergence is achieved around 50 elements, since the 72-element case is almost identical.

6 EFFECTIVE AREA AS A FUNCTION OF SCAN ANGLE

In this section the behaviour of the effective area as a function of scan angle will be investigated in more detail. Fig. 10 shows the normalised effective area as a function of scan angle in the E-plane at different frequencies for a two-element array. At low frequencies the effective area is higher than the physical area. This can be explained by the fact that for a small array the physical area is not well defined. For the physical area we use the area of a

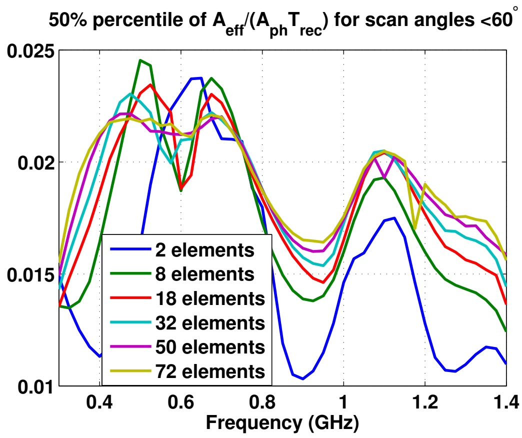

Figure 9: 50% percentile of the normalised effective area for scan angles up to 60° for different array sizes.

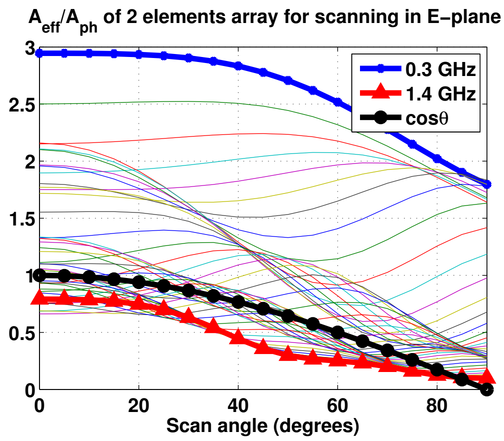

Figure 10: Normalised effective area in the E-plane as a function of scan angle at different frequencies for a two-element array.

unit cell in an infinite array. For higher frequencies, the effective area is less than the theoretical value of an infinite array (the black line). Fig. 11 shows the same for a 72 element array. For this array the effective area is much closer to the theoretical value for an infinite array. At higher frequencies the effective area ($\propto \cos(\theta)$) decreases further due to the onset of grating lobes.

7 CONCLUSIONS

The applicability of the Characteristic Basis Function Method (CBFM) for the analysis of large phased arrays is shown. For a 72 element phased array there is a good correspondence between the measured and calculated centre element active reflection coefficient. By combining electromagnetic and microwave circuit models, the receiver noise

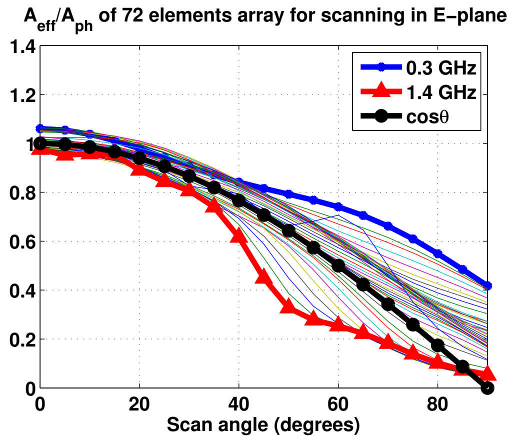

Figure 11: Normalised effective area in the E-plane as a function of scan angle at different frequencies for a 72 element array.

temperature and effective area for arrays of different sizes have been calculated. For large arrays, these values tend to converge to a constant value, as expected. The results can be used to determine the minimal required array size of an antenna tile.

Acknowledgements

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