TRUNCATION EFFECTS IN TAPERED-SLOT ANTENNA ARRAYS FOR RADIO ASTRONOMY APPLICATIONS

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ABSTRACT

Arrays of tapered-slot antennas form a promising technology for future large-scale radio telescopes, because of their very large bandwidth. Due to the three-dimensional structure of the array, the couplings between elements are extremely strong, and the elements near the edges of elementary arrays may present a strongly deviating behavior. We analyze these effects with the help of a finite-by-infinite array approach, and we discuss the consequences of array truncation with regard to the specific requirements associated with high-sensitivity imaging arrays.

INTRODUCTION

The Square Kilometer Array (SKA) is a very large radio telescope being planned by an international consortium [1]. It would operate in a very broad frequency band and have a sensitivity two orders of magnitude larger than the one provided by present-day radio telescopes. The Netherlands Foundation for Research in Astronomy (ASTRON) is studying the possibility of covering the mid-range frequencies (0.2 to 2.0 GHz) with an instrument based on the phased array technology.

At the frequencies of interest, it is expected that the galactic noise will be significantly smaller than the instrumental noise. In order to reduce the latter, it is important to achieve a good matching between the antennas and the LNA's. This requires antenna elements with a very constant input impedance over a very wide frequency band. Arrays of tapered-slot antennas potentially provide such capabilities. These are analyzed and optimized with the help of an infinite-array model, which automatically includes all the effects of mutual coupling. In order to verify the capabilities of these antennas, demonstrators are built at ASTRON. The third demonstrator is the Thousand Elements Array (THEA) [2]. It consists of sixteen 8-by-8 single-polarized arrays operating in the 500 to 1500 MHz frequency band. At the level of a single tile, beamforming is executed in the RF domain, with the help of vector modulators and signal combiners.

As the array is not very large in terms of wavelengths, and given that the couplings between elements are extremely strong, elements near the edge may have a very different behavior, compared to elements in the middle of the array. In order to study systematically the effects of array truncation in one direction at a time, we developed a finite-by-infinite array simulation tool. This allows us to study the effects of truncation in terms of current distributions on the antennas, antenna matching, and element patterns. This is done with the help of a simplified model of the antenna element, made of a metallic plate, fed by a delta-gap source.

This paper is organized as follows. First, we present infinite-array simulation results, which illustrate the bandwidth achievable for this type of antennas. Then, we show the strong couplings and variability in current distributions in an array infinite in one direction only. We also illustrate edge effects in terms of input impedances and element patterns. Finally, truncation effects are discussed, with regard to the high-sensitivity imaging purposes of phased arrays for radio astronomy applications.

INFINITE-ARRAY SIMULATIONS

The reference configuration chosen here corresponds to the THEA array geometry, shown in Figure 1. The array is single-polarized, and the elements are electrically connected to each other in the direction of polarization. This avoids strong resonance associated with the reflection of currents at the end of the antenna. As a result, for operation in a given frequency range, tapered-slot antennas in arrays may be shorter than isolated antennas

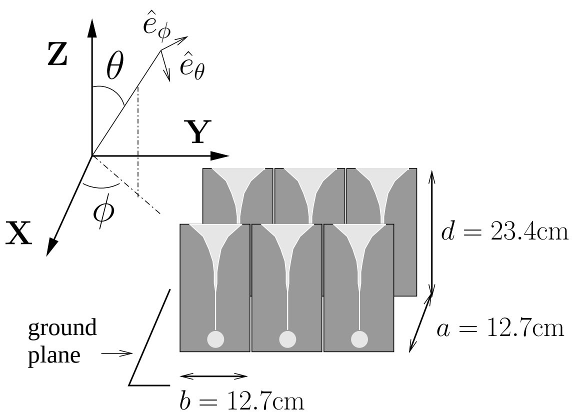

Figure 1: Geometrical configuration of the THEA array.

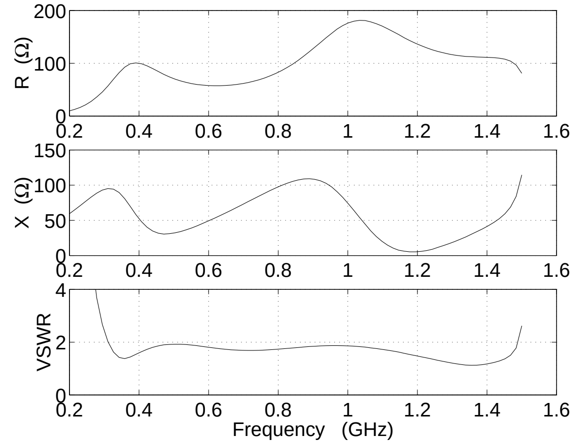

Figure 2: Infinite-array active input impedances, and standig wave ratio w.r.t. 100 Ω, after introduction of a 4 pF capacitance.

of the same type. Of course, the strong couplings created in this way need to be taken into account to realize a good matching for the antennas.

Infinite-array simulations include all the effects of mutual couplings [3]. They are performed with the help of the infinite-array Green's function [4], which is computed in free-space and tabulated over one periodic cell. The elements of the array were assumed to be made of metallic plates, fed by a delta-gap source. The antennas are modelled with 265 triangular roof-top basis functions, including basis functions connecting the antennas with each other, and with the infinite ground plane.

The active input impedances, corresponding to all elements fed in phase, are shown in Figure 2. The inductive behavior of the circular slot cavity is compensated by the introduction of a 4 pF series capacitance. The resulting standing wave ratio, computed with respect to a 100Ω impedance, is shown in the bottom of Fig. 2, where we see that a 5:1 bandwidth can be achieved. More recent designs exhibit a 7:1 bandwidth, with respect to a 50 Ω impedance [5].

CURRENT DISTRIBUTIONS IN FINITE ARRAYS

Research on array truncation has been presented by many authors in the several last decades [3]. These techniques essentially aim at a simple correction for edge elements, with respect to the infinite-array solution. However, these methods are generally based on strong assumptions regarding the type of elements used in the array. In general, they should correspond to minimum-scattering antennas, or support current distributions which vary very slowly over the array. This is not the case for the array under study, especially at the lowest end of the operational frequency band.

Hence, it was decided to study the effects of truncation in the principal directions of the array, by developing a simulation code for finite-by-infinite arrays [4]. The simulation code is based on the MoM method, where the Green's function used corresponds to infinite linear arrays of dipoles. The example shown in Fig. 3 corresponds to arrays infinite in the $\hat{x}$ direction, while the antenna plates are finite in the $\hat{y}$ direction. Only the first antenna on the left side is fed at 750 Mhz, with a unit voltage source having a 100 Ω series impedance. It is clearly visible that the currents can flow from one element to the next. Striking is also the current flowing on the edge of the array. This current can lead to a strong distortion of the element patterns of the first and last antennas.

FINITE-ARRAY EFFECTS ON RECEIVE

For infinite-array situations, the active reflection coefficient, defined for transmitting conditions, also describes the efficiency with which power will be absorbed by the antenna in receiving conditions. For finite arrays, strong

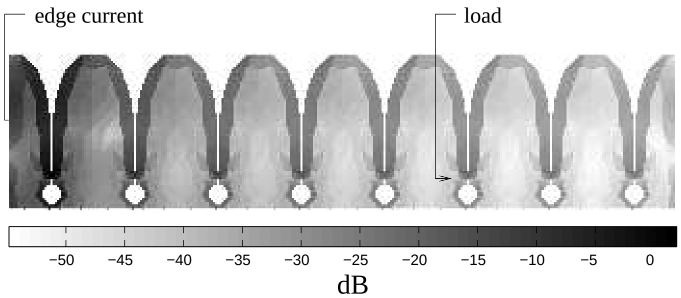

Figure 3: Magnitude of current distribution on the array infinite along $\hat{x}$, at 1 GHz, when the first element only is excited.

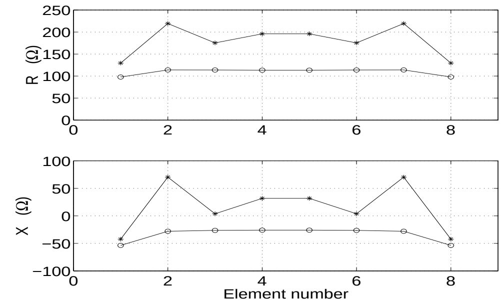

Figure 4: Active ($\star$) and passive ($\circ$) input impedances for an array having 8 elements along $\hat{y}$, scanned at broadside, at 1 GHz.

variations appear in the active reflection coefficient. The active input impedance is represented by stars in Fig. 4, for an array which is finite in the direction orthogonal to the antenna plates. This variation is generally much larger than the variation in the matching of individual antennas ("passive" impedance), when the other elements of the array are terminated by the receiver impedance (circles).

As will be explained below, the active reflection coefficient has some importance in the determination of the effect of noise generated by the amplifier. However, it does not give a complete description of the effects of truncation in receiving conditions. Indeed, the element pattern is described by the active reflection coefficient in infinite array situations only (this can be proven under the assumption of exactly periodic current distributions). A more adequate way of computing edge effects on receive is to explicitly assume an incoming plane wave, and to compute the voltages impressed across the loads of successive antennas. This is the technique used here. An obvious alternative is to compute the pattern of an element in transmitting situation, assuming that the other elements are terminated. However, for a large number of elements, this turns out to be computationally more expensive.

Element patterns are shown in Fig. 5 for an array infinite along $\hat{x}$ at 750 MHz and horizontal polarization. The differences between element patterns can be as large as 5 dB. Fig. 6 show results obtained with the array infinite along $\hat{y}$.

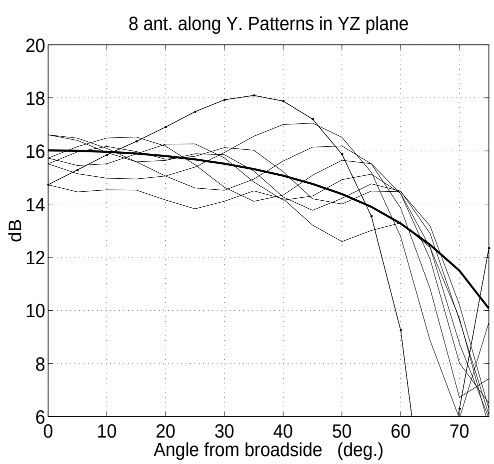

Figure 5: Element patterns for 8 antennas along $\hat{y}$, and an infinity along $\hat{x}$, at 750 MHz.

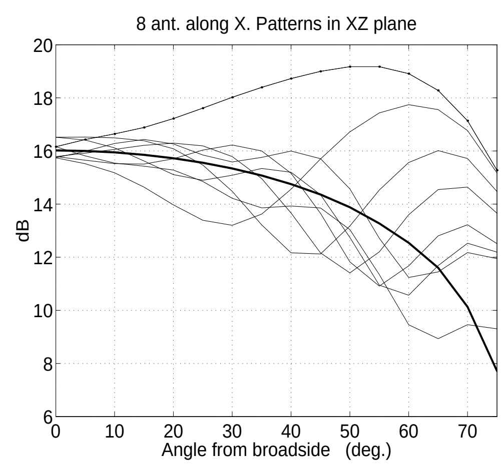

Figure 6: Element patterns for 8 antennas along $\hat{x}$, and an infinity along $\hat{y}$, at 750 MHz.

DISCUSSION

The deviations of the element patterns with respect to the infinite-array solution can be reduced by adding passive ("dummy") elements on each side of the array. However, the examples shown above indicate that a large number of such elements may be necessary before the differences between the patterns are made negligible. Another approach consists of using beamforming algorithms that can cope with different element patterns, which would be known a priori or would be estimated with the help of specific calibration procedures. In this case, the available signal is exploited in a more efficient way. Concerning the effective area of the arrays, we should stress that, in the examples tested so far, no strong reduction of effective area seems to result from the edge effects: the voltage impressed on edge elements can be either larger or smaller than in the infinite-array solution.

High sensitivity also requires low-noise operation. For the frequency band of interest for SKA, the sky noise is negligible compared to the instrumental noise, which is essentially generated by the first amplifier. Low noise operation of these amplifiers requires a specific value for the antenna impedance. In this case, this impedance is the passive input impedance, i.e. the impedance seen at the input of a given antenna, when the other elements of the array are terminated by the input impedance of the amplifiers. It is interesting to realize that this impedance generally suffers much less from edge effects than the active input impedance. However, the latter parameter is also of importance for the noise budget of the array. Indeed, the noise generated by the amplifiers and transmitted towards the antennas couples back via the other elements of the array. It has been shown [6] that this phenomenon can be described by the active reflection coefficient of the array. As the latter parameter can present strong deviations from the infinite-array solution, edge elements can have an important contribution to the total noise obtained at the output of the (RF of digital) beamformer.

CONCLUSION

Edge effects in tapered-slot antenna arrays can be very strong. In terms of signal, they do not necessarily lead to a reduction of the effective area, but they do lead to strong differences between the element patterns. Hence, it may be good to use beamforming algorithms than can cope to a certain extent with varying element patterns. The effects of array truncation on the passive antenna impedance (the other elements of the array are terminated) are not as strong, which means that, if a good noise figure is achieved for the amplifiers inside the array, it will be worse only for a few elements near the edge. The variations of the active impedance are generally stronger and are visible further inside the array. This can influence the reflection of noise via neighboring antennas. Further characterization of the noise generated by the amplifiers is necessary to assess the importance of the latter effect.

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