Modeling the RF Performance of a Small Array

(Invited Paper)

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ABSTRACT - Large phased arrays can be reasonably accurately modelled in finite element programs, such as HFSS using an infinite array model of the embedded element. This approximation is not applicable to small arrays, where each element is in a different electromagnetic environment. Very small arrays of simple elements (of about 10 elements or less) can be modelled as a complete unit, but slightly larger or more complex arrays require additional techniques to be modelled accurately. The predicted performance of several versions of a small array has been compared using HFSS V9.5. The arrays contained either waveguide or printed dipole elements and, within the limits of available computing resources, solutions were generated for (1) complete array models, (2) half and quarter array models with symmetry planes, and (3) infinite array models.

I. INTRODUCTION

A Finite Element program, High Frequency Structure Simulator, HFSS, [1], has been used to compute the performance of an array of 23 elements (Figure 1) over a 5% bandwidth at 10 GHz. The array lattice geometry was determined from the requirements to scan +/- 35 degrees in the Y-direction and +/-15 degrees in the X-direction. These requirements for a small field of view led to the elements being spaced by approximately 1 wavelength at 10 GHz in the X-direction and 0.5 wavelength in the Y-direction.

The objective of the work was to compare the RF performance of two different kinds of antenna elements when used in this small array. The first element was a printed double dipole which had already been developed [2], [3] and the second element was a very simple waveguide element. The major objective of this work was to see if more gain could be obtained from an array of waveguide elements rather than an array of the printed elements.

Since problems might be encountered in the accurate determination of the behaviour of such an array with only 23 elements, the computation of the array behaviour was approached in 3 ways. Firstly the single element was treated as though embedded in an infinite array and the single element performance used to model the array through the use of the array factor. Secondly one quarter of the complete array was modelled using symmetry. Thirdly the array was modelled as a complete unit. The advantages and disadvantages of these methods are discussed as applied to two different radiating elements.

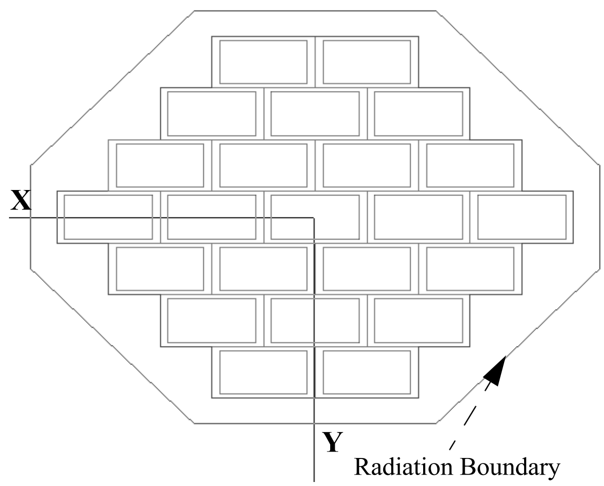

Figure 1. HFSS Geometry of array model showing the outer radiation boundary. The Z-axis is out of the plane of the paper. An Azimuth cut is in the XZ plane and an Elevation cut in the YZ plane.

II. ELEMENTS

Two elements were used. The first was a rectangular waveguide element fitted into the dimensions of the required array lattice (Figure 1). This was compared with a previously designed printed element [2], [3] formed of 2 half-wavelength dipoles plus a T-junction to make a double dipole element [4].

III. WAVEGUIDE ELEMENT

Although a waveguide element with a small aperture of 1 by 0.5 wavelengths is simple to design, there was a requirement for low coupling values. The maximum dimensions available for an element are 1 by 0.5 wavelengths at 10 GHz. A rectangular waveguide was fitted into this area and its dimensions adjusted to get the lowest inter-element coupling between adjacent elements. The Finite Element Analysis, FEA, model for a single element (Figure 2) included the necessary radiation box and converged with 7,400 tetrahedra. The array was modelled in several ways which are described in the next section.

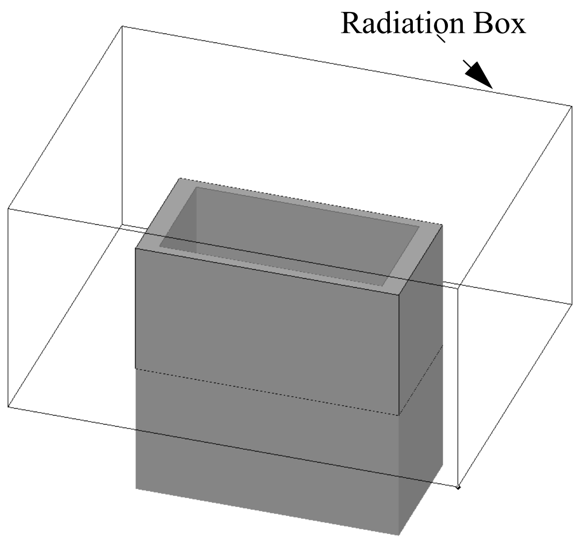

Figure 2. FEA model of final waveguide element in free space showing the surrounding radiation box. The outer dimensions of the element are 1 by 0.5 wavelength at 10 GHz.

A. Rectangular Infinite Array

The complete array of waveguide elements was modelled using the FEA program's inbuilt infinite array facility. Using this facility, a single array element can be modelled which has a boundary box of the same dimensions as the single element in the Z-direction but is cut to lie along the boundaries between adjacent array elements in the X and Y-directions (Figure 3). The array grid is therefore rectangular. The scan angle can be included in the computation. The array factor corresponding to Figure 1 was then applied. The problems with this approach are that:

- the use of an infinite array method for such a small array must be subject to errors,
- the element was modelled with opposing faces as pairs. This is immediately applicable to a rectangular array but is of doubtful validity for a triangular array.

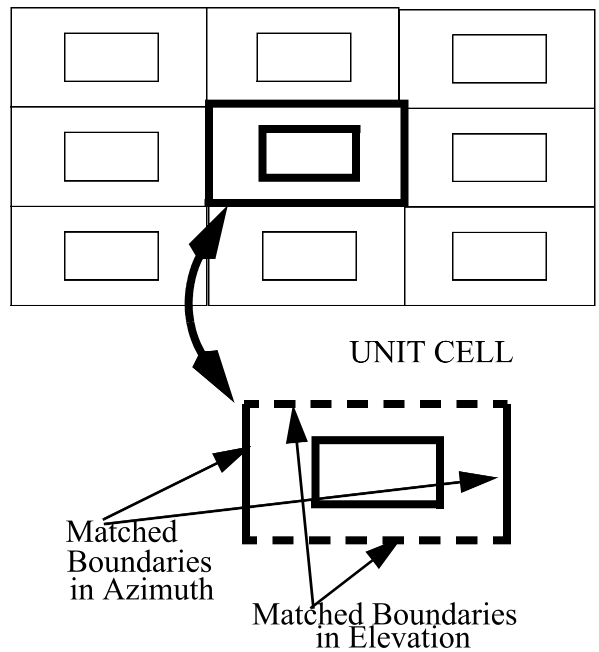

Figure 3. Geometry of infinite array, showing unit cell with matching boundaries to model an infinite array on a rectangular grid.

B. Triangular Infinite Array

The same waveguide element geometry was used as for the infinite rectangular array but the unit walls were set out differently so that the model tessellates exactly into a triangular array (Figure 4 and Figure 5). The array factor corresponding to Figure 1 was then applied.

C. Complete Array

Since the array element is very small in terms of wavelengths and is also simple in geometry, the array geometry was modelled exactly as shown in Figure 1 This avoided the necessity of including any definitions of the arrays. In addition to modelling the complete array, the array was modelled as a half array with E-plane symmetry and as a quarter array (Figure 6) with both E and H-plane symmetry since E and H-plane symmetry boundaries can be exploited within HFSS [1] to reduce the size of the problem. All three of these models gave the same radiation patterns and S-parameters.

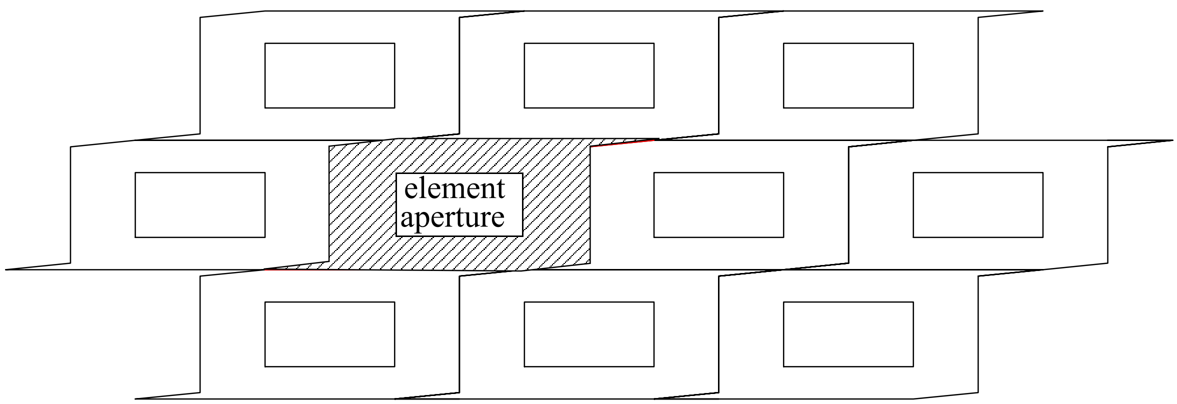

Figure 4. Geometry of triangular array, showing unit cell as hatched.

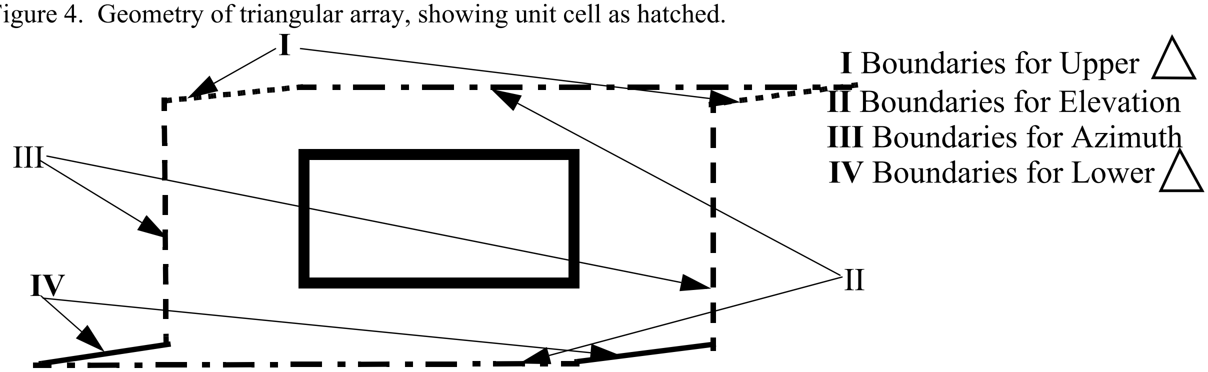

Figure 5. Unit Cell for triangular geometry of an infinite array (see Figure 4) showing matching boundaries.

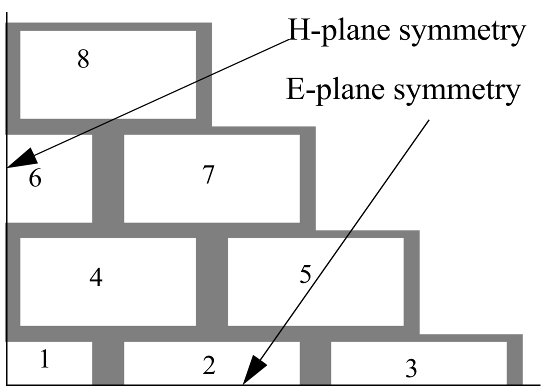

Figure 6. Geometry of one quarter of the complete array showing the use of both E and H-plane symmetry to reduce the model size by a factor of 4.

D. Comparison

The radiation pattern of an isolated waveguide element is shown in Figure 7 and for an embedded element using Methods 2 and 3 above. There is a difference in the backlobe which is greater by 15 dB in the isolated element. This is as expected because the isolated element will have currents running on the waveguide exterior which will contribute to the backlobe whereas the embedded element in Method 2 will have no currents on the exterior. Currents will run only on the array periphery in Method 3.

The crosspolar levels are a maximum in the diagonal plane, that is, Phi = 45.0 degrees. The peak crosspolar levels for these models (Figure 8) are high for the free space element and in the quarter array (-15.6 dB and -13 dB respectively) while that for the triangular infinite array is much lower at -24 dB. The radiation patterns of the complete array computed with different models are slightly different (Figure 9 and Figure 10). The differences in peak gain are less than 0.2 dB. The greatest difference is in the crosspolar levels which rise to -30 dB for the complete array but are less than -40 dB for the infinite array models.

The solution time and the number of tetrahedra used (and therefore computing memory required) for all the above models is shown in Table 1. The efficiency of the infinite array approximations is clearly shown. Use of symmetry gave a large improvement in runtime for the complete array model although extra time is required by HFSS to deal with the symmetry plane. The time quoted is that for convergence at 10 GHz and computation at 20 frequencies between 9 GHz and 11 GHz.

Table 1. Summary of HFSS Performance - Waveguide Element.

Array Model	No of Tetrahedra	Time (minutes)	Peak Gain	Azimuth 1st Sidelobe (dB)	Elevation 1st Sidelobe (dB)	Diagonal 1st Sidelobe (dB)
Infinite Array Method 1	3,046	8	21.52	-23.6	-23.4	-16.0
Infinite Array Method 2	2,750	8	21.33	-24.2	-23.6	-16.6
Complete Array	75,246	60	21.54	-24.5	-22.4	-15.9
Half Array	75,508	94	21.54	-24.5	-22.4	-15.9
Quarter Array	38,042	44	21.56	-24.5	-22.4	-15.9
Free Space Element	7,400	6	NR	NR	NR	NR

The number of tetrahedra and the runtime for the whole array and a half array using symmetry are very similar. The same criterion for convergence was used in all cases and this must be due to the size of the step used in moving from one mesh geometry, 62,923 tetrahedra, where convergence had not quite been achieved, to the next, 75,508 tetrahedra, where convergence was achieved.

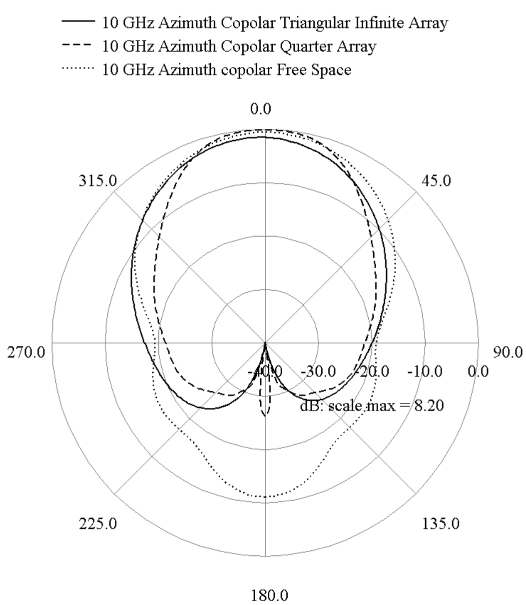

Figure 7. Comparison of Azimuth radiation patterns of a single waveguide element.

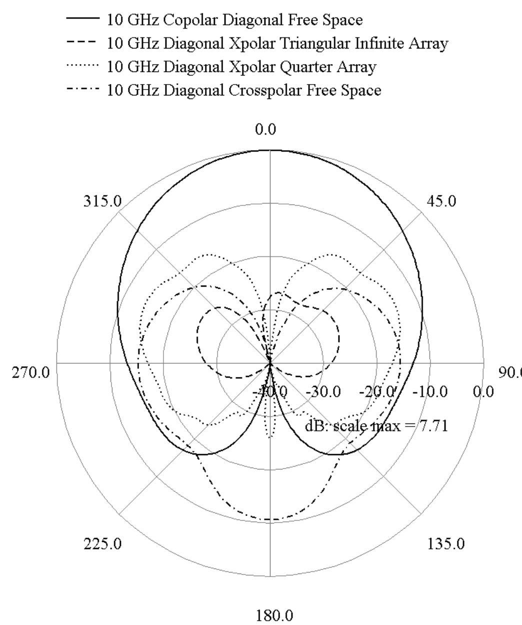

Figure 8. Comparison of diagonal (Phi= 45 degrees) crosspolar radiation patterns of a single waveguide element.

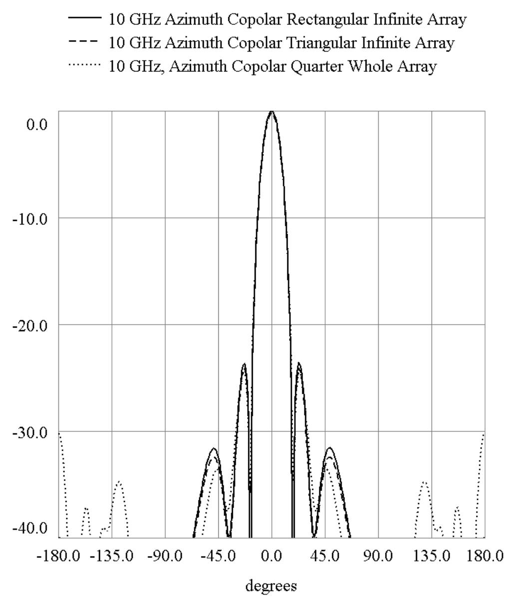

Figure 9. Comparison of array Azimuth copolar patterns with waveguide element. Gain normalised to 21.61 dBi.

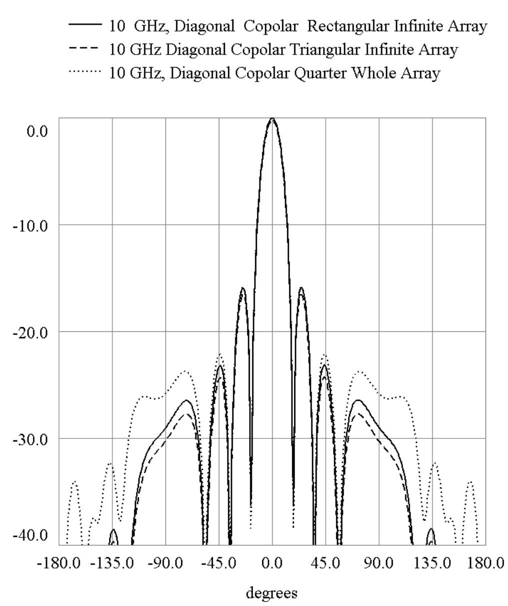

Figure 10. Comparison of array diagonal copolar patterns with waveguide element. Gain normalised to 21.56 dBi.

E. Scattering Parameters

Figure 11 shows that the Return Loss of an element in the two infinite arrays is very similar while that of the central element in the complete array is 4 dB higher and that of the single element is yet higher by 1 dB. This has important implications for the design procedure. To interface with the following electronics, the waveguide element must be terminated in a coaxial transition. An element with an integrated coaxial transition which had been optimised for a single element in free space would no longer be optimised when used in an array. Optimisation of the match in an infinite array will not be satisfactory for the array of 23 elements. Since a coaxial transition will increase the number of tetrahedra in the model, use of a half or quarter array would be beneficial but the transition must have symmetry for this to be possible. Given the close packing of the array, an end-launched transition will be needed and this can be made symmetrical.

The coupling between adjacent elements has been computed by placing 3 elements side by side in the X-direction or the Y-direction. The use of an infinite array (Array Methods 1 and 2) does not provide any coupling results. The use of a complete array does provide such information and this is plotted with the results from a three-element subarray in Figure 12 There is good agreement between the coupling values in the X-direction. In the Y-direction, the results for the row of elements are for 2 elements offset in the Y-direction only and are around -15 dB while the results for the complete array refer to 2 elements which are offset in the X-direction as well as the Y-direction. This triangular lattice improves the coupling by 7 dB so that the coupling between elements is better than -20 dB in the complete array.

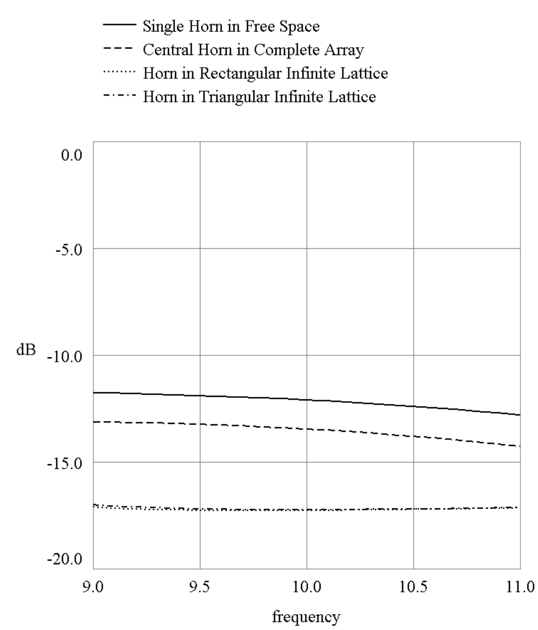

Figure 11. Comparison of predicted Return Loss for waveguide element.

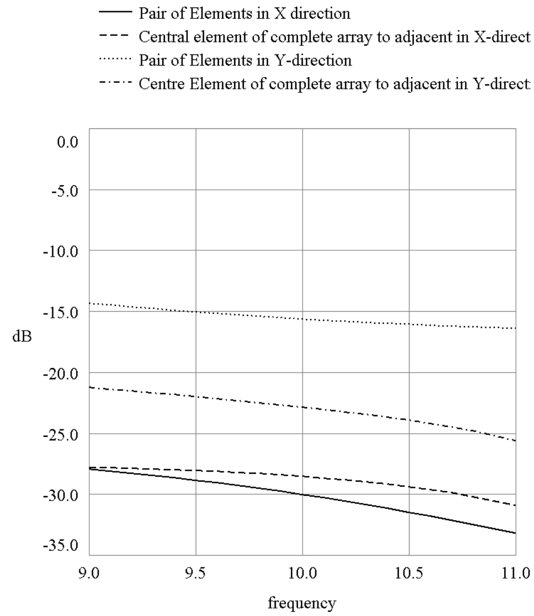

Figure 12. Coupling between adjacent waveguide elements.

IV. PRINTED ELEMENT

The second element that was investigated was a previously designed printed element [2], [3] formed of 2 half-wavelength dipoles plus a T-junction to make a double dipole element [4]. The FEA model of the element is shown in Figure 14 The meshing took 25,000 tetrahedra for a single element, compared to 7,400 for the waveguide element.

Modelling the array can be carried out using the infinite array techniques applied to the waveguide element and 24,910 tetrahedra were required for the model. A complete array of 23 elements would require about 575,000 tetrahedra. HFSS V9.5 is restricted on a Microsoft WINDOWS NT machine to a memory size of about 1.5 GBytes which can accommodate a maximum of about 125,000 tetrahedra. Therefore a complete array cannot be modelled with the available computing software and hardware. It is not possible to use 2 planes of symmetry either because the printed element is not symmetrical and one plane of symmetry (half the array) would still require too many tetrahedra.

When the radiation patterns of the printed element were computed using an infinite array method, they were very similar to the array of waveguide elements (Figure 13).

On the evidence from this work on arrays of waveguide elements with a boresight beam, the final radiation patterns of such a small array will not be very different from those computed for the printed element using an infinite array technique. While the work on the waveguide element showed that the array radiation patterns did not differ much with the modelling method used, the Return Loss did differ. This is also the case with the printed element (Figure 15) where the response in an infinite array is much narrower in bandwidth and shifted down in frequency. The coupling between adjacent printed elements has been modelled in two different configurations (Figure 16 and Figure 17). Compared with the coupling between adjacent waveguide elements (Figure 12) which is 15 dB in the X-direction and 30 dB in the Y-direction, the coupling between adjacent printed elements is poor at 17 dB and 19 dB at 10 GHz. On the basis of these coupling figures, one would expect the Return Loss, when the element is embedded in the array, to be quite different from that in free space.

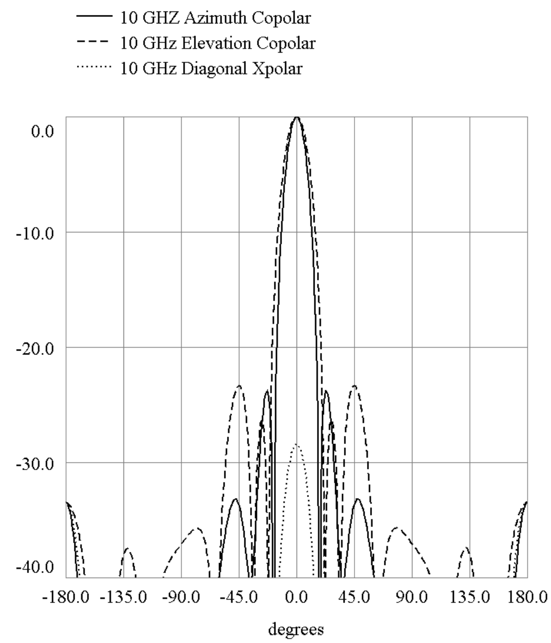

Figure 13. Radiation patterns of a complete array of printed elements - based on an element in an infinite array. Gain normalised to 21.61 dBi.

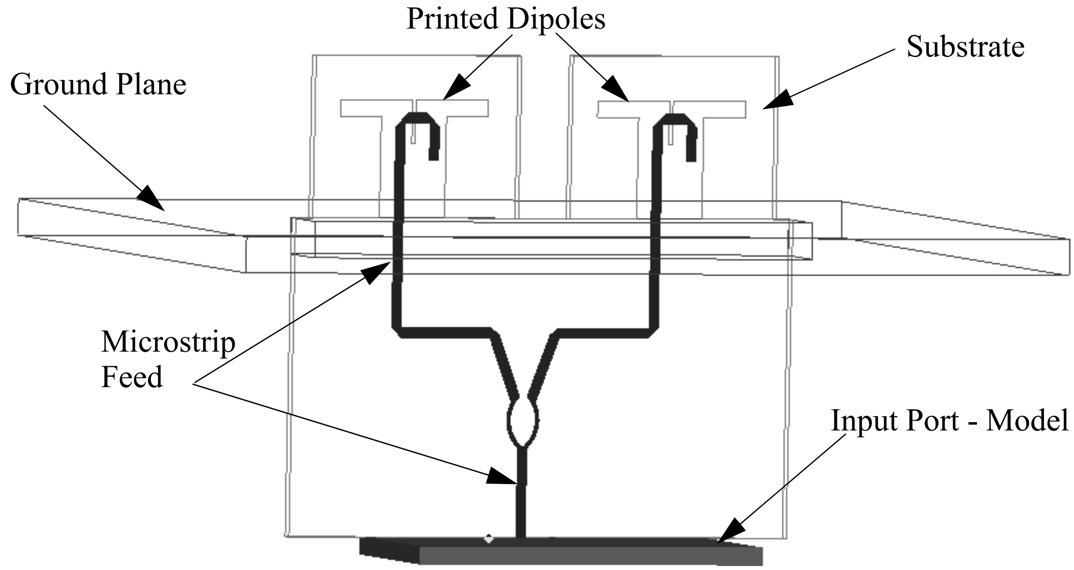

Figure 14. Model of Double Dipole. The centre-line of the dipole arms is 7.9 mm above the ground plane which is 0.263 wavelengths at 10 GHz. Other details may be found in [2].

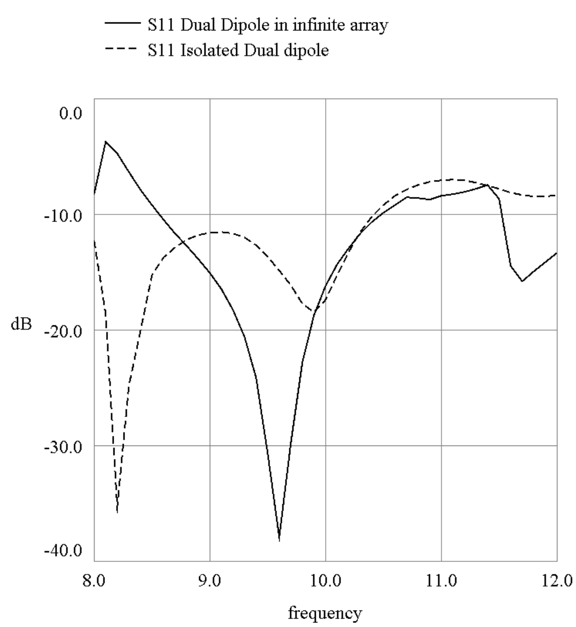

Figure 15. Return Loss for printed element in free space and in an infinite array.

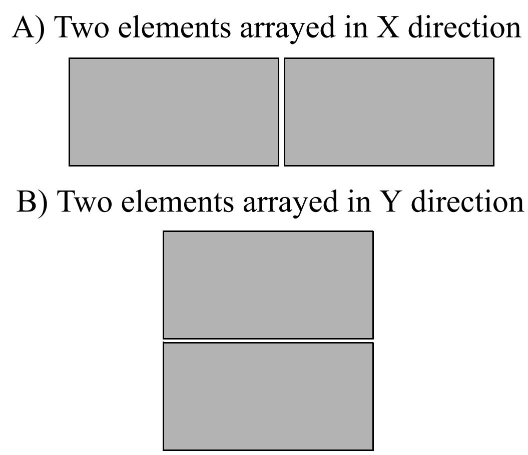

Figure 16. Geometry of two printed elements for coupling computation.

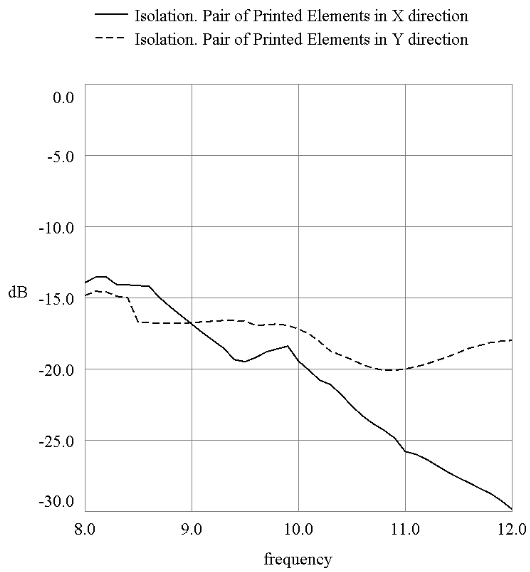

Figure 17. Coupling between two adjacent printed elements.

V. CONCLUSIONS

Two elements, a waveguide element and a printed double dipole, have been considered for use in an array of 23 elements in a triangular lattice. A commercial FEA program, HFSS V9.5, was used in all the computations.

When the waveguide element was modelled in the array using different methods (complete array, two geometries of infinite array), the gain and radiation patterns differed very little. The peak crosspolarisation did differ but values were less than -30 dB in all models. However the Return Loss of a single element varied a great deal according to the array model used. Since it was possible to use a complete array model, the Return Loss could be used to optimise a coaxial transition.

The printed element required far more tetrahedra in the mesh and it was impossible to run a complete array or use symmetry because of memory limitations. The results for the radiation patterns have to be based on the infinite array model but are probably indicative of what could be achieved. The Return Loss in free space and in the infinite array model were very different.

VI. ACKNOWLEDGMENTS

This work has been carried out with the support of the Weapon and Platform Effectors Domain of the UK MOD research programme.

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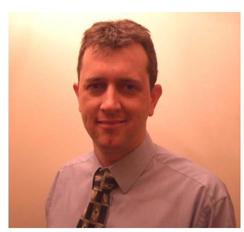

Andrew Wicks BSc MSc CEng MIEE graduated with a BSc in Physics from Exeter University in 1991 and an MSc in Microwave Solid State Physics from Portsmouth University in 1992. He joined QinetiQ, then the UK MoD's Defence Research Agency (DRA), in 1992. Initially designing and testing microwave circuits, his work included the integration of novel microwave heterojunction bipolar transistors in printed circuits. For the last ten years he has been principally involved with airborne active phased array radar programmes, leading activities on microwave transmit/receive module development. This work also included development of antenna elements for phased arrays and the design of antenna arrays. He is currently working on the antenna for Tarsier(r), QinetiQ's 94GHz runway debris monitoring radar.