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Predicting Conformal Aperture Gain from 3D Aperture and Platform Models

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Abstract—Conformal Antenna Arrays are becoming increasingly attractive for aerospace, medical imaging, and 5G communications. While developments in Electro-Magnetic solvers allows accurate conformal array analysis, this study presents a method for predicting the maximum gain pattern for conformal antenna arrays using Standard Triangular/Tessellation Language (STL) models for aperture and obstruction geometry. Using raycasting techniques, the aperture model allows the prediction of the maximum gain pattern in the presence of obstructions. The maximum gain patterns are shown for a conformal antenna array integrated into the curved corner of a building, and a conformal antenna array integrated into the wing leading edge of an aircraft. This technique presents an invaluable tool to assess the viability of a conformal aperture on a structure, while allowing for variation of the structure to assess performance implications for the conformal antenna array. This study shows the increase in maximum beam steering angle of 13 degrees from a purely planar array for the array integrated into a building, and the aeroplane wing leading edge is shown to produce a maximum achievable gain of 41.7dB, which is 1.7dB higher than a conventional nose mounted planar array could be expected to achieve with a greatly increased field of view.

I. INTRODUCTION

Conformal Antenna Arrays, while traditionally employed in the aerospace sector, have hitherto represented a greater risk than planar arrays due to the challenge of predicting the gain of an array, and have been employed when required to meet aerodynamics requirements, rather than for the increased field of scan inherent with conformal antenna arrays. As the global demand for increased mobile communications bandwidth increases, the 5G standard implies a strong need for more base stations with beamsteering capabilities, and there has been some work on integrating antenna arrays within the built up environment [1], reducing planning concerns. Conformal antenna arrays represent an opportunity to further integrate base stations into the built environment.

In the aerospace & defence sector there has been considerable work on the applications of conformal arrays, ranging from a conical nosecone array, which replaces a planar mechanically scanned array [2], to that of a completely spherical array [3]. In all these applications, the conformal aperture gain equation represents a convenient process to predict the maximum far field gain, and with the addition of Standard Triangular/Tessellation Language (STL) files [4], and raycasting techniques [5], allows the extension of this technique in

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the presence of obstructions, such as an aerospace platform, or buildings, in the case of base stations.

This technique can be used as a model based system engineering design tool, allowing Systems Engineers to evaluate the maximum theoretical gain possible for a conformal aperture on a given surface, and the implications of any variations to that surface. This method allows conformal antenna arrays to be considered as a solution for microwave sensor and communications needs without incurring costs of a full design process and complex electro-magnetic simulations.

While there is a great deal of work on the use of ray casting methods, known more commonly as 'shooting and bouncing rays' (SBR) the method is more commonly used for radar cross section (RCS) prediction, [6], [7], [8], and can be very computationally intensive. However, there is some exsisting work on the use of ray tracing to simulate a uniformly illuminated aperture, but the work is based upon the use of coordinate cells conformed to the surface, and thus in inherently limited to planar or singly curved surfaces [9]. The authors do not comment on the computing resources required for their implementation, so no comparison is possible.

II. THEORETICAL MAXIMUM GAIN FOR PLANAR AND CONFORMAL ARRAY ANTENNAS

When considering the gain of a phased array antenna, the effective area of the aperture is directly related to the gain, and the peak directive gain of an array at a pointing angle θ from the normal of an array is shown (Eq 1) as the projection of the array area A onto a plane defined as the normal to the pointing angle θ [10].

$$g_{max}(\theta, \phi) = \frac{4\pi A_{eff}}{\lambda^2} cos\theta \qquad (1)$$

If a conformal array is assumed to be composed of N elements or sub-array facets, then this can be extended as a predictor of the maximum gain that can be expected from a given conformal array (Eq 2). In this case, α_i is the angle between the array broadside, and the sub-array facet i. The $+$ is used to represent that only angles for which $(\theta + \alpha_i) \leq \pm 90^o$, in general terms the local forward half-space for each facet.

$$g_{max}(\theta, \phi) = \frac{4\pi}{\lambda^2} \sum_{i=1}^{N} (A_{i,eff} cos(\theta + \alpha_i))_+ \qquad (2)$$

A_i represents the area of the element or sub-array area, and α_i is the angle between the element and the plane of the array. In this way Eq 2 gives the projection of the conformal array onto a plane defined in the same way as Eq 1. Indeed in
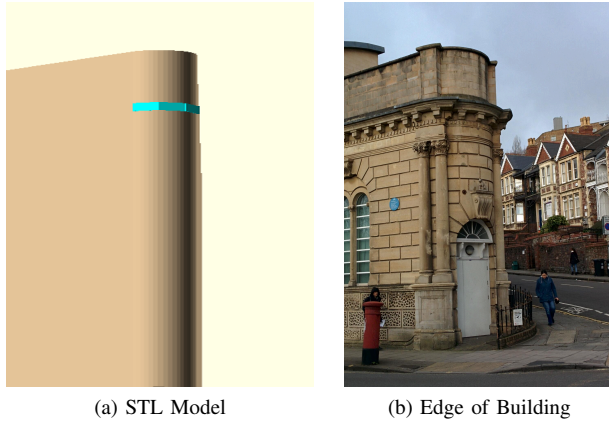
(a) STL Model   (b) Edge of Building

Fig. 1. Notional Conformal Aperture on Merchant Venturers Building at the University of Bristol

Fig. 2. Distributed leading edge arrays integrated into the wings of an aircraft

this way Eq 2 can be considered as the general case, which collapses to Eq 1 for a planar antenna array. Equation 2 is useful for considering arrays in isolation, by selecting the 'visible' sub-arrays for a given angle. However, it does not consider the presence of obstructions, even the array itself. While a 'shadow' algorithm can be implemented for primitive parametric shapes, such as cylinders, parabolas, and simple faceted surfaces this rapidly becomes infeasible as the model complexity increases [11].

III. Modelling Complex Conformal Aperture Gain

A. 3D Models

Illustrated in Figure 1, and Figure 2 are the two use cases considered. These figures are generated using OpenSCAD [12] to define solid objects using cube and cylinder primitives. The scene is then exported using the STL files. This file format describes an object in terms of triangular facets, defined by their three vertices, and a normal vector orientated outwards. While any object can be discretized by triangular polygons, in order to accurately model the objects it was considered reasonable to ensure that any aperture polygon has a size limit of a tenth of a wavelength, with any larger polygons recursively subdivided until the size is less that the specified limit. The model process consists of constructing an STL file for each antenna array, with multiple files for a distributed array, these files are used along with STL files of the obstructions in the environment that are relevant to the antenna array, such as the building edges (Section III-A1), or the general structure of the aerospace platform considered in Section III-A2.

1) Conformal Array for the Edge of a Building: Figure 1 shows a typical building location that exemplifies the type of location where a conformal antenna array could be positioned without causing serious aesthetic impact, while a planar array would be unsuitable. A simplified building model is rendered in tan, with the ground in grey and the nominal conformal array in aqua blue. The planar array is based upon three panels with an area of $0.06m^2$ each, oriented conformal to the surface of the building operating at 2.6GHz and is based upon an
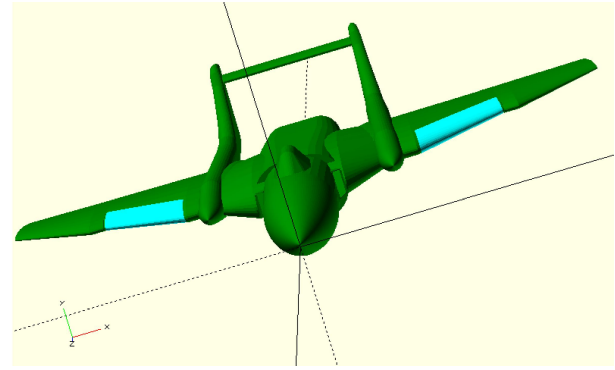
existing design [13]. At this frequency, a planar array of this surface area would be expected to have a maximum theoretical gain of 22.3dBi.

2) Aircraft Leading Edge Conformal Array: The Leading Edge Conformal Antenna Array is based on two conformal arrays with an area of $3.8m^2$ each, mounted on the leading edge of each wing, rendered in Figure 2 in aqua blue. These notional arrays are designed with a centre frequency of 6GHz. Leading edge conformal antenna arrays have been considered both for tactical radar, and synthetic aperture radar imaging [14].

B. Raycasting

As the aperture gain is related to the projection of the aperture onto the far field at a given angle, calculation of the maximum gain of a conformal array in the presence of obstructions requires a method to evaluate what proportion of an array is shadowed by an obstruction for a given angle. This is found with the use of geometrical optics and raycasting [5]. This technique allows a ray to be cast between two coordinates to check for obstructions. If a ray is projected from point P with direction unit vector $\bar{r}$, then it crosses the plane of the object facet with vertices P_1, P_2, P_3, with normal vector $\bar{n}$, with origin Q if Equation 3 holds. If so, point $\dot{P}$ is one the plane of the facet, as shown in Figure 3, and half-space checks (Equations 4,5,6) can be used to determine if the point is within the boundaries of the facet, as a triangle can be defined as the intersection of three half-spaces.

$$((P + t\bar{r}) - Q).\bar{n} = 0 \tag{3}$$

$$(P_2 - P_1) \times (\dot{P} - P_1).\bar{n} \geq 0 \tag{4}$$

$$(P_3 - P_2) \times (\dot{P} - P_2).\bar{n} \geq 0 \tag{5}$$

$$(P_1 - P_3) \times (\dot{P} - P_3).\bar{n} \geq 0 \tag{6}$$

IV. Results

1) Conformal Array for the Edge of a Building: The Conformal array for the edge of the building, with the axes set oriented with the positive z axis as the central array broadside, has a high maximum gain at 2.6GHz of 21.4dBi, as shown in
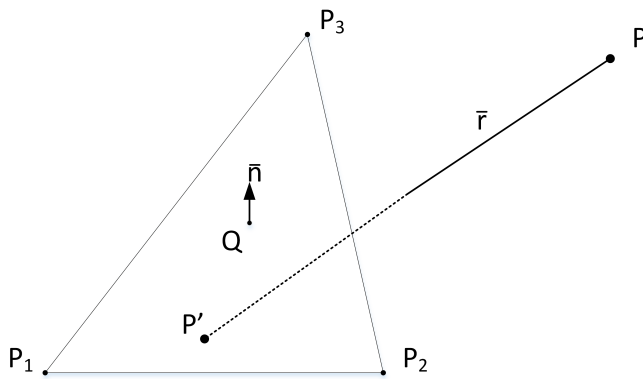
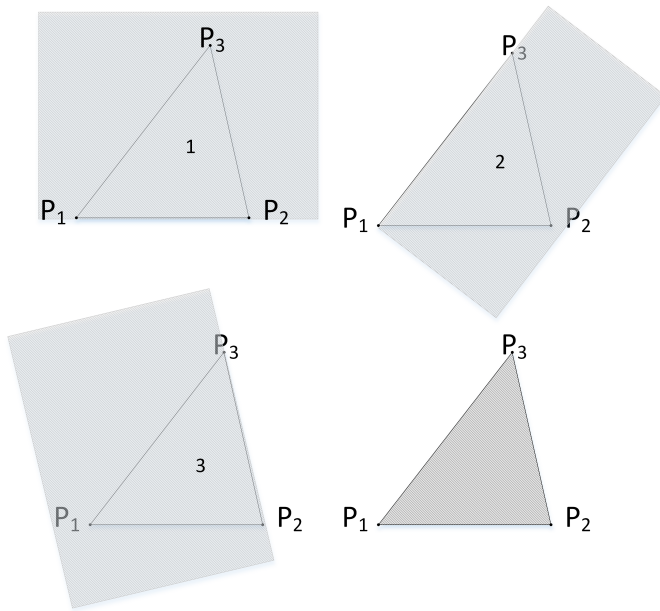Fig. 3. Raycasting & Triangle Intersections

Fig. 4. Half-Space checks, corresponding to Equations 4,5,6
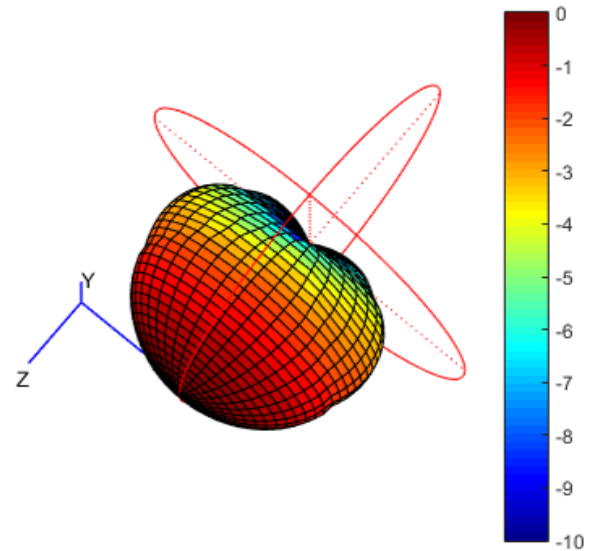

Fig. 5. Conformal Aperture Relative Gain Pattern (Relative to Maximum of 21.4dBi)
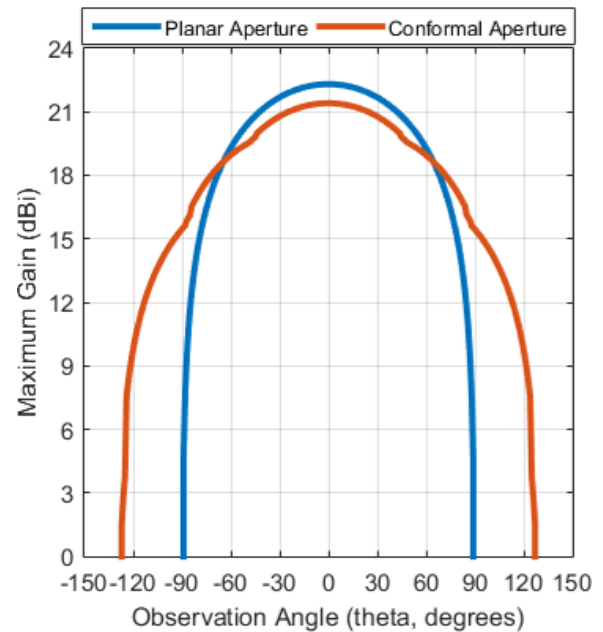

Fig. 6. Comparison of Maximum Theoretical Gain against angle from broadside for Conformal Aperture, and Planar Array of the same area

Figure 5 based upon the projected area calculated using the raycasting technique, and in comparison to that of a planar aperture of the same surface area in Figure 6. While for this particular shape the conventional maximum beam steering angle, (the greatest beam steering angle for which the loss of gain from boresight is less than 5dB). is improved between the conformal and planar apertures from ±71 to ±84, the profile of the maximum gain is interesting. At this frequency, this conformal aperture could offer a maximum of up to 15.4dBi at ±90 degrees off broadside, much more than a planar array could produce, and in a form factor that is much more amenable to mounting on the side of a building, where otherwise a basestation would be out of the question.

2) Aircraft Leading Edge Array: The Leading Edge Aperture, with the same axes set is a much larger array at a higher frequency, so it is not surprising that the maximum gain is higher, at 41.7dBi. The relative gain pattern is shown in Figure 7. A planar aperture of the same area would have a maximum

gain figure of 54.6dBi, a substantial difference, but there is no flat surface of this magnitude on a structure like the aeroplane used in this example. A mechanically scanned aperture within a nosecone radome, based upon a circular aperture, inclined at 30 degrees would be limited by the geometry of the nosecone to a radius of 0.8m and using Equation 1 could not offer more than 40dBi of maximum gain, with a greatly reduced maximum scanning angle compared to the conformal array
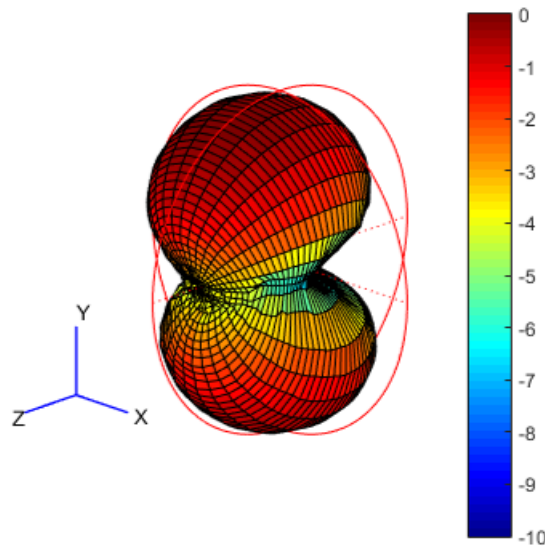
Fig. 7. Conformal Aperture Relative Gain Pattern (Relative to Maximum of 41.7dBi)
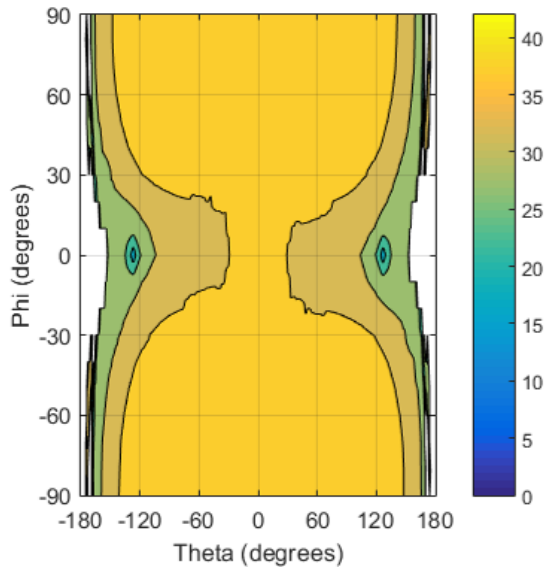

Fig. 8. Contour Plot of the Maximum Gain Pattern of the Leading Edge Array, 5dBi Contours

which can be shown using a flattened projection (Figure 8).

V. CONCLUSION

This method provides a convenient and robust way to predict the maximum gain available in a full pattern for a wide range of possible structures and array geometries, while by no means a full EM solver, it produces useful (first pass) predictions based on easily generated 3D models. This method by itself does not provide a full picture of the utility of conformal antenna arrays in the wide range of potential applications, but presents a tool to allow the design tradeoffs

of an aerodynamics structure or basestation location to be investigated at a very early stage in the design process.

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