An Efficient Hybrid FE-BI-TW-Collective Ray Formulation for Analysis of Large Conformal Arrays

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Abstract

A hybrid numerical and high-frequency asymptotic procedure is presented for efficiently analyzing the electromagnetic radiation from a very large conformal antenna array mounted on a realistic platform, such as an aircraft or ship. The local fields in the finite aperture of the array are computed numerically via the finite element-boundary integral (FE-BI) method, and transformed into a small set of traveling wave (TW) basis functions. Each of these traveling waves existing over the finite aperture has an associated high-frequency asymptotic radiation solution. This solution is generated within the framework of the uniform geometrical theory of diffraction, resulting in geometrical optics, edge and corner diffracted rays which are easy to track throughout a complex platform. This approach is far more efficient than the alternative, which is to track rays from each individual element in the array. Applications include in-situ antenna pattern prediction, and EMI/EMC and radiation hazard (RADHAZ) evaluation.

1. Introduction

The prediction of the electromagnetic (EM) radiation from large conformal antenna arrays remains a challenging problem for antenna system designers [1]. The antenna array itself may be analyzed with a state-of-the-art numerical method such as the domain-decomposition finite element-boundary element (DD-FE-BI) method [2]. However, the much larger platform on which the antenna is mounted remains beyond the capability of numerical methods without the use of very large-scale computer resources. Figure 1 illustrates a typical problem of a large conformal antenna array mounted on an aircraft.

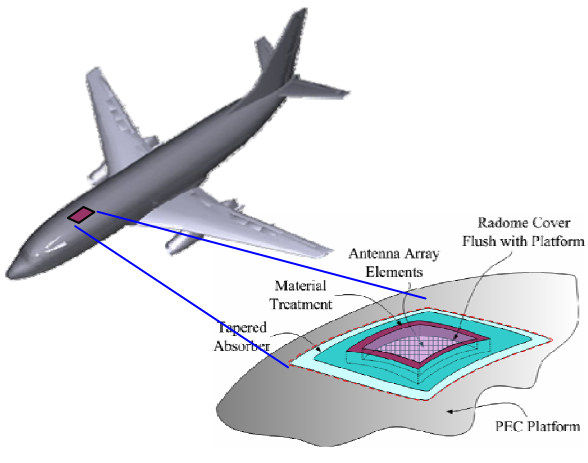

Figure 1: Conformal array antenna installed on an aircraft fuselage.

The antenna itself may be very complex, involving edge treatments, a radome cover, a feed system, and all mounted flush with the outer contour of the fuselage. However, the aircraft outer surface is relatively simple and amenable to ray methods such as the uniform geometric theory of diffraction (UTD) [3]. The problem then is to interface and convert the numerical solution (e.g., FE-BI) for the aperture fields with an efficient ray expansion for the radiated fields. An example of an inefficient approach would be to replace the aperture fields with a set of incremental current sources, and trace rays from each source. This is simple but very computationally intensive because there could be tens of thousands of sources needed, and the massive ray tracing requirement would become the bottleneck. A more efficient approach has been demonstrated in [4] where the aperture fields of a finite periodic array are transformed into a set of traveling waves using the discrete Fourier transform (DFT). A high-frequency asymptotic analysis of the radiation of each traveling wave yields a solution in terms of UTD-type rays diffracted from the edges and corners of the aperture, as illustrated in Figure 2 for a finite periodic array on a smooth perfect electric conductor (PEC) surface. A geometrical optics (GO) type ray also contributes from the interior of the aperture.

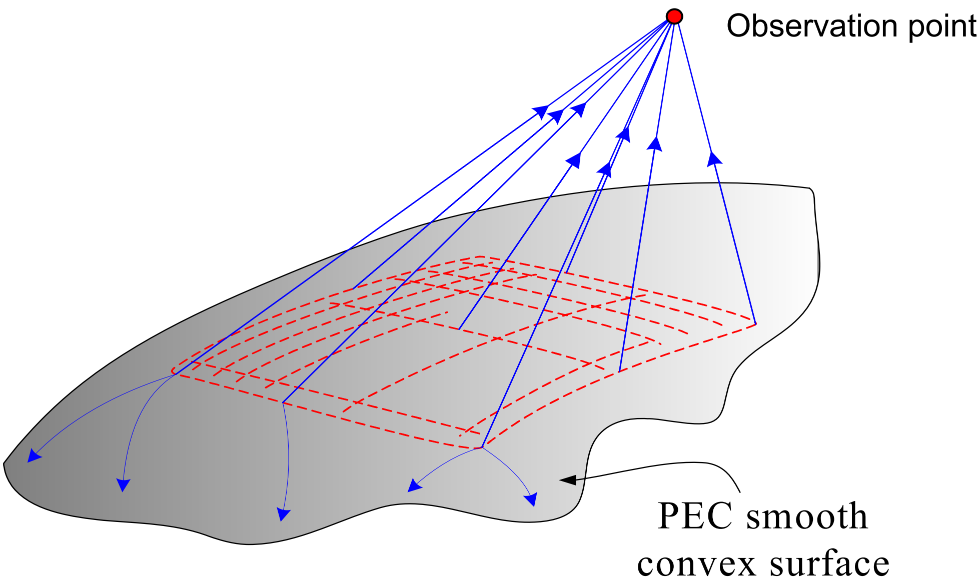

Figure 2: Collective UTD rays associated with a finite periodic array.

Even though the number of DFT terms is typically a small percentage of the total number of array elements, it can still require a fairly large number of rays to be tracked. The corner ray paths are independent of the number of DFT terms, but the edge and GO rays depend on the traveling wave directions of each DFT. Hence, a more efficient traveling wave (TW) expansion was developed in [5]. This new traveling wave expansion is a more natural fit to the actual waves propagating over the aperture of a typical phased array antenna, resulting in a much smaller number of terms that require ray tracing. Section 2 presents the three basic steps of the hybrid FE-BI-TW-collective ray procedure. Details on the different methods employed in the hybrid approach may be found in the references.

2. Hybrid Procedure

This section summarizes the 3-step hybrid FE-BI-TW-collective ray procedure. The first step is the finite element-boundary integral (FE-BI) numerical solution of the antenna array conformally mounted in a smooth surface, as illustrated in Figure 3. As the figure shows, the array geometry may be quite complex and must be analyzed via a rigorous numerical method. The FE-BI method is ideal for this problem because it can handle the complex geometry, including inhomogeneous materials, and provides a natural boundary interface for the external region. The FE region is bounded by a PEC or impedance surface on the inside, possibly with one or more feed ports, and with an arbitrary boundary surface on the outside. The FE-BI solution may be formulated exactly using the Green's function for the external region as the kernel for the boundary integral. The external region consists of the original smooth surface without the antenna array, and the rest of the platform. This Green's function would account for all the multiple interactions between the platform and the antenna, thus solving the entire antenna/platform problem. However, this is an extremely computationally expensive approach because the Green's function must account for the entire large platform, and there could be a very large number of sample points on the boundary integral surface. As a first level of approximation, the higher order coupling back into the antenna may be neglected assuming the antenna has been mounted in a reasonably open area of the platform. Then only the local Green's function for the smooth surface may be employed. This is reasonable because the purpose of this first step is to solve for the EM fields on the surface of the antenna aperture. A UTD solution for this local Green's function on a smooth convex PEC surface has already been developed [6].

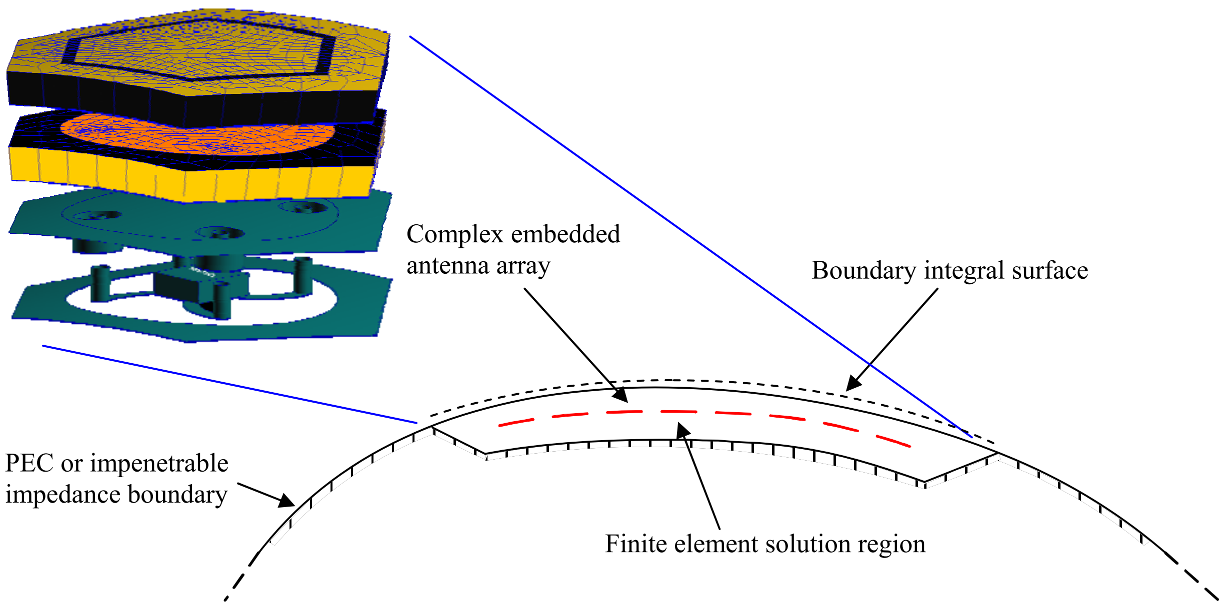

Figure 3: Finite element solution geometry for an embedded antenna array conformal to the surface.

In the second step of the hybrid procedure, equivalent sources are defined in terms of the antenna aperture fields which radiate in the presence of the original smooth surface as illustrated in Figure 4. In this case the surface is a PEC so only magnetic surface currents exist, given by $\overline{M}_s^{eq}(\overline{r}_s) = \overline{E}(\overline{r}_s) \times \hat{n}$ where $\overline{r}_s$ is a point on the antenna aperture surface.

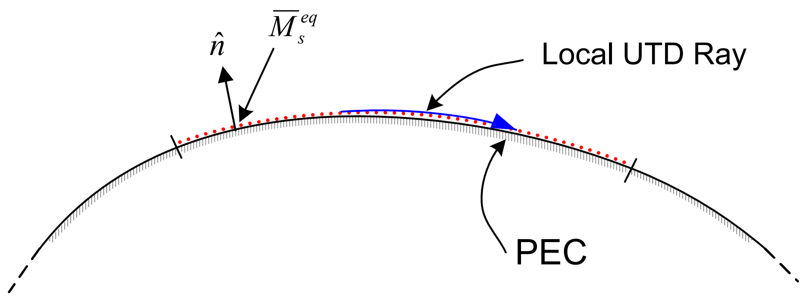

Figure 4: Equivalent magnetic surface current replacing the antenna on a smooth PEC surface.

These sources are expanded into a set of traveling waves over the aperture as,

$$\overline{M}_s^{eq}(\overline{r}_s) \approx \sum_{i=1}^{N} C_i e^{-j(\beta_u^i u + \beta_v^i v)} \tag{1}$$

where (u,v) are parametric tangential coordinates on the surface, $(\beta_u^i)^2 + (\beta_v^i)^2 \leq k^2$ and k is the free space wave number. The wave front directions (β_u^i, β_v^i) are found by a maximum likelihood search and extraction procedure. Because traveling waves are natural wave objects for an array antenna, the number of significant traveling waves N is typically a very small fraction of the number of array elements, and may also be much smaller than the number of corresponding DFT terms [5].

The third step in the hybrid procedure is to apply high-frequency asymptotic analysis to the radiation of the traveling wave expansion over a finite aperture to arrive at a collective ray field representation (see Fig. 2). Details of such an approach may be found in [4,5,7,8]. Each traveling wave term in the aperture may give rise to up to 9 rays: 4

edge diffracted rays, 4 corner diffracted rays, and 1 geometrical optics ray. Then the rays are traced according to UTD throughout the platform environment to an observer or to another antenna on the platform as shown in Figure 5. This completes the 3-step hybrid FE-BI-TW-collective ray procedure for analyzing the radiation from a conformal array on a large complex platform. The receiving problem may be easily formulated in terms of the radiation problem by making use of the reciprocity theorem [9].

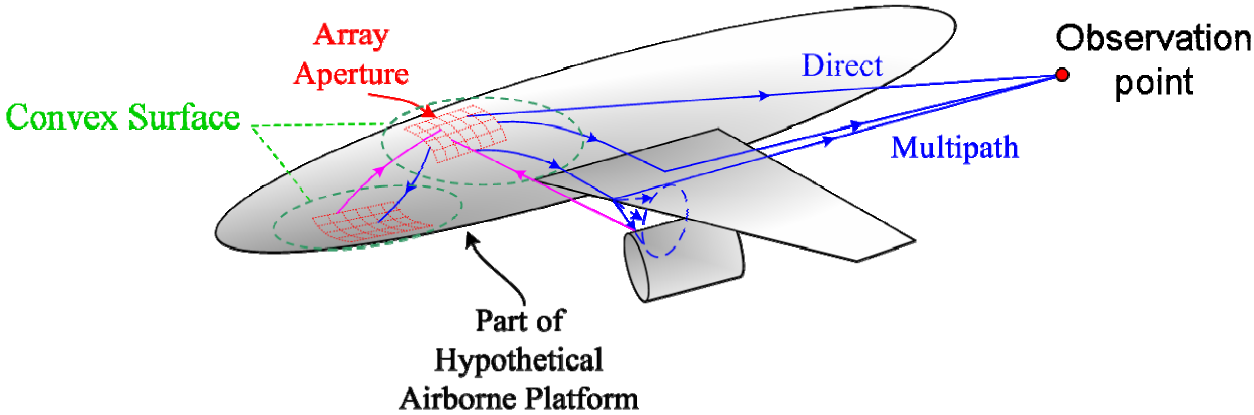

Figure 5: Ray tracing from the antenna aperture to an observer or another antenna.

3. References

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