A New 3D Ray-Tracing Acceleration Technique for the Analysis of Propagation and Radiation in Complex Enviroments

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Abstract **–** A new 3D ray-tracing technique, based on the Angular Z-Buffer algorithm, [1] to speed-up reflection calculations is presented. The technique can be applied to the analysis of propagation in urban or indoor environments, or to the computation of radiation of antennas on-board complex structures amongst other applications. The technique is used in combination with the Uniform Theory of Diffraction (UTD) and shows a large reduction in CPU-time.

I. INTRODUCTION

Electromagnetic asymptotic ray-tracing techniques like UTD [1] have been used to obtain the electrical field at a point or in a direction as the addition of all the rays that reach that point or direction: direct, reflected, diffracted, etc [1 - 3].

Traditionally complex environments have been modeled with facets (hundreds or even thousands of them). Most of the CPU-time in the electromagnetic analysis is spent determining the facets of the environment that obstruct the ray path (shadowing test) and/or produce reflection or diffraction. Several ray-tracing acceleration techniques, such as Space Volumetric Partitioning (SVP), Binary Space Partitioning (BSP) and Angular Z-Buffer (AZB) have been developed which reduce the potential number of facets that need checking in the analysis of the shadowing of the ray-path [2]. In this way, the CPU-time required for the shadowing test is reduced. However, these techniques have been applied to complex environments modeled by flat facets. The proposed approach allows reducing the CPU time associated to the shadowing test for scenarios modeled by the combination or flat and curved facets. Moreover, the technique can be applied to the ray paths involved at the contribution of any kind of ray. In a reflection for instance, the test is performed to check whether any of the following ray-paths are obstructed: the path from the source to the reflection point and the one from the reflection point to the observation point.

Other important task in the ray tracing is to determine the flash-points (reflection or diffraction points) for each contribution. Although, as mentioned above, several fast algorithms have been used to reduce the computational cost associated to the shadowing test, there is not previous experience in the application of these algorithms, for the UTD analysis, to reduce the number of potential facets that must be considered in the effects of reflection of diffraction. The objective, in this case, is to select from all the potential surfaces, those which due to their orientation and position could create a reflection on the field at a point or in a direction. With this objective, an improvement on the AZB technique has been developed in this work in order to reduce the number of facets that are considered as potential reflecting surfaces when the coupling through a reflection is computed. The algorithm can be applied to the any effect in which a reflection is involved, as can be the simple reflection, double reflection, diffraction-reflection, etc. FASANT [3], a code based on UTD, has been updated using this technique for the analysis of antennas on-board complex structures, obtaining accurate results with a huge reduction in the CPU-time.

II. AZB TECHNIQUE FOR THE SHADOWING TEST

The shadowing test is very time consuming, particularly if it is applied to a large number of facets and when the facets are not flat. There is no analytical formula to obtain the intersection point between a ray and an arbitrary surface. In these cases minimization algorithms like the Conjugate Gradient (CG) must be used for the intersection testing. These algorithms are very time consuming; therefore, when the number of surfaces is high the ray-tracing acceleration techniques are needed to reduce the number of facets to test. The AZB technique [2] is based on the Light Buffer technique [4] used in Computer Aided Design (CAD) to find the objects contained in a scene that are visible from a given point (source). To analyze the shadowing of the rays that leave a source a "shadowing window" is defined. The window space is divided into several rectangles, called anxels that correspond to the angular regions which, taking as reference the source-point, cover the entire space seen from the source. The facets of the structure are classified depending on their positions within these anxels (see Fig. 1). Therefore, only the surfaces within the anxel where the ray is located are analyzed in the facet-intersection test to find out if a given ray is shadowed. This previous selection of the facets which can shadow the ray produces an important reduction in the CPU time required for the ray-facets intersection test. The main advantage of the proposed approach is its applicability to scenarios modeled by the combination of flat and curved surfaces. This is very important, because, as mentioned above, the computation time associated to the shadowing test is significantly higher when curved facets are involved because minimization algorithms must be applied to perform this test.

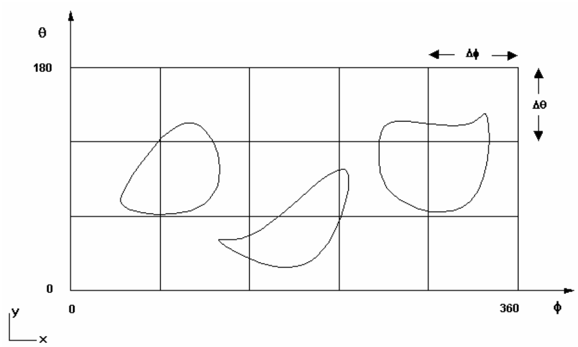

Fig. 1. Curves stored in the AZB plane from the shadowing source window.

The AZB technique can also be applied to speed up the computation of other effects such as of the reflection, diffraction, double-reflection and so on, reducing the time required for the shadowing test associated to each effect. In its original version, the AZB technique was used in combination with the image method to speed up the computation of the shadowing of the reflected fields. The procedure consists on using the image of the transmitter antenna as source [2]. Therefore, a reflection window can be determined for each facet to analyze the potential shadowing of the ray that after reflection leaves the facet.

III. AZB TECHNIQUE FOR THE REFLECTION TEST

As mentioned above, in this work, not only the computation time associated to the shadowing test is reduced but also the time necessary to determine the reflection points associated to the ray path. The objective, in this case, is to perform a previous selection of the facets that, due to their shape, orientation and position may contribute through reflection to the total field. This test is complementary to the shadowing test, because it provides a CPU time reduction to the other part of the ray tracing, as it is the determination of the ray paths using the minimization of the distance. Figure 2 illustrates the problem of the determination of the reflection points in a double reflection. As curved facets are involved, the determination of the points can not be done analytically, but they must be determined from the minimization of the ray distance from the source to the observer ($d_1+d_2+d_3$ in Fig. 2) based on the Fermat´s principle [1]. This distance, in the case of the double reflection, depends on four variables (u_1, v_1, u_2, and v_2, the parametric coordinates which define a curved surface [5]) and its computational cost is very high. If the complexity of the scenario under studio is high, the number of minimization tests necessary increase considerably and the reduction of this number seems very important if the analysis needs to be perform in a reasonable time.

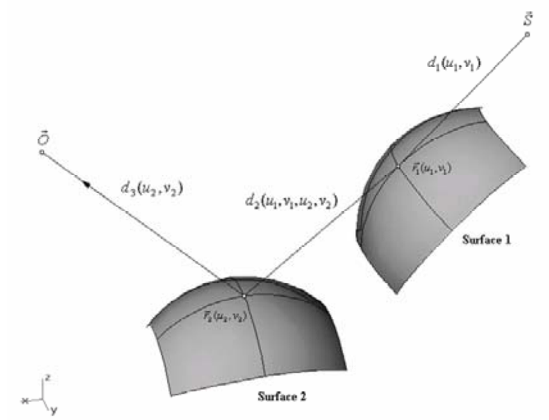

Fig. 2. Example of ray-tracing for a double reflection problem.

In this section the application of the AZB to the reflection test is explained. New AZB windows are defined for this test. The AZB reflection windows divide the space into anxels, which contain the facets that may contribute to the reflected field in the angular sector corresponding to that anxel. The so called reflecting source window is employed to analyze simple reflections. This window divides the space into angular regions, which contain the facets that may contribute to the reflected field in those regions. Only the facets located in the anxel of the reflecting source window that contains a given direction are tested to obtain all the reflected rays in that direction. As in the shadowing check, a lot of CPU-time is saved by not having to test for reflection facets that do not contribute to the reflected fields in that direction, particularly for curve facets, for which there is no analytical formula to find the reflection point. The following procedure can be used to find the anxel or anxels where a facet should be located in the reflecting source window:

1. Five sample points are obtained on the facet: the four vertices and the middle point. The coordinates and the normal vector of these points are calculated.
2. The directions of the reflected rays are obtained for the five sampling points using the Snell law (see Fig. 3). The anxel or anxels corresponding to those directions are identified and stored in a file.
3. The visibility from the source of the facet is checked: if there are one or more sample points not shadowed by any other facet, then the facet should

be included in the reflection source window. If the five points are shadowed, the facet is not included in the reflecting source window.

4. The facet is included in the set of anxels obtained in step 2.

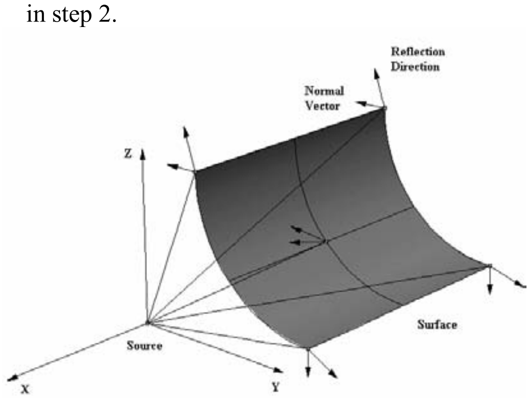

Fig. 3. Direction of the reflected rays for the five sample points of the curved facet.

Only five sampling points are necessary to create the AZB matrix because the facets are not supposed to be convex and concave at the same time. In this case, five points would not be enough. A previous division of the surfaces is performed to avoid that situation. The idea is to have, after the division, facets that are only convex or concave.

The technique, explained above, can be extended to speed up double-reflection field calculations. A reflecting window is associated to each facet in this case. This window allows obtaining efficiently all the facets that may contribute to the double-reflection in a specified observation direction. This window is also divided into anxels that contain the facets that could potentially contribute to the double-reflection in the angular sector corresponding to each anxel. The reflecting window of an arbitrary facet, that will be called facet *i*, can be obtained as follows

1. Using the shadowing window of facet *i*, all the visible surfaces from this one are obtained.

2. The box which encloses the surface is obtained and the eight vertices are used as source points (see Fig. 4).

3. Eight partial reflection windows are obtained (one for each vertex). Each window is determined by its spherical coordinates (θ_{l_max}, θ_{l_min}, ϕ_{l_max} and ϕ_{l_min}) $_{l=1,2,\ldots 8}$.

4. Once determined the partial angular windows, the total angular window (θ_{max}, θ_{min}, ϕ_{max} and ϕ_{min}) is obtained by means of an OR operation between the eight partial windows.

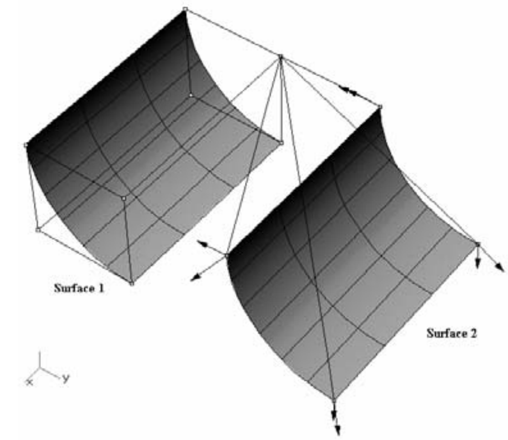

Fig. 4. Example of the estimation of the angular margin of one vertex of the enclosing box.

IV. RESULTS

This ray-tracing technique has been implemented in a computer code called FASANT, [3], developed previously for the analysis of antennas on board complex structures like ships, satellites, etc. This tool is based on UTD and can work with surfaces of arbitrary form modeled by Bezier patches. The electromagnetic kernel of FASANT is divided into two modules: flat and curve modules. In the previous version of FASANT, the flat module included a ray-tracing acceleration technique based on the AZB to efficiently treat the shadowing test problem, while the curve module only had the back-face culling test implemented in order to reject non-visible facets [3]. The new version of FASANT includes the AZB to treat the shadowing and reflection problems in both flat and curve modules.

First of all, a comparison between the results obtained from the proposed approach and measurements of a real scale mock-up of a satellite called Stentor are shown to prove the validity of the method. The measurements were performed by the French institution CNES (Centre National d'Estudes Spatiales, National Center of Space Studies in English). A picture of the mock-up can be seen in Fig. 5 In the left-bottom part of the satellite a GPS antenna is placed. The antenna is pyramidal-shaped as can be seen in Fig. 6 and its free-space radiation pattern is as depicted in Fig. 7. The frequency of analysis is 1.575 GHz.

The geometrical model of the Stentor is shown in Fig. 8. It has 83 flat surfaces and 11 curves. The datellite is completely metallic. The dimensions are 2.3 m × 1.8 m × 0.65 m. The phase centre of the antenna is placed at (-0.815, 1-.24, 0.13).

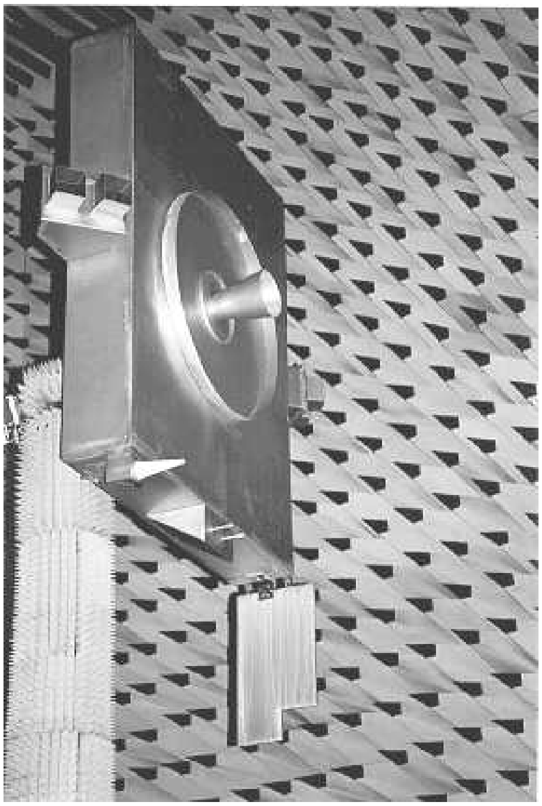

Fig. 5. Real mock-up of the Stentor satellite incide the CNES anechoic chamber.

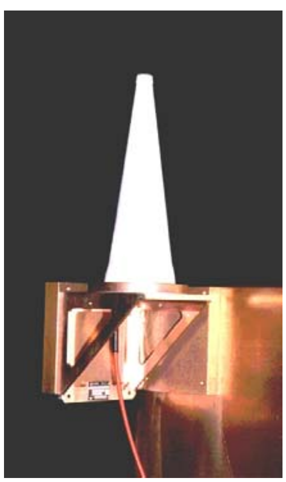

Fig. 6. Pyramidal antenna placed onboard the satellite.

Figures 9 and 10 show the comparison between the measurements and the simulation with FASANT for the theta and phi components of the electric field for a cut with ϕ = 11.25º and θ varying from –180º to 180º. As can be seen, there is good agreement between the measurements and the simulation results.

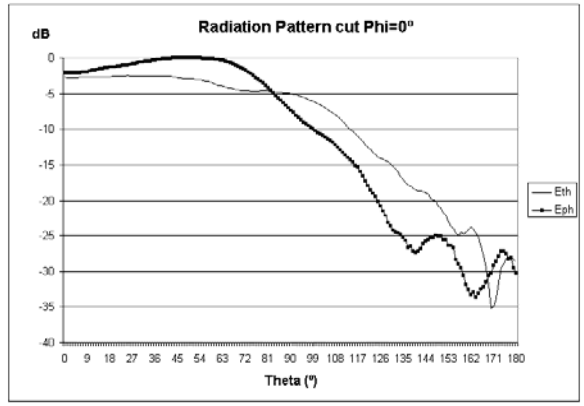

Fig. 7. Free-space radiation pattern of the pyramidal antenna (cut ϕ=0º).

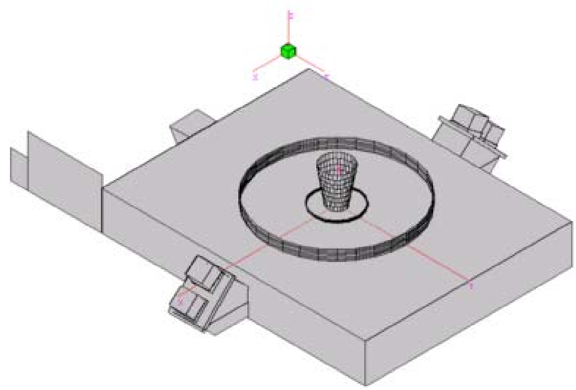

Fig. 8. Geometrical model of the Stentor and position of the antenna.

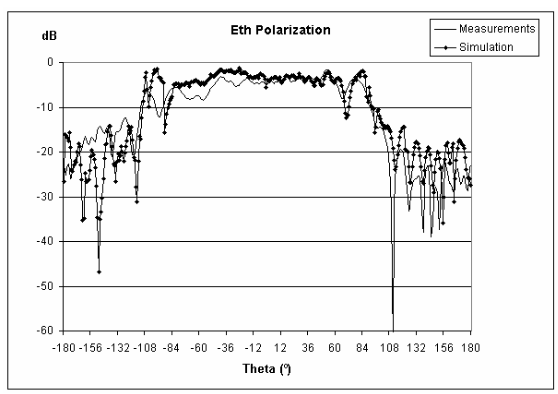

Fig. 9. Comparison between measurements and simulation for the Stentor satellite (Etheta).

On the other hand, several cases of analysis of on-board antennas with different complex structures have been tested to prove the CPU-time reduction provided by the present approach. In all the results, a previous test was performed to check that the final results are the same for both the original and modified versions of FASANT. The only difference between both is the CPU-time required, due to the more advanced ray-tracing acceleration technique introduced in the new version. In all the cases tested, the new version reduces the CPU-time by order of magnitude. In this section, the CPU-time reduction for the analysis of antennas on-board the HISPASAT satellite mock-up is discussed. The computer used was a Pentium IV 1.8 GHz with 1 GB memory PC-800.

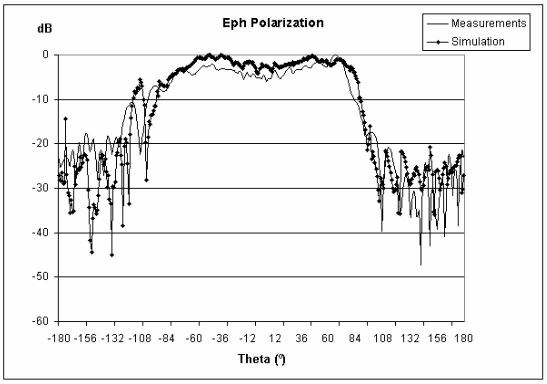

Fig. 10. Comparison between measurements and simulation for the Stentor satellite (Ephi).

The HISPASAT model used has 75 flat facets and 12 curve facets as shown in Fig. 11. To check the increase in speed of FASANT with the new ray-tracing algorithm, simple and double reflections have been selected. In the simulations using both versions of FASANT the antenna was placed in position with Cartesian coordinates 0.5, 0.5, 0.5, as shown in Fig. 3. Two cuts in ϕ have been calculated with angles 90º, 270º. The angular sweep in θ for simple-reflection is of 181 points, from 0º to 180º. For double-reflection, 30 points from 0º to 90º have been considered for the angular sweep in θ 2037 rays were traced for simple reflection and 948 for double reflection.

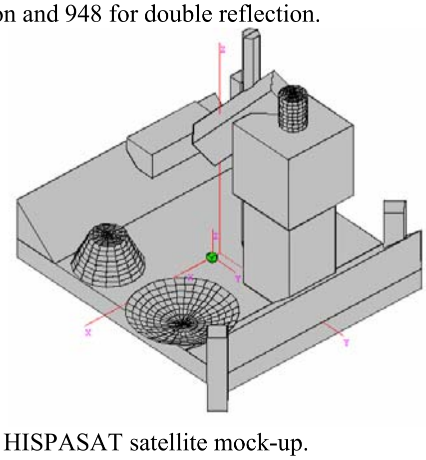

Fig. 11. HISPASAT satellite mock-up.

In the comparison shown in Table I, only the computation time associated to simple and double reflections has been considered. The reason is that the presented approach is only applicable for the reduction of the time associated to the reflections. At the moment, the diffraction is treated in FASANT without any AZB based algorithm to reduce its computational cost. An algorithm applicable to the diffraction effect is being developed at this moment.

Table I. Comparison of the CPU-time used with the two versions of FASANT.

Code	Simple-Reflection	Double-Reflection
Original FASANT	3 min: 21 s	43 min: 21 s
New FASANT	33 s	12 min: 46 s

V. CONCLUSIONS

A new version of the Angular Z-Buffer technique for accelerating the computation of reflected rays in complex environments has been presented. This technique has been tested with the FASANT code, showing a reduction in CPU-time by the order of magnitude. The technique is easily applicable to mobile communications propagation. In this case, the geometrical models will be one or two orders of magnitude higher, but the method is perfectly scalable and, therefore, the time reduction will be similar. The approach can also be applicable for situations in which two or more sources are present. The only difference is that the AZB matrices associated to the method must be created for each source.

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