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A GENERAL METHOD FOR THE RAY-TRACING ON CONVEX BODIES.

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ABSTRACT. A method to compute the ray tracing over complex bodies composed by smooth convex surfaces of arbitrary shape is presented. The bodies are assumed to be electrically large and perfectly conducting. Free-form parametric surfaces are used to describe the structures. The technique is simple and efficient, so it is suitable for complex bodies. Some results obtained with FASANT code, which implements this technique, are presented to prove the efficiency of the method.

1. INTRODUCTION.

The Uniform Theory of Diffraction (UTD) approach is widely used in scattering, radiation and antenna-coupling problems when electrically large bodies are involved. In such problems, when the surfaces of the bodies are smooth, the UTD contribution of the curved surface diffraction (also called creeping waves phenomenon) [1] must be taken into account. Examples of such bodies are aircraft, ships, cars, etc. Usually, their shapes are described in terms of free-form parametric surfaces as NURBS (Non-Uniform Rational B-Spline), Bezier patches, Coons patches, etc. [2]. The main difficulty in the computation of curved surface diffraction of such shapes is the ray tracing.

In the past, the problem of the creeping waves ray tracing has been solved in an analytical way for a great variety of canonical shapes, from cones, cylinders or spheres [3-5], to other more complicated shapes such as ellipsoids [6] and spheroids [7], and even such surfaces as quadric cylinders, ellipsoids, paraboloids, and bodies formed by combination of these shapes [8].

This work presents a method to compute the tracing of surface diffracted rays on complex bodies composed by smooth convex surfaces of arbitrary shape modeled by free-form parametric surfaces. In this method the points along the trajectory over the body are calculated in an iterative way using differential equations. Something similar was presented in [9] and [10], but in both papers the method was applied to canonical shapes, one ellipsoid in [9], and one cylinder in [10], and in both cases the bodies were modeled by using one analytical surface.

In our cases the calculations are made over complex bodies modeled by using free parametric surfaces. The main contribution of this paper is the practical treatment derived of applying the method to these kinds of surfaces. One of the most important features is that the structures where the antennas are placed (aircraft, ships, etc.) are very complex, and have to be modeled with several arbitrary curved surfaces. Then, sometimes the ray is propagated along two or more surfaces. Therefore, a very important issue in the present approach is to evaluate how the ray path crosses from one surface to another.

Moreover, it is important to consider the case that both the transmitter and the receiver can not be on the surface. In this case, it is necessary to calculate the path from the transmitter up to the surface, the propagation along it and the path from the surface up to the receiver. In our approach, the three paths are computed in a general way, in order to be applicable to the surfaces described above.

Results applying the method to a missile and an aircraft are shown. These results have been obtained with a code called FASANT [11] developed by the authors of this paper.

2. RAY TRACING

The trajectory of a surface diffracted ray can be divided in three paths. The first one is a straight path which goes from the transmitter antenna (Tx) to a point (P1) on the surface shadow boundary (SSB). Then, the ray follows a curved trajectory along the surface of the body. The propagation over the surface stops when the ray reaches a point (P2) on the shadow boundary of the receiver antenna (Rx) where the ray follows a straight path to Rx as can be seen in Figure 1.

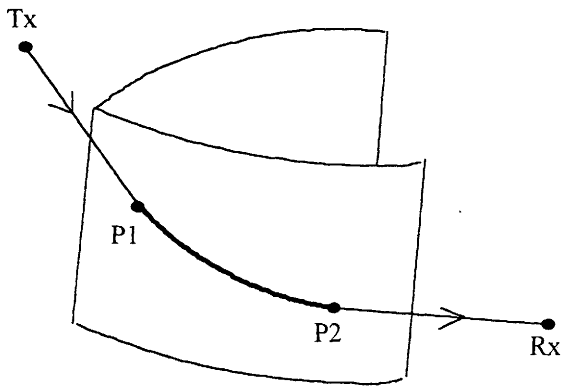

Figure 1. Ray trajectory over a surface.

Moreover, the ray must satisfy the Generalized Fermat's Principle [12], that is, the sum of the three path lengths must be an extreme (maximum or minimum). As a consequence, the ray arrives at the point P1 under grazing incidence, travels on the body surface along a geodesic curve and leaves the surface (at P2) tangentially and pointing to Rx.

The geometric representation of the bodies is given as a collection of Bezier patches. These are parametric surfaces of arbitrary degree whose advantage is that complex surfaces can be described with a very low amount of Bezier patches. Nevertheless, the method is also useful if the surfaces are specified using different kinds of parametric surfaces such as NURBS (Non-Uniform Rational B-Spline), Coons patches, etc. The geometric parameters of the surface (normal vectors, curvatures, etc.) at P1, P2 and at the points of the geodesic curve are necessary to compute the UTD diffracted field. Knowing the parametric coordinates of the above points in the corresponding surface, such geometric parameters can be calculated using closed-form expressions of differential geometry [2]. Therefore, the objective is to compute the parametric coordinates of such points.

The proposed method starts by calculating a set of sampling points on the SSB. The SSB points must satisfy the following condition:

$$(\vec{r}(u,v)-\vec{S})\cdot\hat{n}(u,v)=0 \qquad (1)$$

where u and v are the parametric coordinates of the point, $\vec{r}$ is the position vector of the point, $\vec{S}$ is the position vector of the source (Tx) and $\hat{n}$ is the unit surface normal vector in the point (see Figure 2).

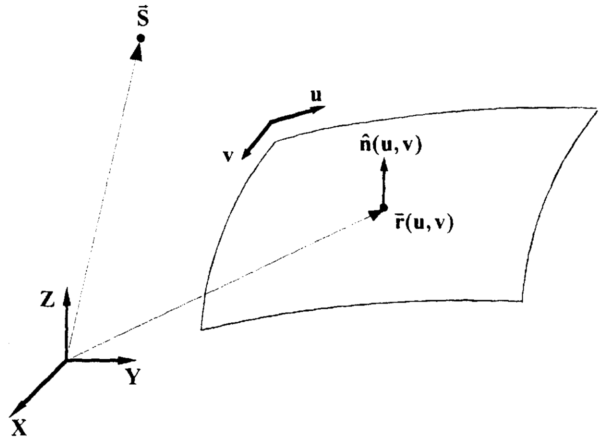

Figure 2. Geometrical parameters involved in the computation of the SSB.

Obviously, only points on partially illuminated surfaces fulfill equation (1). Then, the first step is to determine the surfaces of the body which are partially illuminated. For that, the normal vector is evaluated at a set of points of each surface. If all the points evaluated satisfy the condition $(\vec{r}(u,v)-\vec{S})\cdot\hat{n}(u,v)>0$ then the surface is totally hidden. On the other hand, if $(\vec{r}(u,v)-\vec{S})\cdot\hat{n}(u,v)<0$ for all of them, it is totally illuminated. The partially illuminated surfaces are those where the first condition is satisfied at some of the evaluated points and the second one at the others.

Once these surfaces have been obtained, there are infinitely many points which form part of the SSB on each surface, but only a set of points of the SSB are computed. These ones will be the intersection points between a set of parametric curves and the SSB curve. To compute them, the value of one parametric coordinate is fixed and equation (1) is solved. Repeating this procedure for both coordinates, varying the fixed coordinate from u=0 to u=1 and then from v=0 to v=1, the sample points of the SSB are obtained.

For each of those points, the corresponding geodesic curve is calculated, which starts at the point and satisfies the following equations [13]:

$$\frac{d^2u}{d^2\sigma}+\Gamma^1_{11}\left(\frac{du}{d\sigma}\right)^2+2\Gamma^1_{12}\frac{du}{d\sigma}\frac{dv}{d\sigma}+\Gamma^1_{22}\left(\frac{dv}{d\sigma}\right)^2=0 \qquad (2)$$

$$\frac{d^2v}{d^2\sigma}+\Gamma^2_{11}\left(\frac{du}{d\sigma}\right)^2+2\Gamma^2_{12}\frac{du}{d\sigma}\frac{dv}{d\sigma}+\Gamma^2_{22}\left(\frac{dv}{d\sigma}\right)^2=0 \qquad (3)$$

where Γ_{ij}^{k} are the Christoffel parameters [12] and σ is the arc length along the curve. The Christoffel parameters are functions of the parametric derivatives of the surfaces, so at each point (u,v) they can be calculated easily from the surface description.

Therefore, assuming we are dealing with smooth convex surfaces with continuity in the surface points and their derivatives, we can solve the equations (2) and (3) by invoking the Milne method: Doing this, the next equations are found which allow one to obtain in an iterative way the parametric coordinates of a set of sample points of the geodesic curve, each point being separated by a distance $\Delta\sigma$ from the previous point over the trajectory.

$$u_{k+2} = u_k + 2(u_{k+1} - u_k) - \Gamma_{11}^{1}(u_{k+1} - u_k)^2 - 2\Gamma_{12}^{1}(u_{k+1} - u_k)(v_{k+1} - v_k) - \Gamma_{22}^{1}(v_{k+1} - v_k)^2 \quad (4)$$

$$v_{k+2} = v_k + 2(v_{k+1} - v_k) - \Gamma_{11}^{2}(u_{k+1} - u_k)^2 - 2\Gamma_{12}^{2}(u_{k+1} - u_k)(v_{k+1} - v_k) - \Gamma_{22}^{2}(v_{k+1} - v_k)^2 \quad (5)$$

As can be seen, to calculate one point in the trajectory, two previous points are needed, therefore two starting points are needed to apply the algorithm. The first starting point (with position vector $\vec{r}_1$) will be, obviously, the outline point for which the propagated ray is being calculated and the second starting point (with position vector $\vec{r}_2$) will be calculated (bearing in mind that the incidence to the surface has to be tangential to the propagation trajectory and, therefore, if the step $\Delta\sigma$ is small enough) using the following equation:

$$\vec{r}_2 = \vec{r}_1 + \Delta\sigma \frac{(\vec{r}_1 - \vec{S})}{|\vec{r}_1 - \vec{S}|} \quad (6)$$

where $\vec{S}$ is the source position.

Once the first two points of the path have been found, the parametric coordinates of the third one can be computed by applying equations (2) and (3), obtaining the following points on the ray trajectory in an iterative way.

Because of the complexity of the bodies, they will be modeled by the union of several surfaces. It is important to calculate the path followed by the ray when it crosses from one surface to another in an efficient way. This case happens when the point obtained for the method is out of the limits of a surface (surface 1) and this surface is joined with another different one (surface 2).

First of all, the ray propagation path will continue when the two surfaces present continuity in the normal vector. In other cases the surfaces form an edge and a diffraction of the creeping wave appears. This contribution has not been considered in this work. To evaluate this condition the next criterion must be satisfied if the surface normal is continuous:

$$\hat{n}_1 \cdot \hat{n}_2 = 1 \quad (7)$$

where $\hat{n}_1$ and $\hat{n}_2$ are the normal vectors to each surface evaluated in the border between them.

In case the criterion is satisfied, the Cartesian coordinates of the point obtained outside the limits of surface 1 are computed as if this point was within the limits of the surface. From these Cartesian coordinates the parametric coordinates over surface 2 can be computed. Once they have been obtained the algorithm can be applied again over surface 2.

Two starting points are again needed on the second surface. To obtain the other one, the last point of the trajectory which was on the first surface is used and its parametric coordinates over the second surface are calculated as if the point would be in it, following the steps seen before.

The emission of the ray propagated along the surface is produced when this ray reaches the shadow boundary seen from the observation point. To calculate when a point of the shadow boundary is reached, two conditions have to be evaluated:

1) The receiver is visible from the point, that is to say:

$$\hat{n}_i \cdot \vec{V}_i \geq 0 \quad (8)$$

where $\hat{n}_i$ is the normal vector to the surface at this point and $\vec{V}_i$ is the output vector which joins the point with the observation point.

2) The output ray is emergent, that is to say, the output vector has the same direction as the geodesic curve, therefore:

$$(\vec{r}_i - \vec{r}_{i-1}) \cdot \vec{V}_i \geq 0 \quad (9)$$

All the process described above is made for each point on SSB for Tx calculated before. Then, there will be as many trajectories as outline points. However, not all of them will produce field due to creeping waves. This field will only exist if the output ray is tangential to the geodesic curve or, equivalently, if the output vector at the last point of the curve is tangential to this curve. Therefore, only the trajectory which carries out the tangential condition for the output ray will be valid.

3.- RESULTS.

Two examples are presented. These results have been obtained with the FASANT code which incorporates the creeping wave effect by using the process previously described.

Figure 3 shows the result of applying the method to a missile, modeled with 24 Bezier patches. Although in this Figure, the missile seems to be modeled by using plane facets because of the graphical representation, it is modeled by using curved surfaces. The paths were obtained from one sender to several receivers placed at different heights with respect to the missile. The most interesting thing in this case is to see how for some receivers the ray is propagated only along the top of the missile, while for others the ray propagates only on the body, and for others the ray follows a path which crosses from the missile top to the body. This Figure proves that the method obtains the ray trajectory independently of the shape of the surface where the ray is propagated, even if the ray is propagated along several surfaces and, therefore, the body shape changes along the ray path. The computation time, on a Pentium II 333 MHz with 128 MB of RAM., is 33 seconds to obtain the shadow boundary seen from the receiver and 24 seconds to compute, on average, the trajectory of the ray for each observation point.

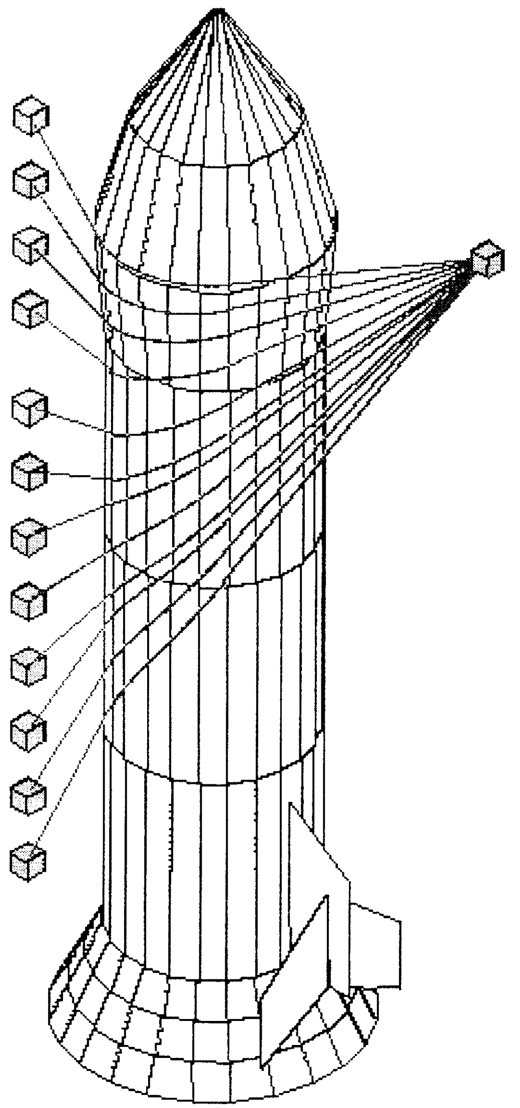

Figure 3. Ray tracing over a missile.

In Figures 4 to 7 the method is applied to an aircraft, modeled with 72 Bezier patches. Here also the results have been obtained for one sender to several receivers Only four paths, from different points of view, are depicted to show them in a clear way. These paths are representative of several trajectories that the ray can follow on the aircraft, to prove the validity of the method with independence of the surface along the ray is propagated. There is one path along the top of the fuselage, another along the bottom, another more along the engine, and a fourth one along the tail. The computation time in this case is 3 minutes 02 seconds for obtain the SSB and 2 minutes 43 seconds, on average, to compute geodesic path for each point. The computer used is the same as for the previous example.

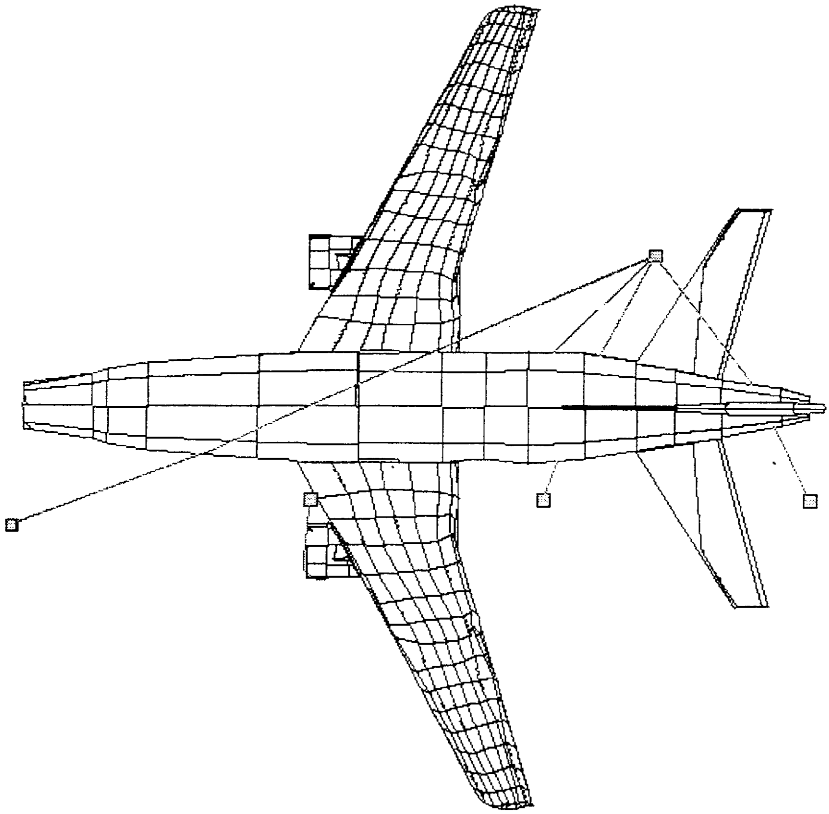

Figure 4. Top plant view of the ray tracing over an aircraft.

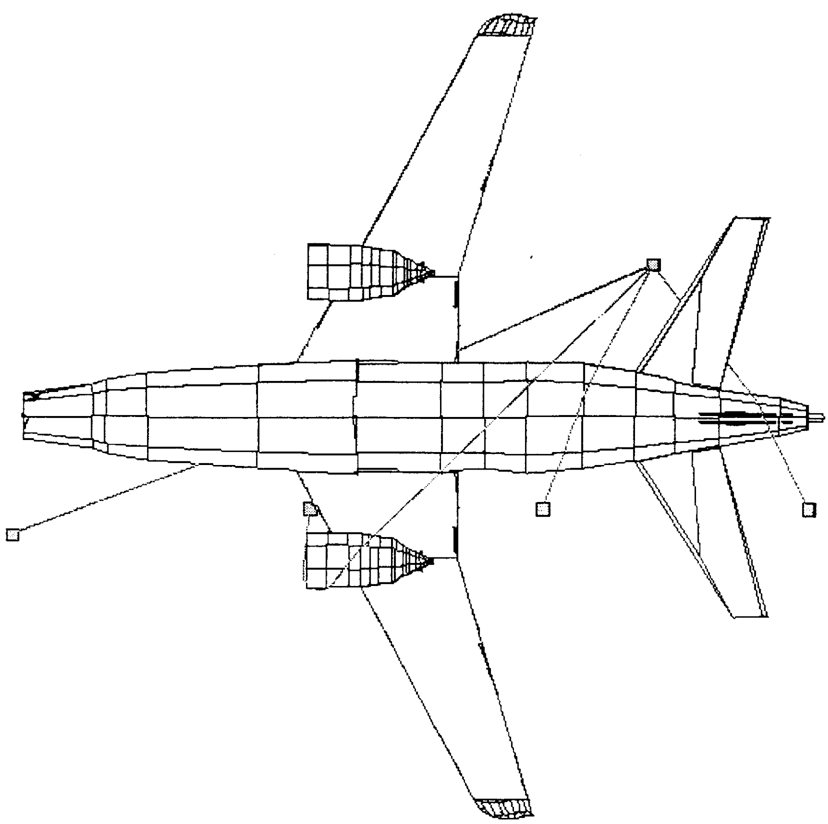

Figure 5. Bottom plant view of the ray tracing over an aircraft.

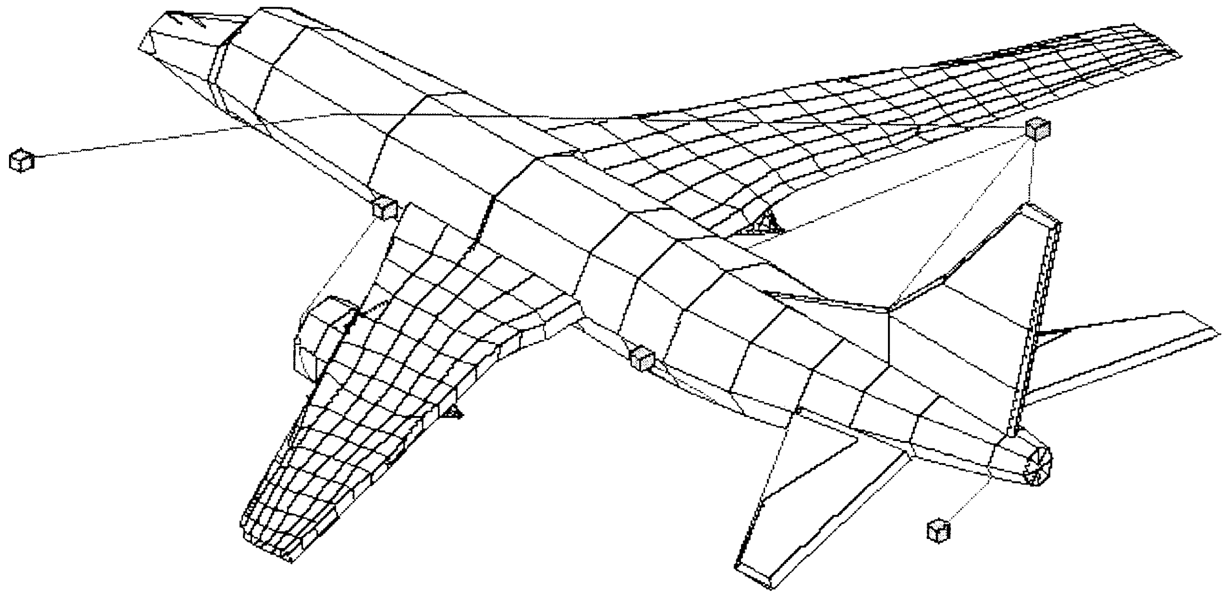

Figure 6. Top isometric view of the ray tracing over an aircraft.

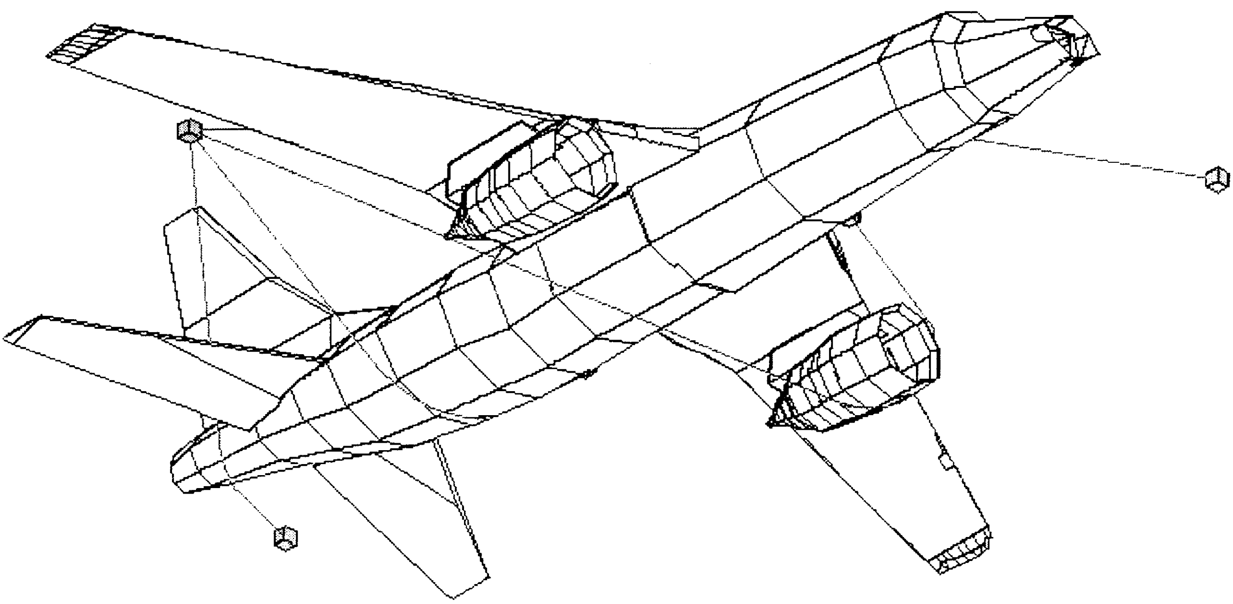

Figure 7. Bottom isometric view of the ray tracing over an aircraft.

4.- CONCLUSIONS.

A general method to compute the creeping wave path along free-form parametric surfaces has been presented. Both the computation of the shadow boundary seen from the transmitter and the path followed by the ray along the surface are computed in a numerical way, which made them applicable to any kind of surface. Also the method is valid for bodies modeled by several surfaces. Some ray tracing results have been shown for realistic models of a missile and an aircraft.

REFERENCES

[1] D.A. McNamara, C.W.I. Pistorius, J.A.G. Malherbe, "Introduction to the Uniform Geometrical Theory of Diffraction", Artech House, 1988.

[2] G. Farin, "Curves and Surfaces for Computer Aided Geometric Design", San Diego, Academic, 1988.

[3] K.K. Chan, L.B. Felsen, A. Hessel, J. Shmoys. "Creeping Waves on a Perfectly Conducting Cone", IEEE Transactions on Antennas and Propagation, AP-25,1977, pp. 661-670.

[4] S.W. Lee, E.K. Yung, R. Mittra, "GTD Solution of Slot Admittance on a Cone or Cylinder", Proceedings of the IEEE, Part H, 26, 1979, pp. 487-492.

[5] P.H. Pathak, N. Wang, "Ray Analysis of Mutual Coupling between Antennas on a Convex Surface", IEEE Transactions on Antennas and Propagation, AP-29, 1981, pp. 911-922.

[6] J.J. Kim, W. D. Burnside, "Simulation and Analysis of Antennas in a Complex Environment", IEEE Transactions on Antennas and Propagation, AP-34, 1986, pp. 554-562.

[7] P.H. Pathak, N. Wang, W.D. Burnside, R.G. Kouyoumjian, "A Uniform GTD Solution for the Radiation from Sources on a Convex Surface", IEEE Transactions on Antennas and Propagation, AP-29, 1981, pp. 609-622.

[8] R.M. Jha, W. Wiesbeck, "The Geodesic Constant Method: A Novel Approach to Analytical Surface-Ray Tracing on Convex Conducting Bodies", IEEE Antennas and Propagation Magazine, 37, April 1995, pp. 28-38.

[9] J. Choi, R.J. Marhefka, "Numerical Techniques to Determine the UTD Bistatic Creeping Wave Paths and Parameters for an Ellipsoid", Applied Computational Electromagnetics Society Journal, vol. 6, no. 1, Summer 1991, pp. 140-158.

[10] X. Zhu, L. Jen, W. Wang, "Accurate ray-tracing method for the creeping wave on a numerically specified surface", Electronic Letters vol.31, no 4, Febraury 1995, pp. 260-261.

[11] J. Pérez, F. Saez de Adana, O. Gutiérrez, I. González, M.F. Cátedra, I: Montiel, J.Guzmán, "FASANT: Fast Computer Tool for the Analysis of On Board Antennas", IEEE Antennas and Propagation Magazine, vol. 41, no 2, April 1999.

[12] J.B. Keller, "Geometrical Theory of Diffraction", J. Opt. Soc. Amer., 52, 1962, pp. 116-130.

[13] L.P. Eisenhart, "A Treatise on the Differential Geometry of Curves and Surfaces", Dover Publications, Inc. 1960.