Astigmatic Beam Tracing application to satellite antenna interactions †

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Abstract. *Antenna pattern modifications, antenna coupling and radio-frequency interference are an increasing source of risk in satellite programmes. Measurements on the complete satellite or on models are expensive and can only take place at the late stage of the satellite development, when corrective measures are both difficult and costly. The use of high frequency techniques, mostly UTD, is well established as a prediction tool to help engineers minimising these risks since the early project phases. However several issues limiting the accuracy and reliability of predictions remain open. The Astigmatic Beam Tracer is a novel ray-tracing technique that addresses some of the shortcomings of other approaches. A recursive spatial subdivision strategy combined with a selection mechanism is used to trace wave front propagation throughout the environment so as to minimise the computational cost while maintaining tight control over the prediction accuracy.*

Introduction

The accurate determination of antenna pattern modifications and antenna coupling, as well as radio-frequency interference, on board satellite is a well-known need in satellite design. Methods for electromagnetic field prediction in complex environments have evolved in recent years to a significant degree of maturity. Nevertheless there still are several issues that remain open [1].

"High-frequency" techniques as UTD, which are routinely used for this type of predictions, require the identification of ray-paths within the spacecraft structure and appendages. The overall accuracy obtained in the predictions depends on the amount of details in the scene that a ray tracer is able to handle, as well as on the ray tracing algorithms that have a strong impact on the sampling of the field propagation. Time efficiency depends both on the desired accuracy in field calculation and on the algorithms.

Of course the complexity of the environment, which embeds the antenna (or antennas, in coupling problems), plays an important role in the computational cost and accuracy. In practice, a small number of objects, of the order of 10, are usually sufficient to create problems. In particular, handling multiple reflection and diffractions determines a factorial explosion of the computation times and a rapid decrease of accuracy. Most codes are actually not able to treat multiple interactions involving more than two diffractions, while assessing very low level coupling (less than –50dB) between antennas located on two opposite sides of a spacecraft often requires higher diffraction orders. The consequent necessity of properly simplifying the satellite layout, usually available in the form of a rather detailed CAD model with hundreds of elements, creates a further complication in the modelling process and is a source of hard-to-quantify inaccuracy. Among others it creates serious problems because of the need of painstaking and hard-to-automate checks of the geometrical description of the environment to ensure its compatibility with the underlying ray-tracing algorithm.

Positioning the antennas in the overcrowded antenna farms of modern telecommunication and Earth observation satellites also requires tools adequate to quick evaluation and visualisation of the electromagnetic field propagation around each antenna so as to ensure the minimisation of interference risk from the very early design phases. An objective which is hard to achieve using typical UTD analysis tools.

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Several attempts have been made in the past to improve high frequency modelling techniques to cope with these problems, focusing in particular on the ray-tracing process. Both backward and forward techniques have been improved in various ways, but to the author's knowledge the origin of the fundamental limitations described above were not removed.

The Astigmatic Beam Tracer is a novel algorithm that takes automatically into account all possible contributions in an environment described by polyhedral objects. The method handles reflections and wedge diffractions as well as their combinations up to any order, so that the choice on the number of interactions to be accounted for can be made on exclusively electromagnetic criteria. In practical terms the Astigmatic Beam Tracer ensures a continuous and complete coverage of the scenario exploiting ray beams to propagate the wave fronts radiated by primary and secondary sources and produces an accurate and controllable sampling of the wave front that leaves the spacecraft toward infinity. In the same way it provides a complete reconstruction of the wave front impinging on a receiving antenna or other (virtual) object within the environment.

This innovative approach to ray tracing is directly aimed at removing the causes of the limitations described above.

Main characteristics of the Astigmatic Beam Tracer

The first property of the Astigmatic Beam Tracer (ABT) is that it is largely based on well-established computational geometry data structures and algorithms, which ensure a complete and safe handling of the environment geometry. These algorithms are used in many other applications and have been extensively studied by dozen of researchers working in different fields. Some of them are used by commercial CAD to internally represent the scene geometry so that it is relatively easy to process typical CAD output files to build the representation used by the algorithm. This first processing step is also quite fast, practically as fast as loading from file the internal representation previously saved to disk. The data structure generated at this stage completely describes polyhedral surfaces by encoding the relations among faces, edges and vertices. Consequently and at a difference with most similar algorithms, the ABT handles flat faceted surfaces of any kind. The use of flat faces is actually not an intrinsic limitation of the algorithm and curved faces could equally be treated with the same approach.

The second processing step is still preparatory and builds a partition of the 3D space congruent with the geometry of the scene, based on recursive splitting of space into closed or open volumes delimited by the polyhedron faces. The technique used was originally developed for scene rendering and searching in computer graphics. Highly optimised algorithms are available for this task and consequently the (space) computational cost is fairly limited, it grows as $O(n\log_2 n)$ with n the number of objects in the scene. The resulting data structure is totally independent from the position of the source and the observer within the 3D space, so it needs to be generated only once for any number of sources and any number of observation locations.

The third phase constitutes the core of the algorithm. It generates all the geometrical and accessory information required to compute the field distribution across the scene in the fourth and final step. Given a source location, a number of rays are traced throughout 3D space by traversing the binary tree generated in the pre-processing phase. These rays are actually arranged in bundles that delimit power flux tubes in the asymptotic frequency approximation and called *ray-tubes* in the following. When a potential interaction between the ray-tube and an element of the environment is detected, the actual intersection between a ray-tube and the element is checked by means of polygon intersection algorithms. This is the most expensive portion of the whole algorithm, but intersection checks are needed in all ray-tracing algorithms and the polygonal intersection check is not significantly more expensive than individually checking the intersection of each ray in the bundle. The main advantage of this particular choice is that it ensures that no objects can be missed. In fact, the beam tracing process is essentially equivalent to propagating through the scene a polyhedral approximation an outgoing wave front from the source. A less obvious, but far reaching consequence of this approach is that small objects present in the scene can be correctly detected and either ignored –possibly in a frequency sensitive way- or treated according to some adequate approximations (e.g. as additional point sources with suitably weighted pattern).

Diffraction is handled as part of this step and without departing from the forward beam-tracing scheme. Whenever a ray-tube is only partially obstructed by a scene element, a new set of tubes is created to represent the diffracted wave front originated by the element edge(s). These tubes, opposite to those created by reflection, are astigmatic since they originate from the two caustics of diffracted ray bundles. The most important feature of ABT is that diffracted ray-tubes are propagated using exactly the same algorithm as the others, intrinsically enabling the handling of multiple interactions of any order. Furthermore, as shown in [3], the congruencies of rays defining diffracted ray-tubes are created according to error measures giving direct control over the wave front sampling error and over the approximation of field divergence, a unique and very valuable feature of ABT.

Another important element of computational efficiency comes from the fact that ray-tubes are generated following an adaptive sampling scheme. The initial unperturbed wave front emanating form the source is partitioned in as few as 6 or 12 or 20 tubes –regular polyhedrons are used as a basis to generate this initial partition- and are split only when interactions occur and according to their geometry. It is also to be noted that since the cost of tracing non-interacting tubes is marginal, the added effort in tracking propagation in uninteresting directions is irrelevant in all practical cases. The full knowledge of the geometrical parameters of the wave front also allows the identification of ray-tubes carrying marginal amounts of power and offers the possibility of eliminating them from the processing lists when the power density –estimated on the basis of isotropic source radiation- drops below a given threshold.

To complete this short presentation of the main features of ABT it is worth nothing that as the asymptotic flux tubes relevant to each chain of interactions are uniformly traced from the source to the observation area the calculation of the field can be based on simple and efficient interpolation of the contribution from each chain. The interpolation is based on the knowledge of the wave front parameters directly associated with the tube geometry and interaction history and can therefore be carried out in a very accurate way. Alternatively, the same information can be used to find *a posteriori* the ray path leading to a selected observation point. The fact that the set of ray tubes associated to a single interaction chain completely determines the associated shadow boundaries, within a polygonal approximation, makes this process much easier, faster and safer than in traditional backward ray-tracing even when applied in combination with some forward schemes.

Computational results

ABT will soon be validated by means of measurements on a scaled model of satellite. Meanwhile a set of numerical tests has been performed by comparisons with other UTD software. Results obtained comparing ABT and NecBsc [4] are shown in the following.

Fig.1 shows the satellite model used for comparison together with a doubly-diffracted ray congruence on edges 11 and 13 that impinges the observation segment labelled 21. The model consists of 10 facets, 20 edges and an isotropic source. The results obtained for reflections of any order agree quite well, however ABT is faster (up to 7 times) for reflections orders greater than the second even in the present not optimised implementation. A good agreement has been obtained also for first order diffraction and second order diffraction by parallel edges (NecBsc does not handle higher diffraction orders).

A disagreement, instead, appears for second order diffraction by oblique edges. An in depth analysis has determined that the source of the discrepancy in the field values lies in the computed position of diffraction points on the wedges. The generalised Fermat’s principle (GFP), applied by means of the algorithm described in [2], was used as reference to determine the displacement of diffraction points calculated by ABT and NecBsc for each ray path.

Fig.2 shows the displacements for the pair of wedges (11,13). Curves 11N and 13N (11A-13A) are the displacements on wedge 11 and 13, respectively, between corresponding diffraction points calculated by GFP and NecBsc (ABT). We observe that ABT is significantly more accurate than NecBsc. The error threshold for diffracted ray-tube generation, defined in [2] and mentioned before, was set to 10^{-3}, a suitable value for the microwave frequency range. Calculations with higher accuracy are possible if desired.
Fig.3 shows the difference in the path length calculated by NecBsc (ABT) with respect to GFP. Beside the smaller error of ABT, this figures illustrates the effect of the approximation of the true Keller-cone rays by means of astigmatic ray-tubes generated using a polygonal approximation of the virtual source caustic.

Conclusions

The Astigmatic Beam Tracer is a novel technique that overcomes some shortcomings of the existing ray-tracing. A recursive spatial subdivision strategy combined with a selection mechanism is used to trace wavefront propagation throughout the environment. These features allow to achieve good accuracy in field calculations. Comparisons with other tools seem to confirm the expectations.

References

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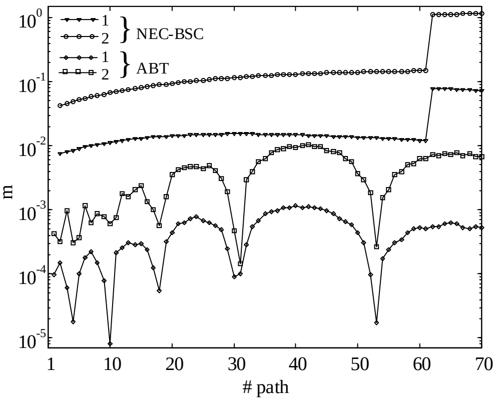

Fig.2 - Displacement of diffraction point on wedges 11 and 13 for 70 ray paths computed with NecBsc and ABT with respect to Generalised Fermat Principle.

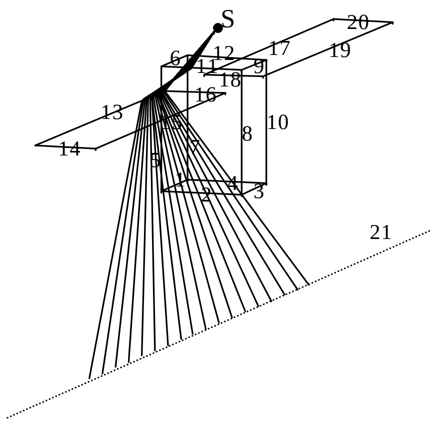

Fig.1 - Satellite model with a double diffracted ray congruence by edges 11 and 13. Line labelled 21 is the observation segment. Source point also shown.

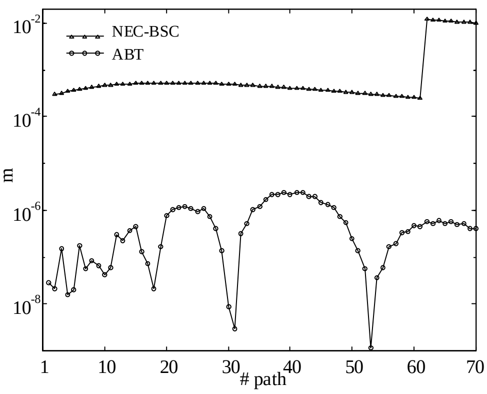

Fig.3 - Difference of path-lengths between GFP and NecBsc (ABT) calculations.