Simulating complex environments for the assessment of millimeter waves sensors

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***Abstract*— Guidance of weapon systems relies on sensors to analyze targets signature. Defense weapon systems also need to detect then identify threats also using sensors. One important class of sensors are millimeter waves radar systems. However, such sensors systems are so complex that they need simulation to be tested. In this context, the SE-Workbench-RF tool is presented. The basic technical choices toward an efficient solution for radar simulation are discussed and the newly included GPU implementation is described from an accuracy and computation costs point of view. RBGM radar simulation is presented as an application example of the computation kernel.**

Keywords—Target and background modelling, SE-WORKBENCH, millimeter waves, ray tracing, asymptotic methods, GPU computation, , RBGM radar

I. Introduction

Signature prediction is very important in the defense domain in order to detect and identify potential threats but also for self-protection system assessment. Indeed, counter measures and camouflage strategies are very dependent on signature prediction capabilities. Radar sensors are very pertinent especially for detection and recognition but also for guidance of weapon systems, which is particularly the case of high frequency radars: indeed, they can perceive details of the size of the wavelength, which is very relevant for high-resolution imagery. For that point of view, radar can efficiently complement electro-optic sensors, especially in the frame of data fusion and Enhanced Vision Systems.

In 2005, OKTAL-SE, in partnership with ONERA French research laboratory and the Science University of Toulouse, set the basis to an original modeling of the radar signatures of complex targets including dielectric scattering on edges that has then been implemented in OKTAL-SE radar simulation tools. The resulting software, SE-Workbench-RF, has been put through its paces by many projects, in the defense and civilian domains, in France, Sweden, Germany, UK, Korea, Singapore and China. This paper presents the technical basis of the SE-Workbench-RF tool, branching out to new techniques for computation time reduction and/or accuracy improvement.

II. Basis of SE-Workbench-RF

A. Asymptotic methods

The physically exact way to compute EM field are the "full wave" methods that are strictly based on the resolution of the Maxwell equations.

Full wave methods often use finite element solvers since they apply the four Maxwell equations for each finite element, assuming the fields remain constant within each finite element. Due to the phase rotation induced by the propagation of the wave, the size of a finite element must be smaller than the wavelength. In computational electromagnetism, a tenth of the wavelength is usually considered a correct first order approximation. As a result, the amount of finite elements, i.e. the time of computation and the memory allocation, increases as the wavelength decreases (i.e. as the frequency increases) and as the size of objects increases. Consequently, full wave methods are not applicable to millimeter waves and large 3D scenes.

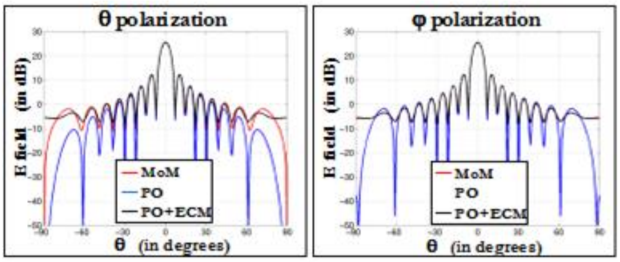

Fig. 1. Comparison of SE-Workbench-RF, with and without diffraction on edges (Equivalent Courant Method) against an ELSEM3D Method Of Moments ONERA software [3]

In order to bypass this impediment, SE-Workbench-RF is based on a computation kernel, SE-RAY-EM, that uses asymptotic methods [2] coupled to ray-tracing [1] to compute scattered electromagnetic fields by large objects at high frequency (the size of the objects is supposed to be large compared to the wavelength). Those two combined techniques identify a set of elementary EM "contributors" whose physical and geometrical properties are known. The resulting field consists in the coherent sum of the response of all these contributors.

In Fig. 1, the theoretical response of a metallic plate (obtained through a Method of Moment computation) is compared with the value given by SE-Workbench-RF: the results are very similar to the "exact" method for a much lower computation time.

Where a few GHz is a high limit for "exact" methods used on this type of objects, it is almost a low limit in terms of physical validity for asymptotic methods. The standard computation range addressed by this approach is roughly between 1 to 100 GHz on far more complex scenes (natural terrain of several kilometers wide with several complex targets inside).

B. Ray-tracing

Ray-tracing is done through the Shooting and Bouncing Rays (SBR) technique. Rays are traced from transmitters through a grid (Fig. 2) and grouped four by four into beams. Then the intersections of theses beams are computed (Fig. 3). There are two types of interactions that are based on three formulations:

- Geometrical Optics (GO) when the beam is reflected by a metallic or dielectric surface,
- Physical Optics (PO) towards the reception points at each interaction.
- Equivalent Current Methods (ECM) for computing edge diffraction toward the reception points.

Fig. 2. SE-RAY-EM emission grid

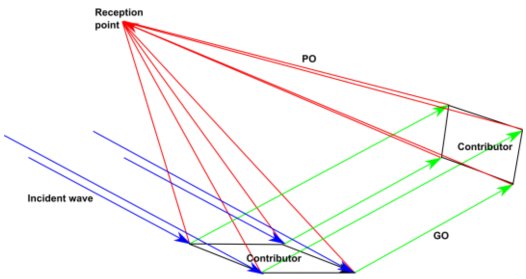

Fig. 3. Principle of beam interactions

C. Adaptive anti-aliasing

The SBR technique has been optimized to calculate efficiently the intersections by using an adaptive anti-aliasing mechanism. It consists in dividing each beam into four new beams (quadtree), when and only when needed, especially when aliasing is detected on the path of a beam (Fig. 4).

Adaptive anti-aliasing is the key for time-efficient EM computations, as the size of the primary grid can be coarse, as long as it is fine enough to detect major features of the scene. Smaller details will be caught by the anti-aliasing during the ray-tracing as needed: adaptive anti-aliasing enables to reduce the number of contributors for which EM models are applied by concentrating them where they are needed.

For example, at 100 GHz, sampled element should be a fraction of λ, say 1 mm (λ/3). For a target of 5 meters, it would mean a grid of 5 000 x 5 000 = 25.10^6 pixels. With adaptive anti-aliasing, the grid could have an initial resolution of 1 m, with anti-aliasing down to 1 mm. These small contributors will only happen on the target boundaries.

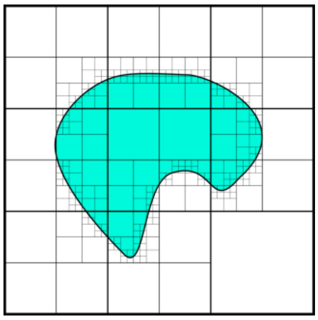

Fig. 4. SE-RAY-EM EM adaptive anti-aliasing principle (a square = a beam cross section)

Beyond the object sampling, adaptive anti-aliasing can be used in order for the computation kernel to always get back to a context where it is applicable. For instance, even if the source is close to the target, the EM contributors are subdivided until the far field approximation applies to each of them. In the same way, contributors on a curved surface are subdivided until they can be considered flat. Thus, results can be as precise as possible for a non-exact method, while concentrating the computation effort only where it is needed.

III. SIMULATION OUTPUTS

A. Test by comparison with specific data measured in an anechoic chamber

In this example (Fig. 5), the exact 3D model of the object has enabled to compare measurements with averaged results given by SE-Workbench-RF in cooperation with FGAN FHR (now Fraunhofer FHR). The object is 30cm wide, 80cm long and made of metal. Measurements were made at 35 +/- 1 GHz.

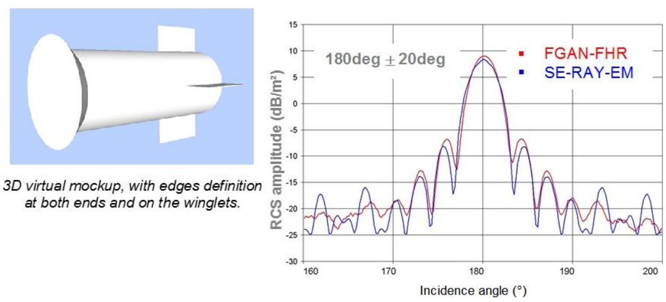

Fig. 5. Comparison of SE-Workbench-RF, with real dedicated measurements

B. Test by comparison with real operational EM measurements

In this example (Fig. 6), in the frame of a NATO group and in cooperation with ONERA and ARL, SE-Workbench-RF has been validated through the comparison of ISAR images simulated using SE-RAY-EM with a set of measurements provided by ARL on a test military vehicle.

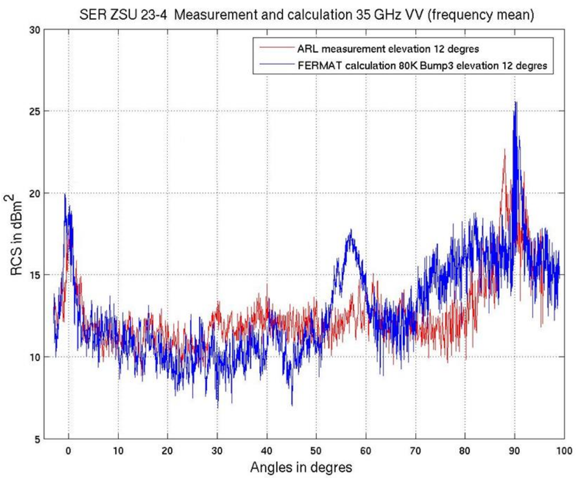

Fig. 6. Comparison of SE-Workbench-RF, with real operational complex measurements.

IV. GPU Computation

The computation method of SE-RAY-EM, i.e. combining the results of elementary EM contributors, has an interesting consequence: it is readily parallelizable. More precisely, Graphic Processors Unit (GPU) have proven to be very efficient for optimizing General Purpose (GP) computations, and particularly ray- tracing applications [2] as SE-RAY-EM. However, several issues have to be taken into account [4].

A. Parallelization

As we have seen, ray-tracing is convenient for parallelization. However, it was initially done by casting 4 rays that form a square-section beam. This beam shares rays with adjacent beams. In order to fully parallelize the process, GPU computation casts conical beams as a volume, where each beam can be processed on its own.

This solution has an interesting by-product: the whole conical volume is scanned for any object, so it is impossible to miss a small object, even if it is smaller than the grid pixel size. The initial grid size constraint for anti-aliasing stated in II.C can be further relaxed.

Then, it has also been noted that frequency only impacts the EM computation, not the generation of geometrical contributors itself. In this new CUDA version of SE-RAY-EM, we postpone the frequency-dependent computations for as long as possible by generating all geometrical contributors first. It allows to maintain good computation file for multi-frequency simulations (for instance to simulate FMCW radars).

B. GPU load

The main drawback of GPU computation is that it should be loaded sufficiently and consistently in order to be efficient. Adaptive anti-aliasing, however, divides sub-beam on an as-needed basis, which can lead to an unpredictable explosion of beams that will need to be stored in buffers on the GPU, impairing the performances.

To solve this issue, beams are serialized: once subdivided, the parent beam is replaced in-place by its first child. Once processed, the first child will be replaced in-place by its sibling. On the contrary, to avoid under-using the GPU, beams can be de-serialized as needed.

Finally, the computation was made as less dependent as possible on the total number of facet. To this end, OKTAL-SE has developed a method based on the BVH (Bounding Volume Hierarchy) method. The BVH is a tree structure applied to the terrain surface and to the objects where all facets of an object are wrapped in simple bounding volumes that form the leaf nodes of a tree. Nodes are grouped within other larger bounding volumes, and so on, recursively. Ray intersection is computed volume by volume until the leaf-most nodes, which limits the number of facets to take into account while computing intersections.

C. Results

The first test (Fig. 7) consists in comparing qualitatively the radar cross section obtained between the GPU and CPU implementation of SE-RAY-EM and the reference from the ONERA MAXWELL3D software [3], which is based on Integral Equation EM approach and Moment Method numerical implementation.

The target is an aircraft, 1000m away, at a frequency of 600 MHz, and the figure focuses on the 180° incidence angle where RCS is maximum. Results computed by the CPU and GPU codes are very similar and include the main features.

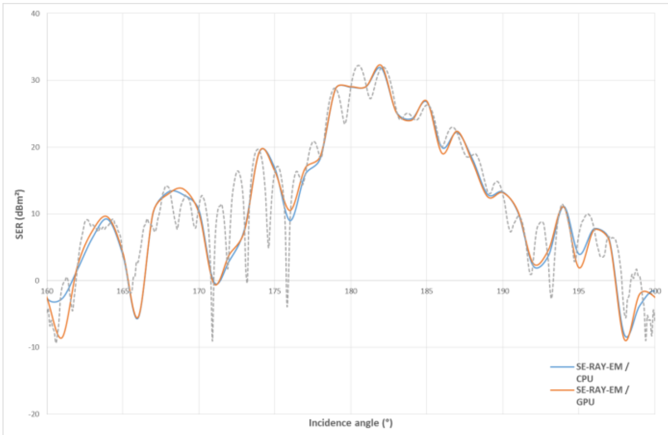

Fig. 7. RCS of an aircraft computed with ELSEM3D (gray dotted line), SE-RAY-EM CPU (blue) and GPU version (orange)

The second test set up consists in the computation of the RCS at 10 000m of a tank with one or 151 frequencies from 8 to 11 GHz.

To compare the performances, the computations have been performed using the standard version of SE-RAY-EM on CPU and using the new parallel implementation on GPU. Both were conducted on a desktop PC with Intel Core I5 3470 (GPU) and Nvidia GeForce GTX Titan (GPU).

TABLE I.

TABLE II. COMPUTATION TIMES

	Intel Core I5	**GPU GeForce Titan**	**GPU/CPU computation time ratio**
Mono-frequency	12.17	0.111	0.91%
151 frequencies	80.40	0.735	0.91%

V. APPLICATION TO RBGM RADAR IMAGE SIMULATION

The main interest of improving the computation time is that time-costly simulations such as RBGM outputs generation based on realistic EM propagation on full scenes is now within reach.

Fig. 8. Synthetic environment (SE)

The following images show the result obtained with the SE-Workbench-RF dedicated tool SE-RAY-RADAR on a realistic scene. The scene is of dimension 500 x 500 m and contains buildings and clutter, with physically realistic materials (concrete, grass …). Computation is done with CPU (Fig. 9) and GPU code (Fig. 10), and identical ray-tracing accuracy parameters.

TABLE III. FULL SCENE PARAMETERS

Frequency / wavelength	30 GHz / 0.01 m
Near range	150 m
Range gate size / number	0.5 m / 1000
Azimuth sampling size / number	0.1 ° / 451
Minimum grid size	0.0625 m
Computation time GPU/CPU	263 s / 1009 s

The CPU image includes computational artefacts and lacks features such as dihedral effects. These issues would otherwise be resolved with higher accuracy parameters (and consequently longer computation time). Not only is the GPU image faster to obtain, but it is also more accurate.

VI. CONCLUSION

By coupling ray-tracing implemented in an efficient algorithmic way and asymptotic methods, we have shown that it is now possible to simulate EM propagation on geometrically and physically complex scenes at millimeters wavelengths. This method can then be implemented on the GPU to obtain accurate and well-rendered RBGM radar or SAR simulations of these scenes with reasonable computation times.

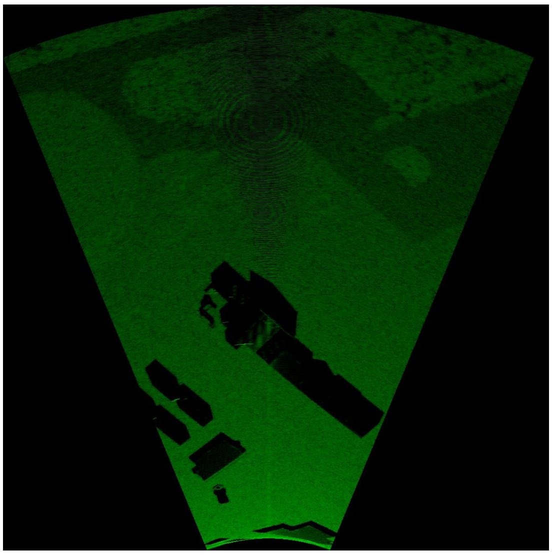

Fig. 9. SE-Workbench RBGM image of the SE - CPU

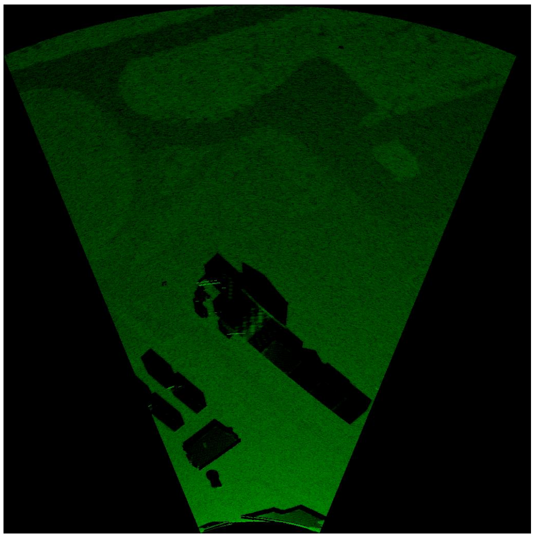

Fig. 10. SE-Workbench-RF RBGM image of the SE - GPU

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