Comparison of Ray-tracing and MoM RCS Solution for Large Realistic Vehicle

Robert Kipp [1] and Milos S. Pavlovic [2],

[2] WIPL-D d.o.o.
Bulevar Mihajla Pupina 10E/1, 11070 Belgrade, Serbia
milos.pavlovic@wipl-d.com

[1] Delcross Technologies, LLC
2009 Fox Drive, Unit K, Champaign, IL 61820, USA
kipp@delcross.com

Abstract: The most difficult cases for EM analysis are large and realistically complex scatterers. Method of moments (MoM) allows efficient and accurate simulation of structures of small to moderately large electrical size. Traditional MoM scales poorly to higher frequencies on a given object, but this problem has been significantly mitigated through such innovations as higher-order basis functions (HOBFs) and the multi-level fast multipole (MLFMM) algorithm. Asymptotic methods, also known as high-frequency (HF) methods, are widely used to efficiently compute the scattering by objects whose overall size and features are electrically large. In this paper, an asymptotic ray-tracing code (Savant) and an MLFMM MoM code (WIPL-D Pro) are used to predict bistatic RCS of an electrically large, realistic vehicle. The accuracy of each method is carefully controlled to effect meaningful comparisons. The results demonstrate the efficacy of MLFMM in significantly extending the frequency reach of traditional MoM and that, at high-enough frequencies, complex objects can be simulated by asymptotic ray-tracing methods with comparable accuracy to direct methods.

Keywords: MLFMM, GO, PO, SBR, WIPL-D Pro, large scatterer, MoM, bistatic, Savant

1. Introduction

Electromagnetic scattering problems are subdivided into 3 groups in respect to scattering body size: the low-frequency, resonant, and high-frequency problems. These terms do not pertain to absolute operating frequency but, rather, to the target size measured in wavelengths.

The most difficult cases for EM scattering analysis are electrically large and realistically complex scatterers. Obstacles and their features are considered to be in the high-frequency (HF) region when their dimensions exceed roughly 10 wavelengths. This region is also referred to as the optics region. In the optics region, scattering mechanisms are highly localized, with the notable exception of geometric optics (GO) multi-bounce. Here, various target elements typically act independently of one another (if an element is not in the shadow region, shaded from the incident wave by another element).

The calculation of radar cross-section (RCS) on large and complex bodies is of great practical interest. Many papers have been published on general and specific topics in electromagnetic scattering in the last 100 years.

2. Method of Moments Solution (WIPL-D)

One of the most powerful techniques used for RCS calculations is the Method of Moments (MoM). In this technique, the surface currents are divided into a collection of finite surface patches (*i.e.*, a CAD model mesh). The form of the solution is specified using surface current basis functions whose weighting coefficients are to be determined (so-called unknowns) [1].

A practical and general question is how to apply MoM to use less memory and perform the simulation in less time without sacrificing accuracy. One answer is to reduce the number of unknowns as much as possible. Common ways to do this are by careful selection of the linear operator equation, test procedure, and basis functions. For example, the Galerkin test procedure requires much fewer unknowns for stable and accurate solutions than other test procedures. The WIPL-D code used in this comparative analysis is a modern implementation of MoM.

In addition, WIPL-D surface currents are expressed in terms of polynomials. That is, its basis functions are higher-order polynomials instead of simple linear (*e.g.*, rooftop) functions. We refer to these as higher-order basis functions (HOBFs), and WIPL-D implements HOBFs up to order 8. Hence, in the case of an equal number of HOBFs and rooftops defined over a surface, HOBFs are capable of expressing a more dynamic current distribution. With conventional basis functions, 150-300 unknowns are required per square-wavelength of target surface area. The number of unknowns can be reduced to 40-70 per square-wavelength if HOBFs are used over triangles with an average length between 0.5 λ and 1 λ [2,3]. This number of unknowns can be further reduced to 25-32 per square-wavelength if HOBFs are used over quadrilaterals with average length between 1 λ and 2 λ [4]. The evaluation of these is vulnerable to problems in convergence and round-off errors, especially if the body is more than a few wavelengths in size, but the special features of WIPL-D MoM implementation overcome this (*i.e.*, improved integral accuracy and double-precision calculations). The solution is applicable to computations for complex targets comprising of hundreds or thousands of elements. A very efficient implementation of MoM enables WIPL-D to simulate a 3D structure with far less memory consumption than any other rigorous numerical code.

Since it offers accuracy beyond the reach of approximate and iterative techniques, and owing to limitations of computer memory, it is not simple to compute the MoM solution. The matrix elements are complex numbers; hence each requires 8 bytes of memory. Normally, a problem requires $8N^2$ bytes of memory for N unknowns. Thus, computer core memory limits the problem scale. Even larger simulations can be done in-core if 64-bit architecture is used instead of 32-bit. However, modern configurations are usually limited to 8 GB of RAM. WIPL-D Pro offers out-of-core calculation as well. This significantly extends the range of the application for large target RCS. For extremely large structures, however, simulation time becomes impractical.

If the RCS body is very large and complex, it is too costly and time consuming to perform all the calculations for direct solution of the interaction matrix. One technique that addresses this is Multilevel Fast Multipole Method (MLFMM). This very common and popular approach both decreases the memory consumption and accelerates the MoM matrix solution. MLFMM is basically an iterative solver, but one that treats interactions between near-neighbor basis functions differently than far-away interactions.

Basis functions are grouped in a multi-level, tree-like grid. Interactions between different groups are then computed instead of the interactions between individual basis functions [5]. Hierarchical grouping of basis functions is done in two levels according to a simple algorithm. The accuracy-speed-memory trade-off is controlled through two parameters: the coarse level group size and the relative distance threshold. This technique allows the dramatic saving of memory and time resources needed for simulation of various classes of electrically large structures.

3. SBR Solution (Savant)

Asymptotic methods, also known has high-frequency (HF) methods, are widely used to efficiently compute the scattering by objects whose overall size and features are electrically large. At high frequencies (or short wavelengths), propagation of EM waves can be approximated by ray bundles, and EM scattering is dominated by local conditions on the scattering body. Perhaps the oldest and most familiar theory is geometric optics (GO). The theory is not without its drawbacks, one of which is its failure to handle diffraction. Various enhancements have been proposed to overcome this limitation, including geometrical theory of diffraction (GTD), physical optics (PO), and physical theory of diffraction (PTD).

For the comparison with WIPL-D MoM, we use the Savant code, which implements the shooting-and-bouncing-ray (SBR) asymptotic method [6], [7]. In this method, many GO rays are launched toward the scattering object using a general-purpose geometric ray tracer for complex CAD models. This effectively determines which surfaces are lit by the source. The launched GO rays are vector-field-weighted by the source and represent diverging volumetric ray tubes that "paint" surface currents on the CAD model according to PO (*e.g.*, $2\hat{n}\times Hinc$ for a PEC surface, where $Hinc$ is represented in the ray). These induced currents are radiated to field observation points or receivers. Next, a set of reflected rays is generated from the first-bounce ray intersection points on the body, with their vector fields updated according to GO. Some of these reflected rays escape, while the remainder hit other surfaces of the CAD model, painting second-bounce currents. The process is continued, and in this way, SBR implements multi-bounce scattering mechanisms.

Among asymptotic ray tracing methods, it is important to bear in mind the joint role of GO and PO in SBR. As in GTD codes, SBR uses GO as an efficient though approximate means of accounting for the dominant mechanisms of interaction between surfaces of the scatterer. However, unlike GTD codes, the GO rays are not of direct interest in determining the scattered fields at observation points and receivers. Instead, that role is played by radiation of PO currents induced by the GO rays. As such, the terminal condition of GO rays is not of interest in SBR. Thus, a search for a few critical rays' paths is replaced with shooting many rays in order to sample the geometry in detail. This results in the ability to handle more varied and realistic geometric shapes.

In SBR, run time scales as *O(Nr)*, *O(No)*, and *O(Nf)*, where *Nr*, *No*, and *Nf* are the number of rays, observation points, and frequencies, respectively. For a convergent result, *Nr* is generally proportional to the surface area of the scatterer measured in square wavelengths. When all of these quantities are large enough, run time scales as $O(Nr\cdot No\cdot Nf)$. However, as a practical matter, this condition is not often satisfied. For instance, the geometric ray-tracing burden is independent of *No* and *Nf*. Hence, when $No=1$, one can often increase *Nf* from 1 to 50 - 100 before doubling run time. Eventually, however, the run time will scale with the number of frequencies. The same can be said for the number of observation points, though its impact is felt sooner. For instance, we observe that for $Nf=1$, run time doubles for *No* going from 1 to 20. Also, once *No* is large enough that ray processing dominates over geometric ray tracing, run time doubles when *Nf* increases from 1 to 4 or 5, at least in Savant's implementation. The memory footprint of SBR does not grow with any of these quantities, other than that needed to hold input and output, and is generally quite modest compared to the capacity of modern systems.

SBR was originally implemented to efficiently model RCS of electrically large cavities [6], and later extended for radar signature modeling of realistic targets [7]-[10]. It was subsequently adapted to installed antenna applications [9]-[10]. Savant is an SBR implementation for predicting the radiation pattern and cosite coupling of antennas installed on platforms and in other complex environments. Specifically, it accepts input of a 3-D CAD model, coating material descriptions, and a characterization of the freestanding antenna. Its outputs are far-field antenna patterns, near-field distributions, and coupling levels to receiving antennas. In this paper, we have adapted Savant to serve in the RCS application. Specifically, Savant is operated in its antenna-to-antenna coupling mode, but with the Tx and Rx antennas placed in the far field of the scatterer. The RCS is then backed out from the scattered field contribution to the coupling Tx-to-Rx coupling ratio, much as would be done in an actual RCS measurement.

4. Example of Helicopter Bistatic RCS

The rescue helicopter model used for comparative RCS calculations is shown in Fig. 1a. The total length is 19.1 meters, while the main rotor blades span is 15.3 meters. The helicopter is 4.7 m tall. The model is excited with a plane wave a) in the aircraft symmetry plane, coming in from the nose and then b) in x0y plane, coming 45 degrees off the nose. Simulation frequency is 0.1, 0.3, 1 and 3 GHz, (at maximum frequency, the helicopter is about 190 wavelengths long). A rigorous MoM formulation would result in 472,264 unknowns for HOBFs, requiring about 1700 GB of memory. This is roughly equivalent to about 5 million unknowns if using conventional basis functions, such as Rao-Wilton-Glisson (RWG) triangle basis functions.

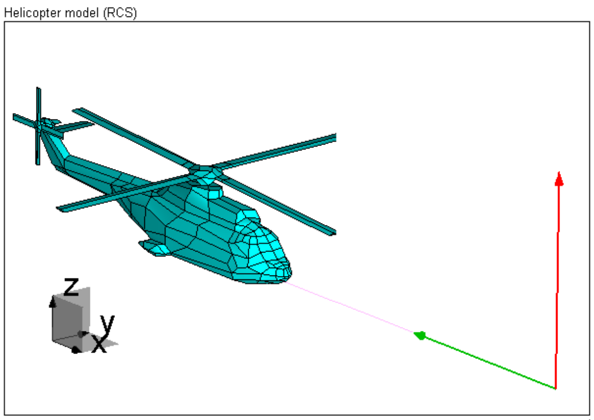

Fig. 1a. WIPL-D model of rescue helicopter

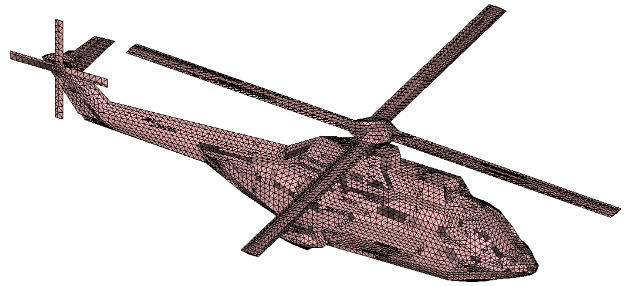
Fig. 1b. Savant input model based on WIPL-D output quad mesh from 3 GHz simulation, 16174 triangles

In executing a meaningful comparison of results between the two simulation methods (*i.e.*, SBR and MLFMM), the first step was to control accuracy of both approximate techniques. For the Savant code, accuracy testing was performed for ray density convergence, far-field convergence and mesh dependence. Savant is an antenna code (not a radar code) and it does not support far-field illumination, but antennas Tx and Rx can be placed at arbitrarily large distance away (far-field convergence). In this case Tx and Rx were placed at 10,000 m range from target, which is well into the target far-field as 3 GHz and below.

The accuracy of MLFMM is controlled by defining relative distance (Rdist) at which the groups are considered to be far-apart. The adopted value of Rdist is 2. Results imply that it is enough to adopt 0.003 for the residual error of iterative procedure. The study of convergence is performed in a separate paper.

After determining suitable simulation parameters, the results were compared using the following procedure. The accuracy metric is mean error (in dB) calculated for all points of the scattered field that have the value above a specified threshold (20 dB, 30 dB, 40 dB, 50 dB).

$$Mean\ Error\ [dB] = \frac{\sum_{i=1}^{N} \Delta G_i\ [dB]}{N} \qquad \Delta G_i = \begin{cases} 0, & G_T < G_{\max} - R \\ \left|G_T - \hat{G}\right|, & G_T > G_{\max} - R \end{cases}$$

Here R stands for threshold, N for total number of directions, G_T is gain considered as accurate.

Table 1: Savant and MLFMM compared with direct MoM method

Threshold [dB]	0.1 GHz, Phi=0 degrees		0.3 GHz, Phi=0 degrees		1 GHz, Phi=0 degrees	
	MLFMM[dB]	**Savant**	**MLFMM [dB]**	**Savant[dB]**	**MLFMM [dB]**	**Savant[dB]**
20	1.01766	6.40633	0.18772	1.87674	0.06715	0.25995
30	1.01766	6.40633	1.1292	6.19175	0.32268	1.27631
40	1.01766	6.40633	1.25875	6.35642	0.71398	4.44554
50	1.01766	6.40633	1.27222	6.36716	1.9915	4.81494
Threshold [dB]	0.1 GHz, Phi=45 degrees		0.3 GHz, Phi=45 degrees		1 GHz, Phi=45 degrees	
	MLFMM[dB]	**Savant**	**MLFMM [dB]**	**Savant[dB]**	**MLFMM [dB]**	**Savant[dB]**
20	0.65123	4.92506	0.02916	0.20174	0.014	0.02758
30	0.89345	5.33237	0.3214	2.49551	0.10268	0.13191
40	0.89345	5.33237	0.68495	3.96294	1.02566	1.59286
50	0.89345	5.33237	0.68495	3.96878	2.27036	3.77014

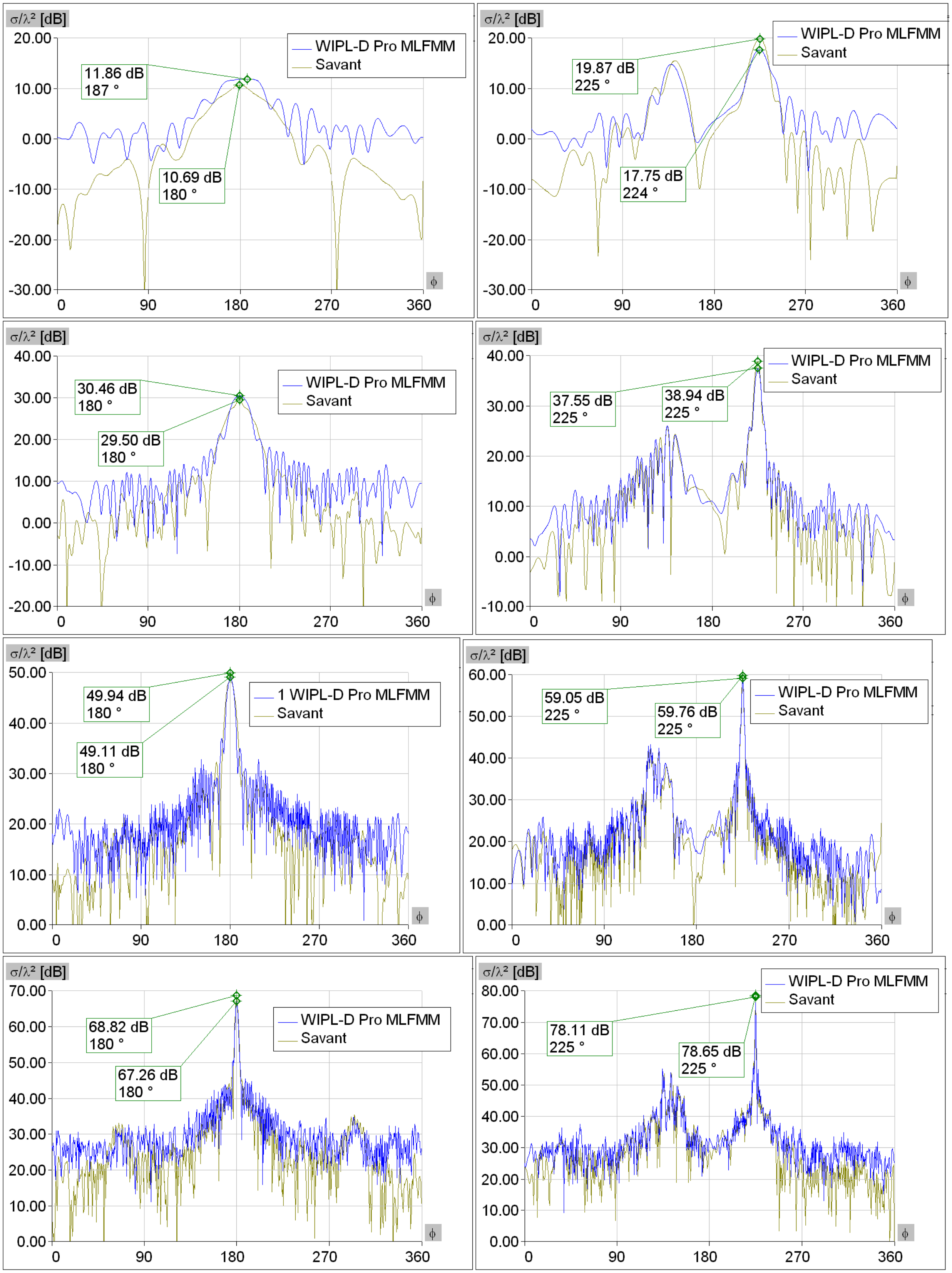

Fig. 3. Resulting RCS in the incident plane, calculated by the MLFMM and Savant at 0.1, 0.3, 1 and 3 GHz, respectivelly for Phi = 0 degrees and Phi = 45 degrees, respectively

Table 2: Savant and MLFMM compared at 3 GHz, Phi = 0 degrees and Phi = 45 degrees

Threshold [dB]	**Difference [dB]**	
	Phi = 0	Phi = 45
20	0.06349	0.00494
30	0.39975	0.05666
40	3.95836	0.28602
50	6.90041	3.42408

Table 3: Savant and MLFMM Simulation times

Frequency [GHz]	Phi = 0 degrees		Phi = 45 degrees	
	MLFMM	Savant	MLFMM	Savant
0.1	28	1.1	29	1.5
0.3	86	4.9	96	6.7
1	510	37	638	51
3	30486	317	36131	383

By applying the MLFMM to the higher order MoM, memory requirements are reduced from 1700 GB to 8.382 GB for frequency of 3 GHz. The simulation, performed on a desktop PC comprising a 2.83 GHz Intel(R) Core(TM)2 Quad Q9550 and 8 GB of RAM, requires 8.47 hours to produce the RCS displayed in Fig. 3. The corresponding result was obtained by SBR in 316.8 s using 9.3 MB of RAM on a 2 GHz Intel Core Duo. Multi-core capabilities of these machines were not exploited in either MLFMM or SBR case.

5. Conclusions

The higher-order MoM is able to simulate structures far beyond reach of any other rigorous CEM method, but it reaches it limits at highest frequencies. MoM codes offer results that can be considered as accurate. Significant computational efficiency of the method can be extended by applying MLFMM to higher order MoM. This is a very efficient algorithm for simulation of various electrically very large structures which are of great interest in several industry areas. If the frequency is large enough, SBR can be successfully used. This technique provides both impressive speed and low memory consumption. With excellent accuracy of below 1 dB for a threshold of 30 dB bellow peak value, these new approximate methods allows fast and efficient simulation. The mentioned techniques and methods are also complementary. These codes allow multiple choices for accuracy-speed-memory trade-offs.

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