Analysis of scattering from electrically large objects using fast far field iterative physical optics

De Vita, Paolo; Mori, Alessandro; Pandolfo, Luca; Bercigli, Mirko; Bandinelli, Mauro; Carluccio, Giorgio; Albani, Matteo

DOI
10.23919/EuCAP.2017.7928709

Publication date
2017

Document Version
Final published version

Published in
2017 11th European Conference on Antennas and Propagation, EUCAP 2017

Analysis of Scattering from Electrically Large Objects Using Fast Far Field Iterative Physical Optics

Paolo De Vita[1], Alessandro Mori[1], Luca Pandolfo[1], Mirko Bercigli[1], Mauro Bandinelli[1],
Giorgio Carluccio[2], and Matteo Albani[3]
[1] IDS Ingegneria Dei Sistemi S.p.A., Pisa, Italy,
{p.devita, a.mori, l.pandolfo, m.bercigli, m.bandinelli}@idscorporation.com
[2]Department of Microelectronics, Delft University of Technology, Mekelweg 4, 2628CD Delft, The Netherlands
g.carluccio@tudelft.nl
[3] Dept. of Information Engineering and Mathematics, University of Siena, Siena, Italy,
matteo.albani@dii.unisi.it

***Abstract*——In this paper, a fast iterative physical optics (FIPO) algorithm is proposed for analysis of scattering from electrically large objects involving multiple reflections. When the scenario to be analyzed is electrically very large, a Fast Far Field Approximation (FaFFA) algorithm, based on a domain decomposition of the scatterer surface, can be conveniently used to greatly speed-up the calculation of the induced currents at each step of the iterative procedure. In this work, an efficient and accurate interpolation scheme has been combined to the standard FaFFA algorithm implementation further reducing the complexity of the computation.**

***Index Terms*—Electromagnetic scattering, fast algorithms, high-frequency techniques, iterative physical optics, physical optics.**

I. Introduction

The Iterative Physical Optics (IPO) is an iterative high-frequency technique, which was originally developed for analyzing the scattering from open-ended cavities with perfectly electrically conducting (PEC) walls [1], [2]. In particular, it was developed to analyze arbitrarily shaped cavities for which analytical waveguide modal methods [3] are not applicable. In [4]–[6] it was extended to the case of impedance boundary conditions, whereas in [7] the possibility of analyze dielectric thin slabs was also been investigated. More recently it was applied to compute the scattered field and the radar cross section of electrically large and realistic complex targets [8], [9], such as tanks, airplanes, etc.

With the aim of analyzing electrically larger and larger objects, the authors made a strong effort to reduce the computational burden and in accelerating the convergence of the IPO algorithm. Techniques based on the domain decomposition of the scatterer surface were introduced in [5], [10], [11]. In particular, in [5] and in [10] the Fast Far-Field Approximation (FaFFA) algorithm [12] was adopted for accelerating the computational burden relevant to the computation of the interactions between the various elements in the scenario under analysis at each iteration. Furthermore, in [5], [10], iterative relaxation techniques, such as the Jacobi Minimal Residual (JMRES), were used in order to control the convergence of the IPO algorithm.

Recently, in [13] the authors discuss the possibility of parallelizing and accelerating the computational burden of the IPO algorithm by using Graphics Processing Units (GPUs) showing how the combination of algorithm acceleration with hardware acceleration can have tremendous impact.

In particular, the combined use of FAFFA and an interpolation scheme allows a strong reduction of the computational time respect to other implementation of the algorithm as in [10], [14].

Some background of the IPO is presented in Section II, although the reader is referred to other sources such as [1]–[11] for more information. Section III is intended to cover some practical aspects of the implementation of the FaFFA algorithm. In Section IV, numerical results for a benchmark problem are presented.

II. An Overview of the IPO Algorithm

A. Electromagnetic Formulation

The Iterative Physical Optics (IPO) algorithm is based on the application of the equivalence theorem for the description of the scattering of a complex scenario. Once that the problem is formulated in terms of an integral equation (IE), it can be proved that, if no shadowing rules are introduced, for PEC scattering objects IPO algorithm coincides with the Jacobi iterative solution of the relevant IE. Typically such approach presents a slow convergence, but accurate results. In order to speed up the algorithm, but loosing accuracy, shadowing rules based on Physical Optics (PO) approximation can be introduced.

In the developed formulation, the equivalent currents are estimated by using the PO approximation for both impenetrable (PEC or impedance boundary condition) and penetrable (thin dielectric slabs) objects. The iterative process allows reconstructing the interactions between the objects without resorting to ray-tracing. In particular, the algorithm reconstructs the reflections from the objects and the forward scattering which produces a shadow behind an object, and then the masking of the incident field on another object or portion thereof located behind the first. At each step further reflection/masking is introduced to the description of scattering. The estimate of equivalent currents is therefore similar to that produced by a tracking algorithm in Geometrical Optics (GO) rays up to an order of interaction equal to the number of steps in the IPO algorithm. On the other hand, the IPO algorithm avoids the ray tracking operation which is replaced by the calculation of the scattered field from the surfaces at each iteration. In addition, the IPO algorithm, compared to the multiple-reflection GO ray-based algorithm, also introduces diffractive contributions (in PO approximation) which, although not asymptotically correct, avoid the sharp boundaries which are present in the estimate of GO ray-based current.

III. Fast Far Field Approximation Algorithm

When the scenario to be analyzed is electrically very large, the IPO algorithm complexity becomes too high to maintain an acceptable run time. In such a case the FaFFA algorithm [5], [10], [12], can be conveniently used to accelerate the calculation of the induced currents at each step of the iterative procedure as well as the PO currents produced by the source and the scattered field. A standard scheme of the FaFFA algorithm was implemented and further accelerated by means an interpolation step.

A. Standard Algorithm Implementation

The FaFFA algorithm is based on a domain decomposition of the structure. The current elements (in which the scenario has been discretized) are grouped into boxes, where the interaction of currents in near-field box pairs, which are closer than a certain far-field distance, is directly evaluated. In our implementation, the well-known far-field distance according to $2D^2/\lambda$ is chosen, where D is the side length of a box (see Fig. 1).

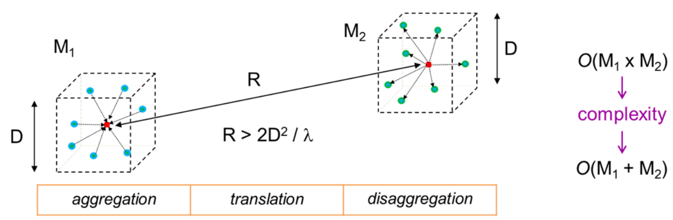

Fig.1 Computation of box interaction. Far-field case with FaFFA acceleration.

The interaction of current elements in far-field box pairs is done in a three-step scheme. First, the field contributions of all currents in the source box are computed respect to the center of the box (aggregation) and then translated on the center of the observation box (translation). Finally, the contributions for all test currents in the observation box are evaluated by applying a location dependent phase shift respect to the center of the observation block (disaggregation). Such a procedure can be formulated, for a generic box pair n and m, as:

$$\vec{W}_m(\hat{R}_{mn})\cdot T(\vec{R}_{mn})\cdot \vec{V}_n(\hat{R}_{mn})$$

where V_n and W_m are the aggregation and disaggregation operators, and T the translation one, whose forms are

$$\vec{V}_n(\hat{R}_{mn}) = \sum_{\substack{source\ i\\ \in Box\ n}} (\boldsymbol{I}-\hat{k}\hat{k})\cdot \vec{s}_i(\vec{r}_i^{\,n})\; e^{jk(\vec{r}_i^{\,n}\cdot\hat{R}_{mn})}$$

$$\vec{W}_m(\hat{R}_{mn}) = \sum_{\substack{test\ t\\ \in Box\ m}} (\boldsymbol{I}-\hat{k}\hat{k})\cdot \vec{s}_t(\vec{r}_t^{\,m})\; e^{-jk(\vec{r}_t^{\,n}\cdot\hat{R}_{mn})}$$

$$T(\vec{R}_{mn}) = e^{-jk|\vec{R}_{mn}|}/|\vec{R}_{mn}|$$

where k is the propagation constant, $\vec{s}_i$ and $\vec{s}_t$ are the source and test current elements centered in $\vec{r}_i$ and $\vec{r}_t$.

Such a procedure reduces the complexity of the algorithm from $O(M^2)$ to $O(M)$, being M the average number of elements per block. It can be demonstrated that, with an optimally chosen number of currents per box $M \propto \sqrt{N}$, the overall computational complexity of the algorithm is $O\,(N^{3/2})$, with N denoting the number of current elements.

The far field distance above assumed as $2D^2/\lambda$ might be reduced/increased by a tradeoff between accuracy and speed. By setting a required accuracy and the corresponding far field distance, the FaFFA performance still depends on the dimension D of the decomposition blocks; therefore, to obtain the best performance, an automatic rule has been implemented in the code to find the optimal blocks dimension.

B. Interpolation Based Algorithm Implementation

A technique to further reduce the complexity of the computation consists of making use of an interpolation procedure in the aggregation and disaggregation steps. The radiation function of the box can be properly expanded through a set of spectral samples [12], [15]. By adopting this technique, named here as FaFFA2, it is not necessary to evaluate the aggregation and disaggregation for each pair of box anymore but only for a certain number of space directions, much smaller than the number of box pair. The box-to-box interactions are therefore obtained by interpolating locally over the latter directions. Well-known law to evaluate a proper number L of spectral samples and the relevant directions P are reported in [15], that are

$$P = 2(L^2+1)\,, \qquad L = kD + d(kD)^{1/3}$$

where d is a parameter used to control the accuracy. In this case the interaction among a pair of box would be

$$\sum_{q=1}^{Np} w_q \vec{W}_m(\hat{k}_q)\cdot T(\vec{R}_{mn})\cdot \vec{V}_n(\hat{k}_q)$$

where $\hat{k}_q$ are the eigenvalues of the spectral expansion, Np is the number of interpolation points and w_q are the interpolation weights. A Lagrange method is used to interpolate the samples locally around the $\vec{R}_{mn}$ direction. This technique reduced the complexity to $O\left(N^{4/3}\right)$.

IV. NUMERICAL RESULTS

In this section a numerical example is reported in order to investigate the speedup provided by the FaFFA algorithm (both for standard and for interpolation based implementation) with respect to direct element by element computation.

In the following, for the sake of brevity, the standard implementation of the algorithm will be referred to as FaFFA1 while the interpolation based implementation will be referred to as FaFFA2.

The "real life" benchmark problem we have selected is a 30 m Near Field Cassegrain antenna operating at 10 GHz (Fig. 2). In the simulation the surfaces of the reflectors were defined by using the data from a real 3D acquisition of the antenna surfaces. No kind of symmetry was exploited in the simulations.

Fig.2 The 30 m reflector antenna of the Helios Command Station in Weilheim (courtesy of DLR) [16].

As described in a previous work by the authors [16], by cascading the full-wave analysis of the illuminating source and the IPO method, it has been possible to configure a mixed-method computational process (see Fig. 3) capable of solving the problem up to X-band. The huge dimension of the problem – the total number of mesh elements is ~38,000,000– requires a highly optimized Fast Algorithm implementation.

As a preliminary step, we modelled the problem at 1.5 GHz for which reference results coming from direct computation are available. The Fig. 4 shows the comparison between the direct radiation pattern (the reference) and the FaFFA results in the elevation plane ϕ = 0°. The good agreement between the curves proves the accuracy of the FIPO algorithm and provides a validation of the method.

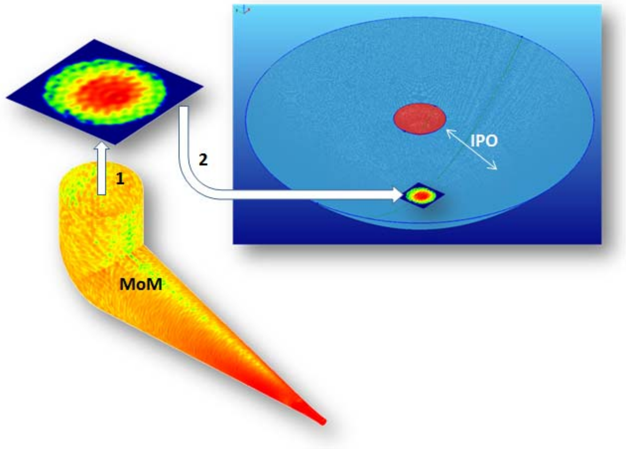

Fig.3 Mixed-methods computational procedure.

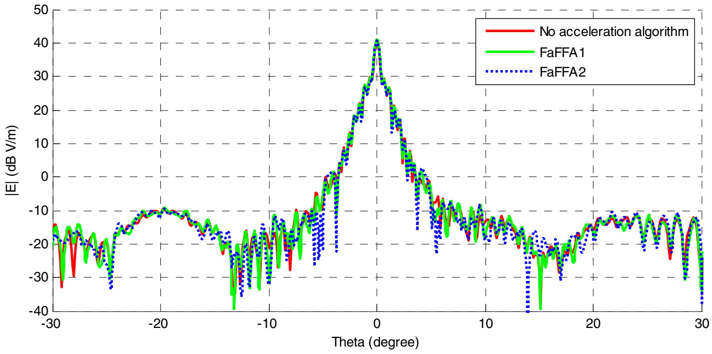

Fig.4 Simulated radiation patterns (on elevation plane ϕ = 0°) at 1.5 GHz.

The details of the computational performance at 1.5 GHz are summarized in Tab I. The hardware used for the simulation is the server Intel® Xeon® CPU E5-2660 v3 @ 2.6 GHz (20 cores in total).

TABLE I. COMPUTATIONAL PERFORMANCE AT 1.5 GHZ

Intel® Xeon® CPU E5-2660 v3 @ 2,60 GHz - 20 threads			
N° facets = 741,185 – JMRES residual = 5.0E-02			
Acceleration Algorithms	***RAM Requirements ratio***	***Speed-up***	***N° iterations***
None / FaFFa2	0.5	56x	4
FaFFA1 / FaFFA2	0.3	3.6x	4

The IPO algorithm applied to the benchmark problem at 10 GHz converges after 3 iterations, and the FaFFA2 predicted current distribution is shown in Fig. 5.

Pattern comparison on elevation plane ϕ = 0° for both FaFFA1 and FaFFA2 solutions are reported in Fig. 6.

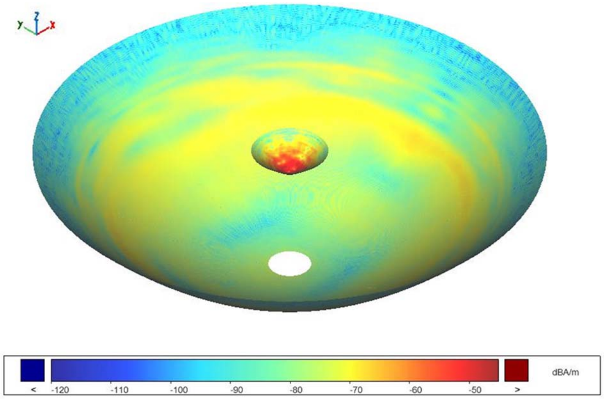

Fig.5 FaFFA2 induced surface currents distribution at 10 GHz.

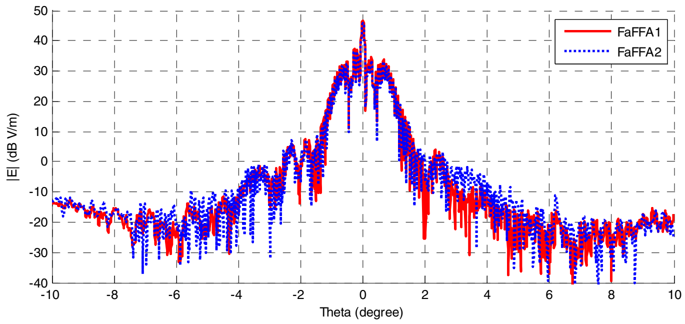

Fig.6 Simulated radiation patterns (on elevation plane ϕ = 0°) at 10 GHz.

The details of the computational performance at 10 GHz are summarized in Tab II. The hardware used for the simulation is the server Intel® Xeon® CPU E5-2660 v3 @ 2.6 GHz (20 cores in total).

TABLE II. COMPUTATIONAL PERFORMANCE AT 10 GHZ

Intel® Xeon® CPU E5-2660 v3 @ 2,60 GHz – 20 threads			
N° facets = 37,743,271 – JMRES residual = 5.0E-02			
Acceleration Algorithms	***RAM Requirements ratio***	***Speed-up***	***N° iterations***
FaFFA1 / FaFFA2	0.5	13.6x	3

V. CONCLUSIONS

In this paper, a fast iterative physical optics (FIPO) algorithm has been proposed for analysis of scattering from electrically large objects involving multiple reflections.

An efficient and accurate interpolation scheme has been combined to the standard FaFFA algorithm implementation further reducing the complexity of the computation.

The performance and the accuracy of the proposed implementation have been tested by a “real life” problem. The scatterer has been assumed as PEC, although extension to arbitrary local boundary conditions can be considered.

Although this work is limited to CPU implementation, the development of the interpolation based FaFFA algorithm for multi-GPU architecture promises further speed up and it is the focus of continued work by the authors.

REFERENCES

[1] F. Obelleiro, J. L. Rodriguez, and R. J. Burkholder, “An iterative physical optics approach for analyzing the electromagnetic scattering by large open-ended cavities,” *IEEE Trans. Antennas Propag.*, vol. 43, no. 4, Apr. 1995, pp. 356–361.

[2] J. L. Rodriguez, F. Obelleiro, and A. G. Pino, “Iterative solutions of MFIE for computing electromagnetic scattering of large open-ended cavities,” *IEE Proc.-Microw, Antennas Propag.*, vol. 144, no. 2, Apr. 1997 pp. 141–144.

[3] P. H. Pathak and R. J. Burkholder, “Modal, ray and beam techniques for analyzing the EM scattering by open-ended waveguide cavities,” *IEEE Trans. Antennas Propag.*, vol. AP-37, no. 5, May 1989, pp. 635–647.

[4] F. Obelleiro, M. G. Araújo, and J. L. Rodriguez, “Iterative physical-optics formulation for analyzing large waveguides with lossy walls,” *Micro. Opt. Tech. Lett.*, vol. 28, no. 1, Jan. 2001, pp. 21–26.

[5] R. J. Burkholder and T. Lundin, “Forward-backward iterative physical optics algorithm for computing the RCS of open-ended cavities,” *IEEE Trans. Antennas Propag.*, vol. 53, no. 2, Feb. 2005, pp. 793–799.

[6] M. F. Cátedra, C. Delgado, and I. G. Diego, “New physical optics approach for an efficient treatment of multiple bounces in curved bodies defined by an impedance boundary condition,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 3, Mar. 2008, pp. 728–736.

[7] R. Hémon, P. Pouliguen, H. He, J. Saillard, and J. F. Damiens, “Computation of EM field scattered by an open-ended cavity and by a cavity under radome using the iterative physical optics,” *Progress In Electromagnetics Research*, vol. 80, 2008, pp. 77–105.

[8] R. J. Burkholder, Ç. Tokgöz, C. J. Reddy, and W. O. Coburn, “Iterative physical optics for radar scattering predictions,” *Appl. Computational Electromagn. Soc. J.*, vol. 24, no. 2, Apr. 2009, pp. 241–258.

[9] P. Pouliguen, R. Hémon, and J. F. Damiens, “Physical optics for large scale electromagnetic scattering problems,” *2010 Proceedings of the Fourth European Conference on Antennas and Propagation (EuCAP)*, Barcelona, Spain, April 12–16, 2010.

[10] R. J. Burkholder, “A fast and rapidly convergent iterative physical optics algorithm for computing the RCS of open-ended cavities,” *Appl. Computational Electromagn. Soc. J.*, vol. 16, no. 1, Mar. 2001, pp. 53–60.

[11] A. Boag, “A fast iterative physical optics (FIPO) algorithm based on non-uniform polar grid interpolation,” *Micro. Opt. Tech. Lett.*, vol. 35, no. 3, Nov. 2002, pp. 240–244.

[12] C. C. Lu and W. C. Chew, “Fast far-field approximation for calculating the RCS of large objects,” *Micro. Opt. Tech. Lett.*, vol. 8, no. 5, Apr. 1995, pp. 238–241.

[13] L. Pandolfo, P. De Vita, M. Bandinelli, G. Carluccio, M. Albani, F. Vernì, “GPU accelerated iterative physical optics algorithm for the analysis of electrically large optics and platforms”, In 36th ESA Antenna Workshop on “Antennas and RF Systems for Space Science”, ESA/ESTEC, Noordwijk, The Netherlands, October 2015.

[14] G. Carluccio, M. Albani, L. Pandolfo, P. De Vita and M. Bandinelli, "Efficient Iterative Physical Optics algorithm for electrically large scatterers", *Radio Science Meeting (Joint with AP-S Symposium), 2014 USNC-URSI*, Memphis, TN, 2014, pp. 169-169.

[15] Chew W C, Cui T J, Song J M. A FAFFA-MLFMA Algorithm for Electromagnetic Scattering. *IEEE Trans Antenna Propagat*, 2002,50:1641–1649.

[16] Di Maria, L. Pandolfo, P. De Vita, G. Guida, M. Bercigli, M. Bandinelli, “High Fidelity Modeling of 30m Near-Field Cassegrain Antenna in X-band”, *Proceedings of the Eighth European Conference on Antennas and Propagation (EuCAP)*, The Hague, The Netherlands, April 6–11, 2014.