

Rigorous Solutions of Large-Scale Scattering Problems Discretized with Hundreds of Millions of Unknowns

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Abstract — We present fast and accurate solutions of large-scale scattering problems using a parallel implementation of the multilevel fast multipole algorithm (MLFMA). By employing a hierarchical partitioning strategy, MLFMA can be parallelized efficiently on distributed-memory architectures. This way, it becomes possible to solve very large problems discretized with hundreds of millions of unknowns. Effectiveness of the developed simulation environment is demonstrated on various scattering problems involving canonical and complicated objects.

1 INTRODUCTION

The multilevel fast multipole algorithm (MLFMA) is a powerful method for the fast and efficient solution of electromagnetics problems discretized with large numbers of unknowns [1]. Nevertheless, accurate solutions of real-life problems often require discretizations with millions of unknowns. In order to handle such extremely-large-scale problems, MLFMA must be parallelized on a cluster of computers [2]–[5]. Unfortunately, efficient parallelization of MLFMA is not trivial due to the complicated structure of this algorithm. In this paper, we present an overview of our efforts to develop parallel implementations of MLFMA for the solution of very large scattering problems discretized with hundreds of millions. We demonstrate the feasibility of accurately solving large-scale problems on relatively inexpensive computing platforms without resorting to approximation techniques.

2 SIMULATION ENVIRONMENT

In this section, we summarize the major components of our simulation environment.

2.1 Formulation and Discretization

Problems considered in this paper involve closed conducting surfaces, which can be formulated with the combined-field integral equation (CFIE). CFIE

is the convex combination of the electric-field integral equation (EFIE) and the magnetic-field integral equation (MFIE), i.e., $CFIE = \alpha EFIE + (1 - \alpha)MFIE$. The coupling parameter α is set to 0.2 for optimal iterative convergence. CFIE is discretized with the Rao-Wilton-Glisson functions defined on planar triangles smaller than $\lambda/10$, where λ is the wavelength.

2.2 Iterative Solutions

Iterative solutions are performed by using the biconjugate-gradient-stabilized algorithm, which is known to provide rapid solutions for CFIE. In all solutions, the relative residual error for the iterative convergence is set to 10^{-3} . Solutions are further accelerated by employing block-diagonal preconditioners that are constructed from the self interactions of the lowest-level subdomains in MLFMA.

2.3 Near-Field Interactions

In MLFMA, there are $\mathcal{O}(N)$ near-field interactions, which are calculated directly and stored in memory to be used multiple times during iterations. We use singularity-extraction techniques, adaptive integration methods, and Gaussian quadratures in order to calculate near-field interactions accurately and efficiently. Typically, near-field interactions are calculated with a maximum of 0.5% error.

2.4 Far-Field Interactions

For each problem, a tree structure is constructed by placing the object in a cubic box and recursively dividing the computational domain into subdomains, until the box size is about 0.25λ . Then, far-field interactions are calculated in three stages, namely, aggregation, translation, and disaggregation. Truncation numbers, sampling rates for radiated and incoming fields, and numbers of interpolation/interpolation points are selected carefully such that far-field interactions are calculated with a maximum of 1% error.

2.5 Parallelization

In order to solve large-scale problems, MLFMA must be parallelized on a cluster of computers, but

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this is not trivial due to the complicated structure of this algorithm. Specifically, distributing the multilevel tree structure among processors has been a major bottleneck for the efficient parallelization of MLFMA. Recently, we proposed a hierarchical parallelization strategy, which is based on the optimal partitioning at each level of MLFMA [5]. In this strategy, both subdomains and their samples are partitioned among processors by employing load-balancing algorithms. The hierarchical strategy offers a higher parallelization efficiency than previous approaches, due to the improved load-balancing and the reduced number of communication events.

2.6 Computing Platform

Solutions presented in this paper are performed on a cluster of Intel Xeon Dunnington processors with 2.40 GHz clock rate. The cluster consists of 16 computing nodes, and each node has 48 GB of memory and multiple processors. For all solutions, we employ four cores per node (a total of 64 cores).

3 RESULTS

In this paper, we present solutions of scattering problems involving four metallic objects depicted in Figure 1, namely, a $1\text{ m} \times 3.5\text{ m} \times 0.1\text{ m}$ rectangular box, a wing-shaped object with sharp edges and corners, the NASA Almond of length 25.23 cm, and the stealth airborne target Flamme with a maximum dimension of 0.6 m.

3.1 Rectangular Box

The rectangular box is investigated at 75 GHz. At this frequency, the size of the box corresponds to 875λ and its discretization with $\lambda/10$ triangles leads to matrix equations involving 174,489,600 unknowns. The box is illuminated by two plane waves propagating on the x - z plane at 30° and 60° angles from the z axis. The electric field is polarized in the θ direction. Two solutions are performed in a total of 13 hours. Figure 2 depicts the co-polar bistatic RCS (dBms) on the x - z plane as a function of the bistatic angle θ . In addition to the forward-scattering direction, RCS values make peaks at two reflection directions, i.e., at 150° and 330° for the 30° illumination and at 120° and 300° for the 60° illumination.

3.2 Wing-Shaped Object

The wing-shaped object with a maximum dimension of 1 m is investigated at 150 GHz. The object is discretized with 172,228,608 unknowns, and it is illuminated by two plane waves propagating on the x - y plane at 30° and 60° angles from the x axis.

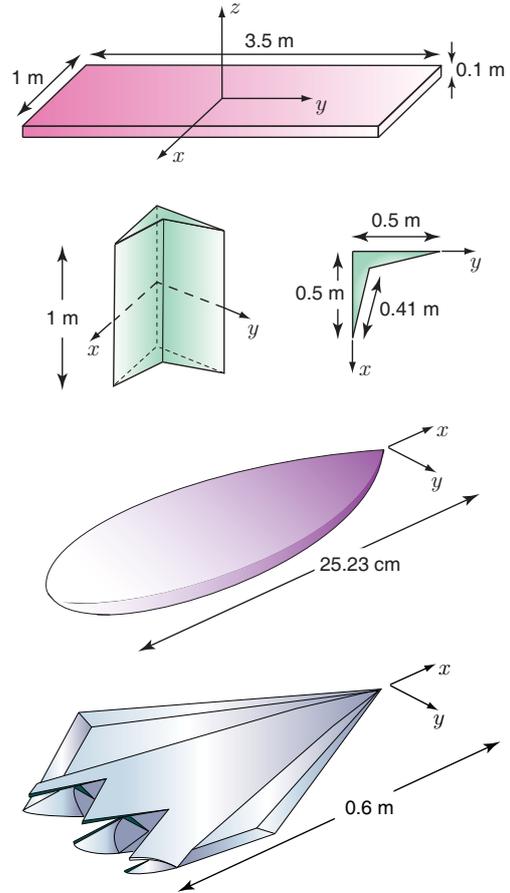


Figure 1: Large metallic objects, whose scattering problems are solved by the parallel MLFMA implementation.

The electric field is polarized in the ϕ direction. Two solutions are performed in a total of 15 hours. Figure 3 depicts the co-polar bistatic RCS (dBms) on the x - y plane as a function of the bistatic angle ϕ . We observe that RCS values of the wing-shaped object make peaks at three directions due to reflections, in addition to the forward-scattering direction.

3.3 NASA Almond

The NASA Almond is discretized with 203,476,224 unknowns and investigated at 1.1 THz. The maximum dimension of the target corresponds to 915λ at this frequency. The target is again illuminated by two plane waves propagating on the x - y plane at 30° and 60° angles from the x axis (from the nose). The electric field is polarized in the θ direction. Solutions are performed in a total of 22 hours. As depicted in Figure 4, the NASA Almond has a stealth ability with very low back-scattered RCS compared to the forward-scattered RCS.

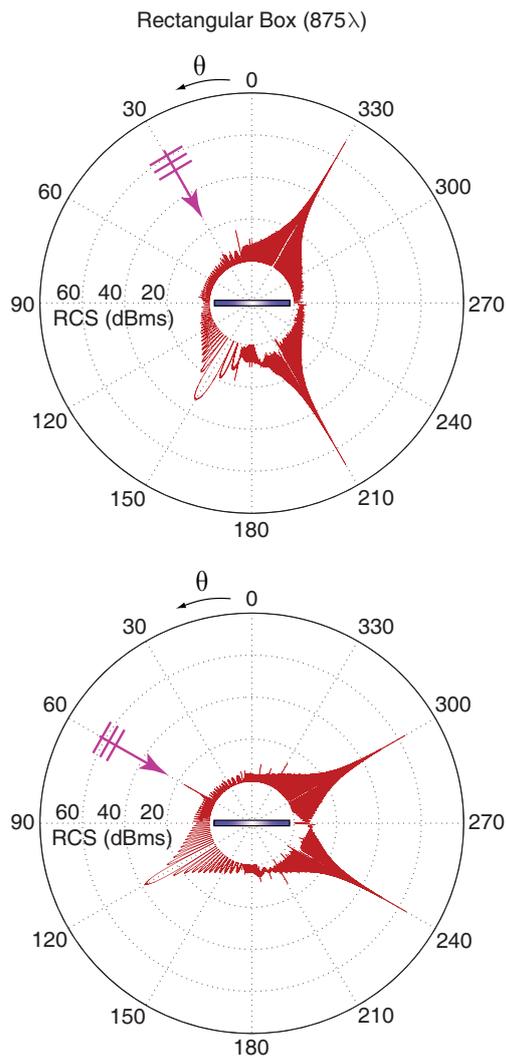


Figure 2: Co-polar bistatic RCS (dBms) of the rectangular box in Figure 1 at 75 GHz.

3.4 Flamme

Finally, the stealth airborne target Flamme is investigated at 440 GHz. The scaled size of the Flamme is 0.6 m and corresponds to 880λ at this frequency. Discretization of the target with $\lambda/10$ triangles leads to matrix equations involving 204,664,320 unknowns. Similar to the wing-shaped object and the NASA Almond, the Flamme is illuminated by two plane waves propagating on the x - y plane at 30° and 60° angles from the x axis with the electric field polarized in the θ direction. Solutions are performed in a total of 44 hours. Figure 5 shows that the back-scattered RCS of the Flamme is very low due to the stealth ability of this target, similar to the NASA Almond. In addition, depending on the illumination, we observe that the Flamme RCS ex-

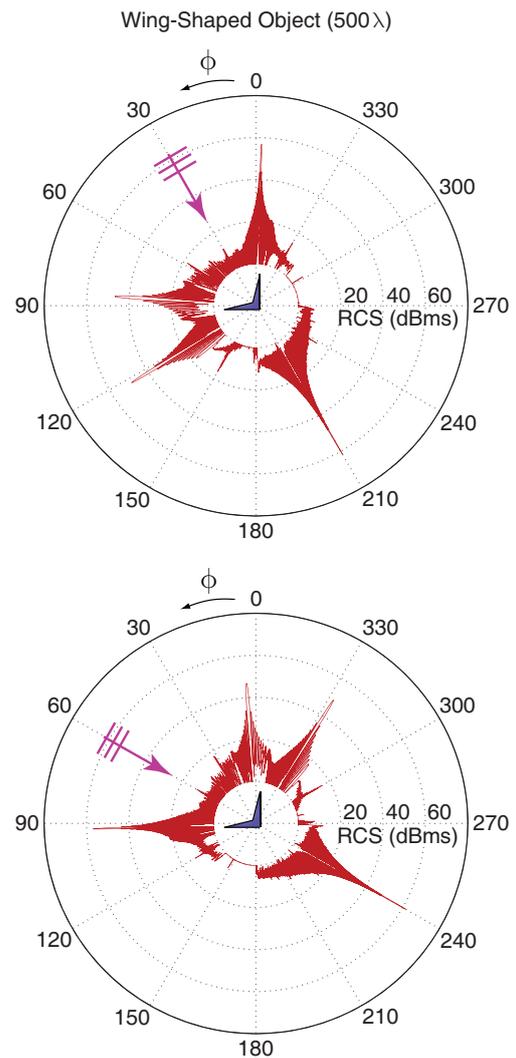


Figure 3: Co-polar bistatic RCS (dBms) of the wing-shaped object in Figure 1 at 150 GHz.

hibits several peaks in various directions.

4 CONCLUSION

This paper presents rigorous solutions of scattering problems discretized with hundreds of millions of unknowns using a parallel implementation of MLFMA in order to demonstrate the feasibility of accurately solving large-scale problems on relatively inexpensive computing platforms without resorting to approximation techniques.

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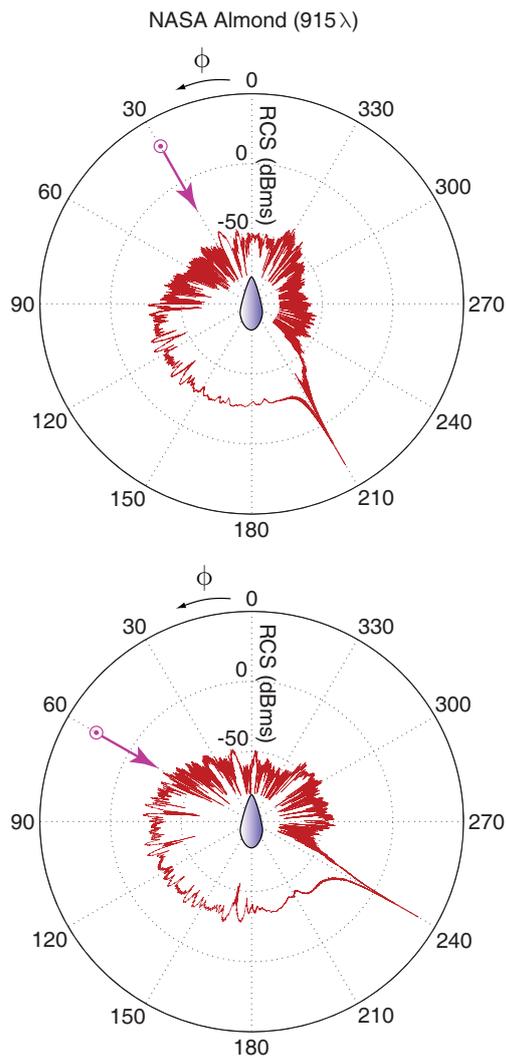


Figure 4: Co-polar bistatic RCS (dBms) of the NASA Almond in Figure 1 at 1.1 THz.

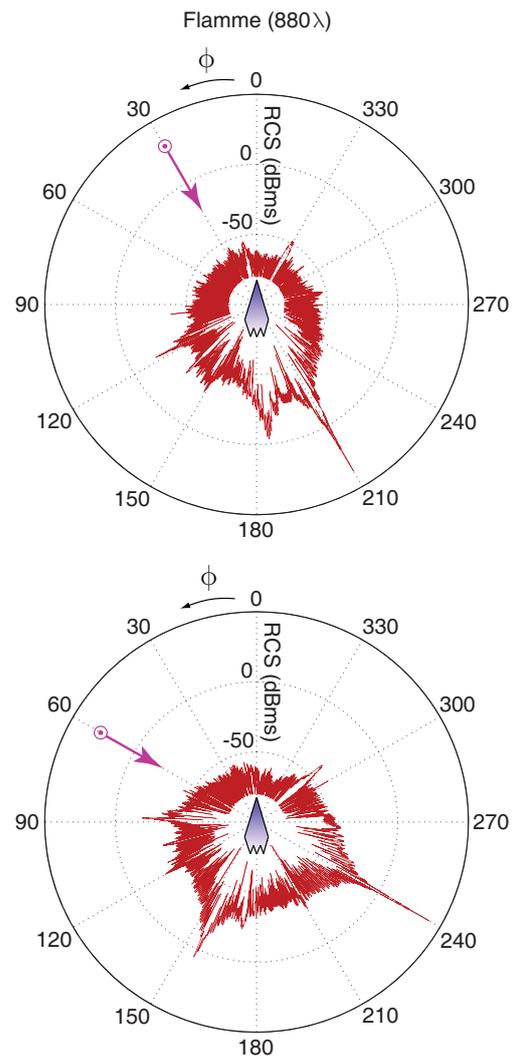


Figure 5: Co-polar bistatic RCS (dBms) of the Flamme in Figure 1 at 440 GHz.

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