Efficient Simulation of Radiation Pattern Diagrams for Complex Electromagnetic Problems

In advanced electromagnetic (EM) simulations, certain applications demand the calculation of a large number of radiation patterns across a wide range of directions. These scenarios are becoming increasingly relevant, especially in defense, aerospace, and wireless communication industries. Two notable examples include:

- **Bistatic Radar Cross Section (RCS) calculations**, where radiation patterns must be evaluated in many directions for a number of excitation scenarios.
- **Large-scale antenna array simulations**, particularly where each element must be analyzed individually for advanced beamforming designs.

While the motivation behind Bistatic RCS analysis is widely recognized, the need for individual element simulation in antenna arrays—often referred to as the "One Element at a Time" method—may require additional explanation. This approach becomes especially beneficial for projects involving complex beamforming.

Beamforming in Phased Arrays

Beamforming is a critical technique used in phased array antennas, allowing directional control of the radiated beam without physically repositioning the antenna. This control is achieved by adjusting the amplitude and phase of the signals fed into individual antenna elements.

In a typical simulation process, all elements of the array are excited simultaneously, with carefully tuned amplitudes and phases. The resulting radiation pattern is computed based on the superposition of contributions from all elements. By reconfiguring feeding parameters, the resulting beam points in different directions. However, this method requires a separate simulation for each configuration, which becomes time-consuming for large arrays and numerous directions.

WIPL-D Simulation Tools and Optimization Strategy

WIPL-D provides two powerful 3D EM simulation tools that use the same advanced numerical engine based on the Method of Moments (MoM) applied to surface integral equations (SIEs). These tools support detailed modeling of complex antenna systems, including the ability to independently control excitation for each element in an array.

In the standard simulation approach, beam steering is performed by adjusting amplitude and phase settings across the array. While straightforward and nearly linear in behavior, this technique requires a complete simulation for each beam direction, which can be computationally expensive.

To address this inefficiency, WIPL-D has developed a post-processing optimization method designed to dramatically reduce simulation time while maintaining high accuracy.

The One Element at a Time Post-Processing Method

In this approach, a single simulation is performed where each antenna element is excited independently—i.e., one at a time. This simulation takes slightly longer than a single standard simulation because radiation patterns for each individual element must be computed separately. However, once completed, the data can be post-processed to generate the total radiation pattern for any combination of element excitations.

By simply loading a configuration file containing desired amplitude and phase settings, the cumulative radiation pattern can be calculated almost instantaneously. This enables rapid design iterations and beam-steering evaluations without the need to rerun full EM simulations.

Performance Considerations and Optimization Goals

For this method to be advantageous, it is critical that the time required for calculating individual radiation diagrams remains significantly lower than that for complete simulations involving all elements. This is particularly important when the number of required directions or excitation scenarios becomes very large.

To that end, WIPL-D has focused on maximizing the efficiency of its radiation pattern calculation engine. The goal is clear: enable ultra-fast computation of a large number of radiation patterns across many directions, thereby unlocking new capabilities in large-scale antenna and RCS simulation workflows.

Accelerations

To maximize the efficiency of the "One Element at a Time" method, WIPL-D has implemented a set of algorithmic and computational enhancements designed to significantly accelerate the calculation of radiation patterns across large numbers of directions and excitations.

The core idea behind the acceleration strategy is to restructure the radiation pattern evaluation as a matrix operation, enabling substantial reuse of intermediate results. This is particularly effective when dealing with:

- A large number of observation directions
- Multiple excitation scenarios (e.g., beam-steering configurations or bistatic RCS)

Matrix-Based Acceleration Techniques

Two key acceleration techniques have been introduced:

1. **Single excitation / multiple radiation direction:**

For a given excitation (i.e., a single element excited or single excitation wave direction), the current distribution over all integration points is computed only once. This distribution is then used to evaluate the radiation pattern across all specified directions.

Rather than calculating the far-field contributions direction-by-direction, the summation across all observation angles is vectorized as a row-to-matrix product.

This approach eliminates redundant evaluations and leads to a dramatic reduction in runtime for high-resolution radiation patterns.

2. **Multiple excitation / multiple radiation direction:**

When evaluating different excitation configurations—such as during beamforming or bistatic RCS—all phase delay terms across all integration points and all radiation directions are computed just once.

Subsequent field evaluations for any excitation scenario become matrix-to-matrix multiplications.

This structure allows for extremely efficient post-processing, where hundreds or thousands of beam directions can be synthesized in a matter of seconds.

Practical Impact

These acceleration methods optimize the only step that differs between the "All Elements" and "One Element at a Time" simulation modes: radiation pattern evaluation. By transforming a loop-heavy computational bottleneck into highly parallelizable matrix operations, WIPL-D enables simulations that are both scalable and fast.

Moreover, this approach is hardware-friendly—well-suited for future GPU offloading—laying the groundwork for even more powerful simulation capabilities in the next development phase.

Beamforming with a Large Antenna Array

To illustrate the effectiveness of the acceleration and post-processing techniques, a representative case study is presented involving a large antenna array configured for dynamic beamforming applications.

Array Configuration:

- **Geometry:** Planar 8×8 array (64 elements)
- **Frequency:** 0.5 GHz
- **Radiation Pattern Sampling:** 361 (azimuth) × 181 (elevation) directions

Figure 1 shows the layout of the simulated antenna array.

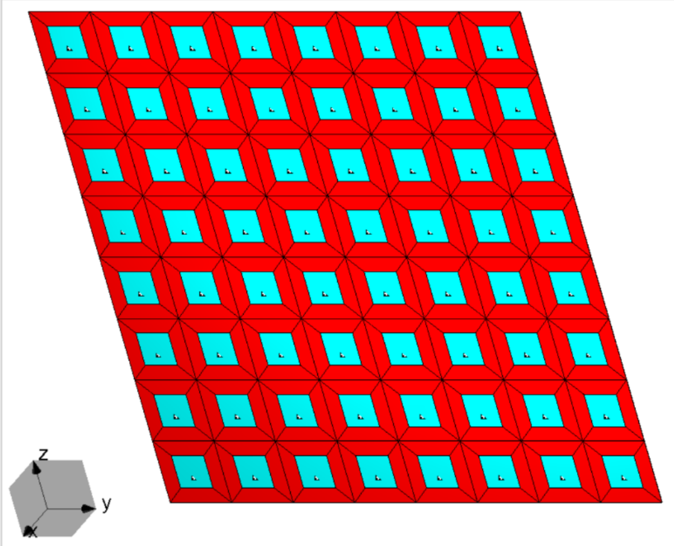

Figure 1. Planar 8×8 antenna array.

The simulation is performed using the "One Element at a Time" method, a sequence of simulations where each element is individually excited. Initially, all elements are simulated with equal amplitude and in-phase excitation. This baseline setup, after the applied post-processing, results in a radiation pattern with a beam directed orthogonally to the plane of the array, as shown in Figure 2.

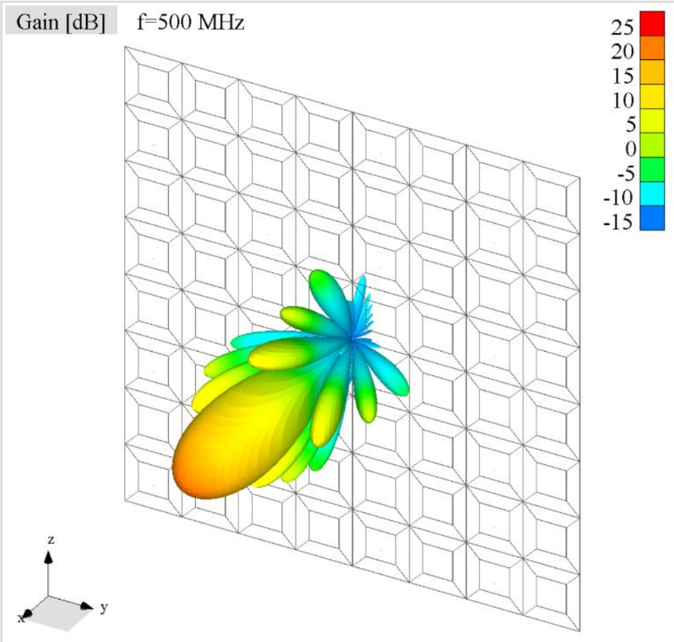

Figure 2. Default radiation pattern with all elements excited in-phase.

With this data as a foundation, multiple beamforming configurations are evaluated in post-processing. By simply loading new amplitude and phase configurations, different beam directions are achieved without re-running the simulation. Figures 3–6 show the beam steered to selected directions:

- (ϕ,θ) = (20°, 20°)
- (ϕ,θ) = (40°, 10°)
- (ϕ,θ) = (15°, -25°)
- (ϕ,θ) = (-15°, -10°)

ϕ and θ are azimuth and elevation angles.

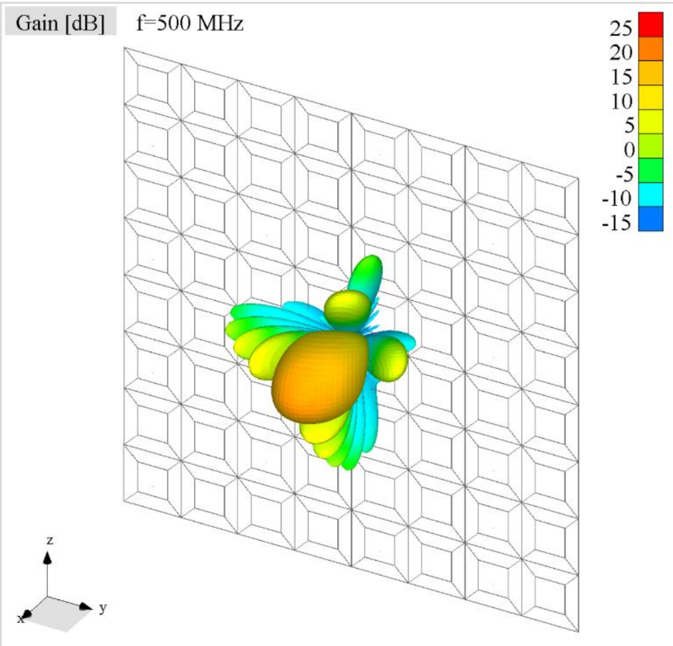

Figure 3. Beam steered to (ϕ,θ) = (20°, 20°).

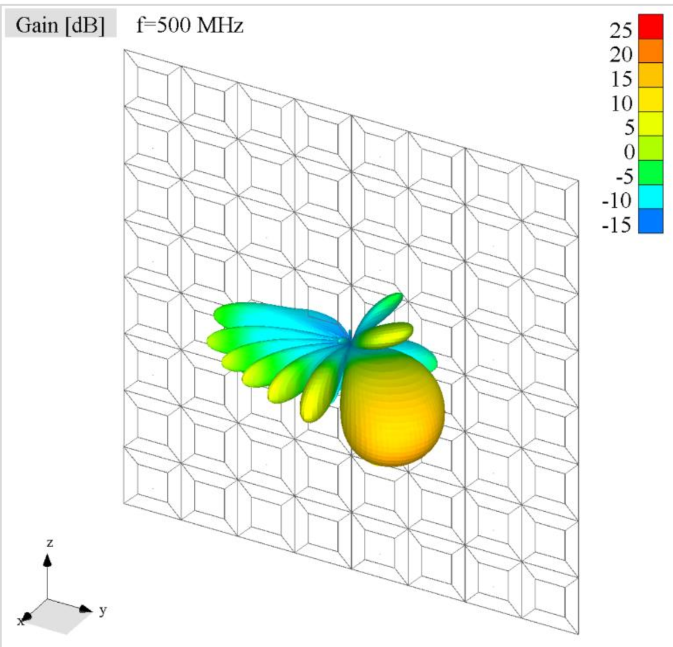

Figure 4. Beam steered to (ϕ,θ) = (40°, 10°).

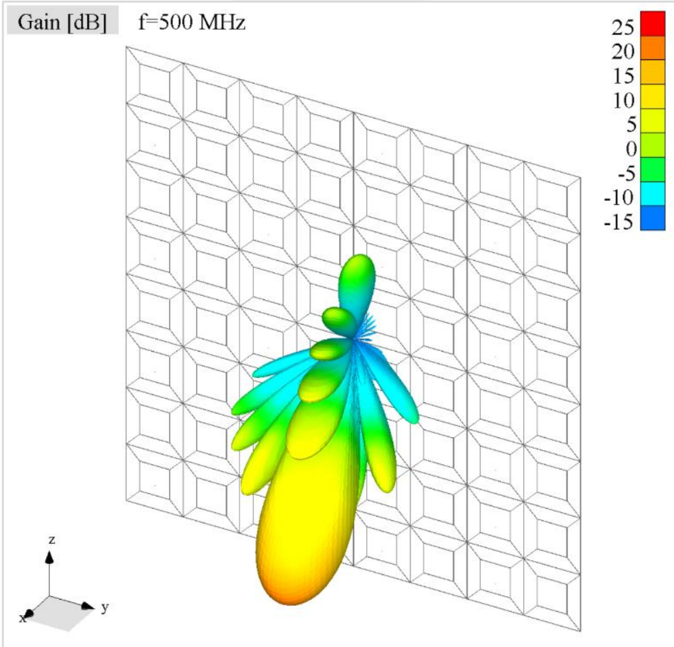

Figure 5. Beam steered to (ϕ,θ) = (15°, -25°).

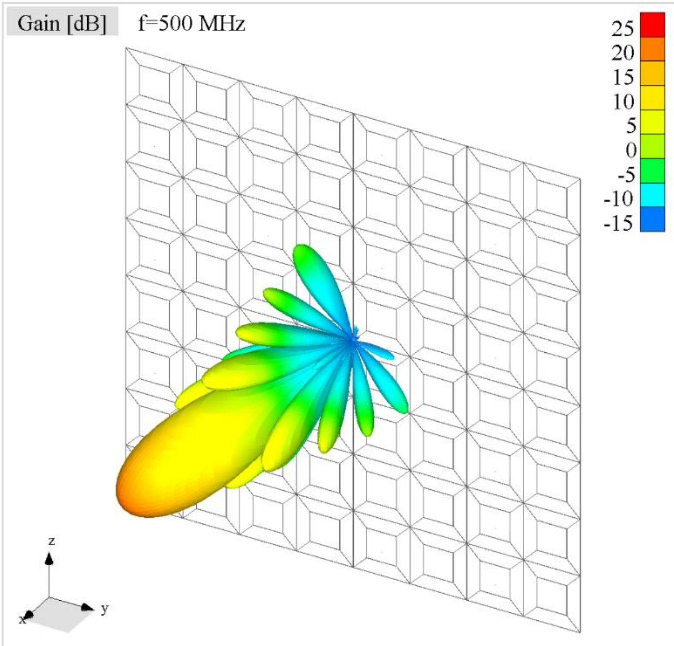

Figure 6. Beam steered to (ϕ,θ) = (-15°, -10°).

These examples underscore the speed and flexibility offered by the post-processing strategy. Design iterations that once required full re-simulations are now reduced to simple matrix operations.

Performance Metrics

Simulations were executed on a desktop machine with the following configuration:

- **CPU:** Intel® Core™ i7-10700 @ 2.90 GHz
- **RAM:** 32.0 GB
- **GPU:** NVIDIA RTX A5000 (used for matrix inversion)

Table 1 summarizes the number of unknowns and compares simulation times across different configurations—before and after applying the proposed radiation pattern acceleration techniques. It is important to emphasize that the acceleration techniques introduced have no impact on the accuracy of the results. The results remain entirely unchanged before and after the application of these techniques.

Table 1. Simulation times with and without acceleration

Model	*Number of unknowns*	*Simulation Mode*	*Simulation time before acceleration [sec]*	*Simulation time after acceleration [sec]*
Patch Array	23,360	One Element at a Time	1265.31	307.84
Patch Array	23,360	All Elements	131.64	116.98

Simulation time is mostly a sum of three intervals: time spent in matrix filling, time spent in matrix inversion and time spent in calculation of radiation pattern. As only the radiation pattern calculation is modified, the difference in calculation times is solely due to this step. The most significant time savings occur in the "One Element at a Time" mode, where radiation patterns for all elements are individually computed. The enhanced algorithm reduces radiation pattern computation, dramatically improving the viability of this approach for large-scale simulations.

Application to Bistatic RCS Simulations

In addition to antenna array scenarios, the proposed acceleration techniques were applied to a bistatic radar cross section (RCS) simulation involving a metallic cuboid. This test case was designed to assess performance in scattering problems where multiple plane wave excitations and a dense angular sweep are required. The simulation was configured at 2 GHz, with RCS calculated over 721 azimuth and 361 elevation directions. Figure 7 illustrates the geometry of the simulated scatterer and wave excitations. As in the previous antenna array example, the acceleration targeted the radiation pattern evaluation stage, which becomes increasingly dominant in total runtime as the number of observation directions grows. The cuboid model included 28,812 unknowns and was simulated on the same desktop platform. Table 2 summarizes the results, showing a reduction in simulation time from 564.28 seconds to 173.50 seconds after acceleration was applied. This demonstrates that the matrix-based optimization approach is broadly applicable—not only to beamforming in antenna arrays, but also to high-resolution scattering problems in bistatic RCS analysis.

Table 2. Simulation times with and without acceleration

Model	*Number of unknowns*	*Simulation time before acceleration [sec]*	*Simulation time after acceleration [sec]*
Cuboid	28,812	564.28	173.50

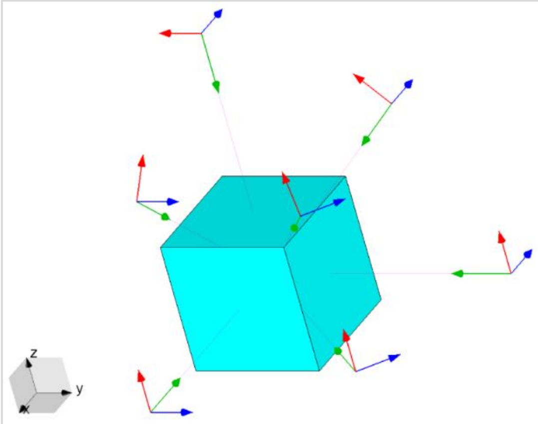

Figure 7. Cuboid scatterer.

Conclusion

This work presents two complementary strategies to address the computational challenges associated with large-scale electromagnetic simulations involving numerous excitations and observation directions.

First, a general-purpose acceleration technique is introduced for efficient radiation pattern evaluation across many directions and excitations. By reformulating the far-field calculation as matrix-vector and matrix-matrix operations, the method significantly reduces redundant computation. This is applicable to a broad class of problems, including bistatic radar cross section (RCS) simulations—where multiple incident wave directions are required—as well as antenna array simulations where each element is excited independently. The acceleration enables scalable analysis of complex systems while maintaining accuracy and reducing runtime by a substantial factor.

Second, a post-processing approach is proposed for phased array antenna simulations using the "One Element at a Time" method. After computing radiation patterns for each individual element, arbitrary beamforming configurations can be synthesized through linear superposition, without rerunning full electromagnetic simulations. This enables rapid evaluation of beam steering and pattern shaping scenarios, offering both computational efficiency and design flexibility.

Together, these methods support a wide range of high-fidelity electromagnetic modeling tasks, from radar signature prediction to adaptive antenna system design, with considerable savings in simulation time and resource usage.

Future Work

Future development will focus on GPU acceleration of the matrix-based radiation pattern computation. Offloading matrix-matrix product operations to the GPU is expected to further improve performance, particularly in applications involving thousands of excitation directions, dense angular sweeps, or iterative design processes.