A Benchmark Suite for Quantifying RCS Simulation Performance on Modern Computers

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***Abstract*—A computational benchmark suite is presented for quantifying the performance of modern RCS simulations. The suite contains a set of scattering problems that are organized along six dimensions and range from basic to challenging. It also includes reference solutions, performance metrics, and recommended studies that can be used to reveal the strengths and deficiencies of different simulation methods.**

I. Introduction

Simulation tools that effectively use limited and evolving computer resources to predict radar cross section (RCS) of complex airborne targets have been pursued for more than four decades. This era has seen large improvements in cyber infrastructure, including orders of magnitude improvements in the performance of computing hardware (from desktops to supercomputers), software compilers, high-performance numerical linear algebra libraries, and visualization tools. Novel and powerful algorithms have been developed and implemented in many electromagnetic simulations. Indeed, the archival literature is replete with simulation results that demonstrate how a new or improved computational system (whether formulation/algorithm, software, hardware, or some combination) makes feasible a hitherto impossible electromagnetic simulation.

Despite the abundance of data in the literature from computational experiments, which can be categorized as *case studies* [1], empirically and objectively evaluating the performance of computational systems is becoming increasingly more difficult [2]. This is in part because the case studies in publications that introduce a new or improved method, which are generally designed to demonstrate and validate the proposed method, are prone to various biases (e.g., confirmation bias). Moreover, we find it difficult, if not impossible, to use published simulation results (and associated system performance data) for systematic literature review and comparison of electromagnetic simulation methods. This is mainly due to two reasons. First, the data we find is almost always generated for different problems (typically, those that highlight a new method's strengths). Second, we find that the computer systems used to perform electromagnetic simulations are generally underreported or underspecified, resulting in incomparable cost data across disparate sources. A promising path for judging electromagnetic simulation methods is to benchmark them [1]–[4].

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II. Benchmarking

Well-defined computational benchmarks can help address the important and growing need to quantitatively and objectively compare alternative computational systems for electromagnetic simulations. Data resulting from benchmarks can be used to fairly and impartially compare the capabilities of different simulation methods. Such comparisons can also reveal strengths, weaknesses, and performance bottlenecks of competing computational approaches. The information derived from these comparisons can then be used to increase confidence in, or reduce the risks associated with, the development, adaptation, or purchase of a novel/advanced computational system for electromagnetic simulations. To be used for these purposes, benchmarks must contain [2]:

1) precisely defined problems that span a range of difficulty levels,
2) completely defined quantities of interest (e.g., monostatic or bistatic RCS, surface/volume currents, coupled energy, etc.),
3) accurate reference data (analytical solutions, measurements, or higher-accuracy simulations), and
4) performance metrics that include both error and cost measures.

This article focuses on RCS simulations and introduces a computational benchmark suite (the Austin RCS Benchmark Suite) that accounts for various aspects of RCS simulations. Unlike previous work [5], which can be classified as "proto-benchmarks" [1] (i.e., benchmarks missing one or more of the components listed above), the proposed benchmark suite not only includes a wider range of problems and more precisely defined quantities of interest, it also supplements these with error definitions and computational cost data [6].

III. Benchmark Organization

The proposed benchmark suite is intended to emphasize and exercise the features of electromagnetic simulation methods that are relevant to scattering problems in aerospace applications. Recognizing the large variety and complexity of electromagnetic problems that can be solved on modern computers [7], we organize the benchmark suite along six dimensions:

1) Geometrical fidelity. The geometrical complexity of the models in the benchmark suite increases from canonical shapes such as spheres, plates, almonds toward toy platforms, fuselages, jet inlets.
2) Material fidelity. The material complexity increases from perfect electric conductors (PECs) and thin metal surfaces toward dielectric, magnetodielectric, and anisotropic coatings.
3) Physical lengths. The scattering object sizes increase from commercial drones and unmanned aerial vehicles toward passenger and cargo airplanes.
4) Frequency. The frequencies of interest increase from HF toward X band frequencies.
5) Simulation accuracy/error. The accuracy requirement increases from high overall correlation toward low average errors in dB-scale RCS patterns.
6) Simulation cost. The computational cost constraints increase toward shorter wall-clock time, smaller memory requirement, and higher parallel efficiency.

To demonstrate how the dimensions are organized, let's consider Problem I-A "PEC spheres" in the benchmark suite, which are the simplest problems in the first two dimensions of the suite. As shown in Fig. 1, the problems cover a physical length scale of 256$\times$ and frequency range of 1024$\times$ in the 3rd and 4th dimensions. In the benchmark suite, these two dimensions are logarithmically sampled, i.e., diameters in the set $\{0.3, 0.6, \ldots, 76.8\}$ m and frequencies in the set $\{10, 20, \ldots, 10240\}$ MHz are included. This gives rise to 99 problems only 19 of which are unique for Problem I-A; these correspond to sphere diameters that double in size from ~ 0.01 to ~ 2623 wavelengths. Next, consider the 5th and 6th dimensions in the benchmark suite: Ideally, to quantify simulation errors, costs, and error-cost trade-offs, each of these 99 problems would be simulated at multiple (typically 3–5) different error levels (or as a proxy, at 3–5 different mesh densities) and the simulation costs would be observed for each case. While this would comprehensively quantify the error-cost trade-off for a simulation method, it would also give rise to $\sim$300–500 increasingly difficult simulations as the sphere diameter and frequency are varied for Problem I-A.

As Problem I-A demonstrates, exhaustive performance benchmarking of modern RCS simulations requires a significant number of simulations for each computational system being evaluated. To ameliorate the benchmarking costs, we recommend to sub-sample the space of simulations in the 3rd, 4th, and 5th dimensions by performing 3 important sweeps: (i) *Error-vs.-cost sweep*: Pick sample length and frequency values, simulate 3–5 error levels, and plot error vs. cost. (ii) *Frequency sweep*: Pick sample length and error-level values, simulate all frequencies of interest, and plot cost vs. frequency. (iii) *Size sweep*: Pick sample frequency and error-level values, simulate all lengths of interest, and plot cost vs. length. Typically, 4 samples are picked (2 different values in each dimension) for each sweep, which gives rise to only 12–20 accuracy, 44 frequency, and 36 length-sweep simulations for Problem I-A.

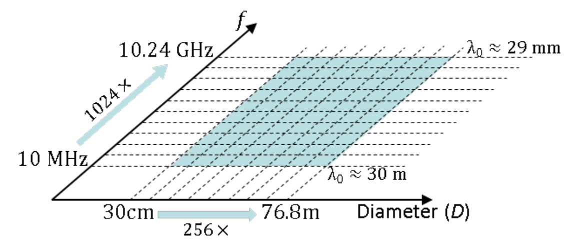

Fig. 1. Logarithmic sampling of the length scale and frequency range of interest yields 99 problems in Problem I-A of the benchmark suite.

The accurate reference data for Problem I-A is obtained using the analytical Mie series [8]. For other problems, the reference data is obtained using higher-accuracy simulations that are ideally cross-validated with at least one measurement.

IV. Conclusion

We proposed and organized a benchmark suite for quantifying RCS simulation performance on modern computers that satisfies the criteria listed in [2]. Performance data for various simulation methods using the Austin RCS benchmark suite will be presented at the conference to demonstrate the suite's suitability for evaluating different computational systems.

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