Extremely Large, Wide-Area Power-Line Models

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ABSTRACT

The electric and magnetic fields around power lines carry an immense amount of information about the power grid, and can be used to improve stability, balance loads, and reduce outages. To study this, extremely large models of transmission lines over a 49.5-sq-km tract of land near Washington, DC have been built. The terrain is modeled accurately using 1-m-resolution LIDAR data. The models are solved using the boundary element method, and the solvers are parallelized across Army Research Laboratory's Centennial supercomputer using a modified version of the domain decomposition method. The code on each node is accelerated using the fast multipole method and, when available, GPUs. Additionally, larger test models were used to characterize the scaling properties of the code. The largest test model had 10,020,913,152 elements, and was solved across 1024 nodes in 3.0 hours.

CCS CONCEPTS

• **Applied computing** → **Physics**; • **Computing methodologies** → *Massively parallel and high-performance simulations*; • **Theory of computation** → *Massively parallel algorithms*;

KEYWORDS

power lines, electric field, boundary element method, domain decomposition method, parallel algorithms, supercomputers

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1 INTRODUCTION

The United States spent $381 billion in 2016 for electricity, which is more than a billion dollars a day [1]. The power grid delivers this electricity over high-voltage power lines carrying alternating current, and these voltages and currents generate electric and magnetic fields around the lines. These fields have been measured experimentally and modeled in software by many authors [5, 16, 21–23, 27, 29], and high-quality sensors are available [2, 3, 12]. The relationship between the voltages and currents on the lines and the electric and magnetic fields around them is linear, so the latter can be used to estimate the former. They can also be used to estimate the line geometry. As a result, the fields carry an immense amount of information about the power grid, and can be used to: improve the stability, conserve power, and reduce outages on national grids and tactical microgrids [11, 28]; detect sagging lines and encroaching trees ready for trimming; and map downed or damaged lines and transformers during disaster recovery or nation building efforts.

Many of these effects are city-sized, so to study these large-scale effects, we have built extremely large models of transmission lines over a 49.5-sq-km tract of land near Washington, DC. For the magnetic field, the sources (currents) are specified, so the field can be computed directly from them. For the electric field, the sources (charges) are not specified, but rather the voltages. Thus, we must solve a boundary value problem (BVP) to compute the charges for the given voltages. We use the boundary element method (BEM) to solve these BVPs.

We previously developed FMM/GPU-accelerated BEM software for computational magnetics and electrostatics problems [4]. Our software can solve problems with up to 10 million elements on a single workstation with 128 GB of memory. However, the 49.5-sq-km power-line model has over 100 million elements, and so a parallelized version of the software is necessary. One strategy for doing so is to parallelize the FMM. This has been done by several authors [6, 13, 14, 17, 19, 20, 30]. However, we wished to continue using our software largely unchanged, so we sought another parallelization strategy: the domain decomposition method (DDM).

Our software runs on Army Research Laboratory's (ARL's) Centennial supercomputer. The 49.5-sq-km, 100-million-element power-line models were solved across 56 nodes in 1.68 hours. Additionally, larger test models were used to characterize the scaling properties of the code. The largest test model had 10,020,913,152 elements, and was solved across 1024 nodes in 3.0 hours.

2 APPROACH: MODIFIED DOMAIN DECOMPOSITION METHOD

The DDM has been used by many authors for parallelizing the BEM [7–10, 15, 18, 24]. The DDM partitions the BVP into several smaller BVPs by decomposing the original domain into several subdomains [26]. Each subdomain is assigned to a different compute node. The BEM is used to solve each subdomain, and the solutions are coupled together to enforce continuity along shared boundaries. We have modified the DDM so that this coupling is accomplished via coupling matrices, which yields a single large system of equations, solvable through one global solution process. This is in contrast to the traditional DDM, where the subdomains are solved independently of each other, and then linked together in a separate optimization process. In the modified DDM (MDDM), the linear system takes the following form: $(\mathrm{C}_1\mathrm{S}_1 + \mathrm{C}_2\mathrm{S}_2)\,\boldsymbol{\sigma} = \mathbf{b}$, where S_1 and S_2 are the dense system matrices arising in the BEM, and C_1 and C_2 are the coupling matrices. The system matrices are block diagonal, each block corresponding to a different subdomain.

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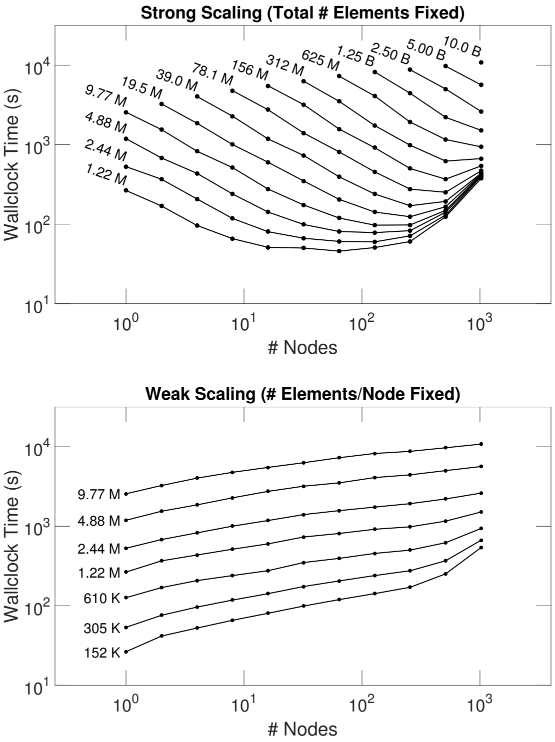

Figure 1: The scaling performance of the software.

Matrix-vector products (MVPs) involving these blocks are computed on their corresponding compute nodes, and are accelerated using the fast multipole method [4]. The coupling matrices are highly sparse, and MVPs involving them are parallelized across the nodes using an efficient I/O scheme, where the nodes share information among themselves. GMRES is used to solve the linear system [25], and the Arnoldi process is parallelized across the nodes. A diagonal preconditioner was used to improve convergence. All problems converged to a relative tolerance of 10^{-5}. And GMRES was restarted after every 100 iterations with unlimited restarts.

3 SCALABILITY TESTING

We investigated: (1) strong scaling, where the total number of elements is held constant; and (2) weak scaling, where the number of elements per node is held constant. To characterize the scalability of the software, we varied the number of elements per node and the number of nodes for a standard problem (energized cube(s) in a grounded box), timed the software for each problem, and plotted the results (see Fig. 1). The scaling was very good, but not ideal. For example, 9.77 M elements per node on 1024 nodes (10 B total elements) took 4.2 times longer than on only one node (9.77 M total elements), scaling approximately as $O\left(P^{0.21}\right)$, where P is the number of nodes. This non-ideal scaling is attributable to the behavior of GMRES: in general, larger problem sizes and node counts require more iterations to converge. In this particular case, 10 B total elements required 5.6 times as many iterations as 9.77 M total elements.

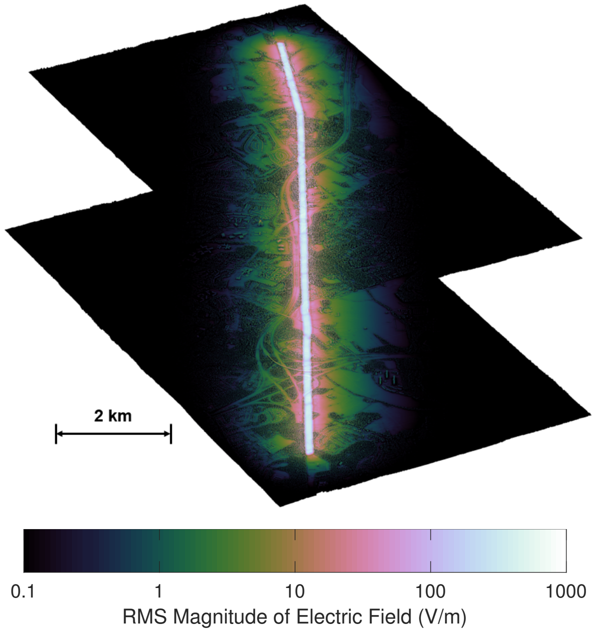

Figure 2: The rms magnitude of the electric field along the terrain.

4 POWER-LINE MODELS

We modeled four 230-kV, three-phase, transmission-line circuits along a 9.9-km section of right of way northeast of Washington, DC. This section of right of way is part of a larger transmission link that runs between Washington, DC, and Baltimore, MD, and connects to many others running throughout the region. The power lines in the model run northeasterly between the Metzerott Road and Burtonsville substations. There are thousands of miles of other power lines in the surrounding region, but these have been omitted from the model, although we plan to add them in the future. The 49.5 sq km of terrain surrounding the power lines was modeled accurately using a 1-m-resolution LIDAR dataset courtesy of the Army Geospatial Center. The rms magnitude of the electric field along the terrain is shown in Fig. 2. The field peaks near 1 kV/m inside the right of way, but drops fairly quickly to below 100 V/m just outside, and decreases farther away from the lines. The field generated by the power lines highlights several interesting features along the terrain, including I-95, which runs roughly parallel to the right of way. Also visible are the tops of trees and buildings, which act as flux concentrators and enhance the field.

5 CONCLUSIONS

The electric and magnetic fields around power lines carry an immense amount of information about the power grid. To study the behavior of these fields, we have built extremely large models of transmission lines near Washington, DC. The power-line models were solved using the BEM, and the solvers were parallelized across hundreds of nodes on ARL's Centennial supercomputer using the MDDM. The software demonstrated good scalability, solving a 10-billion-element test problem across 1024 nodes in 3.0 hours.

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