Journal of Computational Physics 236 (2013) 367–379

Contents lists available at SciVerse ScienceDirect

Journal of Computational Physics

journal homepage: www.elsevier.com/locate/jcp

Parallel 3D-TLM algorithm for simulation of the Earth-ionosphere cavity ☆

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ARTICLE INFO

Article history:
Received 10 May 2011
Received in revised form 27 September 2012
Accepted 26 October 2012
Available online 26 November 2012

Keywords:
Parallelization
Shared memory
Multi-core efficiency
Superlinear speedup
Schumann resonances
TLM

ABSTRACT

A parallel 3D algorithm for solving time-domain electromagnetic problems with arbitrary geometries is presented. The technique employed is the Transmission Line Modeling (TLM) method implemented in Shared Memory (SM) environments. The benchmarking performed reveals that the maximum speedup depends on the memory size of the problem as well as multiple hardware factors, like the disposition of CPUs, cache, or memory. A maximum speedup of 15 has been measured for the largest problem. In certain circumstances of low memory requirements, superlinear speedup is achieved using our algorithm. The model is employed to model the Earth-ionosphere cavity, thus enabling a study of the natural electromagnetic phenomena that occur in it. The algorithm allows complete 3D simulations of the cavity with a resolution of 10 km, within a reasonable timescale.

1. Introduction

For some years, CPUs have been evolving into a new paradigm. The maximum speed for processors seems to have reached its peak, due to issues regarding power dissipation. Manufacturers are no longer trying to increase the speed of CPUs, reducing it instead, in order to obtain better consumption ratios [1]. Despite the use of GPUs, which is growing as an emergent technology for large scientific calculations [2,3], the new approach of CPU manufacturers is to ship computers which include multiple CPUs [4]. Not long ago, if you wanted to speed up your algorithm, according to Moore's law, you had only to wait for a new CPU to appear on the market. With the new paradigm, the algorithms must be revised, adapted and rewritten to take advantage of multi-CPU computers, and to keep them competitive, in order to solve problems of increasing complexity.

Numerical simulations are an important tool for the study of electromagnetism and for designing electromagnetic devices [5,6]. Depending on the problem, analytical solutions are often impossible and experimental approaches are frequently too expensive for a trial and error iteration; or they may not even be feasible when studying natural effects, like the electromagnetic cavities of planets and moons in the solar system. When simulating Maxwell equations, the transmission-line modeling method (TLM) offers certain advantages over other methods, including, for example, its inherent stability [7], or the

☆ This work was partially supported by the Consejería de Innovación, Ciencia y Empresa of Anadalusian Government and Ministerio de Ciencia e Innovación of Spain under projects with references PO7-FQM-03280, FIS2010-15170, co-financed with FEDER funds of the European Union.
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0021-9991/$ - see front matter
http://dx.doi.org/10.1016/j.jcp.2012.10.047

availability of E and H fields at the same point and time, these being its main differences from FDTD, or that unlike random-walk algorithms, it calculates solutions for every point of the lattice [8].

The Schumann resonances (SR) are a natural electromagnetic phenomenon which occurs in the Earth-ionosphere cavity (and in other celestial bodies with an atmosphere). Both the Earth's surface and the lower ionosphere can be considered as perfect conductors for low frequencies, forming an electromagnetic cavity filled by the atmosphere. They were first predicted by Schumann [9], and measured by Balser and Wagner [10]. An excellent historical review of their study can be found in [11]. Interest in them has grown significantly with the work of Williams [12], who related the SR to the global temperature of Earth. Other studies focus on a study of the surface and atmospheric conditions of other bodies in the solar system [13,14], or the possible link between SR and the ionospheric conditions prior to an earthquake [15,16].

The main difficulty in numerically simulating such a cavity arises from the asymmetry of the dimensions. The radius of Earth is approximately 6370 km, while the height of the lower-ionosphere is only about 100 km. This makes a huge but thin spherically shaped cavity. Different works [17–19] have simulated the Earth-ionosphere cavity, providing invaluable information about it. They use the inherent symmetries of the cavity in order to extract the resonances with minimum computation. The works of [20,21] report the first full-3D-FDTD models of the cavity. In this work, we go one step further by providing a full-3D parallelized TLM solution. This model enables the possibility of studying complex problems, like the interaction of multiple storms in arbitrary positions, the day–night asymmetry, the influence of solar proton events, or the influence of the varying lithosphere.

In Section 2, we review the TLM method with the symmetric condensed node (SCN). Section 3 is an introduction to the Earth-ionosphere cavity. In Section 4, we describe the parallelization of the TLM method, present our algorithm approach and show some benchmarking results of the parallelization over different-sized problems, run on different platforms. In Section 5, we apply the algorithm in order to find the resonances of the Earth-ionosphere cavity, using two different models and comparing the results to analytical solutions as well as experimental values.

2. The 3D-TLM numerical method

The Transmission-Line Modeling (TLM) numerical method is an approach devised in the time domain, which has been extensively used for the computer simulation of wave propagation problems, mainly of an electromagnetic nature, but also for problems in acoustics or particle diffusion [7,22,23]. The method is not only a numerical model for solving certain phenomena, but also a conceptual approach that, rather than solving approximately the analytical equations governing the phenomena, deals directly with the original phenomenon by means of an equivalent transmission line circuit. The conceptual nature of TLM makes this method a powerful tool that allows us to consider challenging problems from a hybrid numerical-conceptual point of view and to do so in an elegant and appropriate way.

The TLM method sets up a spatial discretization, associating a cell unit or TLM node with each elementary volume, so that node and the actual elementary volume contribute with the same capacitance, inductance and electrical conductance for each spatial direction. Thus, the TLM nodes conform a three-dimensional transmission line network where voltages and currents behave similarly to the electromagnetic fields in the original system. This method has been developed in different geometries and using different node structures [24,18]. In this paper, a Cartesian network with cubic nodes is used in order to reduce numerical dispersion which increases considerably with nodes of unequal dimensions [25], and to simplify the

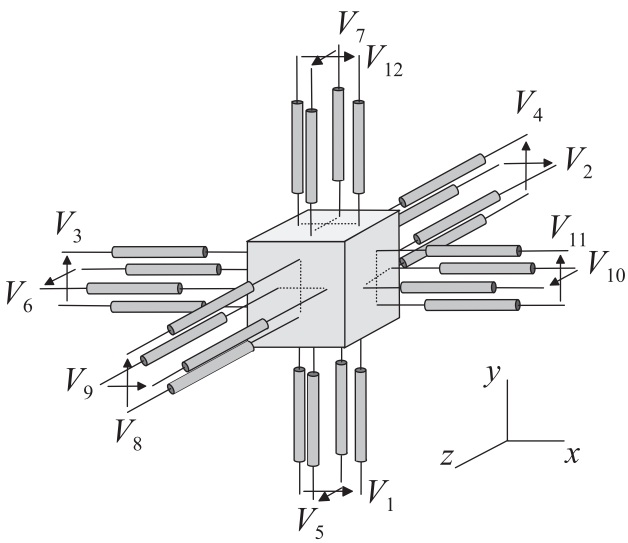

Fig. 1. Basic 12-lines scheme for symmetrical condensed node (SCN).