IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 28.No.6, DEC 2000

# High Performance Computer Methods Apllied to Predictive Space Weather Simulations

C. Robert Clauer, Tamas I. Gombosi, Darren L. DeZeeuw, Aaron J. Ridley, Kenneth G. Powell, Bram van Leer, Quentin F. Stout, Clinton P. T. Groth, and Thomas E. Holzer

Presented By: Jing Zhang

zhjing75@cs.umanitoba.ca



## Overview

- Introduction
- Michigan Multi-scale MHD Model
- Parallel Implementation: Adaptive Blocks - A High Performance Data Structure
- Parallel Performance
- Applications
- Conclusions & Future Work
- A Little Thoughts



## Introduction to Sun-Earth System

- Above the visible Sun is the Sun's corona, where the solar wind originates. The Sun interacts with the Earth is through the solar wind, which is magnetized plasma with superfast speed at hundreds of km/s, interacting with the planets.
- **Why it is important?**
  - Space storms caused by CME's can severely affect satellites orbiting Earth($200million AT&T satellite failure on Jan.10, 1997)
  - Also have effects in the lower atmosphere of the earth, causing regional power-grid failures
  - Astronauts are vulnerable to energetic radiation that may occur in certain space station altitudes
- **Space Weather** refers to the conditions in the sun-earth system (from the Sun surface to the Earth's upper atmosphere including the solar wind, magnetosphere, ionosphere and thermosphere, etc.)



## Advanced Numerical MHD Modeling

- Increasing need to develop physics-based, high performance models of the sun-earth system which operates faster than real time and provide reliable predictions
- Michigan adaptive-scale MHD (Magneto-HydroDynamic) model, which models the entire region from the solar surface to the Earth's upper atmosphere.
- Developed with support from the NASA HPCC and NSF
- BATS-R-US(**B**lock **A**daptive-**T**ree **S**olar-Wind **R**oe-type **U**pwind **S**cheme) is based on an ideal MHD equations.
- It's a multi-scale model
  - temporal scales: range over at least 10^5
  - spatial scales: range over at least 10^9
- Three key elements: modern numerical methods, solution-adaptive techniques, and massively parallel implementation.

## The Michigan MHD Model

The model spans multiple scales, from tens of kilometers in the ionosphere to the radius of the Earth($R_e$) to the radius of the Sun($R_s$), to the Sun-Earth distance (AU)



## Solution Adaptation Techniques

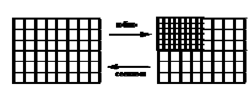
- Equal-sized grid approaches may grossly under-solve much of the problem, while over-resolving relatively uninteresting regions
- A solution adaptive grid is desirable for the disparate length scales.
  - for low-gradient regions, spend less computation
  - for high-gradient regions, elaborate more computation
- Ideal for both sequential algorithm and parallel algorithm



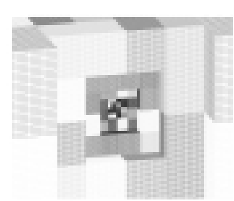
## Parallel Implementation

- Block Adaptive Mesh Refinement (Block-AMR)
- Three-dimensional block of grid cells, typically 8x8x8 cells
- Initially, all the blocks are at the same level of refinement.
  - If a block needs to be refined (by some suitable criteria), it's replaced by 2^3 sub-blocks.
  - If coarsening is needed, then 8 children is replaced by their parent.





•A two dimensional Adaptive Block Decomposition.



•A three-dimensional adaptive block decomposition .

## Parallel Implementation - Cont.

- **Domain Decomposition -** Partition the data blocks. All the data blocks look the same to a processor, no matter they are a large block or a small block
- **Communication:** Most computation is done within blocks, inter-block communication is among neighbour blocks.
- **Agglomeration:** combine the neighbour blocks together to reduce the communication time. The No. of blocks/processor depends on the applications
- **Mapping:** The tasks are assigned to each processor equally. If refinement (coarsen) is needed, the load has to be balanced dynamically.



## Parallel Implementation – Cont.

**Advantages:**

- Refinement is focused on the regions that need it most
- Each block is a uniform grid, which provides natural framework for the numerical approaches & optimizations.
- Locality -- Most computation is done within a data block
- Low communication cost -- Inter-block connectivity is defined using pointers, pointing to the neighbouring blocks
- Load balance -- achieved by balancing the amount of blocks per processor

**Disadvantages:**

- Choosing the size of the block is important, may introduce load imbalance if the size not properly selected.
- For high-gradient regions, excessive numbers of refined cells can be created, increasing the amount of time&storage space
- Overheads for the dynamic load balancing.



## Parallel Performance

The BATS-R-US code was developed in Fortran 90, with MPI for explicit message passing

Figure 2. Parallel Performance of BATS-R-US code for several parallel architecture



## Applications of MHD Model

- Simulation of a CME
- The response of the magnetosphere to the CME
- Solar wind interaction with comets and the origin of cometary x-rays
- Solar wind interaction with Earth
- The interaction of Io with the magnetosphere of Jupiter
- Etc.

Simulation of a coronal mass ejection (CME)

Nov. 04.2003 *Jing Zhang* 13

The response of the magnetosphere to the CME.

Nov. 04.2003 *Jing Zhang* 14

## Conclusions & Future Work

- Provides a powerful global modeling tool which has significantly advanced our understanding of the space weather.
- Achieved performance at about 2 time faster than real time using 2 million cells in the CME simulation for the entire Sun-Earth system.
- The adaptive block data structure helps resolve the vastly disparate scales and exhibits excellent parallel efficiency.
- Future Work
  - a more realistic ionosphere and upper-atmosphere model
  - a higher order accuracy numerical algorithm
  - a more powerful parallel machine, etc.

Nov. 04.2003 *Jing Zhang* 15

## A Little Thoughts

- No Theoretical Analysis
- Performance Analysis is too general

Nov. 04.2003 *Jing Zhang* 16

## References


1. BATS-R-US: Milestone Release Notes, hpcc.engin.umich.edu/HPCC/codes/index.html
2. D.L. DeZeeuw, T.I. Gombosi, A.F. Nagy, K.G. Powell, and J.G. Luhmann, A new axisymmetric MHD model of the interaction of the solar wind with Venus, J. Geophys. Res., 101, 4,547-4,556, 1996.
3. T.I. Gombosi, K.G. Powell, Q.F. Stout, E.S. Davidson, D.L. De Zeeuw, L.A. Fisk, C.P.T. Groth, T.J. Linde, H.G. Marshall, P.L. Roe, B. van Leer, Multiscale modeling of heliospheric plasmas, High Performance Computing 1997. This paper can be obtained at www.eecs.umich.edu/~qstout/abs/HPC97.html.
4. R.M. Häberli, T.I. Gombosi, M.R. Combi, D.L. DeZeeuw, and K.G. Powell, Modeling of cometary X-rays caused by solar wind minor ions, Science, 276, 939-942, 1997.
5. B. van Leer, Towards the ultimate conservative difference scheme. V. A second order sequel to Godunov's method, Journal of Computational Physics 32, 1979.
6. T.J. Linde, T.I. Gombosi, P.L. Roe, K.G. Powell, and D.L. DeZeeuw, The heliosphere in the magnetized local interstellar medium: Results of a 3D MHD simulation, J. Geophys. Res., 103, 1889-1904, 1998.
7. K.G. Powell, P.L. Roe, T.J. Linde, T.I. Gombosi and D.L. De Zeeuw, A solution-adaptive upwind scheme for ideal MHD, submitted to Journal of Computational Physics, 1998.
8. Q.F. Stout, D.L. DeZeeuw, T.I. Gombosi, C.P.T. Groth, H.G. Marshall, K.G. Powell, Adaptive blocks: A high-performance data structure, Proceedings SC'97, 1997. This paper can be obtained at www.eecs.umich.edu/~qstout/abs/SC97.html.




*The End*



*Thank You*

*Questions and Comments?*