Building a 3D Hall MHD model using the Overture framework

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We have developed a 3D Hall magnetohydrodynamic (MHD) model for the simulation of space plasmas, which uses the capabilities of the Overture package. The code solves the conservative Hall MHD equations and applies boundary conditions using operators and grid functions included in the Overture framework. The equations are solved on a regular cartesian grid using a finite volume method, with periodicity in one dimension. Our presentation will highlight the advantages and difficulties of building such a code within the Overture framework, provide preliminary benchmarking results against classic problems, and demonstrate certain features of the Overture grid classes by solving the equations on a variety of single or overlapping curvilinear grids.

1. Introduction

The ideal magnetohydrodynamics (MHD) computational framework has become a workhorse among global space science simulations in recent years. MHD lends itself to large scale simulation because a fluid description of space plasma is computationally feasible, and the assumptions that underlie a fluid approximation are valid for large spatial scales and long time scales. This provides a reasonable first order description of the entire system, whether the simulation is computing coronal, solar wind, or magnetospheric domains.

The Center for Integrated Space Weather Modeling (CISM) is a Science and Technology Center funded to develop expertise in space weather forecasting by coupling large scale numerical codes together. The core models simulate the solar corona, the solar wind, geospace, and the ionosphere separately. All models except the ionospheric model are large scale MHD codes. In addition to coupling the codes together, CISM includes a directed validation effort, where scientists assess a model’s output through comparison with observations (Spence et al., 2004). This process of validation has illuminated several shortcomings of the core CISM models, including the geospace MHD model, which we will discuss below.

Global models solving the ideal MHD equations are applicable to most of the geospace volume, but the approximations are not appropriate to certain portions of that volume. Specifically, a fluid description of a plasma is a poor approximation to the processes occurring in thin current sheets, prevalent structures in space plasmas. In the near-Earth central plasma sheet, for example, transport processes in the tail are driven by the size scale of a reconnection instability. That size scale is determined by intrinsic processes in nature, but CISM validation efforts have revealed that scale seems to be determined by code resolution in the ideal MHD model (J. Lyon, private communication).

To address this particular ideal MHD shortcoming, we plan to investigate the importance of the Hall term in the MHD equations in this region. The Hall term has been shown to generate extremely rapid growth of the Rayleigh-Taylor instability (Hassam and Huba, 1987, Huba 1987), and could potentially impose a grid-independent size scale on the ideal MHD simulation in the plasma sheet. We have written a generic Hall MHD code using the high-level software tools for solving partial differential equations known as Overture. Once tested and benchmarked, we plan to couple this Hall MHD code into the geospace MHD model (Lyon-Fedder-Mobarry, or LFM model) in the near tail region and determine if the additional Hall term changes the nature of the localized instabilities that lead to Earthward transport. This paper reports on the development of a Hall MHD code using the Overture software framework.

2. Hall MHD

Hall MHD refers to the set of ideal MHD equations which additionally includes the Hall term modifying the ideal MHD Ohm’s Law. The ideal MHD Ohm’s Law for electrons

$$\mathbf{E} + \frac{\mathbf{V}_e}{c} \times \mathbf{B} = 0$$

implies that the electrons are frozen to the magnetic field. If we use the definition of current ($\mathbf{J} = ne(\mathbf{V}_i - \mathbf{V}_e)$), then we can rewrite the electric field in terms of the ion velocity and the current as

$$\mathbf{E} = -\frac{\mathbf{V}_i}{c} \times \mathbf{B} + \frac{1}{nec} \mathbf{J} \times \mathbf{B}$$.  

The second term on the right hand side of Equation (2) is referred to as the Hall term. Thus, whenever $\mathbf{J}$ is large, notably in thin current sheets, the Hall term serves to decouple ions from electrons on ion inertial size scales.

3. Software tools

3.1 Overture

Overture (Brown, Henshaw and Quinlan, 1997) is a framework of C++ classes to solve partial differential equations on single or multiple overlapping computational grids. It includes programs to generate regular or unstructured grids as well as operators to solve PDEs and impose boundary conditions on those grids. Overture is based extensively on the A++/P++ serial/parallel array class library discussed in the next section to enable easy transition from serial code development to parallel code implementation. We use these
high-level tools to develop the Hall MHD code discussed in section 2 above.

3.2 A++/P++ Array Class Library

The A++/P++ array class libraries (Quinlan, 2000) provide the C++ language array functionality similar to Fortran 90 syntax. The A++ class is used for serial codes, the P++ class is used for parallel codes, and both are designed to manage array data on one or multiple processors using local memory and message passing between processors. This design consideration significantly reduces parallel code development time, since the A++/P++ array class does most of the array management “under the hood”. It also helps to make parallel codes more portable, insulating them from architecture specific parallel design. (Quinlan, 2000)

4. Future Work

We plan to couple this Hall MHD code into the plasma sheet region of the LFM model in the coming months. Overture will provide us grid interpolation and overlap functionality, and the Intercomm runtime library (Wu and Sussman, 2004) will provide real time data transfers between multiple parallel codes. With it we hope to investigate the role of the Hall term on the size scales of localized Earthward transport in the geomagnetic tail.

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References


