The Space Weather Modeling Framework

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The Space Weather Modeling Framework (SWMF) provides a high-performance flexible plug-and-play type framework for physics based space weather simulations. The SWMF integrates numerical models of the Solar Corona, Eruptive Event Generator, Inner Heliosphere, Solar Energetic Particles, Global Magnetosphere, Inner Magnetosphere, Radiation Belt, Ionosphere Electrodynamics and Upper Atmosphere into a high performance coupled model. All of the components can be replaced with alternatives, and any physically meaningful subset of the components can be used. The SWMF enables simulations that were not possible with the individual physics components. Using reasonably high spatial and temporal resolutions in all of the coupled components, the SWMF runs significantly faster than real time on massively parallel supercomputers.

1. Introduction

The Center for Space Environment Modeling (CSEM) at the University of Michigan and its collaborators have recently built a Space Weather Modeling Framework (SWMF). The SWMF is designed to couple the models of the various physics domains in a flexible yet efficient manner, which makes the prediction of space weather feasible on massively parallel computers. Each model has its own dependent variables, a mathematical model in the form of equations of evolution, and a numerical scheme with an appropriate grid structure and temporal discretization. The physics domains may overlap with each other or they can interact with each other through a boundary surface. The SWMF is able to incorporate models from the community and couple them with modest changes in the software of an individual model. In this paper we present the design and implementation of the SWMF.

2. Physics Domains and Their Couplings

The current version of the SWMF includes nine physics domains ranging from the surface of the Sun to the surface of a planet (usually the Earth). The nine physics domains are the following: (i) Solar Corona (SC), (ii) Eruptive Event Generator (EE), (iii) Inner Heliosphere (IH), (iv) Solar Energetic Particles (SP), (v) Global Magnetosphere (GM), (vi) Inner Magnetosphere (IM), (vii) Radiation Belt (RB), (viii) Ionosphere Electrodynamics (IE), and (ix) Upper Atmosphere (UA). Each physics domain corresponds to a component of the framework as depicted in Figure 1.

Below we briefly describe all nine physics domains, the typical coordinate systems, the equations to be solved, the boundary conditions, and the couplings with the other domains.

2.1 Solar Corona (SC)

The Solar Corona domain extends from the surface of the Sun to approximately $24 R_S$ (solar radii). The physics of this domain is well approximated with the equations of magnetohydrodynamics, however, additional source terms are required to take into account the heating and acceleration of the solar wind [Groth et al., (2000), Usmanov et al., (2000)]. The inner boundary of the SC component is driven by the density, pressure, velocity and magnetic field defined just above the photosphere. The magnetic field may be obtained from magnetograms, or a simple dipole may be assumed. The boundary conditions for the temperature and mass density at the Sun may vary with longitude and latitude to achieve the most realistic solar wind near the Sun and at 1AU. The velocity components at the inner boundary should maintain line-tying of the magnetic field. The flow at the outer boundary is usually superfast (faster than the fast magnetosonic speed of the plasma), so no information is propagating inward. Sometimes, however, when a coronal mass ejection (CME) passes the boundary, the solar wind speed may become subfast for short periods of time. During such periods, the SC component needs to receive the outer boundary condition from the Inner Heliosphere.

2.2 Eruptive Event Generator (EE)

The EE domain is embedded in the Solar Corona, and it is restricted to the region responsible for the eruptive event,
or in other words, a coronal mass ejection (CME). The EE component can be represented as a boundary condition for the SC component, or it can be a (non-linear) perturbation of the SC solution. In short, the EE component interacts with the SC component only. Due to the multitude of possibilities, the EE component is integrated into the SC component in the current implementation of the SWMF. Multiple EE versions are possible, but all the EE versions belong to one SC version only.

2.3 Inner Heliosphere (IH)

The IH domain extends from around 20 solar radii all the way to the planet. It does not have to cover a spherical region, it may be rectangular and asymmetric with respect to the center of the Sun. The physics of this domain is well approximated with the equations of ideal MHD. The IH component is usually in an inertial frame.

The inner boundary conditions of the IH component are obtained from the SC component or measurements. The flow at the outer boundary of the IH component is always superfast (the interaction with the interstellar medium is outside of the IH). The Inner Heliosphere provides the same information to the SP component as the Solar Corona. The IH component also provides the outer boundaries for the SC component when the flow at the outer boundary of SC is not superfast. Finally the Inner Heliosphere provides the upstream boundary conditions for the Global Magnetosphere (GM).

The IH and GM domains overlap: the upstream boundary of GM is typically at about 30 \( R_E \) (Earth radii) from the Earth towards the Sun, which is inside the IH domain.

2.4 Solar Energetic Particles (SP)

The SP domain consists of one or more one dimensional field lines which are assumed to advect with the plasma. The physics of this domain is responsible for the acceleration of the solar energetic particles along the field lines. There are various mathematical models that approximate this physical system. They include the effects of acceleration and spatial diffusion, and can be averaged [Sokolov et al., (2004)] or non-averaged [Kota and Jokipii, (1999)] with respect to pitch angle.

The geometry of the field line and the plasma parameters along the field line are obtained from the SC and IH components. The boundary conditions can be zero particle flux at the ends of the field line(s). The SP component does not currently provide information to other components.

2.5 Global Magnetosphere (GM)

The GM domain contains the bow shock, magnetopause and magnetotail of the planet. The GM domain typically extends to about 30 \( R_E \) on the day side, hundreds of \( R_E \) on the night side, and 50 to 100 \( R_E \) in the directions orthogonal to the Sun-Earth line. The physics of this domain is well approximated with the resistive MHD equations except near the planet, where it overlaps with the Inner Magnetosphere (IM).

The upstream boundary conditions are obtained from the IH component or from satellite measurements. At the other outer boundaries one can usually assume zero gradient for the plasma variables since these boundaries are far enough from the planet to have no significant effect on the dynamics near the planet. The inner boundary of the Global Magnetosphere is at some distance from the center of the planet, usually at 1 to 3 planet radii. The inner boundary conditions are partially determined by the Ionosphere Electrodynamics, which provides the electric potential at the inner boundary of the GM. The potential is used to calculate the electric field and the corresponding plasma velocities, which are used as the inner boundary condition for the GM. The GM component also receives pressure and possibly density corrections from the Inner Magnetosphere along the closed magnetic field lines (field lines connected to the planet at both ends). These are used to ‘nudge’ the MHD solution towards the more accurate inner magnetosphere values [De Zeeuw et al., (2004)].

The GM component provides the field aligned currents to the IE component. These currents are mapped from the GM down to the ionosphere along the magnetic field lines. The Global Magnetosphere provides the Inner Magnetosphere with the field line volume, average density and pressure along closed field lines. Depending on the needs of the IM component, the GM could also provide the geometry of the closed field lines and the distribution of plasma parameters along field lines.

2.6 Inner Magnetosphere (IM)

The IM domain consists of the closed field line region around the planet. This component solves equations describing the motion of the keV-energy ions and electrons. Kinetic effects are important for these particles, and the physics of this domain can be approximated in different manners. The Rice Convection Model [Wolf et al., (1982)] uses a two dimensional bounce averaged description of a multi-energy plasma with gradient and curvature drift.

The Inner Magnetosphere obtains the geometrical and plasma information about the closed field lines from the Global Magnetosphere. It also obtains the electric potential solution and the radial current from the Ionosphere Electrodynamics. The IM component provides the density and pressure corrections along the closed field lines to the GM component.

2.7 Radiation Belt (RB)

The RB spatial domain is coincident with that of the Inner Magnetosphere component. This component solves equations for the relativistic electron distribution near the Earth which are responsible for some of the most detrimental space weather effects. Gradient and curvature drift dominate the motion of these particles around the Earth, and the kinetic equation is sometimes drift-shell averaged as well as gyro- and bounce averaged. Diffusion is the primary transport mechanism left in the equation. The Radiation Belt receives similar information from the Global Magnetosphere as does the Inner Magnetosphere. The RB component does not provide information to the other components.

2.8 Ionosphere Electrodynamics (IE)

The IE domain is a two dimensional height-integrated spherical surface at a nominal ionospheric altitude (at around 110 km for the Earth). In the current version of the SWMF, the IE component is a potential solver, but there is nothing in the design that would exclude the incorporation of other
types of IE models.

The Ionospheric Electrodynamics obtains the field aligned currents from the Global Magnetosphere and Upper Atmosphere, which is used to generate an auroral precipitation pattern. The UA component also provides IE with the Hall and Pedersen conductivities. In case the UA component is not used, the auroral pattern and the solar illumination are used to generate Hall and Pedersen conductances. The IE component provides the electric potential to the GM, IM and UA components. In addition, it provides the radial currents to the IM component and the particle precipitation to the UA component.

2.9 Upper Atmosphere (UA)

The UA domain includes the thermosphere and the ionosphere and it extends from around 90 km to about 600 km altitude for the Earth. The physics of the Upper Atmosphere is rather complicated. It can be approximated with the equations of multi-species hydrodynamics including viscosity, thermal conduction, chemical reactions, ion-neutral friction, coupling of the ions to the electric field, source terms due to solar radiation, etc.

The lower and upper boundaries of the UA domain are approximated with physically motivated boundary conditions. The Upper Atmosphere obtains the electric potential along the magnetic field lines and the particle precipitation from the Ionospheric Electrodynamics. The gradient of the potential provides the electric field which is used to drive the ion motion, while the auroral precipitation is used to calculate ionization rates. The UA component provides field aligned currents and the Hall and Pedersen conductivities to the IE component. The conductivities are calculated from the electron density and integrated along field lines.

2.10 Coupling the IM GM Modules

The IM to GM coupling is the most challenging computationally. The GM component needs to know where each of its 3D grid points are mapped onto the IM grid along the closed magnetic field lines in order to apply the pressure and density corrections. This means that field lines must be traced from possibly millions of grid points. In addition, the magnetic field information is typically distributed over many processors of the GM component. Since the GM grid structure and the magnetic field is inherently known by the GM component, it is the responsibility of the GM component to find the mapping of its 3D grid along the closed field lines. For our implementation of the GM component, we have developed a highly parallel method which can accomplish this task in a few seconds.

The IM to GM coupling is also challenging computationally. The IM needs the magnetic field line flux tube volumes and the average density and pressure in the flux tubes connected to its 2D spherical grid points. This requires the integration along many (thousands of) magnetic field lines in GM. Field line integration is an inherently serial procedure. A further complication is that the domain decomposition of the GM component may distribute each field line over several processors. We have developed an efficient parallel algorithm which can trace and integrate along the field lines in a fraction of a second of CPU time. The framework provides a library which takes care of the information exchange and the collection of data among the processors of GM, but the GM component is responsible for the tracing and integration along field lines within the subdomain corresponding to one GM processor.

3. Architecture of the SWMF

The SWMF provides a flexible and extensible software architecture for multi-component physics-based space weather simulations, as well as for various space physics applications. The main SWMF design goals are: (i) incorporate computational physics modules with only modest modification, (ii) achieve good parallel performance, and (ii) make the SWMF as versatile as possible. These design goals are orthogonal to each other, and the actual design represents a trade-off. One can minimize the changes in the physics modules at the expense of performance and flexibility, or one may maximize software reuse and integration at the expense of the other design goals. The SWMF design focuses on achieving good performance while the versatility of the SWMF and the minimization of code change are taken into consideration as much as possible. The initial investment into the integration of the physics modules pays off in the flexibility, usability and the performance of the SWMF. In our experience, it takes about two weeks to integrate a new physics module into the existing framework.

One of the most important features of the SWMF is that it can incorporate different computational physics modules to model different domains of the Sun-Earth system. Each module for a particular domain can be replaced with alternatives, and one can use only a subset of the modules if desired.

The framework’s layered architecture is shown in Figure 2. The Superstructure Layer, Physics Module Layer, and
Infrastructure Layer constitute the “sandwich-like” architecture.

The Superstructure Layer contains the Component Interface (wrappers and couplers) and the Framework Services. The latter consists of software units (classes) which implement component registration, setting up the parallel layout, reading and distributing the input parameters, control of component execution and coupling, and the SWMF parallel coupling toolkit which can be used by the component couplers.

The Physics Module Layer contains the physics modules, which have been integrated into the SWMF, and provide appropriate entry points for the Component Interface. Each physics module may have multiple versions. The physics module may contain additional code for stand alone execution.

The Infrastructure consists of utilities, which define physics constants, transformation between different coordinate systems, time conversion routines, time profiling routines and other lower level routines. The Infrastructure can be used by the physics modules as well as by the Superstructure.

4. Performance

![Graph showing simulation and CPU times as a function of the number of processors](image)

Fig. 3. The ratio of simulation and CPU times as a function of the number of processors on various supercomputers. The SWMF can run faster than real time on all 3 platforms, and it runs almost twice faster than real time on 256 CPU-s of the SGI Altix.

The SWMF can reach faster than real time performance on modern supercomputers. Figure 3 shows the ratio of simulation and CPU times on up to 256 processors of three supercomputers: the SGI Altix system at NASA Ames (Columbia), the SGI Origin 3800 at NASA Ames (Lomax) and the Compaq ES45 at NASA Goddard Space Flight Center (Halem). On 256 CPU-s of Columbia, which is the fastest (per CPU) of these supercomputers, the SWMF can run almost twice as fast as real time. We emphasize that this speed is achieved with reasonable spatial and temporal resolution: the components use about 47 million state variables in the discretized physics domains!

There are several design and algorithmic choices which make this performance possible. The concurrent execution of the components allows good scaling up to a large number of CPU-s. Even if the components do not scale perfectly to hundreds of CPU-s, the whole SWMF can, because the components can use independent sets of CPU-s and they can progress concurrently. It is also important that the SWMF allows the overlap of the component layouts, since the IH runs much faster (due to the large time steps) than the other computationally expensive components, still it needs a lot of CPU-s for its large grid and the corresponding memory requirements. The SC uses explicit time stepping with small (0.4 s) time steps on a fine, but relatively small grid. The IH can use much larger time steps (60 s) on its large but much coarser grid. Finally the GM uses an efficient explicit/implicit time stepping scheme [Toth et al., in preparation] on its fine grid, so the time step is not limited by the numerical stability condition. The optimal performance is achieved with 4 s time steps, which speeds up the GM component by about a factor of 30 relative to an explicit scheme. The efficient coupling of the GM with the Inner Magnetosphere is also crucial in achieving faster than real time performance. The two components are coupled every 40 seconds of simulation time and each coupling involves the mapping the 1.3 million GM grid cells to the IM grid along the dynamically changing magnetic field lines. Due to the efficient parallel field line tracing algorithm each coupling takes a couple of seconds only.

5. Summary

Our purpose is to introduce the Space Weather Modeling Framework to the space physics community, describe its potentials, and encourage participation in its future development. More information about the SWMF can be found at http://csem.engin.umich.edu/SWMF/.

The SWMF has been successfully ported to the Community Coordinated Modeling Center (CCMC) and it will be available for community use soon. The SWMF is continuously improved and extended. It is our hope that the space physics community will join us in our efforts to integrate new component versions and new components into the SWMF.

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References


