Improving Space Weather Forecasts with Data-Driven Models of the Solar Atmosphere and Inner Heliosphere

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Abstract

Space weather forecasts are lacking accuracy because they are based on the models describing the system of inter-related physical models, each of which has its own response to uncertainties in the boundary conditions. We address this issue systematically, by developing a new, open-source software to support data-driven, time-dependent models of the solar atmosphere and heliosphere suitable for near real-time predictions of the SW properties at Earth’s orbit and in the interplanetary space.

1. A new Open Surface Flux Transport (OFT) model which evolves information to the back side of the Sun and its poles and updates the model flux with new observations using data assimilation methods.
2. A new potential field solver (POT3D) combined with the output from the traditional WSA model, and with remote coronal and situ solar wind observations. WSA and the new potential field solver (PFSS and PFCS) are both validated using the maps from the OFT.
3. A highly parallel, adaptive mesh refinement (AMR) code (HelioCubed) for the Reynolds-averaged, ideal MHD equations describing the solar wind flow in the region between R = 10–20 R⊙ and 1–3 au. These equations will be accompanied by the equations describing the transport of turbulence. These are built upon the Multi-Scale Fluid-Kinetic Simulation Suite (MSFLUKSS) collaboratively developed at UAH using the Chombo AMR framework. The new version of our software is built on Chombo 4 and allows us to perform simulations with the fourth order of accuracy in time and space, and use cubed spheres to generate meshes around the Sun.
4. Machine learning is used to find a hypothetical member of the CME ensemble with the best predictive properties.

The Inner Heliospheric Model: HelioCubed

1. We use finite volume method to solve hyperbolic, Reynolds-averaged MHD equations in conservative form with 4th order of accuracy in space and time.
2. The average values of primitive variables are calculated on R and L side of the faces with the 4th order accuracy and a Riemann problem solver is used to find the 4th order accurate fluxes through these faces.
3. The 4th order accurate RK method is used to integrate the equations with time. Limiters specially designed for the 4th order accurate methods are used (McCorquodale et al 2011).
4. The MHD equations are solved using mapping functions that preserve exact radial solutions. Non-physical non-radial flows are damped using high order artificial linear viscosity.
5. Our approach solving this problem is based on the following ideas: a cubed-sphere representation of space, that has most of the same advantages as the widely-used spherical coordinate system, but does not have a polar singularity, a method-of-lines discretization of the evolution equations, with high-order accurate discretizations (fourth or fifth-order) in both space and time; and block-structured AMR.

Data Acquisition and Processing: MagMAP

We have developed MapMag, a python codebase that facilitates acquisition and processing of data products to a computation-ready format for HipFT. The current code supports full processing of JOSCO HMI M720s line-of-sight (LOS) magnetograms to a radial-flux Carrington Rotation (CR) Map. This extensible software will also serve as a prototype/example for future users to incorporate magnetograms from alternative observatories. For data acquisition of HMI LOS magnetograms, OFT acts as a Python wrapper for product query and download from the Stanford JOSCO. Figure at the bottom shows an example. We are presently comparing this mapping to a mapping product developed by the Stanford team for use by ADAPT.

Comparison of OFT (left column) with AFT (right column)

- 11-year run, 2011 to 2022 (only 2014 to 2021 shown)
- Convective flows from Conflow
- 1 hr data assimilation of HMI magnetograms
- 13 hour run time for OFT (NVIDIA GPU)
- 5 days, 12 hours for AFT
- HipFT has been extended to compute ensembles with MPI
- It can be run with very low diffusion – we are testing the implications

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