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Modeling the propagation of solar disturbances to Earth for the EU H2020 SafeSpace project

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Introduction

The EU H2020 SafeSpace project aims to develop a prototype pipeline that connects several tools in a modular fashion to address the physics of the Sun - Interplanetary space - Earth's magnetosphere with the ultimate goal to forecast radiation belts dynamics (Fig 1) with a lead time of 2 – 4 days, much improved from the current capability of a few hours.

Helio1D is a part of the pipeline (Fig 1c) that is dedicated to forecasting the solar wind properties at the Lagrangian L1 point. In particular, we aim to forecast the properties of the regular solar wind, as well as Corotating Interaction Regions (CIRs) and their high-speed streams which are most geo-effective (for radiation belts in particular).

Here we present the Helio1D pipeline status, as well as its benchmarking and calibration in order to provide optimum forecasting in real-time .

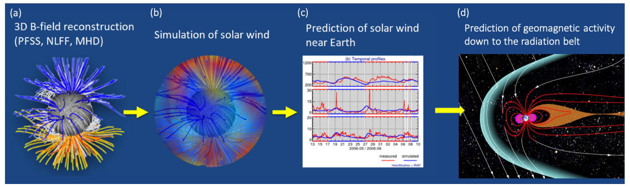

Fig 1 SafeSpace pipeline for connecting model predictions of solar wind conditions at the Sun (a,b), the interplanetary space (c), and in the Earth's magnetosphere and the radiation belts (d).

Methodology

Helio1D models solar wind propagation using input data obtained from the MULTI-VP model (Pinto & Rouillard, 2017; Fig 2), which itself models solar wind emergence near Sun based on magnetograms and coronal field reconstruction. The Multi-VP model yields solar wind emergence near the Sun at 0.14 AU that contains precursors for CIRs for the past 24 hours and the next 2 days as shown in Fig 2.

We then propagate the solar wind emergence from Multi-VP to 1 AU (at L1) using a 1-D MHD code (Tao+2005), which assumes an ideal MHD plasma in a 1-D spherically symmetric coordinate system. The 1-D MHD code is commonly used to propagate the solar wind observations at L1 to upstream of the solar-system planets or target spacecraft positions (http://heliopropa.irap.omp.eu/).

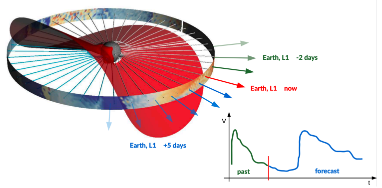

Fig 2 Production of solar wind conditions with a lead time of 2 days at 0.14 AU using the Multi-VP model.

By propagating near-Sun solar wind conditions to 1 AU using the 1-D MHD code, we obtain an extra propagation time of 2 to 7 days (limited to 2 days).

We benchmark the Helio1D pipeline using a long dataset generated from WSO magnetograms, covering the solar cycles 23 and 24 (2005-2018).

Automated Pipeline

The Helio1D pipeline prototype for CIR forecasting shown in Fig 3 consists of three main parts: (1) the preparation of inputs containing the key velocity gradients at 0.14 AU, (2) the propagation and formation of CIRs from 0.14 AU to 1 AU using the 1D MHD code, and (3) the preparation and post-processing of the outputs. The pipeline is separated into two branches where the historical-mode branch is for benchmarking and calibration with past data while the daily-mode branch is for operational daily forecasting.

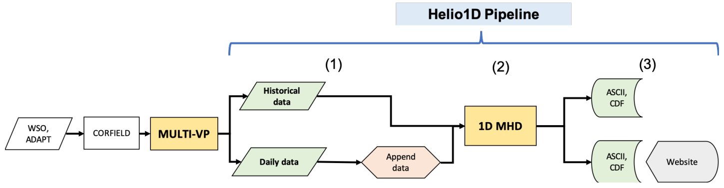

Fig 3 Diagram of the Helio1D pipeline

The pipeline is scheduled to run every day for the daily data; an example of daily forecast with a lead time of 2 days on the IRAP's SWiFT website is shown in Fig 4 in comparison to the observation for the past 24 hours. To improve the quality of the output, we benchmark the pipeline with historical data; the results are shown in Fig 5 for the declining phase and solar minimum of the solar cycle 23 (from 2007 to 2009).

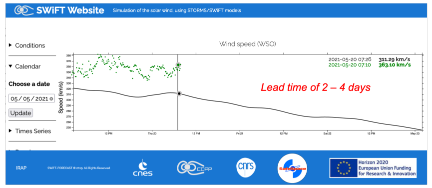

Fig 4 Example of the Helio1D pipeline output for the operational forecasting on the SWiFT website.

In Fig 5, the Helio1D results in purple are compared tothe observation (OMNI) data in black. The radial speed (Vx) and tangential magnetic field (By) from Helio1D correctly produces the expected large-scale modulation of CIRs. This shows that the automated Helio1D pipeline correctly produces long-term solar wind fluctuations.

Quality of the Helio1D's CIR prediction

We find that the Helio1D pipeline correctly produces CIRs containing compressed stream interfaces with adjacent fast and slow streams.

However, there are strong compressions that result in extreme peaks in the ion density and temperature at the stream interfaces due to the over-compression, as a result of the ideal MHD fluid and 1-D assumptions.

We alleviate the over-compression problem by performing a post-calibration to the outputs.

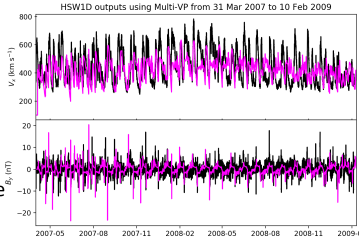

Fig 5 Helio1D output for the long-series data for benchmarking and calibration (purple) compared to observations (black).

Calibration & Ensemble Approach

To calibrate the density and temperature of CIR prediction from Helio1D, we first consider mapping the stream interfaces from the model to the observation in order to accurately map the compression regions within two time series as shown in Fig 6.

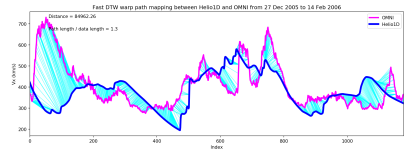

Fig 6 Example of the mapping between the predicted CIR structures and the OMNI using the FastDTW algorithm

We apply Fast Dynamic Time Warping (DTW) technique (Salvador & Chan, 2007) that allows us to map large scale features in 1-D data and obtain calibration plots based on the mapping paths found for the radial velocity (Vx) shown in Fig 6. A calibration function is obtained for the density and temperature.

To provide an error estimation of the prediction, we propagate ensemble members of the near-Sun solar wind conditions at various targets around the sub-Earth point to 1 AU. Fig 7 shows Helio1D results (blue) at L1 together with the error estimation (yellow shade) using 21 targets up to 15° away from the Earth compared to the observation (black), for Vx, By, density (N), and temperature (T). The results show that the observation falls within the error estimation obtained from the ensemble members.

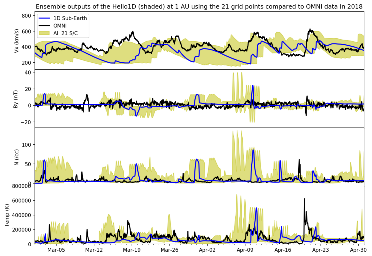

Fig 7 Helio1D outputs using various targets around the Earth as ensemble members.

Summary & Perspectives

We have developed the Helio1D pipeline prototype for automatic solar wind forecasting containing CIRs with a lead time of 4 days at L1 by connecting the near-Sun prediction from Multi-VP and propagating them using the 1-D MHD code.

We benchmark the Helio1D pipeline using several years of solar wind data from Multi-VP. We find that there is an over-compression at stream interfaces due to the ideal MHD and 1-D assumptions made by the 1-D MHD code. We alleviate the issue by performing a post-calibration on the Helio1D outputs.

We also use ensemble forecasting using solar wind time-series data at various targets around the Earth. The quality of the forecast may be improved by exploiting combination of various ensemble members in near future.

The Helio1D pipeline will be connected to the neural network model for prediction of the Kp index as well as the radiation belt dynamics for the SafeSpace project.

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