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Modeling efforts for multi-mission science

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Abstract. The Solar Orbiter spacecraft, launched in February 2020, is equipped with both remote-sensing (RS) and in-situ (IS) instruments to record novel and unprecedented measurements of the solar atmosphere and the inner heliosphere. To take full advantage of these new datasets, we have developed tools and techniques to facilitate multi-instrument and multi-spacecraft studies. In particular the yet inaccessible low solar corona below 2 $R_\odot$ can only be observed remotely and techniques must be used to retrieve coronal plasma properties in time and in 3-D space. These properties are useful to drive numerical models and test the different theories proposed to describe the fundamental processes of the solar atmosphere. In addition, the last decades of research have shown that the coupling between the solar corona and the heliosphere is most efficiently studied by combining RS with IS data. During one of the last Solar Orbiter remote sensing windows (March 2022), planned for the Solar Orbiter instruments, we ran complex observation campaigns to maximize the likelihood of linking IS data to their source region near the Sun, by directing some RS instruments to specific targets on the solar disk just days before data acquisition. We show how it is possible to achieve these results directed to improve our understanding of how heliospheric probes connect magnetically to the solar disk.

Keywords. Sun: atmosphere, Sun: magnetic fields, Sun: corona, Sun: activity

1. Introduction

The Solar Orbiter (SolO) mission (Müller et al. 2020) is equipped with a unique dedicated payload of 10 remote-sensing (RS) and in-situ (IS) instruments measuring from the photosphere into the solar wind, designed to observe the Sun and the heliosphere.

One of the SolO's main science goal is to establish the link between the RS observations and the IS measurements in order to link heliospheric phenomena back to their sources on the Sun.

This task is very challenging to achieve since it requires the availability of good coronal and heliospheric models of the sun's magnetic field configuration that can be run very quickly, ingesting daily information from the IS instruments to inform promptly the spacecraft about the pointing of the RS instruments. Robust, stable operational models able to establish the most likely connection between the spacecraft and the solar surface are therefore needed but they do not need to be necessarily the most complex and/or sophisticated scientific ones.

In order to take care of this issue, i.e., coordinating modeling and theoretical support for SolO science to be able to choose targets and update the pointing, the European Space Agency (ESA) established the Modeling and Data Analysis Working Group (MADAWG) for the Solar Orbiter mission.

The MADAWG, during the years, had also to take care of the following topics:

- Defining the format of SolO instrument datasets and their metadata;
- Defining how SolO instruments data archives will exchange SolO data;
- Preparing data analysis tools to relate different SolO datasets.

An exhaustive description of the community-led effort guided by the MADAWG to develop models, tools, and techniques in order to test different theories to explain the physical processes that occur in the solar plasma, can be found in the Rouillard et al. (2020) paper. The present contribution can be considered a brief update of it, since it reviews, in particular, the effort made during the last two remote sensing windows of the SolO instruments (March and October 2022), to direct the pointing of the RS instruments, starting from the modeling results combined with the RS and IS data, to maximise the likelihood of linking IS data to their source region near the Sun.

Several RS instruments on board SolO, indeed, can be directed to specific targets situated on the solar disk just days before data acquisition, enabling coordinated campaigns to point to the predicted source region of different phenomena (like slow/fast solar wind), that will be measured by IS payload at time of arrival at spacecraft.

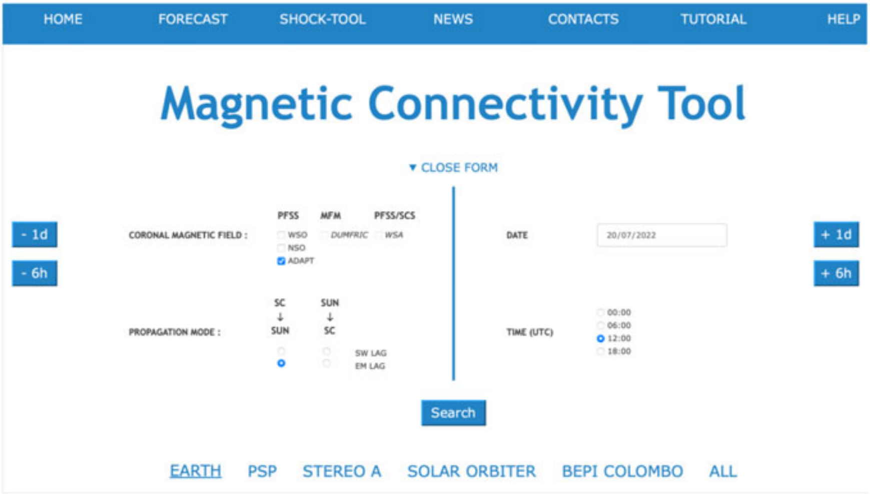
2. Magnetic Connectivity Tool

In order to forecast where to point the RS instruments, we need to apply models based on coronal magnetic field extrapolations and different techniques to retrieve coronal plasma properties in time and in three dimensional (3D) space. This is because we are not able to measure directly the Sun's magnetic field in the corona.

To predict the connectivity points on the solar disk (i. e., the footpoints of magnetic field lines connected to a spacecraft, SolO in our case), the MADAWG selected the use of one particular tool, the Magnetic Connectivity tool (`http://connect-tool.irap.omp.eu/`, operational since 2018, Rouillard et al. 2020).

Figure 1 shows the main page of the Magnetic Connectivity Tool web interface that enables the operator to choose different combinations of parameters to estimate the connectivity points close to Sun's surface. There is the possibility to chose how to model the inner solar corona ("coronal magnetic field" keyword) and the tool also enables the inclusion of forward or backward propagation at solar wind speed or speed of light ("propagation mode" keyword). The list at the bottom of the page gives the possibility to select the preferred vantage point (Earth or a S/C).

The SolO RS windows campaigns performed in March and October 2022, took advantage of the Magnetic Connectivity Tool to forecast the pointing of the spacecraft and all the extrapolations assumed the same model that we are describing in the following. The idea at the base of the assumed magnetic field model is to use the simplest approach, i.e. to describe the interplanetary magnetic field by a Parker spiral up to a certain distance in the corona and below that height (inner corona) to describe the field by using a potential field source surface (PFSS). The different approach at different heights in the solar atmosphere, is needed because in the inner corona we have open field lines that are deviated by closed magnetic field lines (see Fig. 2). The PFSS model (Altschuler & Newkirk 1969; Schatten et al. 1969), in particular, computes the magnetic field between 1 and 2.5 $R_\odot$, by extrapolation from the measured photospheric magnetic field, assuming that the field is current free and radial at 2.5 $R_\odot$. The photospheric magnetic field that consists in the boundary condition for the coronal extrapolations is derived from Air Force Data Assimilative Photospheric Flux Transport (ADAPT) synoptic maps of the radial component of the magnetic field (Arge et al. 2010; Hickmann et al. 2015), that are in turn constructed from Global Oscillation Network Group (GONG;



CORONAL MAGNETIC FIELD : PFSS ☐ WSO ☐ NSO ☑ ADAPT; MFM ☐ DUMFRIC; PFSS/SCS ☐ WSA

PROPAGATION MODE : SC ↓ SUN ○ ●; SUN ↓ SC ○ SW LAG ○ EM LAG

DATE 20/07/2022

TIME (UTC) ○ 00:00 ○ 06:00 ● 12:00 ○ 18:00

Figure 1. Interface of the Magnetic Connectivity Tool (`http://connect-tool.irap.omp.eu/`).

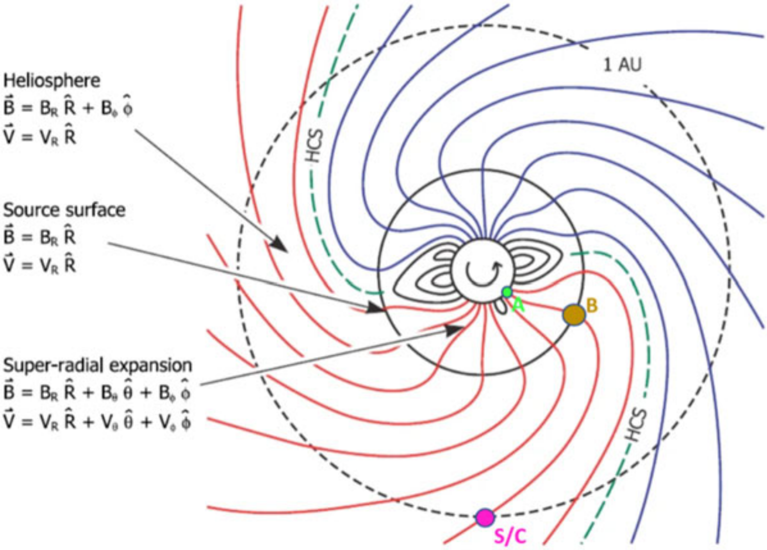


Figure 2. Schematic (from Owens & Forsyth 2013) illustrating how magnetic connectivity is established in the Magnetic Connectivity Tool, showing the location of a spacecraft (S/C), the intersection of the Parker Spiral (B) and the photospheric/low corona magnetic footpoint of field line (A).

Hill et al. 1994, 1996) magnetograms by evolving them using a photospheric flux transport model (Worden & Harvey 2000). Therefore, ADAPT generates global solar photospheric magnetic field maps using flux transport providing synchronic solutions every 24 hours. The result of this extrapolation are 12 maps for each predicted time. The connectivity tool is equipped with an automated evaluation of PFSS reconstructions by combining the position of the Heliospheric Current Sheet (HCS or neutral line) with the position of the streamers in the coronagraphic white light maps (Poirier et al. 2021). Currently, the code is exploiting the SOlar and Heliophysics Observatory/LASCO-C2 -C3 (SOHO, Domingo et al. 1995) maps in real time and a combination of the maps

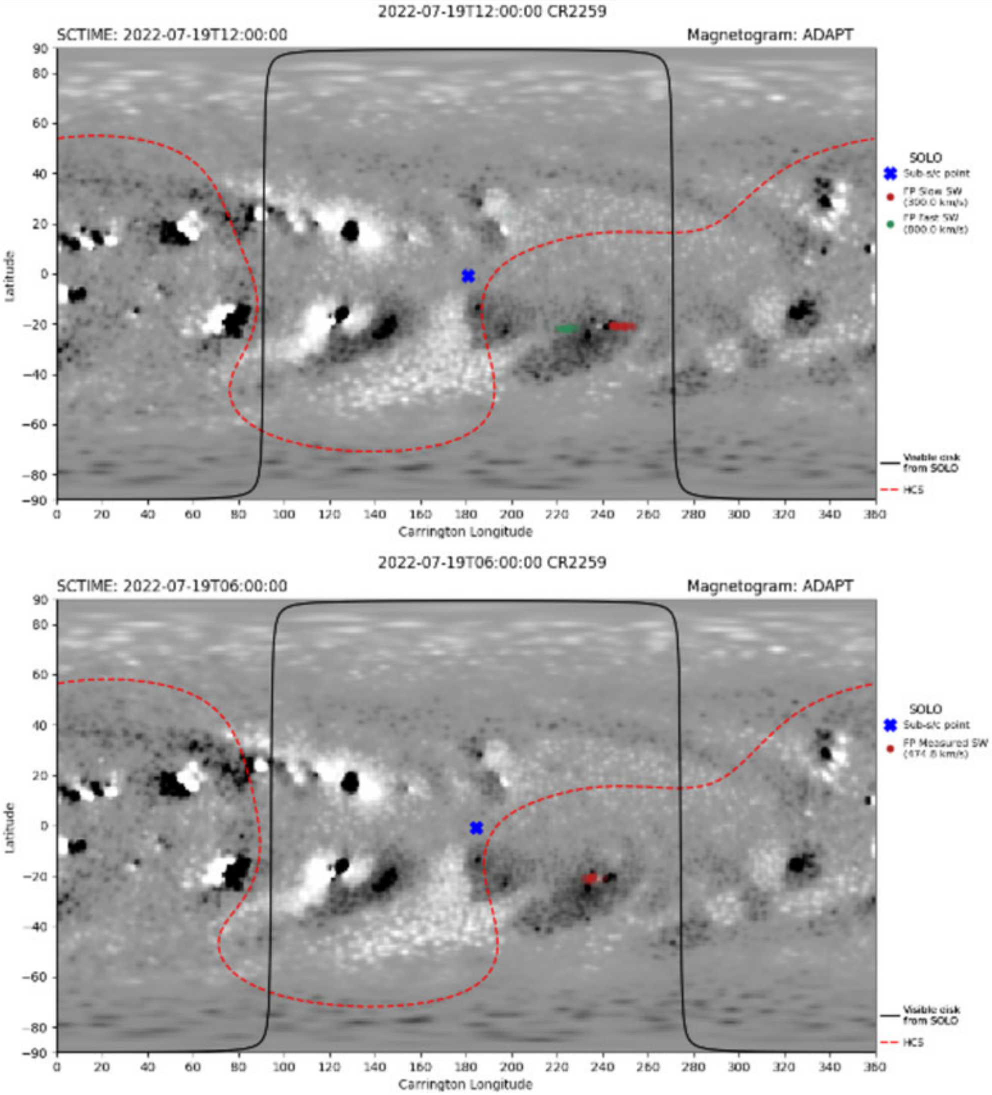


Figure 3. Examples of a connectivity map estimated without (top panel) and with (bottom) the integration of the measured solar wind speed from the SWA/PAS LLD. The red line is the HCS while the green and red dots represent the fast and slow wind connection points, respectively.

obtained by combining the data from SOHO/LASCO-C2 and Solar-TErrestrial RElations Observatory/SECCHI–COR1 (STEREO, Kaiser et al. 2008) for post-analysis, following the example of the work of Sasso et al. (2019). There is on-going work to integrate in the magnetic connectivity tool pipeline also SolO/Metis (Antonucci et al. 2020) Low Latency Data (LLD) and to use a combination of magnetograms, including SolO/Photospheric and Helioseismic Imager (PHI, Solanki et al. 2020) ones.

The top panel of Fig. 3 gives an idea of a connectivity map forecasted by the connectivity tool using ADAPT/GONG magnetic field maps with an estimate for the speed of the wind stream reaching the S/C (SolO on this example). The red line gives and estimation of the position of the HCS while the green and red dots represent the forecasted positions of the fast and slow wind connection points, respectively.

The bottom panel of Fig. 3 shows how it's possible to integrate the measurements of the solar wind speed coming from the IS instruments on board SolO to get a better estimate of the position of connection points. At the time it was created the map in the bottom panel of Fig. 3, the tool found information on the measured solar wind speed coming from the Proton-Alfa Sensor (PAS) LLD of the SWA instrument (Owen et al. 2020) on-board SolO. For this reason, in the bottom map, the tool gives only one estimation of the solar wind speed (red dots) and not two (green and red dots) as in the top panel of the same figure. Indeed, the connectivity tool has been implemented with a pipeline that automatically downloads SWA/PAS LLD data when they are available. SolO LLD data are fundamental to help establishing the most likely source of plasma in these maps.

3. SolO RS instruments campaign

SolO is a more likely a planetary mission with its typical operational constraints such as limited available telemetry due to the characteristics of the orbits, variable data latency due to the variations of the distance of the spacecraft from Earth, and limited data storage on-board. These particular conditions do not permit continuous observations for the RS instruments and force the need for long-term planning of top-level science operations (Zouganelis et al. 2020). Therefore, there are three 10-day windows every orbit (six months long), called the remote sensing windows (RSWs), typically centred around perihelia and minimum and maximum heliographic latitudes, where RS instruments can run their high resolution campaigns. Outside the RSWs, the RS instruments perform synoptic observations monitoring the Sun at low data acquisition rate, while the IS instruments are operating continuously along the orbit.

During the RSWs, there is the possibility to plan coordinated observations involving the SolO instruments with the possibility of deciding the spacecraft pointing just some days in advance. The science planning foresees what is called a very short term planning (VSTP) of science operations, inside the long-term plan (LTP, programmed 3 months before the observations, was formerly 6 months) and the short-term plan (STP, 1 week before). This possibility is there since high-resolution science requires fine-pointing to a target which position cannot be pre-planned, being solar activity unpredictable so much time in advance. During the planning of the LTP, the observing campaigns, called SOOPs for Solar Orbiter Observing Plans, are inserted and consists in the building blocks of the Science Activity Plan (SAP, Zouganelis et al. 2020).

During the latter VSTPs campaigns (March and October 2022), the MADAWG, the SolO Science Operations Centre (SOC), and the SOOP coordinators were working in close contact to forecast the location of targets and their magnetic connection with the S/C to choose RS targets and update the pointing. A big effort was done by the IS community to provide LLD that, as we described in Sect. 2, have an important role in the connectivity tool, helping retrieving the most reliable magnetic connection with the spacecraft.

At the time we are writing this contribution, first results are coming from two "Slow Wind Connection" SOOP campaigns held in the period March 3–6, and March 17–22, 2022. Both SOOPs were aiming at catching, with the RS instruments, the dynamics of an open-closed field boundary, while the wind associated with such a boundary would then be measured in situ. The target of the SOOPs were, therefore, active region/coronal hole boundaries and the science goal was to understand what are the release mechanisms of the slow solar wind at an open-closed magnetic field boundary.

The campaign consisted in coordinated observations involving the following SolO instruments: spectra from the Spectral Imaging of the Coronal Environment (SPICE, SPICE Consortium et al. 2020), 1 hr/day high resolution Extreme Ultraviolet

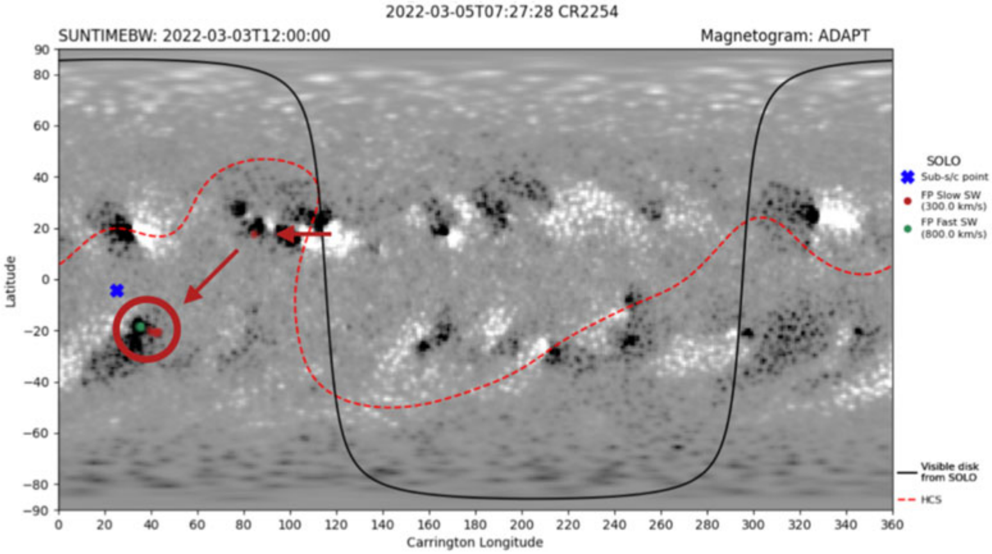


Figure 4. Connectivity map forecasted three and two days before the planned observation. The red point outside the red circle indicates the slow wind connection point forecasted for the 2nd of March, while the red point inside the red circle indicates the slow wind connection point forecasted for the 3nd of March. As in Fig. 3, the red line is the HCS while the green dots represent the fast wind connection points.

Imager (EUI, Rochus et al. 2020) images and PHI magnetograms, and continuous EUI/PHI/STIX (Spectrometer/Telescope for Imaging X-rays, Krucker et al. 2020)/SolOHI (Heliospheric Imager, Howard et al. 2020)/Metis synoptics and in-situ measurements.

Figure 4 shows an example of a connectivity map forecasted during these SOOPs. In particular, it shows the connectivity map obtained two days (3rd of March) before the planned observation, the 5th of March. On the map we have also superimposed the slow wind connection point forecasted for the 2nd of March (the red point outside the red circle). We see that connectivity moves from northern to southern active region (AR) during one day and this episode underlines the importance of having the forecasting and the decision on the pointing done as close as possible to the observations' day. After consulting the maps, SolO was predicted to be connected to the southern AR that was just rotating into spacecraft view on the 3rd of March.

Preliminary results coming from both observing campaigns, currently analyzed by a group coordinated by the SOOPs coordinator, S. Yardley, show that slow wind was measured at the SolO spacecraft during both windows.

4. Conclusions

We described the on-going effort by ESA's MADAWG to provide data-analysis tools and models that can support mission operations as well as help improving SolO science outputs with a particular focus on tools that exploit the coordinations between RS and IS instruments and the comparison of their data.

The preliminary results coming from the first coordination campaigns involving the majority of instruments on-board SolO aimed at forecasting magnetic connectivity between the particles arriving at the IS instruments and their sources back to the Sun, by using MADAWG's tools, are very encouraging and we are sure our work will help improve our understanding of the solar magnetic corona and heliosphere.

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Clementina Sasso from INAF (Italy) talking about “magnetic connectivity tools” to investigate the relationship between in-situ measurements and their source regions on the Sun.