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A propagation tool to connect remote-sensing observations with in-situ measurements of heliospheric structures

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ABSTRACT

The remoteness of the Sun and the harsh conditions prevailing in the solar corona have so far limited the observational data used in the study of solar physics to remote-sensing observations taken either from the ground or from space. In contrast, the 'solar wind laboratory' is directly measured in situ by a fleet of spacecraft measuring the properties of the plasma and magnetic fields at specific points in space. Since 2007, the solar-terrestrial relations observatory (STEREO) has been providing images of the solar wind that flows between the solar corona and spacecraft making in-situ measurements. This has allowed scientists to directly connect processes imaged near the Sun with the subsequent effects measured in the solar wind. This new capability prompted the development of a series of tools and techniques to track heliospheric structures through space. This article presents one of these tools, a web-based interface called the 'Propagation Tool' that offers an integrated research environment to study the evolution of coronal and solar wind structures, such as Coronal Mass Ejections (CMEs), Corotating Interaction Regions (CIRs) and Solar Energetic Particles (SEPs). These structures can be propagated from the Sun outwards to or alternatively inwards from planets and spacecraft situated in the inner and outer heliosphere. In this paper, we present the global architecture of the tool, discuss some of the assumptions made to simulate the evolution of the structures and show how the tool connects to different databases.

1. A propagation tool for heliospheric research

The analysis of remote-sensing observations and in-situ measurements require very different expertise. The physical processes that are remotely sensed must be analysed by first accounting for the mechanisms that generate or scatter the observed electromagnetic radiation. These mechanisms will differ according to the wavelength detected and the height at which the solar atmosphere is observed. In the optically thin corona for instance, each image pixel detects light integrated along the line of sight that passes through an extended region of the corona. At photospheric and chromospheric altitudes the medium is optically thicker. In-situ measurements made further out in the solar wind provide directly the physical parameters of the plasma at a single point. Remote-sensing observations are our only source of information of the state of the

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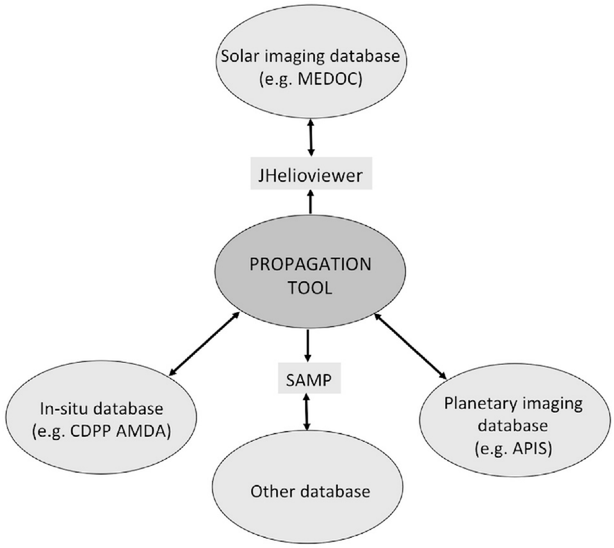

Fig. 1. The links currently working between the propagation tool and various databases that hold in-situ data (CDPP), solar imagery (MEDOC) and planetary imaging (APIS).

Type of propagation	Mode of J-map usage	
Radial propagation (ballistic radial propagation)	Carrington/In situ	Specify a CME's properties
	Catalogue of fits	Use existing CME catalogues
	J-map click	Locate a CME by J-map clicking
Corotation (ballistic radial + corotation)	Carrington/In situ	Specify a CIR's properties
	Catalogue of fits	Use existing CIR catalogues
	J-map click	Locate a CIR by J-map clicking
SEP propagation (ballistic particle trajectory along a Parker spiral)		

Fig. 2. The three types of propagation and the different ways in which J-maps can be used to track heliospheric structures. Only the radial propagation and the corotation methods allow usage of J-maps.

low corona, and solar imagery also provides a large-scale view of the physical processes at play. By combining both remote-sensing observations and in-situ measurements we can gain a more complete picture of the Sun-Earth system over a wide range of spatial and temporal scales.

The very different nature of remote-sensing observations and in-situ measurements coupled with the large distances that separate the solar corona with current in-situ measurements, meant that solar and solar wind research evolved separately over many decades, all too often without those involved consulting each other when working on the same problem. The databases used by researchers also evolved independently and little concerted effort was made to link them. Rare attempts have been made to connect some datasets by carrying out ballistic tracing of heliospheric structures between the Sun and planets, or probes. One example of such an undertaking was the first propagation tool developed by the HELIO FP7 project (http://hfe.helio-vo.eu/Helio/). These first attempts lacked the observational support to validate such ballistic tracing and the user was left uncertain about the validity of the tracing method. The launch of the Heliospheric Imagers (HI) instruments onboard the Solar-Terrestrial Relations Observatory (STEREO) in 2006 has provided imaging of the solar wind with sufficient resolution and cadence to enable plasma structures to be clearly identified and tracked as they propagate through the inner heliosphere (see for example review by Rouillard, 2011). The Propagation Tool developped at the Institute of Research in Astrophysics and Planetology (IRAP), accessible at http://propagationtool.cdpp.eu/, and presented in this paper exploits, in particular, heliospheric imagery as observational support to connect solar imagery with in-situ measurements.

The tool was created to support research in heliophysics by establishing connections between different databases that often hold complementary datasets on the sources, evolution and effects of propagating heliospheric structures. The different databases that are currently connected to the Propagation Tool are shown in Fig. 1. They include the MEDOC solar imagery datacenter (https://idoc.ias.u-psud.fr/MEDOC), the CDPP in-situ datacenter (http://cdpp.eu) and the Auroral Planetary Imaging and Spectroscopy (APIS) database (http://apis.obspm.fr/). In addition the tool has access to the Simple Applications Messaging Protocol (SAMP) that allows the exchange of data with other tools or users through a central hub and the Virtual Observatory for Planetary Science (VESPA) which can be interrogated to access a number of other databases. Once the trajectory of a heliospheric structure is determined by the tool, the various databases can be interogated to determine if interesting data is available along its trajectory.

Structure and aim of the paper. After a brief introduction of the different types of propagation that can be carried out with the tool and the corresponding exploitation of heliospheric imaging (Section 2.1), we describe the general layout of the components visible by default in the main interface (Section 3.1). Each component is then described separately by illustrating some of its functionalities (Section 3.2–3.5). We also show how different databases can be interogated directly from the tool (Section 3.7) and how the latter has been used so far for various studies published in the litterature (Section 4.1). The aim of the paper is to highlight the rich set of functionalities provided by the tool, a good understanding of how the tool works and its full potential can only be achieved by using it.

2. Components of the propagation tool

2.1. An overview of the propagation methods

In order to establish connections between the effects of a particular solar wind structure (CME, CIR, streamer blob, jet, …) at different locations in the corona/heliosphere system, the propagation time between the start and end points, as well as the spatial extent of the solar wind structure, must be computed as accurately as possible. The propagation time is calculated once the kinematic and spatial properties of that propagating structure are either specified by (1) the user manually, (2) the selection of a catalogue of pre-identified heliospheric structures or (3) a bespoke analysis undertaken with the tool. Heliospheric imagery, presented in the tool in the form of time-elongation maps (Sheeley et al., 1997; Davies et al., 2009) of solar wind density variations, provides the crucial information needed to confirm the trajectory of the outflowing structure. The tool provides a visualisation interface to these time-elongation maps (often called J-maps). The J-maps extend in elongation from the solar corona, imaged by coronagraphs, through the inner heliopshere, out to 1AU and beyond imaged by heliospheric imagers. The generation of these maps will be discussed in more detail in Section 3.6. As the signal within a pixel integates along the line-of-sight, a specific elongation does not correspond to a unique height above the solar surface and analysis techniques must be applied to determine the 3-D trajectory of the heliospheric structure of interest. These techniques are usually based on ballistic propagation techniques and assumptions concerning the geometry/shape of the initial structure at the inner boundary (see Section 3.6).

The Propagation Tool offers three simple types of propagations that allow users to:

- propagate radially-outflowing structures (CMEs) sunward or anti-sunward (Radial Propagation method),
- propagate corotating structures (CIRs) forwards in time (Corotation method),