Constraining Solar Structure Propagation in the Heliosphere : A Multipoint Approach

A. Gonnet[1,2], N. André[1], A. Marchaudon[2], M. Rojo[2], V. Réville[2], J-B. Dakeyo[3], E. Vellard[1], I. Plotnikov[2], P. Garnier[2]

[1] Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), Université de Toulouse, Toulouse, France [2] Institut de Recherche en Astrophysique et Planétologie (IRAP), CNRS-UPS-CNES, Toulouse, France [3] Space Sciences Laboratory, University of California, Berkeley, Berkeley, CA, USA

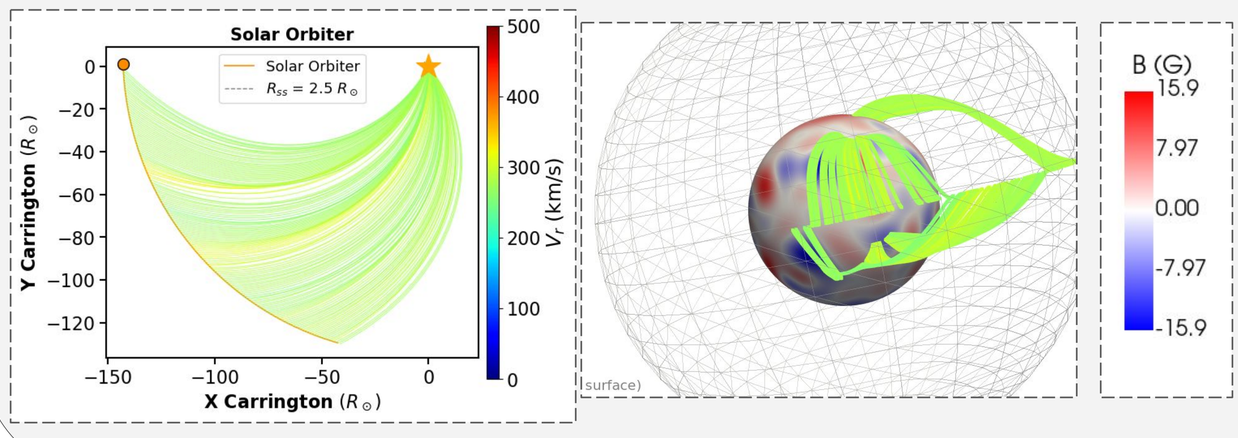
Abstract

Multi-spacecraft conjunctions involving BepiColombo, Parker Solar Probe, Solar Orbiter, and STEREO-A offer a unique opportunity to derive upstream conditions constraining Sun-planet magnetospheric interactions. Here, we compare in-situ plasma and magnetic observations from Parker Solar Probe and STEREO-A over a two-month interval during which the spacecraft were first aligned along the same Parker spiral, then radially aligned. We compute the time lag between them using magnetic connectivity and cross-correlation with the Dynamic Time Warping algorithm, tracing back STEREO-A observations to Parker Solar Probe's orbit. We show that both spacecraft observed similar solar wind conditions. Finally, we attempt to apply the same method to the flybys of Mercury by BepiColombo in order to derive the solar wind context. Only two other use cases (flybys 1 and 3) currently yield satisfactory results.

Methods

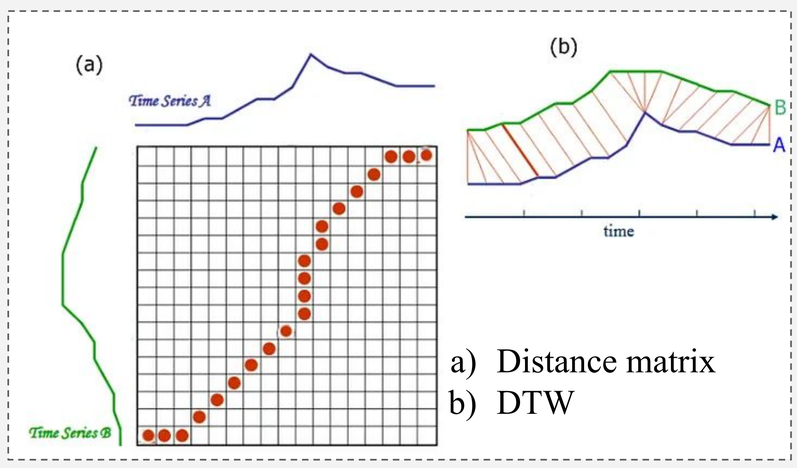
1 Magnetic connectivity at the source surface of the Sun

- Magnetic connectivity tool[a]
- Parker Spiral and Potential Field Source Surface (PFSS) models
- The spacecraft **magnetic footpoints** give the **source of the measured Solar Wind**



2 Cross-correlating temporal series: Dynamic Time Warping[b] (DTW)

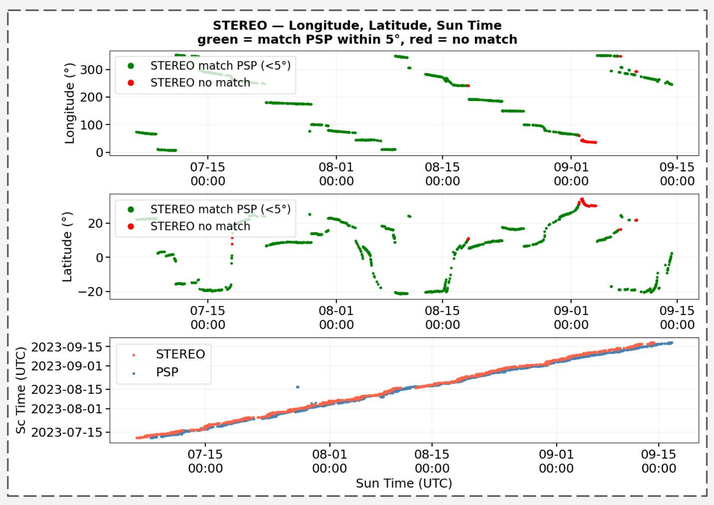
- **Algorithm** for measuring **similarity** between two **temporal sequences**
- DTW gives a non-linear (elastic) alignment between two-time series
- The best alignment matches similar shapes even if they are out of phase in the time axis

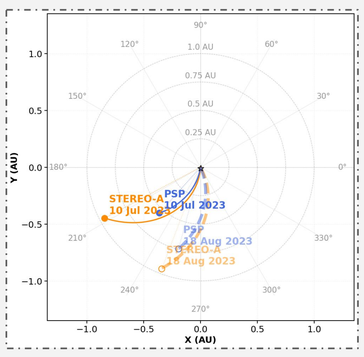


Source: Chathurangi Shyalika, Dynamic Time Warping, *Medium*

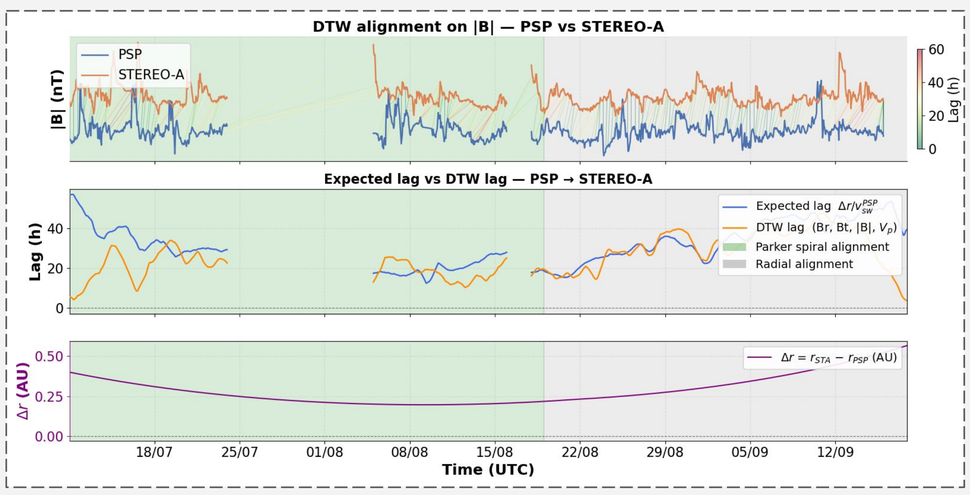
Use case 1: PSP and Stereo-A conjunction

- We use in-situ plasma and magnetic field measurements from SWEAP/SPC and FIELDS/MAG (PSP) and PLASTIC and MAG (Stereo-A) to compute the magnetic footpoints and cross-correlate the observations.





The spacecraft share close Parker Spirals from July 10th 2023 to August 13th 2023, and become radially aligned within 5° until September 18th 2023.

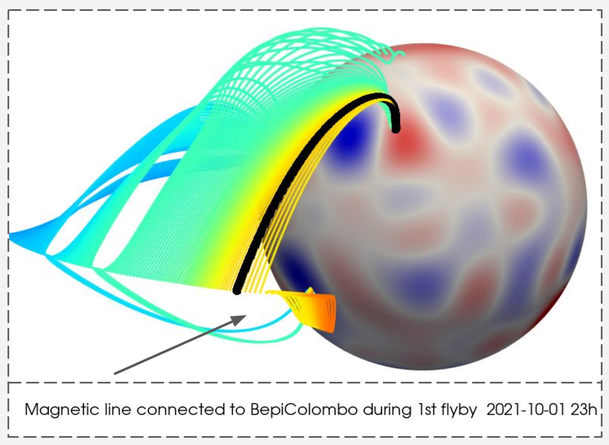


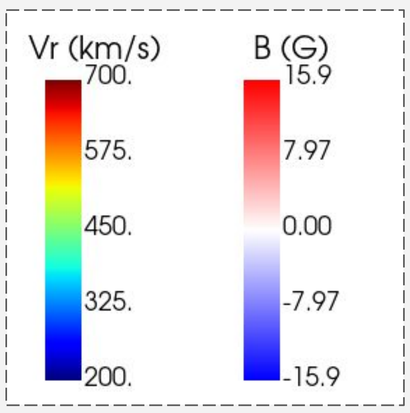
The **solar wind sources are aligned** most of the time, and **DTW reconstructs the temporal lag** between observations. After validating this method, we apply the first step to BepiColombo's Mercury flybys.

Use case 2: BepiColombo's Mercury flybys

We check if observations of PSP, Solar Orbiter and Stereo-A can be backmapped to the orbit of Mercury, to derive the solar wind conditions at the time of five flybys.

- We use SW speed data from SUSANOO[c] simulations and magnetic field measurements from MPO/MAG (BepiColombo) to trace the solar wind source region during the BepiColombo Mercury flybys.





We look for magnetic footpoints of PSP, Solar Orbiter or Stereo-A that closely match BepiColombo's footpoint at local Sun time (at the corresponding flyby time).

	Flyby 1	Flyby 2	Flyby 3[d]	Flyby 4	Flyby 6
PSP	✗	✗	✓	✗	✗
Solar Orbiter	✓	✗	✗	✗	✗
Stereo-A	✗	✗	✗	✗	✗

Predictions for deriving solar wind conditions during the Mercury flybys

Solar Orbiter and **PSP** are connected to the **same solar wind source** (within 5°) **simultaneously** with BepiColombo during the **1st** and **3rd flybys**, respectively, and *could* therefore provide **similar solar wind observations** with a time lag.

Conclusions

1. We present a **two-step method** to compare plasma and magnetic field series between two or more spacecraft in the solar wind.
2. We show that Parker Solar Probe and STEREO-A measured **similar solar wind sources** over a two-month interval from July to September 2023. The DTW algorithm successfully estimated the **temporal lag separating the observations.**
3. We applied the first step of our method to **five BepiColombo's Mercury flybys** to identify whether any other spacecraft was connected to the same solar wind source during each flyby.
4. Based on simulated solar wind speed values upstream of Mercury, **only Solar Orbiter and PSP could provide propagated observations** of the solar wind context during the **1st** and **3rd** Mercury flybys, respectively.

Perspectives

The next step is to confirm the magnetic connectivity using **in-situ plasma measurements from SERENA/PICAM**, the ion monitor onboard MPO/BepiColombo, noting that the resulting connectivity is sensitive to the measured solar wind speed.

We will then reconstruct the **time lag between the spacecraft** using DTW, before checking whether our **predictions are compatible** with the **observed state of the magnetosphere** during the dedicated flybys.

[a] connect-tool.irap.omp.eu / github.com/vreville/mini_connect_tool *Rouillard et al (2020)*
[b] *Giorgino. Computing and Visualizing Dynamic Time Warping Alignments in R: The dtw Package. J. Stat. Soft., 31 (2009)*
[c] *Shiota, D., and R.Kataoka (2016) - SUSANOO-CME*
[d] *Rojo et al (2025)*