KU LEUVEN

SHINE HONOLULU 2022

Calibrating the WSA model in EUHFORIA based on PSP observations: challenges and limitations toward the improvement of solar wind forecasting

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Abstract: Coronal models, usually extending between the solar photosphere and ~30 Rs, are an integral part of many space weather forecasting tools. They reconstruct the magnetic field in the solar corona and provide the necessary plasma conditions for initiating heliospheric models such as EUHFORIA and Enlil. A big gap in literature is identified when it comes to the validation of coronal models because of lack of observations, especially in situ. Nevertheless, the launch of the Parker Solar Probe (PSP) has provided, for the first time, in situ measurements very close to the Sun that can help with the evaluation of such models. In this work, we aim to calibrate the Wang-Sheeley-Arge (WSA) semi-empirical velocity formula used in EUHFORIA for the reconstruction of plasma and magnetic parameters at 0.1 AU. For that, we exploit PSP in situ measurements obtained from the first 8 perihelia. We show how a parametric study of the WSA velocity formula influences the modeled velocity distributions both close and further away from the Sun, how these distributions are compared to what PSP has measured, and present the relevant forecasting results at both the PSP position and Earth. Finally, we apply the Dynamic Time Warping technique to evaluate the performance of our solar wind time series at Earth and conclude whether the approach we follow leads to improved solar wind predictions.

A. Motivation

Heliospheric domain of EUHFORIA
(Pomoell & Poedts, 2018)

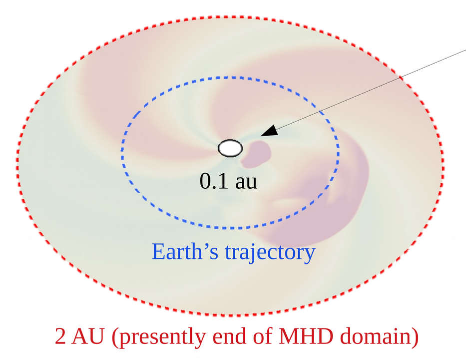


Figure 1: Equatorial plane of EUHFORIA's heliospheric MHD domain. The inner boundary (0.1 au) is shown in black, Earth's trajectory in blue and the present end of the domain in red. *Image credits: Jens Pomoell.*

WSA model
(Arge et al., 2003/2004; Van der Holst et al., 2010)

$$u_{1\,AU} = 240 + \frac{675\{1-0.8e^{[-(\frac{\theta_b}{0.02})^{1.25}]}\}^3}{(1+f_s)^{1/4.5}}$$

How was this relationship initially derived?

- Ballistic propagation until 1 au
- GONG synoptic magnetograms

B. Calibrating V_0

- V_0: lowest solar wind velocity observed at 0.1 au *(McGregor et al., 2011)*

$$u_{0.1\,AU} = V_0 + \frac{V_1\{1-0.8e^{[-(\frac{\theta_b}{w})^{\beta}]}\}^3}{(1+f_s)^{1/4.5}}$$

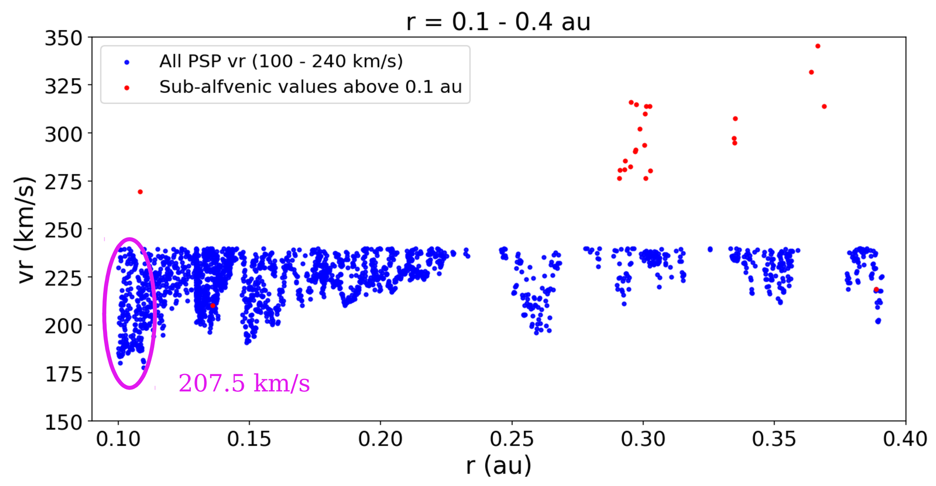


Figure 2: The lowest speeds observed by PSP between 0.1 – 0.4 au during the first eight encounters. The velocity range is restricted between 100 – 240 km/s and the sub-alfvenic values are indicated in red. The average velocity value around the boundary (0.1 – 0.11 au) is 207.5 km/s.

C. Calibrating V_1, w, β

- w, β: determine how far from the coronal hole boundary the transition between the slow and fast solar wind takes place, and how abrupt this change is, respectively
- V_1: maximum solar wind velocity at 0.1 au

$$u_{0.1\,AU} = 207.5 + \frac{V_1\{1-0.8e^{[-(\frac{\theta_b}{w})^{\beta}]}\}^3}{(1+f_s)^{1/4.5}}$$

First approach: comparison between observed and EUHFORIA-modeled velocities at PSP between 0.1 – 0.8 au

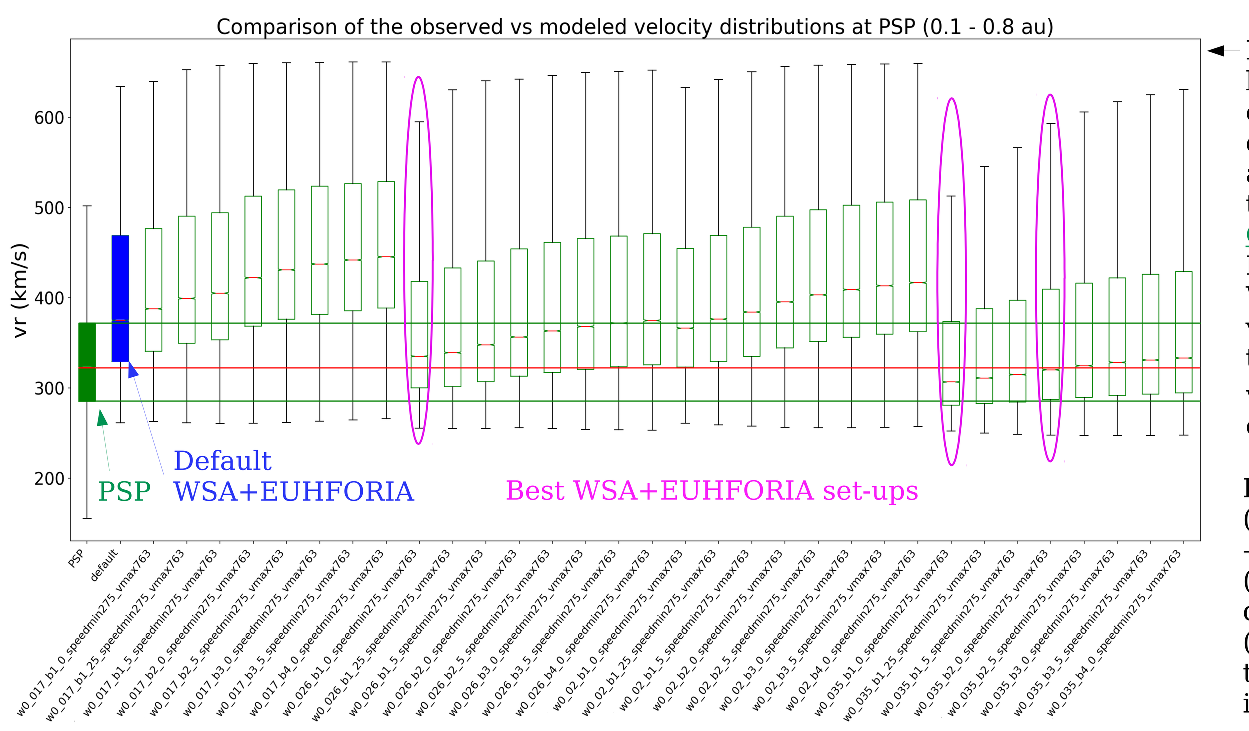


Figure 3: Box-whisker plot of velocities at PSP between 0.1 – 0.8 au during the first eight encounters. Each box corresponds to a velocity distribution with a median value shown in red, and the first and third quartiles represented by the lower and upper box edges, respectively. Green box: observed PSP velocities. Blue box: PSP velocities as modeled by the default WSA+EUHFORIA set-up. All other boxes: PSP velocities as modeled by WSA+EUHFORIA, for the optimized values V_0, V_1, w, β. The set-ups which are in best agreement with the observations, are circled in magenta.

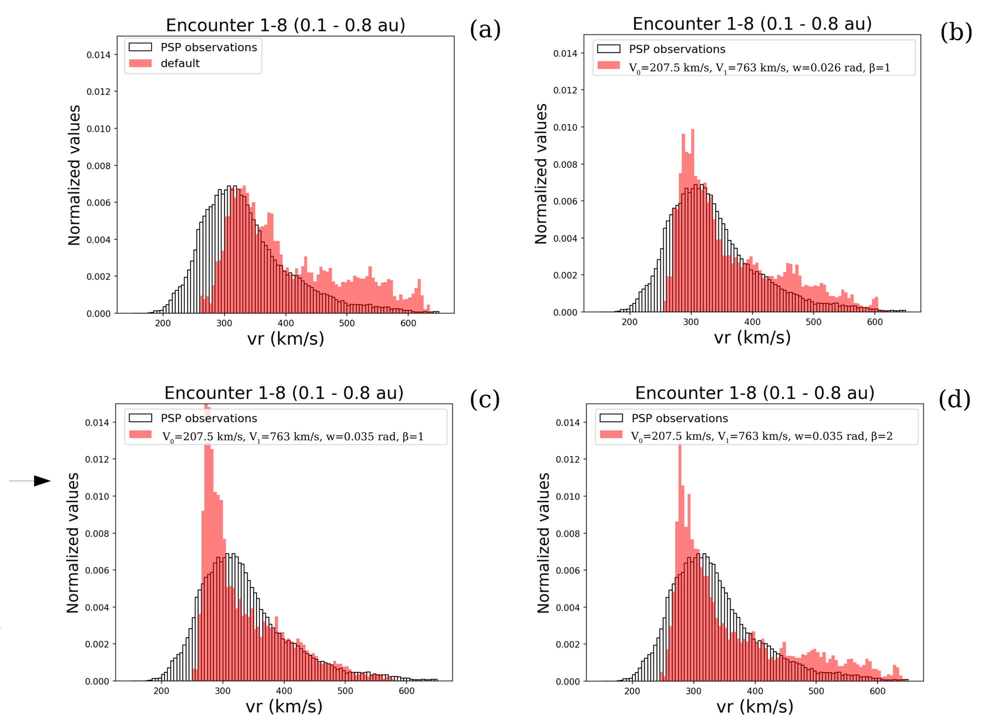


Figure 4: Observed (white) versus modeled (red) PSP distributions of velocities between 0.1 – 0.8 au during all first eight encounters. Panel (a): modeled distribution corresponds to the default WSA+EUHFORIA set-up. Panels (b), (c), (d): modeled distributions correspond to each of the three optimized set-ups circled in magenta in Figure 3. See legends for more details.

Second approach: comparison between observed PSP velocities close to the Sun (0.1 – 0.4 au) and WSA velocities at 0.1 au
(inspired by *McGregor et al., 2011*)

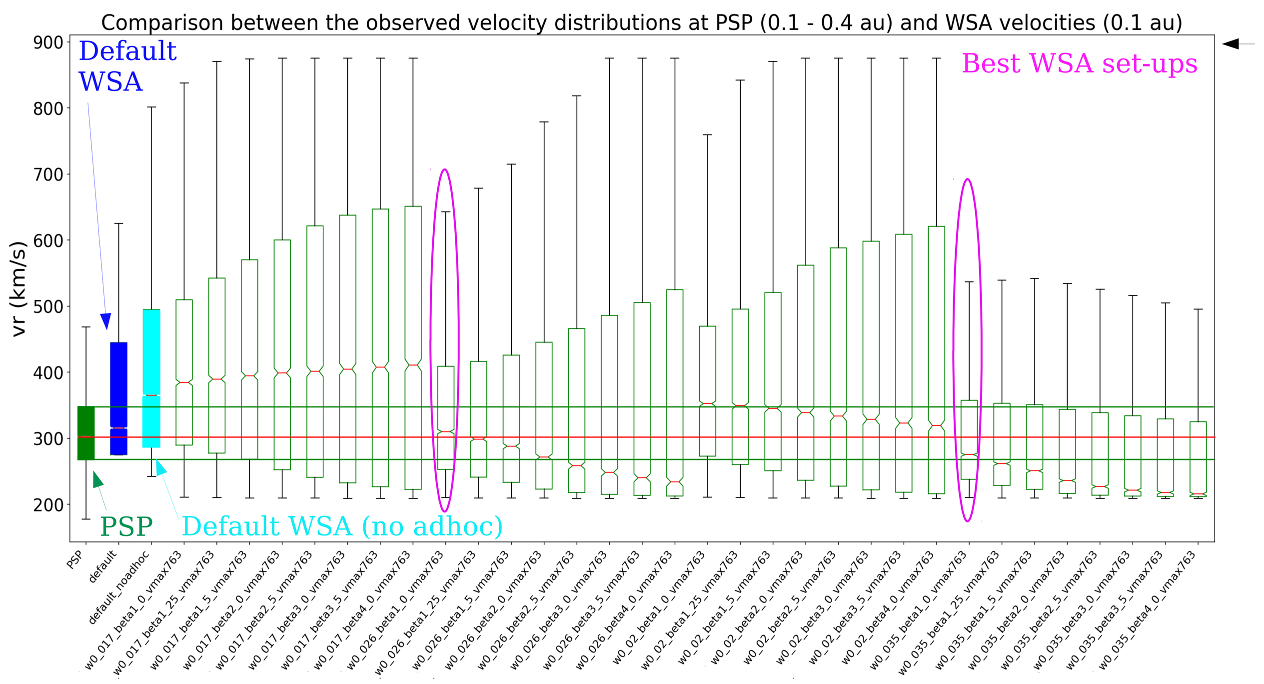


Figure 5: Same as figure 3 but the comparison is now between PSP observed velocities close to the Sun (0.1 – 0.4 au) and WSA velocities at 0.1 au. Light blue box: corresponds to the default WSA set-up but without the adhoc assumptions of clipping the velocities between 275 km/s and 625 km/s at the boundary, and subtracting 50 km/s from them.

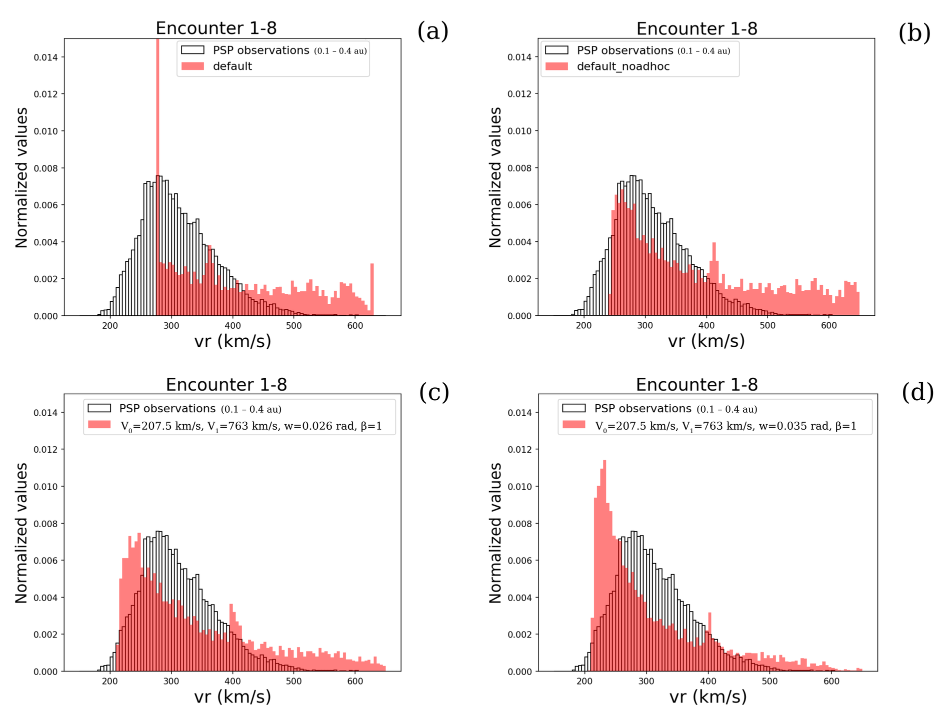


Figure 6: Same as figure 4 but the comparison is between PSP observed velocities close to the Sun (0.1 – 0.4 au) and WSA velocities at 0.1 au.

D. Time series at PSP & Earth

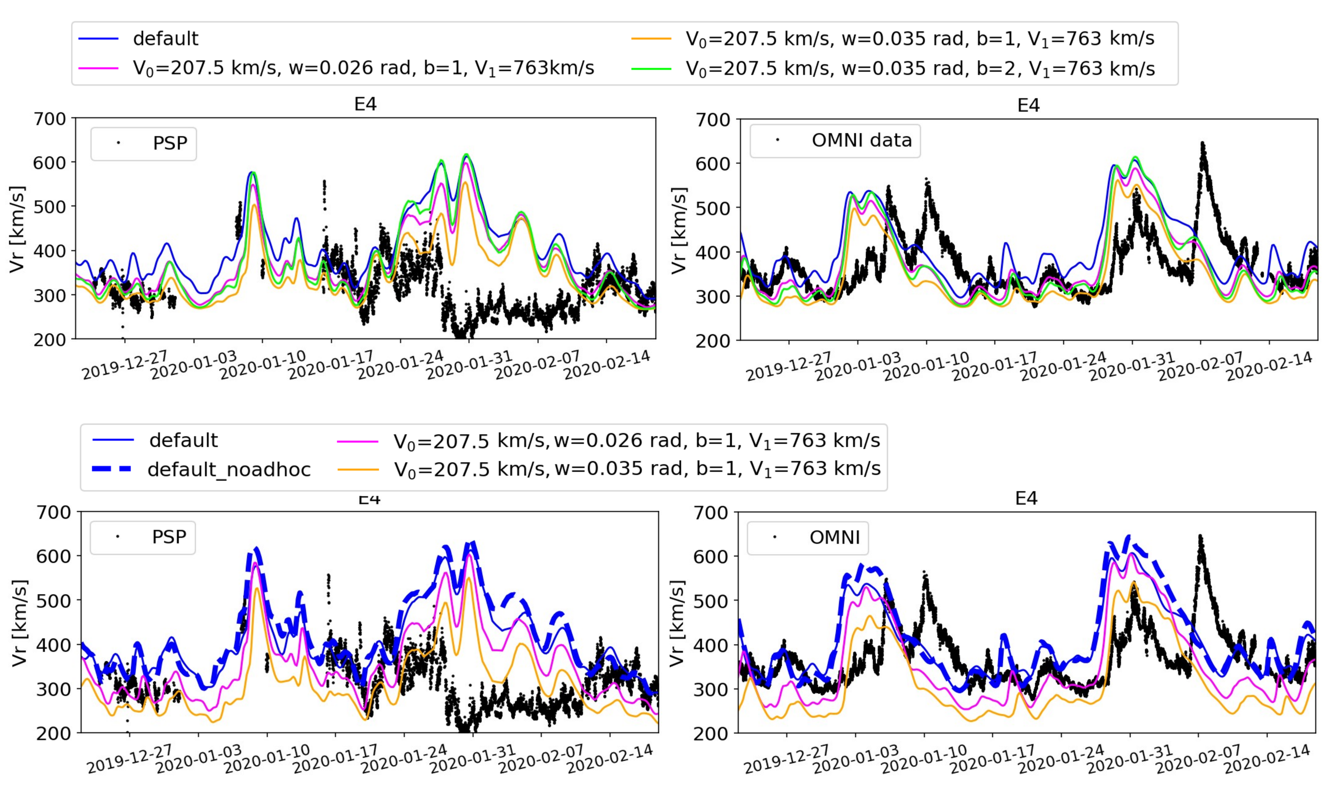
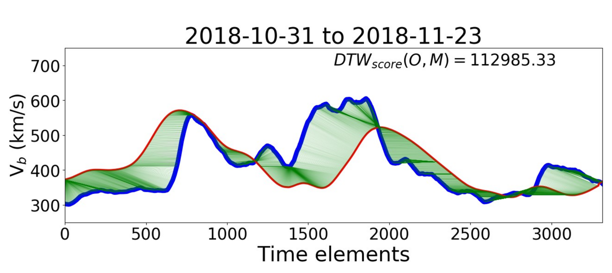


Figure 7: Solar wind velocity time series at PSP and Earth during the time period of encounter 4 (E4). Blue time-series correspond to the default WSA+EUHFORIA set-up while the rest of the colorful lines correspond to the best modeled set-ups identified based on the first approach (upper panels) and second approach (lower panels).

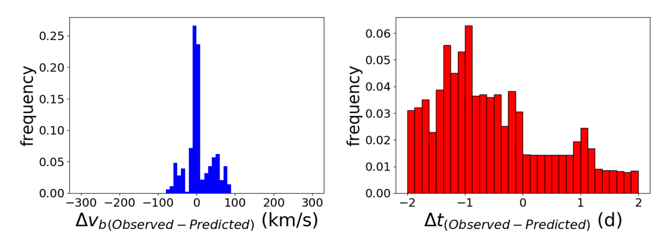
E. Evaluation of results with DTW

Application of the Dynamic Time Warping (DTW) technique as a metric to quantify the performance of solar wind time series; see *Samara et al., 2022, ApJ*, for more details.

Step 1: time series alignment



Step 2: quantification of amplitude and time differences



Step 3: definition of a skill score metric by employing an "ideal" and a "reference" prediction scenarios, as follows:

- Ideal prediction = predicted time series identical to observations (DTWcost = 0)
- Reference prediction = straight-line (averaged line of the observed dataset) or any other reference model the user wants to employ (DTWcost is just a number)

SSF (Sequence Similarity Factor) = $DTWcost_{(Obs.vsModeled)}/DTWcost_{(Obs.vsReference)}$, SSF = [0, 1]

F. Results & conclusions

First approach: solar wind forecast at Earth was improved in 50% of the cases (4/8 encounters) based on the results of DTW. More runs need to be executed to evaluate the performance of WSA+EUHFORIA with the updated WSA formula, for an extended solar minimum period.

Second approach: solar wind forecast at Earth was improved in 10% of the cases (1/8 encounters) based on DTW → calibration of the WSA velocities close to the boundary did not lead to improved results at Earth but to underestimated velocity values.

The following question arises: How did McGregor et al., 2011 managed to improve the velocities at Earth by calibrating the WSA formula with the Helios data (0.3-0.4 au) following the second approach?

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Acknowledgments

Special thanks go to Michael Stevens from CFA, Harvard for providing the curated PSP data for all eight encounters.