Data Assimilative Optimization of WSA Source Surface and Interface Radii using Particle Filtering

Grant Meadors[1], Humberto Godinez[2], Kyle Hickmann[1], Carl Henney[3], Shaela Jones[4], and Charles Arge[4]

[1]Los Alamos National Laboratory
[2]Los Alamos National Lab
[3]Air Force Research Laboratory Kirtland AFB
[4]NASA Goddard Space Flight Center

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Abstract

The Wang-Sheeley-Arge (WSA) model estimates the solar wind speed and interplanetary magnetic field polarity at any point in the inner heliosphere using global photospheric magnetic field maps as input. WSA employs the Potential Field Source Surface (PFSS) and Schatten Current Sheet (SCS) models to determine the Sun's global coronal magnetic field configuration. The PFSS and SCS models are connected through two radial parameters, the source surface and interface radii, which specify the overlap region between the inner SCS and outer PFSS model. Though both radii are adjustable within the WSA model, they have typically been fixed to 2.5 R sol. Our work highlights how the solar wind predictions improve when the radii are allowed to vary over time. Data assimilation using particle filtering (sequential Monte Carlo) is used to infer the optimal values over a fixed time window. The Air Force Data Assimilative Photospheric Flux Transport (ADAPT) model generates an ensemble of photospheric maps that are used to drive WSA. When the solar wind model predictions and satellite observations are used in a newly-developed quality-of- agreement metric, sets of metric values are generated. These metric values are assumed to roughly correspond to the probability of the two key model radii. The highest metric value implies the optimal radii. Data assimilation entails additional choices relating to input realization and timeframe, with implications for variation in the solar wind over time. We present this work in its theoretical context and with practical applications for prediction accuracy.

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Grant David Meadors[1,2], Shaela I. Jones[3,4], Kyle S. Hickmann[1], Charles N. Arge[3], Humberto C. Godinez-Vasquez[2], Carl J. Henney[5]

[1] Los Alamos National Laboratory, XCP-Division, Verification & Analysis, Los Alamos, NM, [2] Los Alamos National Laboratory, T-Division, Applied Mathematics & Plasma Physics, Los Alamos, NM, [3] NASA Goddard Space Flight Center, Greenbelt, MD, [4] Catholic University of America, Washington, DC, [5] Air Force Research Laboratory, Space Vehicles Directorate, Kirtland AFB, NM

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Abstract

- *Wang-Sheeley-Arge* (WSA): model estimates solar wind & polarity
- Potential Field Source Surface (PFSS) & Schatten Current Sheet (SCS) used to determine Sun's global coronal magnetic field
- 2 radial parameters: source surface & interface radii $\theta \equiv (R_{ss}, R_i)$
- **Idea**: optimize predictions by tuning – time-varying – radii

Introduction

- CR1901-2 (1995-09-29/1995-11-24) chosen, as difficult in past work

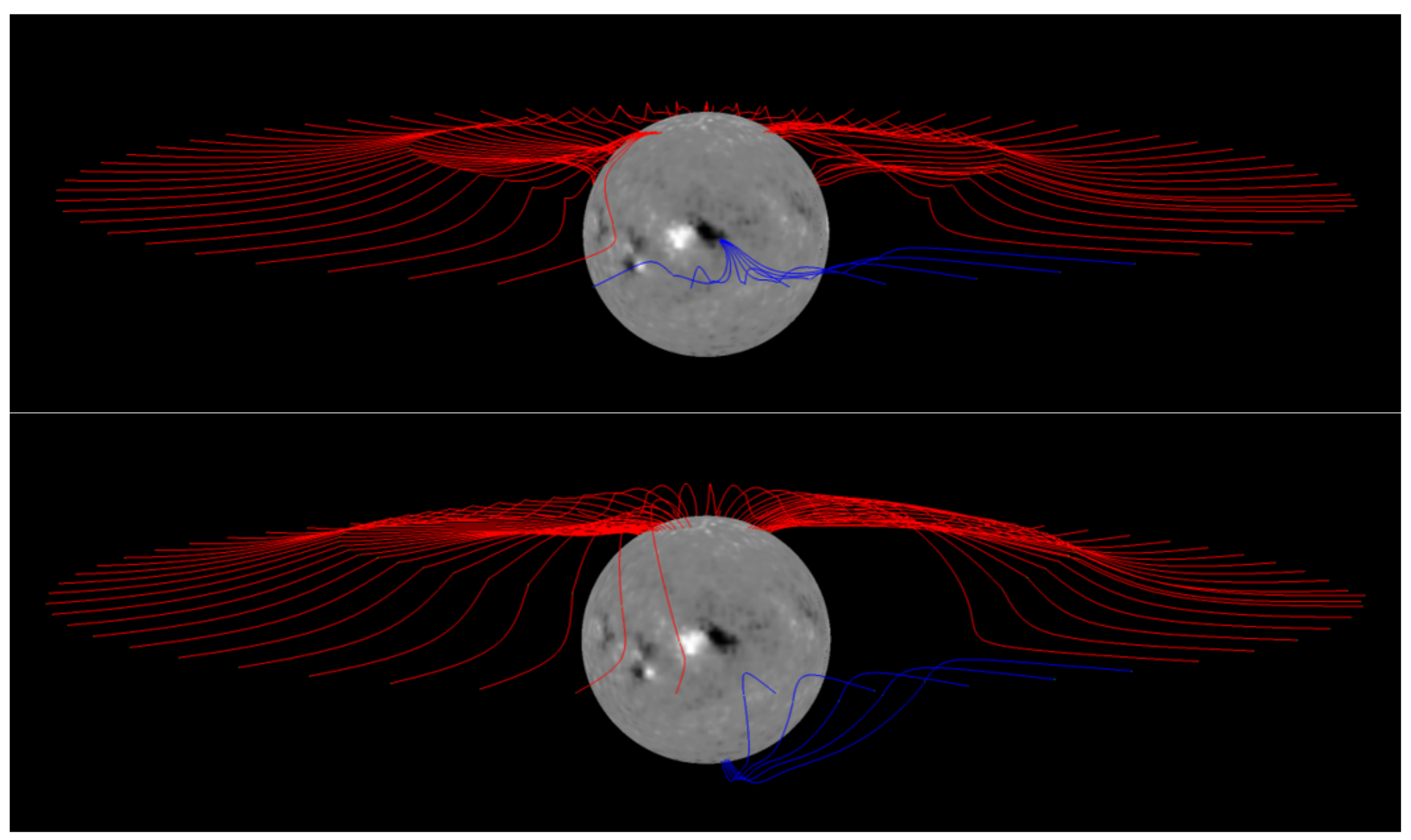

Figure: Magnetic field lines for different (R_{ss}, R_i): standard $(2.51, 2.49)$ (ABOVE) vs one optimum $(3.50, 2.51)$ (BELOW) as predicted by WSA model. Particle filtering minimizes error between model & data, which also helps smooth unphysical kinks.

Best (R_{ss}, R_i) appear to vary in time, based on kinking, coronal holes. A metric $H =$ (fractional polarity)/(RMS residual **v**), measures fit. Instead of fixed radii, can **optimize** fit by maximizing peak H over radii.

Particle filtering

Like Monte Carlo but **resample** $\propto$ metric H w/ N samples $\theta = (R_{ss}, R_i)$:

$$\text{Prior}(\theta(R_{ss} > R_i)) = \text{Uniform}(1.5R_\odot, 4.0R_\odot).$$

Data assimilation – apply resampling, with Gaussian perturbation kernel, to incoming ADAPT map data. Converge over iterations k:

$$q(j) \equiv \min_j \{j | c_j > U(0,1)\}, \text{ where } c_j = \sum_{i=0}^{j} H(\theta_i) / \sum_{m=0}^{N} H(\theta_m),$$

$$\theta_j^{k+1} = \theta_{q(j)}^k + \left(2\pi\sigma^2\right)^{-1} \exp\left(-\theta^2/\left[2\sigma^2\right]\right).$$

Samples move toward high H (good fit), adapting as (R_{ss}, R_i) evolve.

Sensitivity & twin testing: simulation and inference

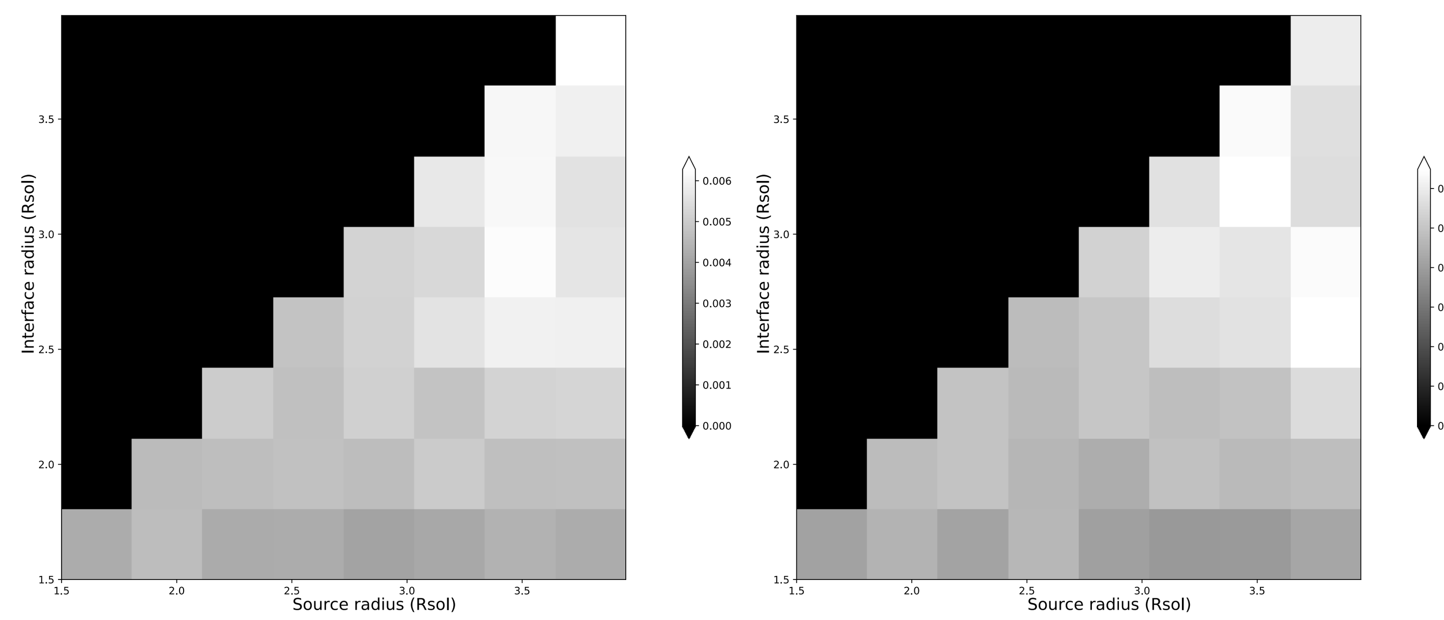

Figure: Heatmaps of H for 36 points on the R_i vs R_{ss} plane for 2 ADAPT synoptic maps. $H \uparrow$ (lighter) is more accurate. The upper, black, triangles are outside of physical bounds (R_i must be $< R_{ss}$). Particle filtering can refine H near *optima*.

R_{ss} ($R_\odot$)	R_i ($R_\odot$)	H (km^{-1} s)
3.000001	2.900000	48.64546334
3.000010	2.900000	31.11168033
3.000100	2.900000	0.54772908
3.000000	2.900001	68.66813214
3.000000	2.900010	0.44581968
3.000000	2.900100	0.45486562

Table: Source *simulated* at $(R_{ss}, R_i) = (3.000, 2.900)$. Predictions used as observations for sensitivity analysis 7-day window time: 1995-10-05/1995-10-12.

'Twin testing' validates that the particle filter finds **optimal** radii. WSA, at an arbitrary point, makes a prediction set to *simulate* WIND satellite data. Then the particle filter is run, using the predictions in place of observations. The filter works if it can infer that point $\rightarrow$ it does.

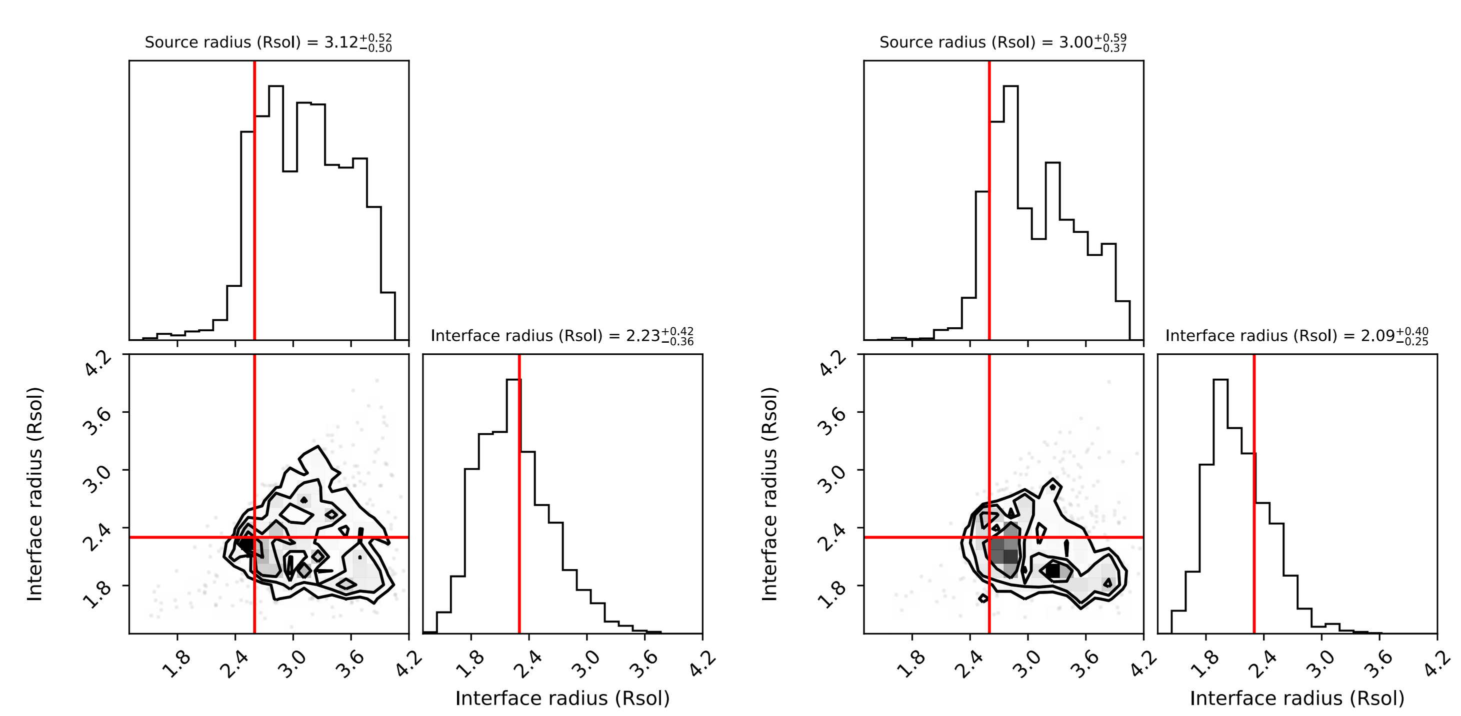

Figure: *Simulated* $(R_{ss}, R_i) = (2.6, 2.3)$ (red line). 512 samples, 7-day windows, ADAPT map 05 – 1st (LEFT) & 2nd (RIGHT) of CR 1901 simulated wind + polarities. Gray dots at sample points. 2D histogram (w/ 1D projections) show favored radii.

Real data analysis on Carrington Rotation (CR) 1901

Particle filtering converges in real data, with greater uncertainty.

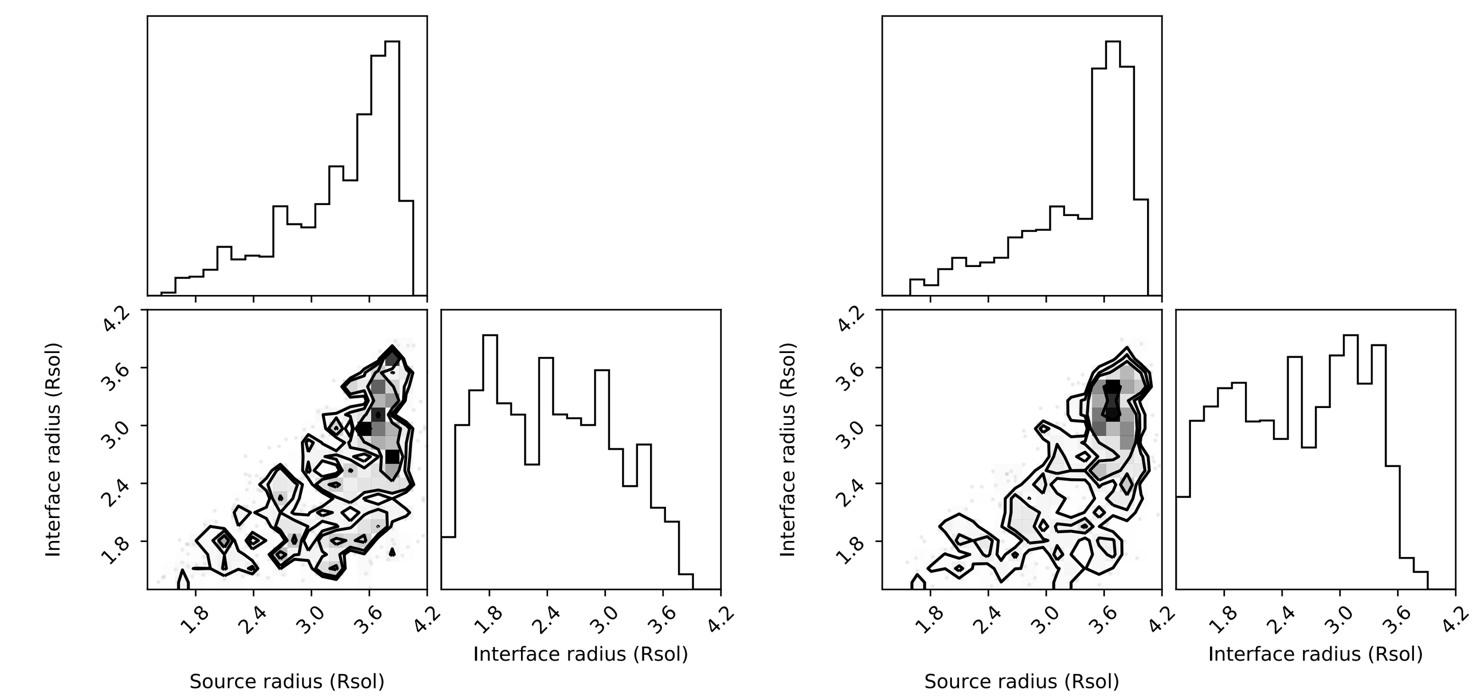

Figure: 512 samples, 7-day windows (start: 1995-09-29), ADAPT map 05 – 1st (LEFT) & 2nd (RIGHT) of CR 1901 real data. H metrics weight particle-filter resampling. Peak emerges at high source radius: $R_{ss} > 3.5R_\odot$ fit WIND data. Note: triangular-shaped prior distorts 1D projections, with effect smaller in later iterations.

Conclusions and future work

Demonstrated (for 2 Carrington Rotations): particle filtering can optimize and improve solar wind predictions. While this work is exploratory, it demonstrates how modern adaptive assimilation techniques are useful for space weather applications. Future ideas:

- More Carrington Rotations: show improvement across solar cycle
- ADAPT maps: another dimension to optimize
- Metrics? (1) field-line kinking (2) magnetic flux (3) more satellites

Acknowledgments

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