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

Grant Meadors\textsuperscript{1}, Humberto Godinez\textsuperscript{2}, Kyle Hickmann\textsuperscript{1}, Carl Henney\textsuperscript{3}, Shaela Jones\textsuperscript{4}, and Charles Arge\textsuperscript{4}

\textsuperscript{1}Los Alamos National Laboratory
\textsuperscript{2}Los Alamos National Lab
\textsuperscript{3}Air Force Research Laboratory Kirtland AFB
\textsuperscript{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 $2.5 \text{ R}_\odot$. 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.
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

Particle filtering
- Instead of fixed radii, can minimize error between model & data, which also helps smooth unphysical kinks.
- One optimum

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

\[
\begin{align*}
R_{SS} & (R_i) \quad R_i (R_{SS}) \quad H \ (\text{km}^{-1}) \quad \text{s} \\
3.000000 & 2.900000 & 31.1168033 & 0.44581968 \\
3.000000 & 3.000000 & 0.54772006 & \\
3.000000 & 2.900000 & 0.45486562 & \\
3.000000 & 2.900000 & 0.45486562 & \\
3.000000 & 2.900000 & 0.45486562 & \\
3.000000 & 2.900000 & 0.45486562 & \\
\end{align*}
\]

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.

- Sensitivity & twin testing: simulation and inference

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

\[
\text{Prior}(\theta | R_{ss} > R_i) = \text{Uniform}(1.5 R_i, 4.0 R_i)
\]

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

\[
q(j) \equiv \min \left\{ q_i | c_i > U(0.1) \right\}, \quad c_i = \sum_{i=1}^{N} H(\theta_i) \sum_{m=0}^{N} H(\theta_m).
\]

\[
\theta^{k+1} = \theta^{k} + [2\pi\sigma^2]^{-1} \exp (-\theta^2 / [2\sigma^2]).
\]

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

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. H1 metrics weight particle-filter resampling. Peak emerges at high source radius: \( R_{ss} > 3.5 R_i \) 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

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