Simulating observations of the corona/inner heliosphere with Parker Solar Probe/WISPR by raytracing software

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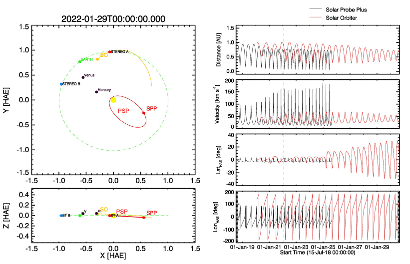
1. Introduction

The Wide-Field Imager for Parker Solar PRobe (WISPR) consists of 2 cameras that will take white-light images of the corona/inner heliosphere, offset from the Sun and covering an overall range of elongation angles between 13.5 and 108 deg, with high temporal (0.05-60 min) and spatial resolution (plate scale of 1.2-1.7 arcmin per pixel at 1 AU) [1]. Such images will be taken from unprecedented points of observation thanks to the highly-eccentric orbits of Parker Solar Probe (PSP), which will reach the minimum perihelion distance below 10 $R_{\odot}$ in 2024.

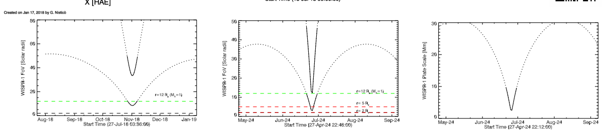
2. Aims

- Providing a collection of synthetic WISPR images for different coronal structures [2] by using the raytracing tools (*rtraytracewcs.pro*) available in SolarSoftWare (SSW) [3].
- Studying the influence of the varying radial distance and the high orbital speed of PSP (~200 km s^{-1}) on the resulting Field-of-View (FoV).
- Investigating the possibility of 3D reconstruction with WISPR.

3. PSP orbit and FoV for the Telescope 1 of WISPR (13.5 – 53.5 deg)



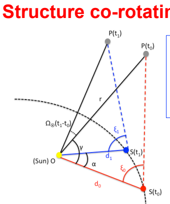
Left: Plot of the orbits for PSP (red) and Solar Orbiter (yellow) (*left* panels). Temporal variation of the radial distance, orbital speed, latitude and longitude in the HAE reference frame for PSP (black) and SO (red). A movie is available on www.astro.physik.uni-goettingen.de/~nistico/cgauss_psp.html



Top: horizontal extension of the FoV in solar radii for WISPR-1 at the first perihelion in November 2018 (*left*), and at the perihelion in June 2024 (*middle*). The plane of sky has been taken as a reference when converting angular distances to linear ones. The pixel size for WISPR-1 is showed in the *right* panel in units of Mm.

5. 3D reconstruction - Trigonometric analysis (PSP orbital plane approximation)

a) Structure co-rotating with the Sun (e.g. streamers, funnel)

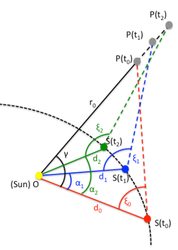


$$\frac{r}{\sin\xi_0} = \frac{d_0}{\sin(\gamma+\xi_0)},$$
$$\frac{r}{\sin\xi_1} = \frac{d_1}{\sin\left[\gamma+\Omega_{\odot}(t_1-t_0)+\xi_1-\alpha\right]}.$$

$$\tan(\gamma) = \frac{d_0\sin\xi_0\sin\left[\Omega_{\odot}(t_1-t_0)+\xi_1-\alpha\right]-d_1\sin\xi_0\sin\xi_1}{d_1\cos\xi_0\sin\xi_1-d_0\sin\xi_0\cos\left[\Omega_{\odot}(t_1-t_0)+\xi_1-\alpha\right]}.$$

- d_i: PSP-Sun distance.
- α: angular separation between two PSP positions.
- $\Omega_{\odot}$: Sun's rotation angular velocity
- r : distance of P from the Sun
- γ: azimuthal angle relative to $S(t_0)$.
- ξ_i: elongation angles measured with WISPR for a feature P co-moving with the Sun and observed at different instants of time from PSP (S).

b) Structure radially moving out from the Sun with constant speed v (e.g. CMEs, jets)



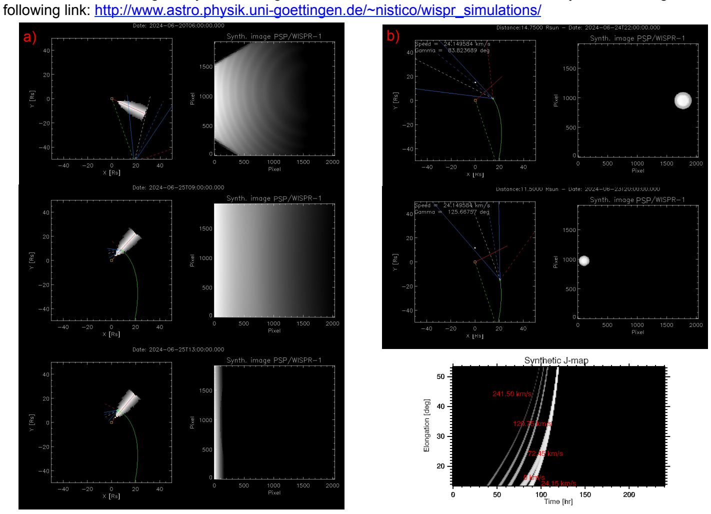
$$\frac{r_0}{\sin\xi_0} = \frac{d_0}{\sin(\gamma+\xi_0)},$$
$$\frac{r_0+v(t_1-t_0)}{\sin\xi_1} = \frac{d_1}{\sin(\gamma+\xi_1-\alpha_1)},$$
$$\frac{r_0+v(t_2-t_0)}{\sin\xi_2} = \frac{d_2}{\sin(\gamma+\xi_2-\alpha_2)}.$$

Similarly to what shown in [3], we have applied the law of sines to the triangles $OS(t_0)P(t_0)$ and $OS(t_1)P(t_1)$. The system of equations can be solved for r and γ.

The same basic idea is applied to this case, with r_0 the distance of P from the Sun at time t_0, γ the azimuthal angle measured relatively to $S(t_0)$, and v the constant speed, which have to be determined. However, expliciting the unknowns from the systems is more difficult and does not lead to manageable expressions (γ would be associated with a quadratic equation).

4. Simulations of WISPR-1 images

A list of movies showing the synthetic images of different coronal structures observed by WISPR-1 is given at the following link: http://www.astro.physik.uni-goettingen.de/~nistico/wispr_simulations/



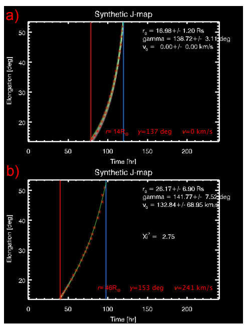
Left: *a)* simulation of a slab streamer with density spherically distributed and radially stratified (model 14 of the raytracing code) observed at different instants of time during the perihelion in June 2024.
Right: *b)* snapshots showing a plasma blob (model 58) with radius of 1 $R_{\odot}$ moving outwardly from the Sun with speed of ~24 km s^{-1}. Different tests have been performed with the plasma blob at rest and at different speed values. The feature is moving approximately on the orbital plane of PSP. A J-map constructed from a horizontal slit at y=0 in the synthetic images traces the different curves (elongation vs. time) associated with the different speeds (*bottom* panel).

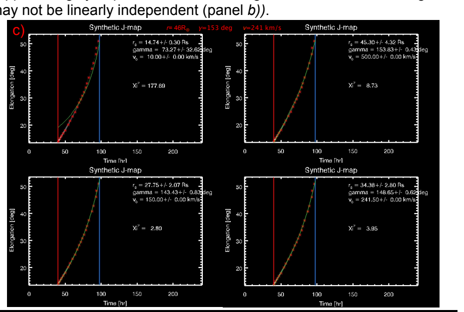
6. 3D reconstruction – Fitting analysis

Fitting function

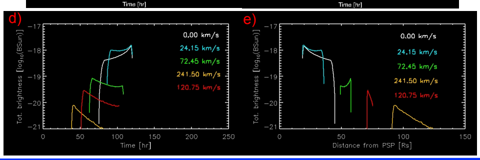
$$\xi(t) = \tan^{-1}\left[\frac{(r_0+vt)\sin(\gamma-\alpha(t))}{d(t)-(r_0+vt)\cos(\gamma-\alpha(t))}\right]$$

We tested the fitting function on the curves traced in the J-maps obtained from the simulations in *b)* of Sect. 4. The tracks have been manually sampled by a finite number of data points (t_i, ξ_i). We used MPFIT routines for robust least-squares curve fitting method [5]. The fit is sufficiently accurate when regression is performed with v fixed and known (panels *a)* and *c)*). In general, the set of solutions appears highly dependant on the initial guessed values, indicating that r, v, and γ may not be linearly independent (panel *b)*).





A further constraint on the determination of the set of parameters may be given by studying the variation of the total brightness of the structure moving away from the Sun. Panel *d)*: total brightness vs. time; panel *e)*: total brightness vs. distance between the structure and PSP.



7. Results and conclusion

- PSP/WISPR will provide us for the first time with images taken from inside the Sun's atmosphere.
- We created synthetic images of WISPR with the raytracing code available in SSW, simulating the approach and/or crossing of coronal structures by PSP.
- Basic tools for geometric triangulation with WISPR have been developed.
- Fitting analysis of tracks in J-maps can be used to determine the 3D position of coronal features.
- Analysis of the total brightness variation can be useful to further constrain the motion of structures in the WISPR FoV.

Acknowledgements

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8. References

[1] Vourlidas et al. SSR, 240, 83, 2016.

[2] List of coronal structure models in the raytracing software: https://secchi.nrl.navy.mil/synomaps/scraytrace/doxy/index.html

[3] Thernisien et al. ApJ, 652, 763, 2006

[4] Liu et al. ApJL, 710, L82, 2010

[5]Markwardt et. al, ASPC, 449, 251, 2009.

Poster

6. Science together with future facilities

Simulating observations of the corona/inner heliosphere with Parker Solar Probe/WISPR

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The Wide-Field Imager for Parker Solar Probe (WISPR) consists of two cameras designated to observe the Thomson-scattered emission of the corona/inner heliosphere. The overall field-of-view is offset from the Sun's centre, and covering 13.5–108 deg of elongation angles. Thanks to the highly-eccentric orbits of Parker Solar Probe (PSP), which will achieve the closest perihelion below 10 solar radii in 2024, the WISPR images will be taken from unprecedented points of observation at high temporal (0.05–60 min) and spatial resolution (plate scale of 1.2-1.7 arcmin per pixel). Therefore, it is important to understand how WISPR images will look during the perihelion phases and when PSP will eventually fly throughout various coronal structures (e.g. streamers, expanding flux ropes, and jets). Here, we present simulations of WISPR images for different coronal structures by using the raytracing tools available with the SolarSoftWare package. We will discuss the effects due to the varying radial distance and the high orbital speed (200 km/s) of PSP on the WISPR images, including the possibility of 3D reconstruction and the determination of the correct kinematics for expanding flux ropes and/or jets. Future joint observations between PSP/WISPR and other facilities like IRIS will provide new insights on the complex processes occurring in the solar atmosphere.