SynCOM: An Empirical Model for High-Resolution Simulations of Transient Solar Wind Flows

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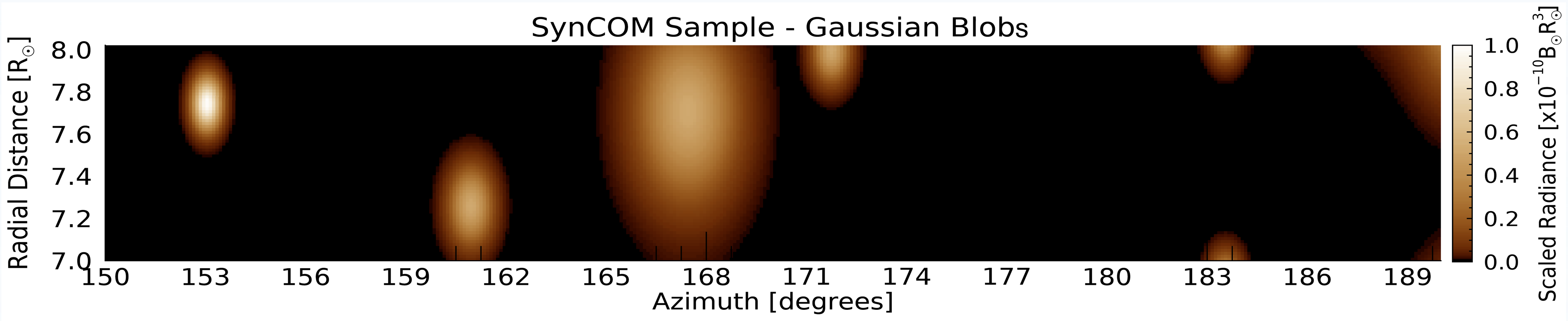
OBJECTIVE

A key objective of SynCOM is to provide a synthetic dataset that can be used to train and test solar wind tracking algorithms. Current algorithms developed on observational data have the limitation that there is no "ground truth" to assess their accuracy. By creating a synthetic model with similar spatial and temporal properties, we can provide the exact measurements of e.g. flow speed. Analysis algorithm developers can then assess the performance of their methods and use the ground truth measurements to determine where and how the algorithms could be improved.

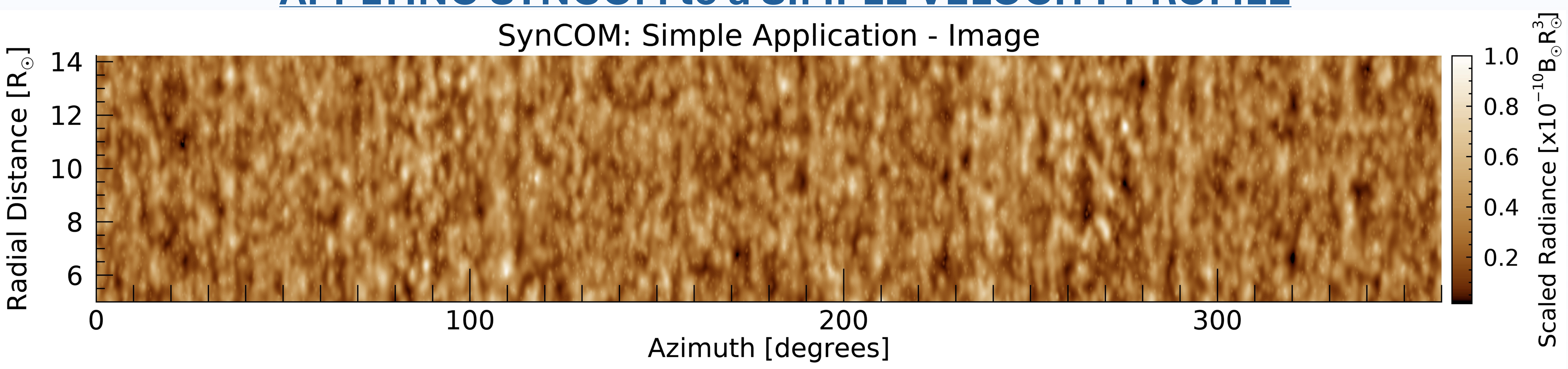
GAUSSIAN BLOB

$$G(\theta,r)=G_0 exp\left(-\left[\frac{(\theta-\theta_0)^2}{2L_\theta^2}+\frac{(r-r_0(t))^2}{2L_r^2}\right]\right) \text{ and } r_0(t)=r_B+V(\theta)t$$



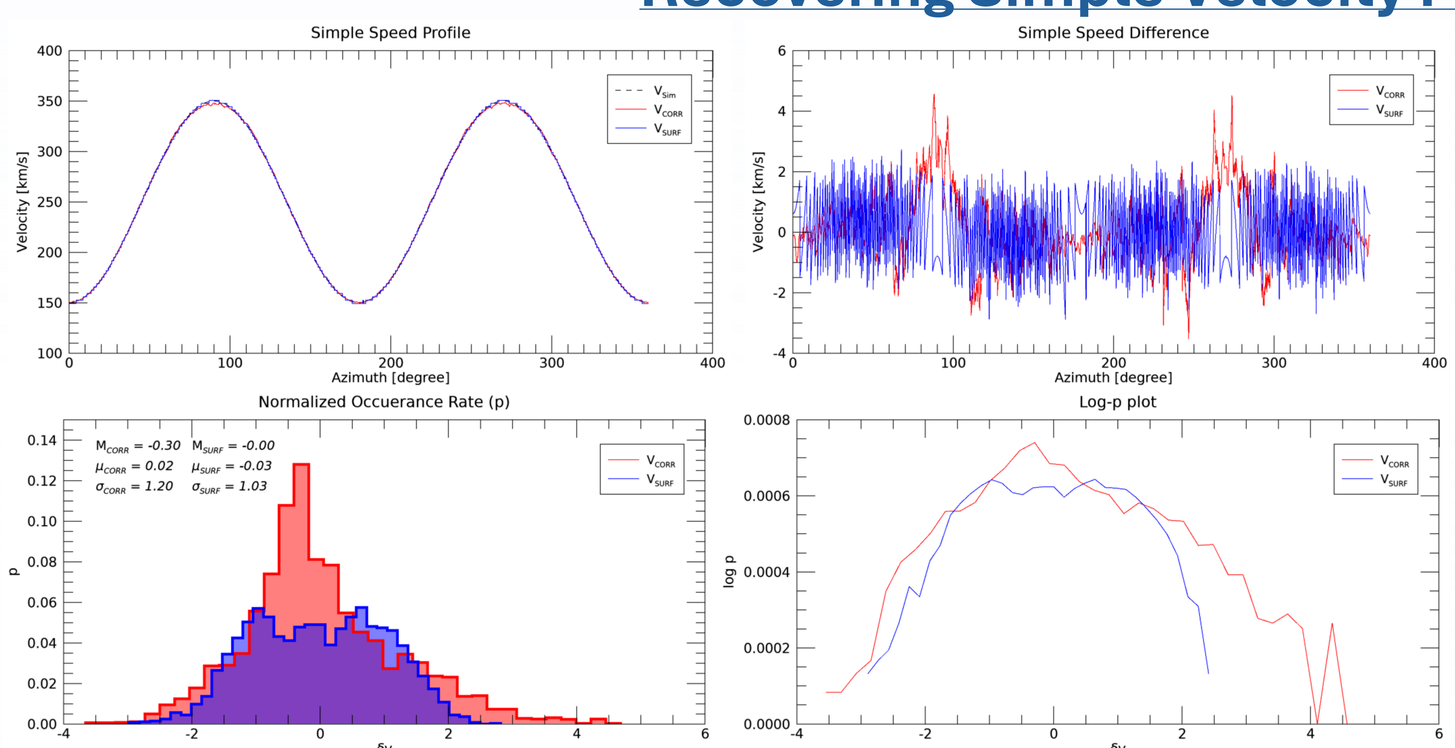
Each Gaussian blob is represented by a two-dimensional intensity array that evolves over time. The position and shape of the blob are determined by four adjustable parameters: the central azimuthal position (θ_0), the central radial position ($r_0(t)$), and the characteristic sizes in the azimuthal (L_θ) and radial (L_r) directions. For simplicity, θ_0 is kept time-independent, ensuring strictly radial propagation of the blobs. Currently, the model uses an arbitrary function to control central radial position of the blobs for its initial release, r_B is the blob's position at the observation boundary, $5R_\odot$ and $V(\theta)$ is the radial velocity for a specific θ. This approach allows for precise modeling of the intensity and movement of solar features.

APPLYING SYNCOM to a SIMPLE VELOCITY PROFILE



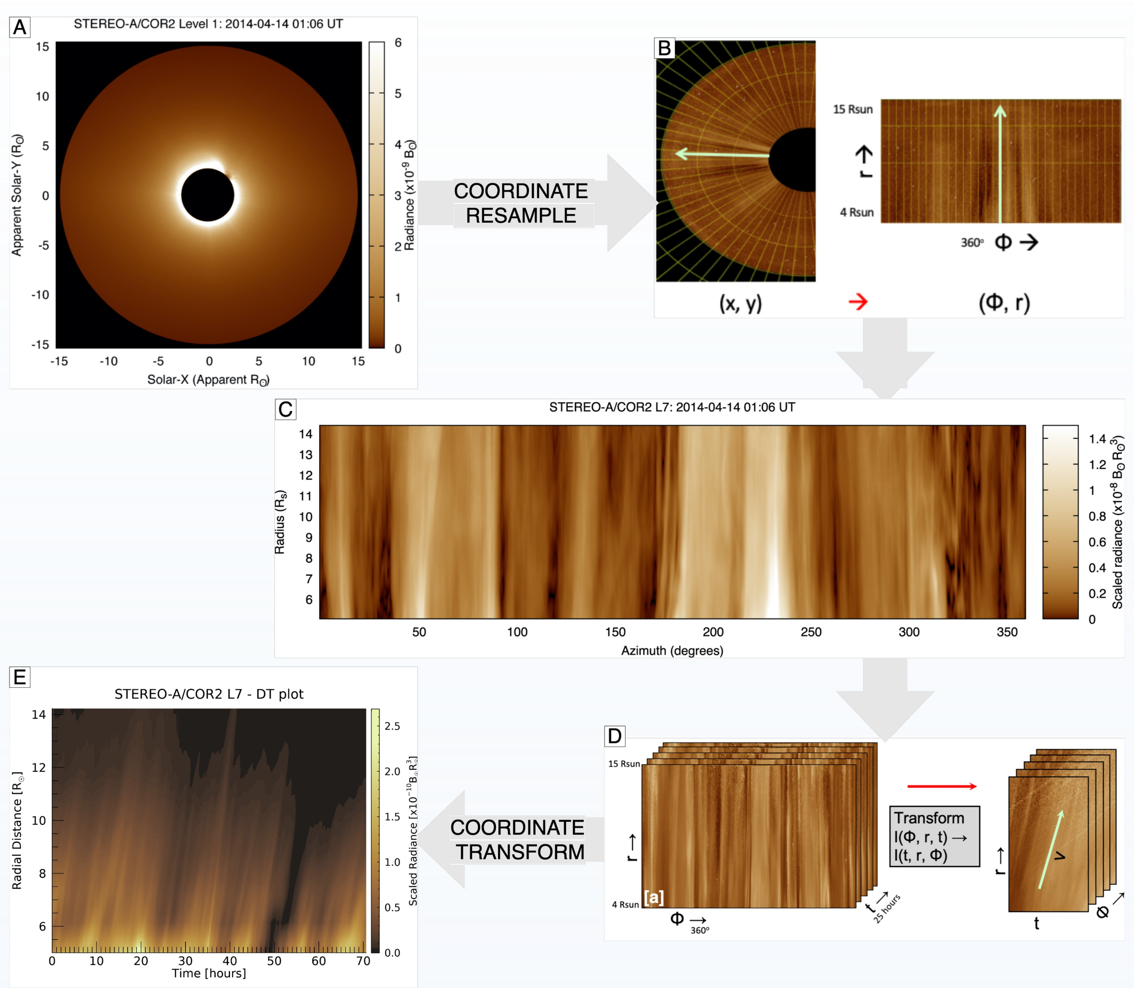
SynCOM simple numerical application featuring 5,000 blobs. It can simulate coronal outflows with any velocity profile and other input parameters, such as period and blob radius. We used simple profile distributions for each parameter, generating SynCOM images with defined flow dynamics resembling solar images. The parameters utilized in these images are not physically significant but serve to evaluate the model's functionality. The velocity follows a sinusoidal function with a range of 150 to 350 km/s. The period and blob radius have ranges of 1.5 to 4.5 hours and 0.1 to 1.0 degrees, respectively.

Recovering Simple Velocity Profile



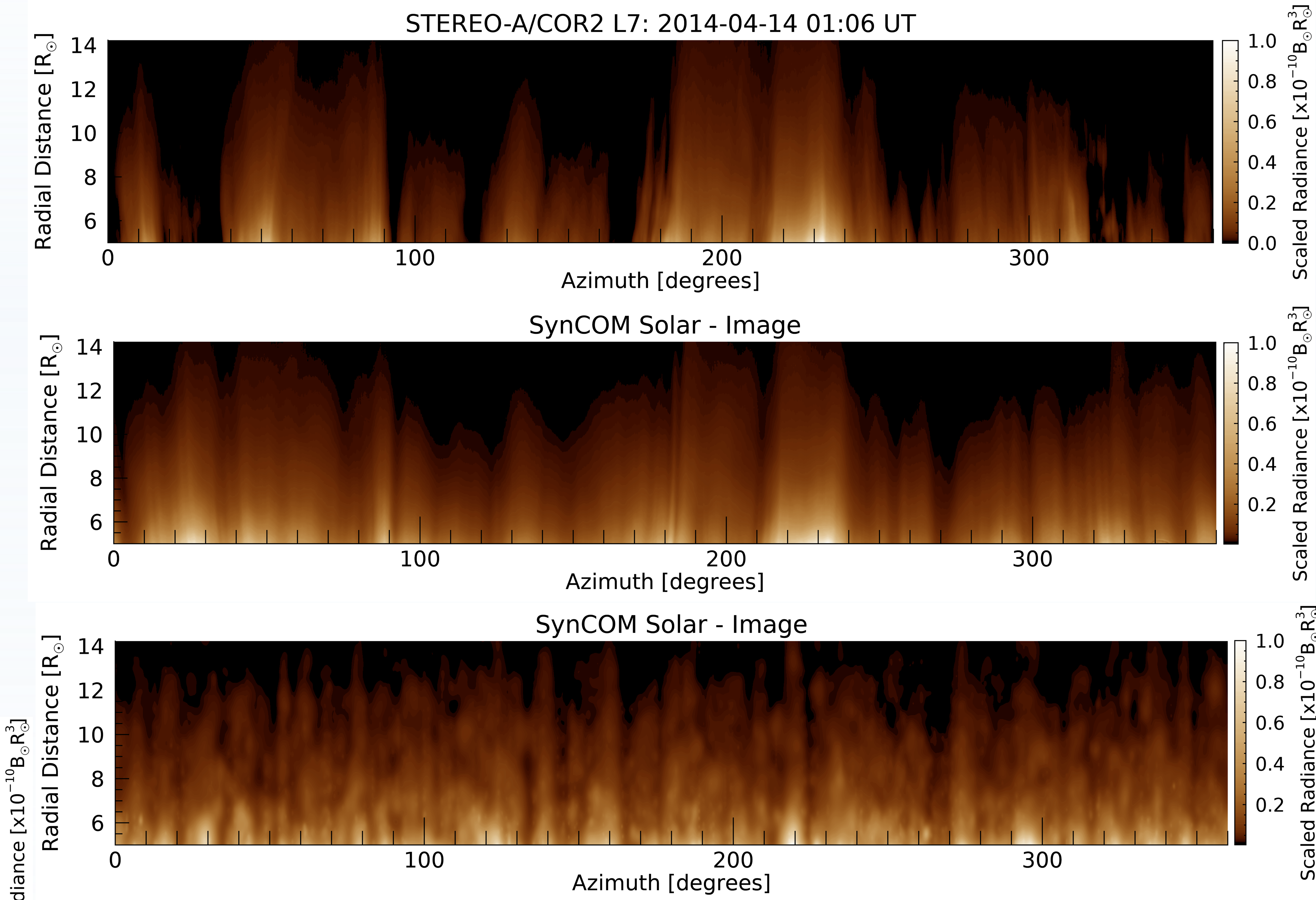
The surfing transform and correlation methods provided reasonable velocity profiles, but the correlation method exhibited greater variability. The histogram shows the accuracy of the correlation method, which aligns with a normal distribution of errors. Despite the surfing transform's accuracy, it is computationally intensive. Thus, the correlation method offers a faster and precise alternative, confirming SynCOM's robustness for various scenarios.

COR2 TRAINING DATA



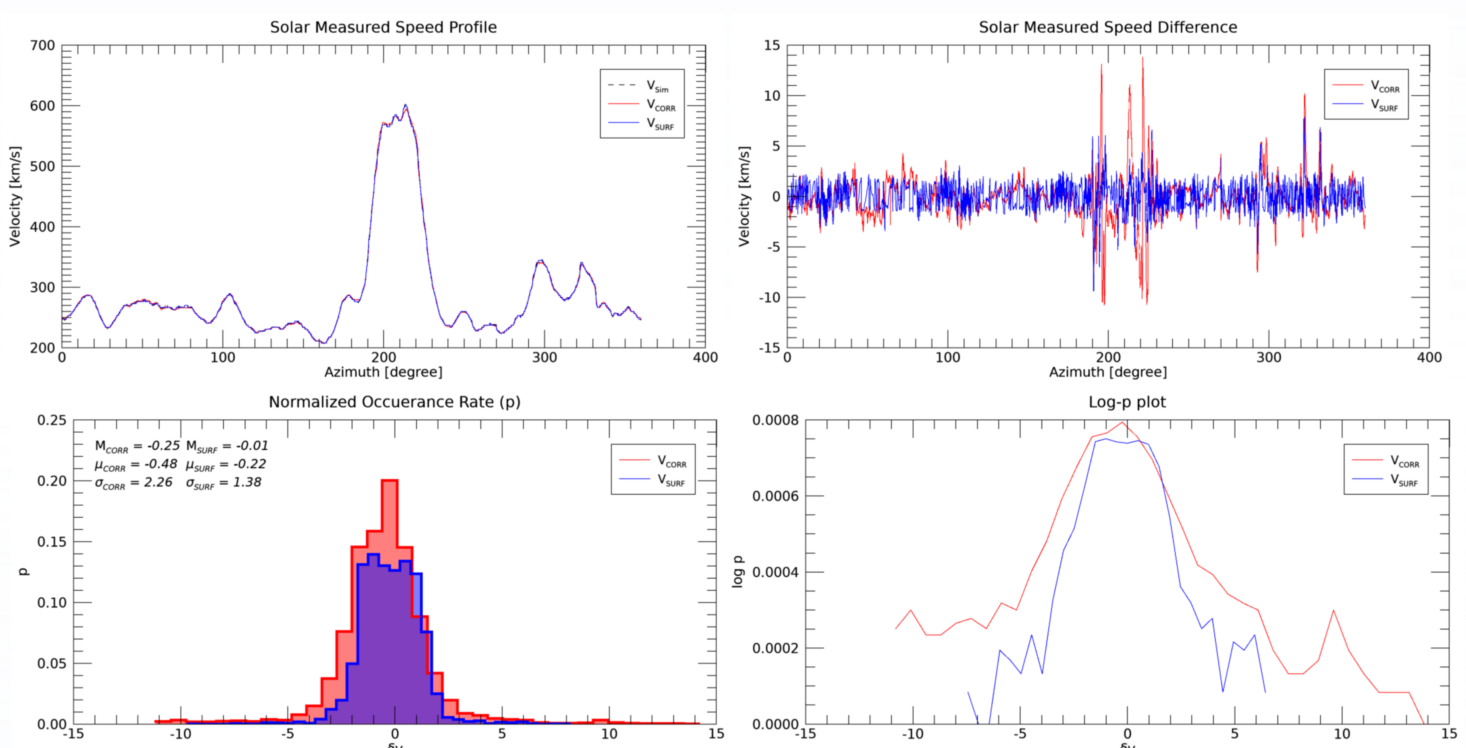
(A) Level 1 (L1) data is generated using SECCHI software, producing a 2048 x 2048 pixel image that is unpolarized and calibrated in units of average solar radiance along the x and y axes (Source: DeForest et. al 2018). **(B)** Illustration of coordinate resampling, where image coordinates are converted from Cartesian to polar coordinates (Source: Thompson et. al 2018). **(C)** Level 7 (L7) image represents a final phase in the data preparation sequence, following extensive modifications and filtering. Processing includes exposure-time adjustments, polar coordinate transformations, resampling, normalization, despiking to remove stars, and temporal smoothing. The resulting image shows the solar corona outflow in polar coordinates (φ, r), with radiance adjusted by r^3 (Source: DeForest et. al 2018). **(D)** J-maps are created by selecting a thin segment from a series of solar images and aligning these segments vertically in time order, illustrating the kinematic progression of solar events. **(E)** The STEREO-A/COR2 DT map shows the temporal and spatial progression of features, with inclines indicating the velocity of the features for that segment.

APPLYING SynCOM to COR2 DATA



Comparison between a COR2 and a SynCOM simulated image; (**top**) Training data set from STEREO-A/COR2 instrument (Source: DeForest et. al 2018). (**middle**) SynCOM simulation using solar constraints with 5,000 blobs. The blob sizes are doubled, making the image appear more natural compared to COR2 images. (**bottom**) SynCOM simulation using solar constraints with 5,000 blobs. The smaller blob sizes highlight its fine-scale structures. (**QR code**) Website showcase the different versions of synthetic outflows coming from the corona. The boundary begins at $r_B = 5R_\odot$.

Recovering COR2 Velocity Profile



The measured velocity profiles matched the simulations. Both methods estimated solar constraints accurately, with the correlation method providing speed measurements at various altitudes. Errors were similar, but the surfing transform had fewer sharp peaks, while the correlation method showed mild variations. Histogram analysis confirmed the correlation method's precision, aligning with normal distribution errors, while the surfing transform showed a non-Gaussian profile. SynCOM's model produced synthetic images matching COR2 data, validating its reliability for solar wind analysis and enhancing our understanding of solar wind behavior.

CONCLUSION AND FUTURE WORK

SynCOM offers an efficient solution for generating high-resolution, statistically representative simulations of solar wind dynamics. It provides a valuable synthetic dataset for training and testing solar wind tracking algorithms, offering a reliable "ground truth" for accuracy assessment. SynCOM has been successfully tested using both sinusoidal functions and STEREO-A/COR2 data, demonstrating its capability to closely match real solar wind flows. Key findings include:

- High-resolution simulations that accurately represent solar wind flows
- Successful validation of flow-tracking techniques using SynCOM's outputs
- Consistency between SynCOM simulations and STEREO-A/COR2 measurements

Future work will focus on integrating SynCOM with the FORWARD framework to produce polarized coronal images. This integration will enhance SynCOM's predictive capabilities and provide synthesized datasets that align with PUNCH mission observations, offering new insights into solar corona behavior. Additionally, we will update the SynCOM flow-tracking challenge with new versions. For more information, visit our website: https://physics.catholic.edu/faculty-and-research/space-weather-lab/flow-tracking-challenge.html

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