Turbulence Investigations Across Space and Time with PUNCH

W H Matthaeus

U Delaware Team: Victoria Wang, Rohit Chhiber, Francesco Pecora, Yan Yang

Craig Deforest + the PUNCH team

PUNCH 7 Science Meeting
May 12 to May 14, 2026, Boulder, Colorado

Anisotropy of correlations and spectra

Yan Yang+
Pecora+
this meeting;

- a well-established in homogeneous MHD and in local solar wind observations of turbulence (Oughton et al, 2015). Correlation anisotropy may be revealed in images, as demonstrated by DeForest et al (2016) by computing local structure functions (see Yang et al, this meeting). PUNCH substantially broadens the scope by providing a huge field of view that may be partitioned into small segments. Structure functions parallel and perpendicular directions can be computed and time averaged, revealing the presence and development of anisotropy at scales and heliospheric positions that have been previously completely inaccessible.

1/f noise -- structures and source

Jiaming Wan+
this meeting

- **Assertion** (is this obvious?):

Very low frequency signals at 1 s/c

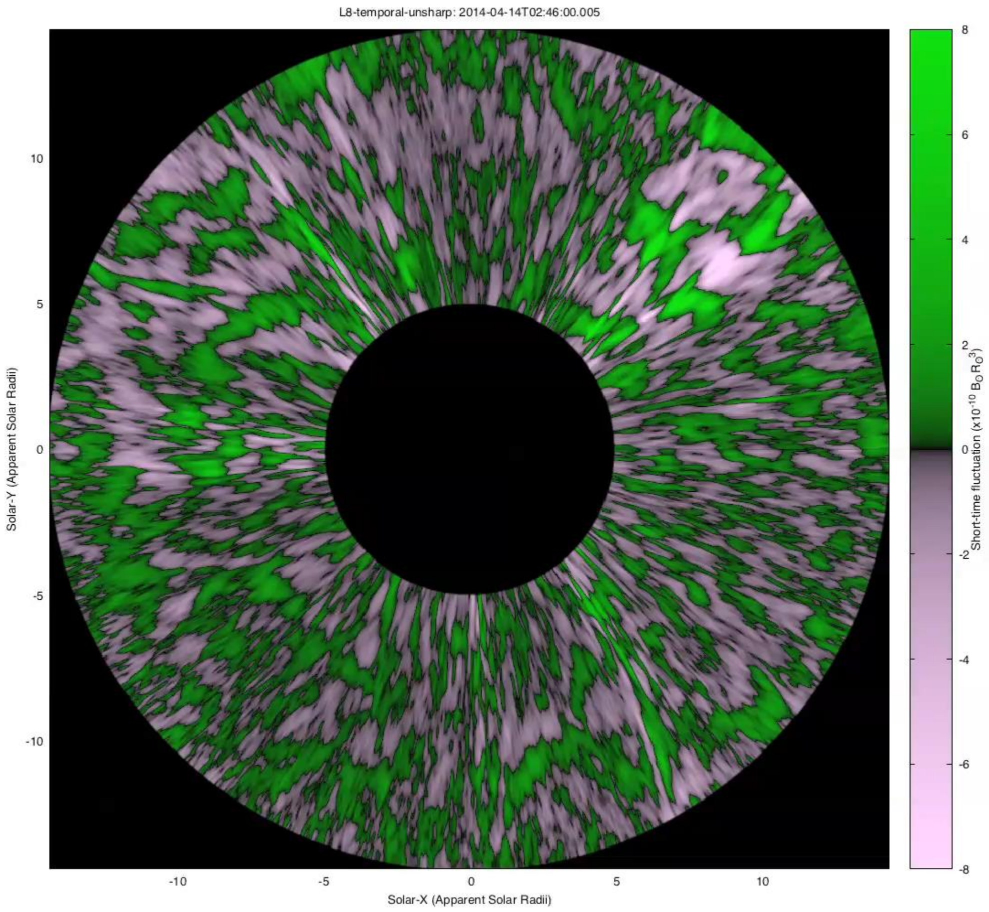
become

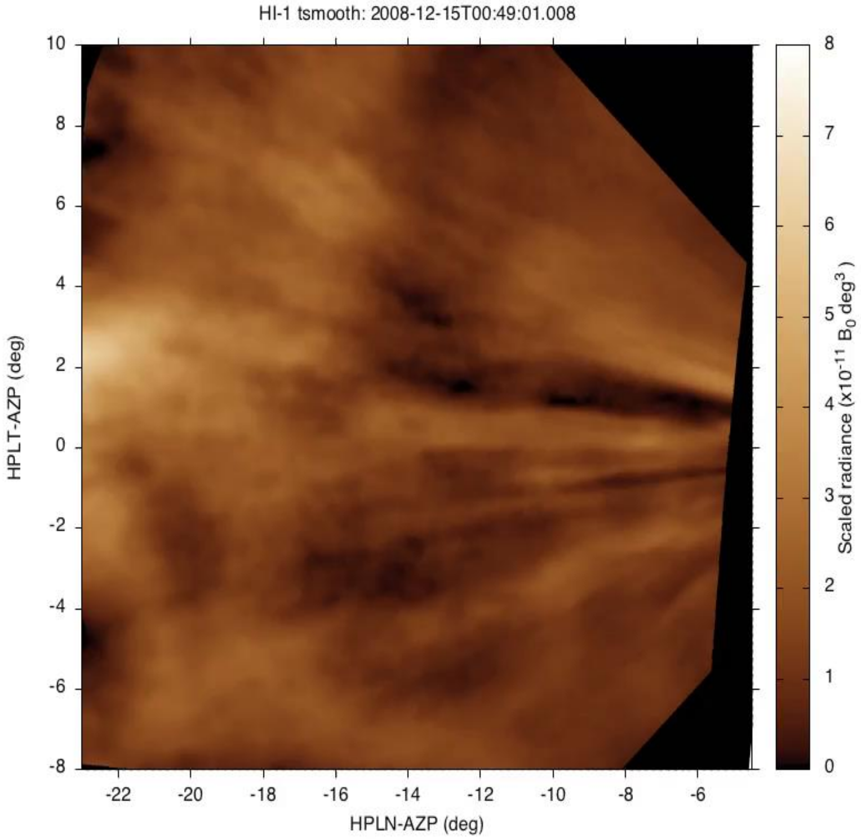
Very large scale structures in PUNCH images

very large (or low frequency) structures observed in situ at 1au are sufficiently separated in space that MHD processes cannot have influenced them in passage from the Alfven zone.

At inferred scales of more than a few correlation lengths, these signals are associated with most of the observed “1/f” flicker noise seen in the interplanetary magnetic field (see Wang et al, 2024 for a review).

Corona ane newborn solar wind: is 1/f signal embedded here?





1/f (continued)

- Even if these are not mutually interacting in passage to the earth, the associated spatial structures are estimated to be present in the PUNCH images. The search for this correspondence may be proceed in at least two ways:
- First, a single PUNCH image can be sampled along a streamline (assuming steady flow)) so that an expected signal at 1 au can be extracted after renormalizing by the secular density variation (perhaps r^2) .
- Second, the time dependent PUNCH images provide a more direct observation, tracking structure from source to point of observation. In this way we can “see” the 1/f noise signal.

Space-time

- PUNCH enables computation of the space-time correlation function, a fundamental quantity in turbulence theory (Matthaeus et al, 2012; Pecora et al 2025).
  - Related to "k-omega" analysis that has been used in the PUNCH project
  - flow tracking methodologies Chhiber+ this meeting

- Analysis of PUNCH images will provide space time correlation at scales and at positions never before accessible. This may enable discovery of the sources of the 1/f noise as well as a quantifying diffusion coefficients (such as viscous drag on CMEs), and the onset of local turbulence interactions

Basic ideas for analyzing space and time correlations

PRL **116,** 245101 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

Ensemble Space-Time Correlation of Plasma Turbulence in the Solar Wind

W. H. Matthaeus
Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA

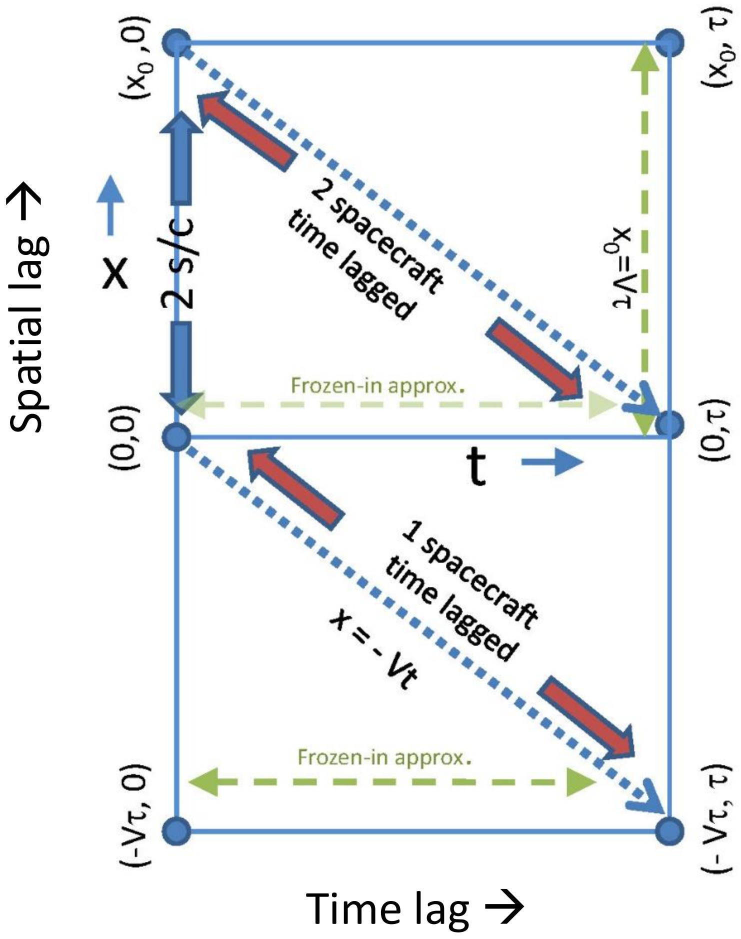
J. M. Weygand
Institute for Geophysics and Planetary Physics, University of California, Los Angeles, California 90095, USA

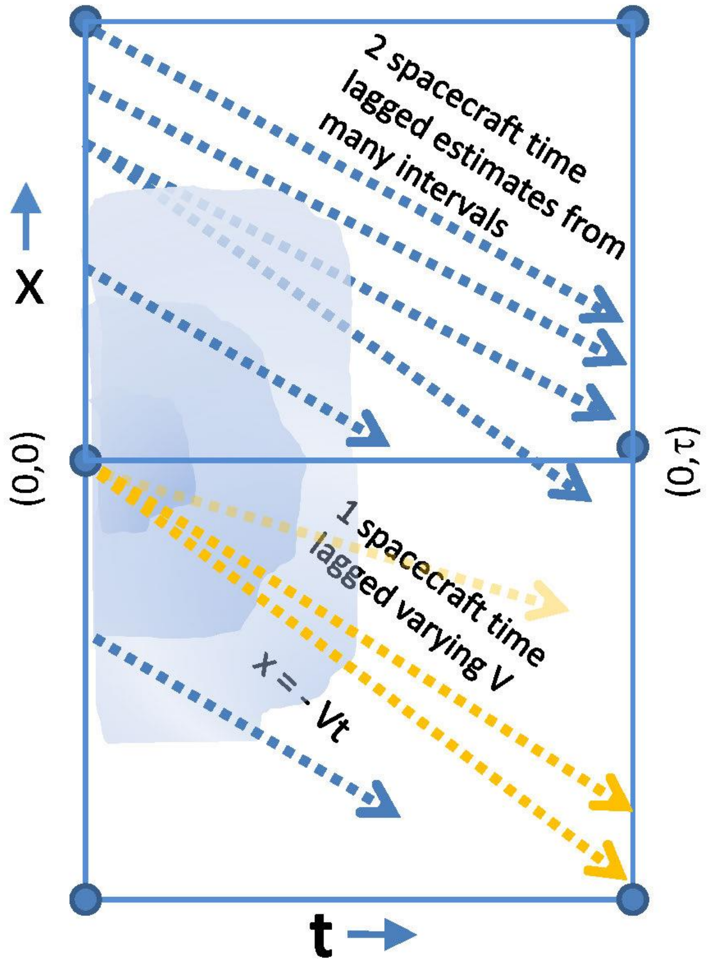
S. Dasso
Instituto de Astronomía y Física del Espacio (IAFE) and Departamento de Ciencias de la Atmósfera y los Océanos and Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, 1428 Buenos Aires, Argentina

(Received 27 December 2015; revised manuscript received 12 April 2016; published 14 June 2016)

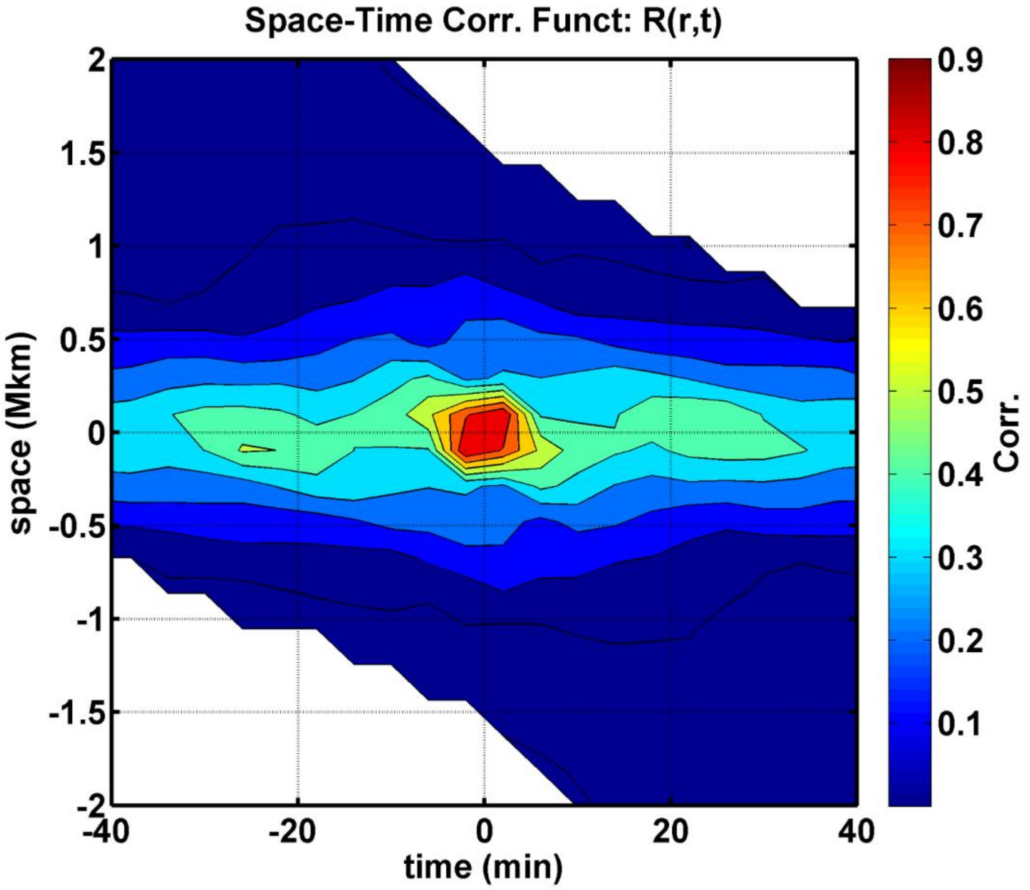
Single point measurement turbulence cannot distinguish variations in space and time. We employ an ensemble of one- and two-point measurements in the solar wind to estimate the space-time correlation function in the comoving plasma frame. The method is illustrated using near Earth spacecraft observations, employing ACE, Geotail, IMP-8, and Wind data sets. New results include an evaluation of both correlation time and correlation length from a single method, and a new assessment of the accuracy of the familiar frozen-in flow approximation. This novel view of the space-time structure of turbulence may prove essential in exploratory space missions such as Solar Probe Plus and Solar Orbiter for which the frozen-in flow hypothesis may not be a useful approximation.

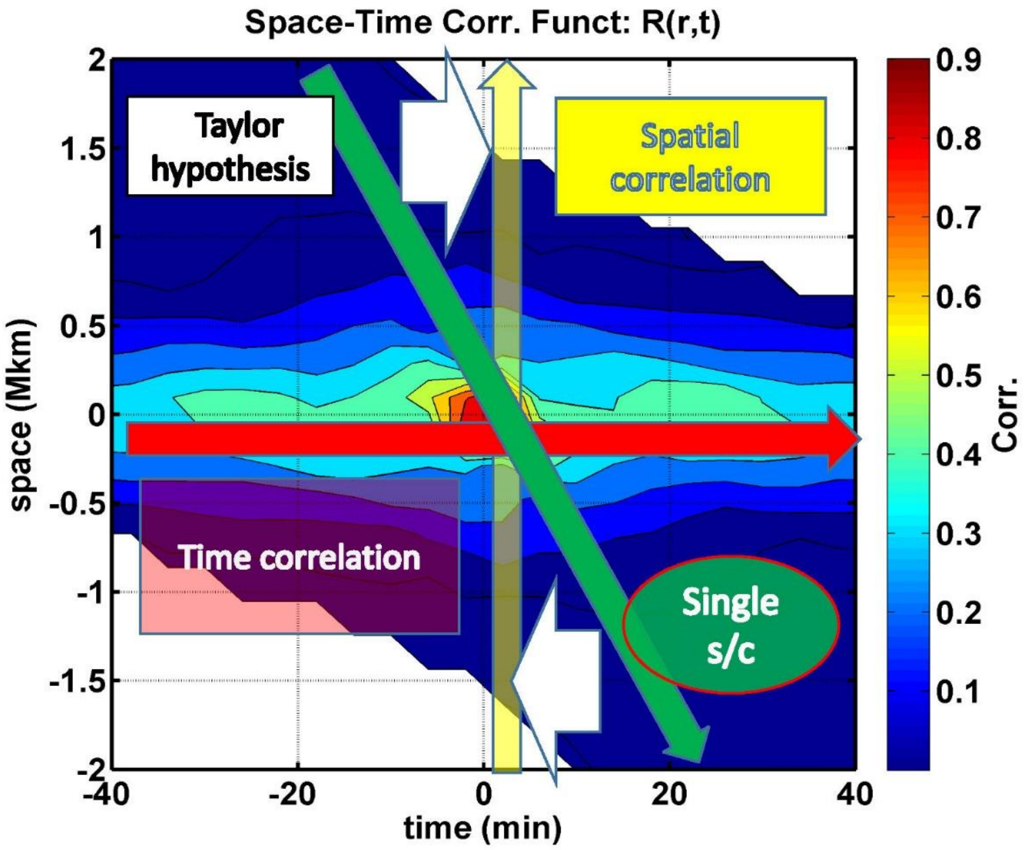
Space-time (continued)



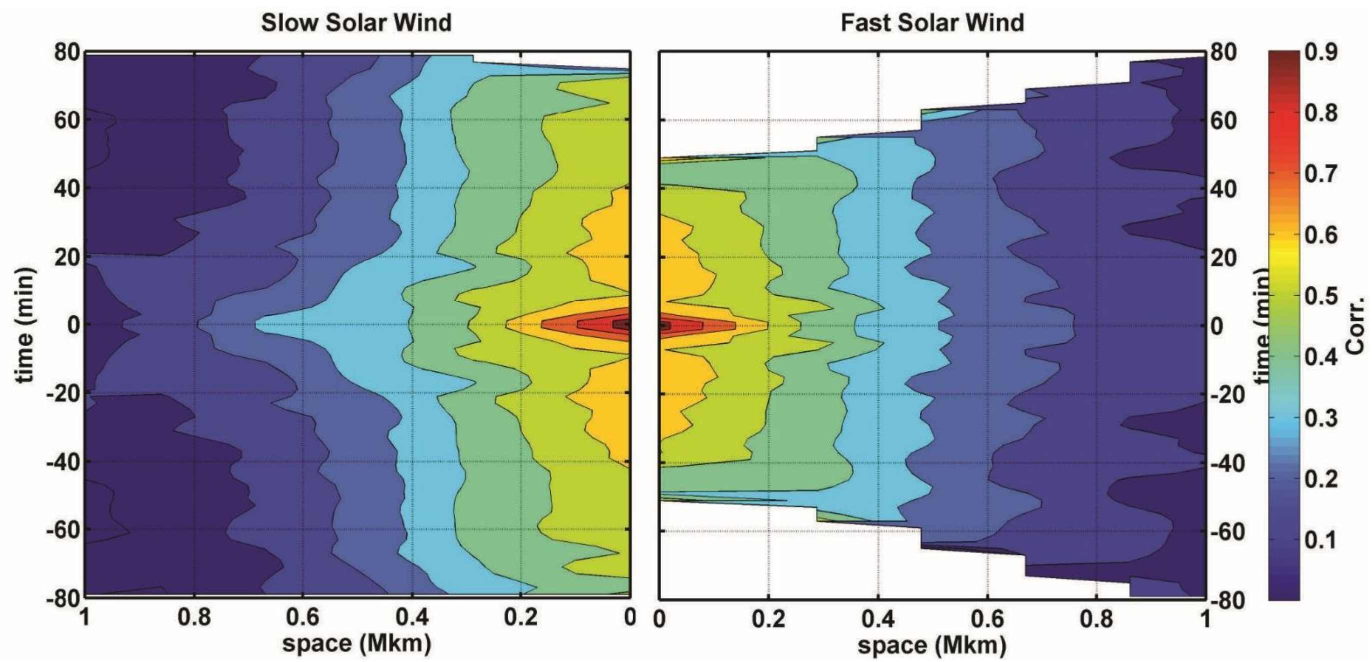


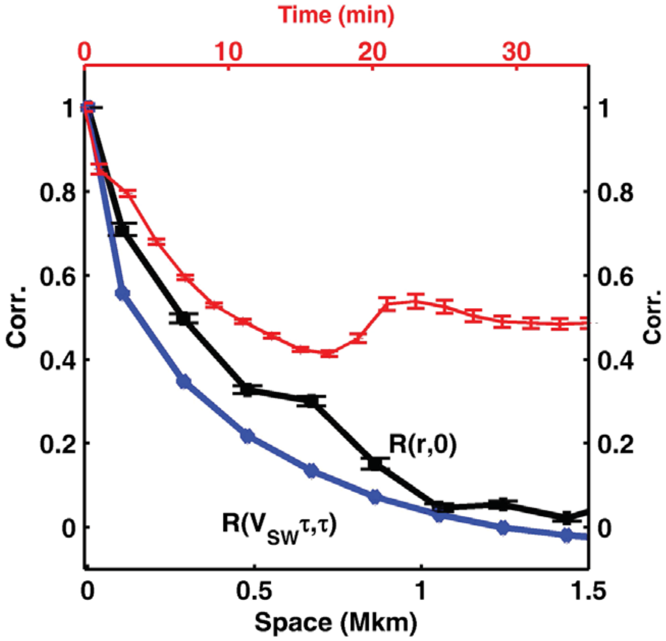
Space-time


Space-Time Corr. Funct: R(r,t)
space (Mkm)
time (min)
Corr.


Space-Time Corr. Funct: R(r,t)
Taylor hypothesis
Spatial correlation
Time correlation
Single s/c
space (Mkm)
time (min)
Corr.

Space-time correlation in sw





Pecora+PNAS 122 (2025)

MMS space time

- 6 inter s/c pairs and 1180 magnetosheath intervals to get good coverage in space and time.

- This enables estimation of the scale dependent time decorrelation (the “propagator”) a fundamental quantity in mathematical turbulence theory …see Pecora+PNAS

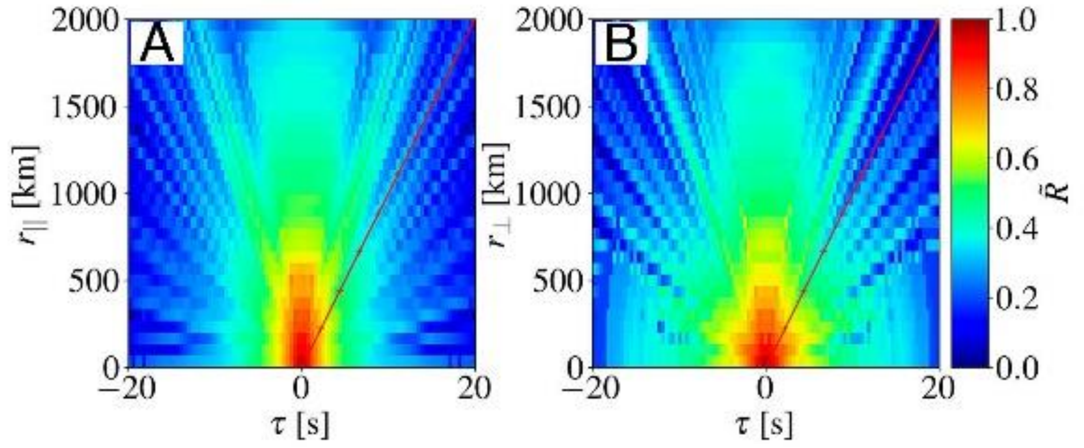
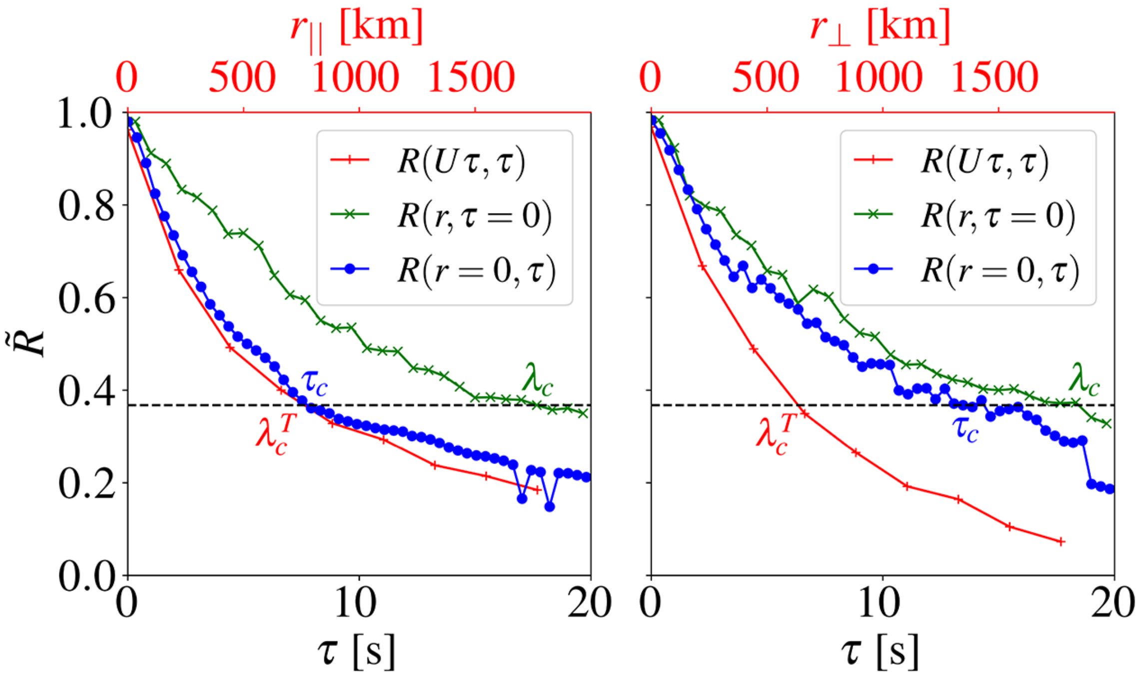


Fig. 1. Space-time correlation function with complete coverage of the $(\tau, r_{||})$ plane (*A*) and the $(\tau, r_{\perp})$ plane (*B*). The red oblique line is the direction along a plasma parcel flowing at a speed of 100 km/s.



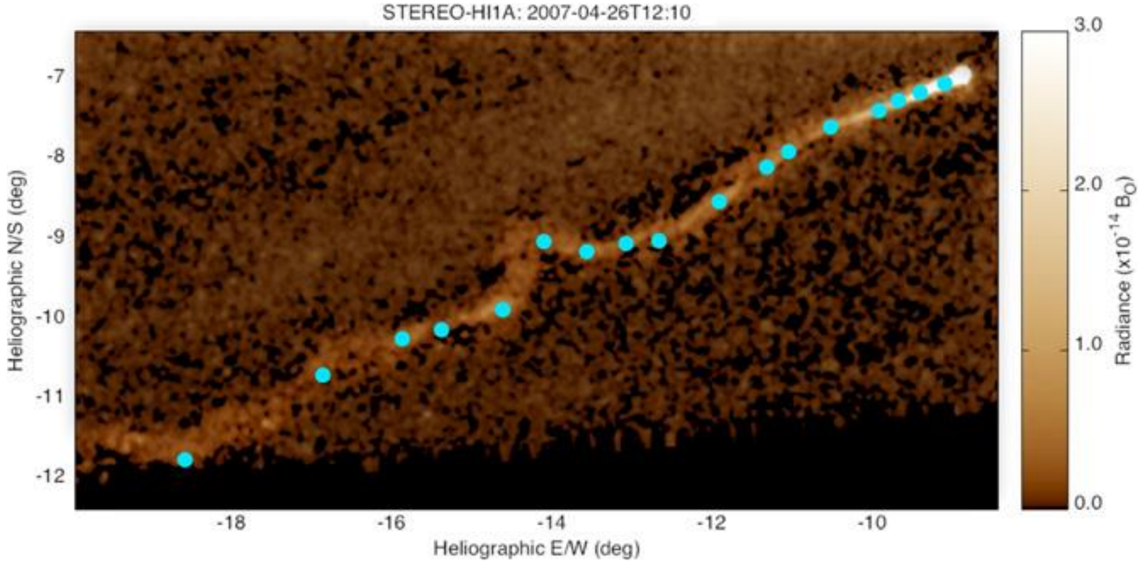
Comet tracking

- Tracking features such as comets in the PUNCH field of view enables computation of lagrangian turbulence statistics –

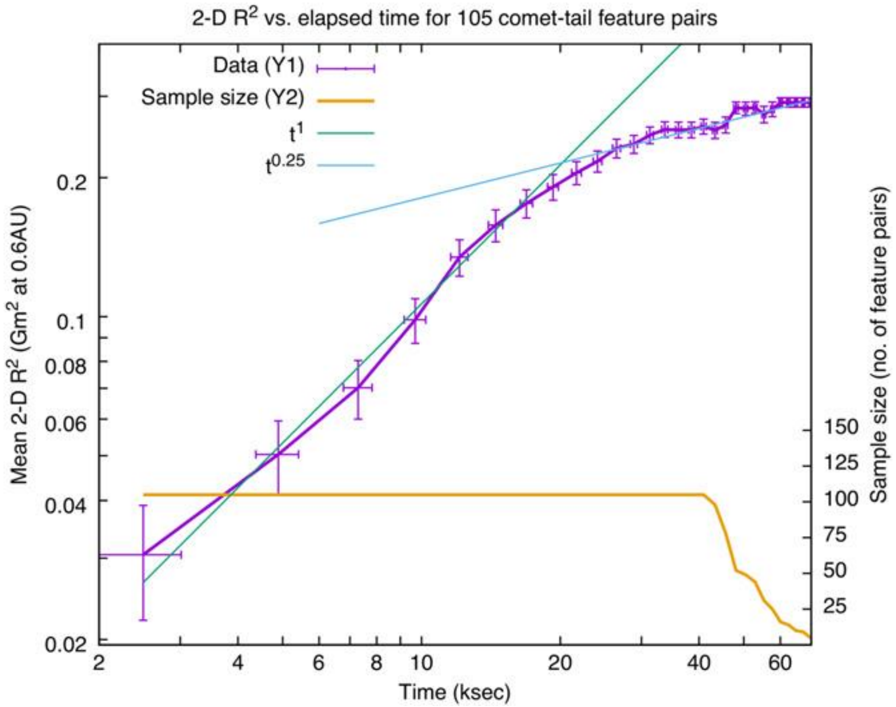
→ Deforest+ 2015 established that heliospheric imaging can track cometary ejecta (bright spots on the images) based on analysis of Comet Enke

- The statistics of the velocity and positon of the bright points can be analyzed in terms of Langevin with drag and random forcing. Such empirical results can be translated into direct measurement of turbulence statistics. PUNCH is expected to observed the passage of numerous comets, thus enabling a much deeper dive into interplanetary turbulence from this unique perspective.

Comet Encke



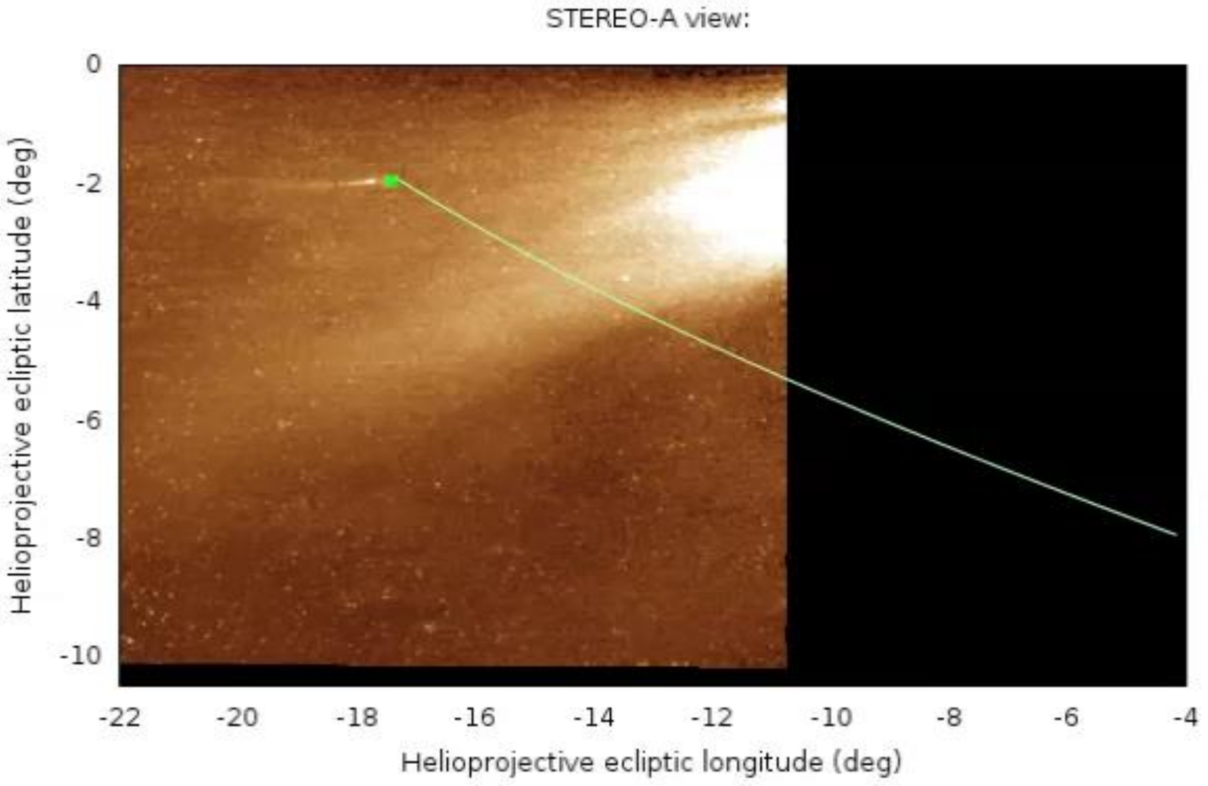
STEREO-HI1A: 2007-04-26T12:10
Heliographic N/S (deg)
Heliographic E/W (deg)
Radiance (x10^-14 B_O)
-7
-8
-9
-10
-11
-12
-18
-16
-14
-12
-10
3.0
2.0
1.0
0.0



2-D R² vs. elapsed time for 105 comet-tail feature pairs
Data (Y1)
Sample size (Y2)
t¹
t^0.25
Mean 2-D R² (Gm² at 0.6AU)
Sample size (no. of feature pairs)
Time (ksec)
0.2
0.1
0.08
0.06
0.04
0.02
150
125
100
75
50
25
2
4
6
8
10
20
40
60

Turbulence from imaging

Stereo imaging analysis of solar wind & Comet Enke by Craig DeForest



Quantitative analysis from images →

DeForest et al, ApJ, 812, 108 (2015)
DeForest et al, ApJ, 828, 66 (2016)

Summary

- PUNCH affords numerous opportunities for innovative studies related to solar wind and coronal mesoscale structure, as well as smaller scale turbulence properties
- Some of the requisite techniques are “partially developed” and need further refinement and testing.
- Complications due to depth of the image occur through out , but we will proceed anyway.
- Go PUNCH!
- And congrats to Sarah!

References

For additional topics and further details on turbulence methods:
See Pecora+ (this mtg); Wang+ (this mtg); Chhiber+ (this mtg); Yang+ (this mtg)

- DeForest, C. E., W. H. Matthaeus. T. A. Howard and R. R. Rice. Astrophys. J. 812, 108 (2015)
- DeForest, C. E, W. H. Matthaeus, N. M. Viall, and S. R. Cranmer, Astrophys J., 828, 676 (2016)
- Matthaeus, W. H, J. M. Weygand, and S. Dasso, Phys Rev. Letter, 116, 245101 (2016)
- Oughton S, Matthaeus WH, Wan M, Osman KT. 2015. Phil. Trans. R. Soc. A 373: 20140152.
- Pecora F, W. H. Matthaeus, A. Greco, P. Dmirtuk, Y. Yang. V. Carbone and S. Servidio, PNAS 2025 Vol. 122 No. 47 e2519635122 https://doi.org/10.1073/pnas.2519635122
- Wang, J., W. H. Matthaeus, R. Chhober, S. Roy, R. A. Pradata, F. OPecora and Y. Yang. Solar Physics (2024) 299:169 https://doi.org/10.1007/s11207-024-02401-z