Turbulence in the solar wind, spectra from Voyager 2 data

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Vortical Structures & Wall Turbulence,
Prof. Orlandi Anniversary

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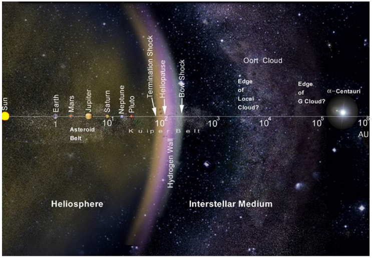
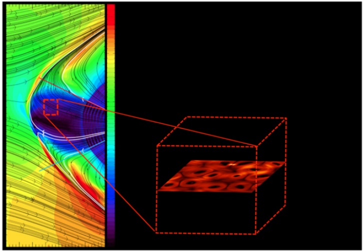
Voyager 2 Interstellar Mission

- *Voyager 2* is flying now at 15.6km/s, 104.7 *AU* from Earth, in the *Heliosheath*, the outermost layer of the heliosphere where the solar wind is slowed by the pressure of interstellar gas
- *Termination Shock* was passed on Sep 5, 2007



source: http://voyager.jpl.nasa.gov

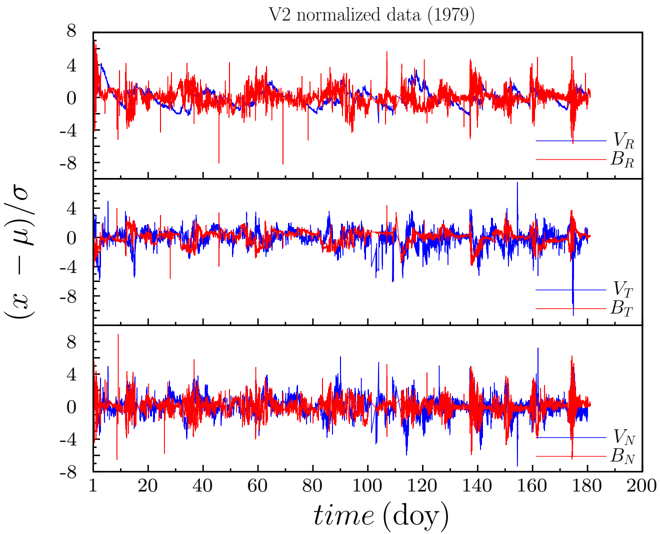


source: M. Opher et al.

A turbulence hypothesis for the magnetic field in the *Heliosheath*
M. Opher et al, ApJ 734, 2011
"*Is the magnetic field in the Heliosheath laminar or a turbulent sea of bubbles?*"

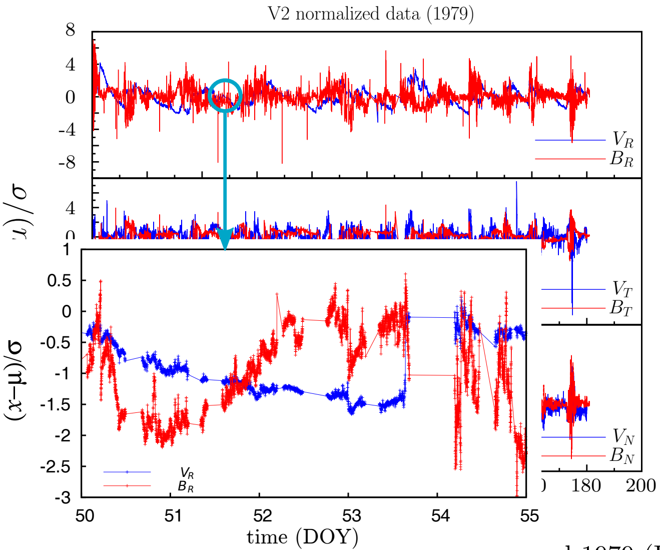
L.L. Orionis colliding with the Orion Nebula.
Hubble Space Telescope, February 1995
(Credit: NASA, The Hubble Heritage Team (STScI/AURA))

Year 1979: V and B data



Velocity and magnetic field data from V2, period 1979 (DOY 1–180). RTN heliographic reference frame.

Year 1979: V and B data



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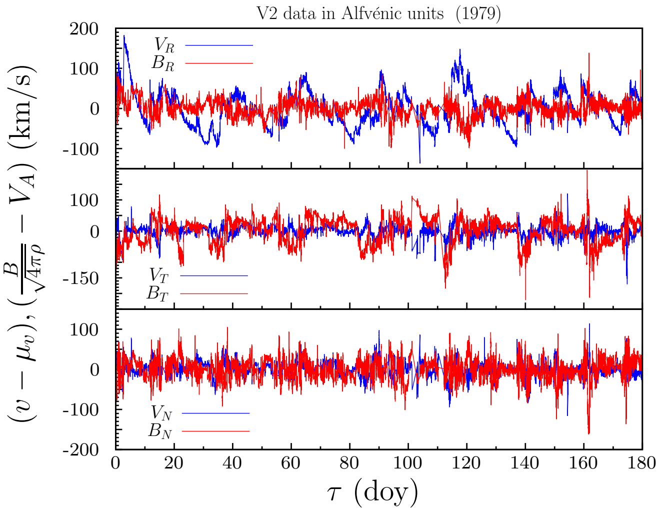
Year 1979: V and B data

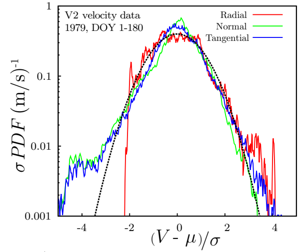


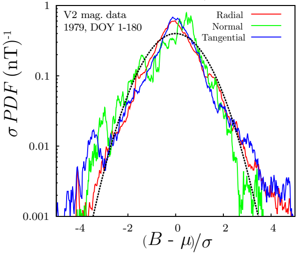
Year 1979: V and B moments and PDFs

	μ	σ^2	Sk	Ku
V_R	454	1893	0.43	3.41
V_T	3.21	252.9	-0.99	7.35
V_N	0.51	250.3	-0.36	5.80
B_R	-0.04	0.173	0.53	6.71
B_T	0.06	0.85	-0.72	10.2
B_N	0.10	0.34	-0.24	7.65

units: km/s, nT

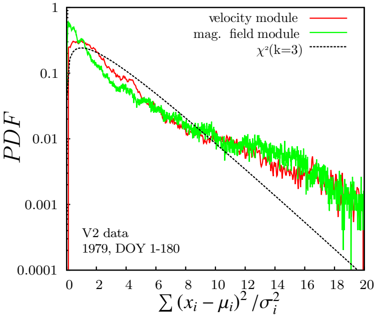
$\langle n_i \rangle$ (cm^{-3})	0.23
$\langle T \rangle$ (K)	27038
β_p	0.225
V_A (km/s)	47.7
c_s (km/s)	19.3
f_{ci} (Hz)	$1.49 \cdot 10^{-2}$
f_{pi} (Hz)	101
$f*$ (Hz)	0.44
r_i (km)	158
λ_D (m)	5.5





normalized PDF of V and B – comparison with a Normal distribution.
Evidence of anisotropy

Year 1979: V and B moments and PDFs

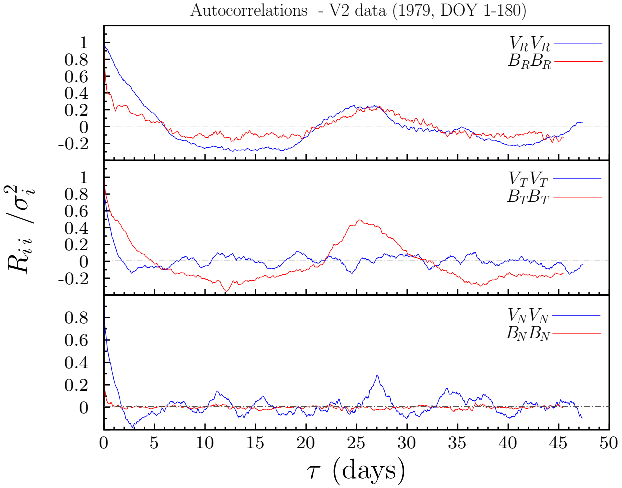


← kurtosis ∼ 10

PDF of module – comparison with a χ^2 distribution. High intermittency?

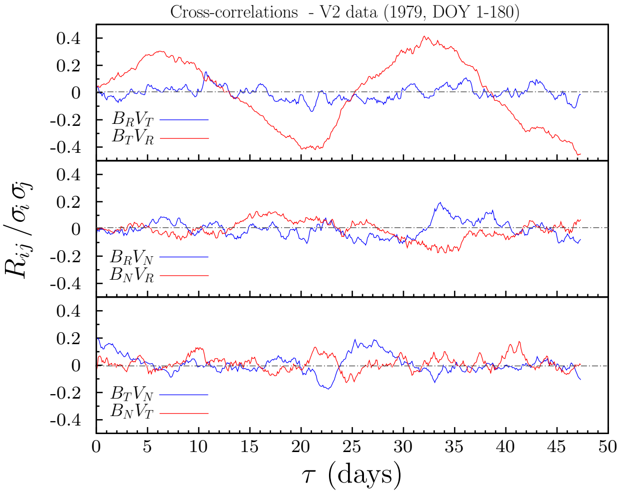
- Evidence of high **Ku**(> 3)
- origin of "intermittency": advected coherent structures (flux tubes, etc), stochastic Alfvénic fluctuations generated at solar corona and "frozen" in the wind?
- Intermittency interests a broad range of scales

Autocorrelations



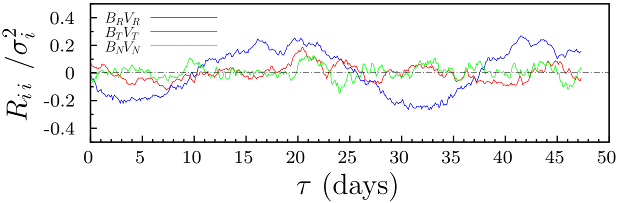
$$R_{ii}(\tau) = < x(t)x(t+\tau) >$$

Cross-correlations tensor: off-diagonal terms



$$R_{ii}(\tau) = < x(t) y(t+\tau) >$$

Cross-correlations tensor: diagonal terms



Summary:

- Averages are computed on 57970 points for V, and 124080 points for B, spanning the whole 180 days period
- Evidence of a 25 days periodicity. Minimum of solar activity in 1979
- High cross-correlation $V_RB_R \rightarrow$ not in-phase
- High cross-correlation $V_RB_T \rightarrow$ not in-phase
- Low Alfvénic one-point correlation (this is often the case in the slow-wind periods)

Data reconstruction techniques

V2 velocity and magnetic field data are discontinuous and irregularly spaced. In the whole year 1979 there is 45% of missing velocity data, These values are about 97% in 2012.
To perform an accurate spectral analysis on these kind of data sets, a reconstruction technique may be mandatory. In the following, the effect of two interpolation/recovery methodologies on averaged turbulent spectra will be discussed.

- Linear interpolation
- Maximum likelihood reconstruction and realizations constrained by data[1]

[1] Rybicki & Press, ApJ 398, 1992

Data reconstruction techniques: test

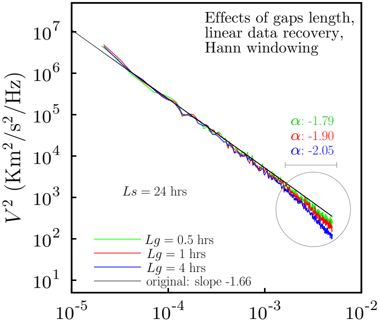
To test the effects of averaging,interpolating and windowing techniques, two 1D sequences of synthetic turbulence data have been generated from imposed spectral properties:

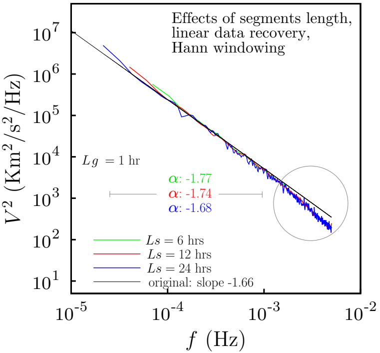
- **Synt 1**→ $E_{3D}(n/n_0) = \frac{(n/n_0)^\beta}{(n/n_0)^{\alpha+\beta}}$
- **Synt 2** → $E_{3D}(n/n_0) = \frac{(n/n_0)^\beta}{(n/n_0)^{\alpha+\beta}}\left[1 - exp(\frac{n-n_{tot}}{\gamma} + \epsilon)\right]$

$\beta = 2$, $\alpha = 5/3$, $n_0 = 11$, $\gamma = 10^4$, $\epsilon = 10^{-1}$
Synt 1 mimics the Kolmogorov inertial range of fluid turbulence, **Synt 2** mimics both the inertial and the dissipative part of the spectrum.

- Synthetic data are scaled on a 180 days time grid ($\Delta t = 100\ s$, $n_{tot} = 155520$)
- The same gaps of V2 velocity data are projected on these sequences
- Spectral analysis is carried out.

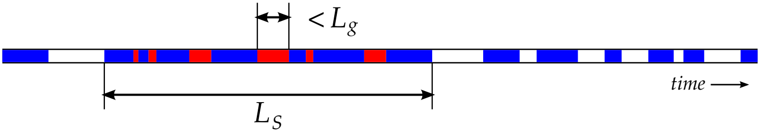
Effect of interpolation on **Synt 1** data



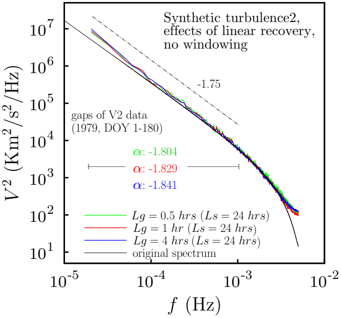


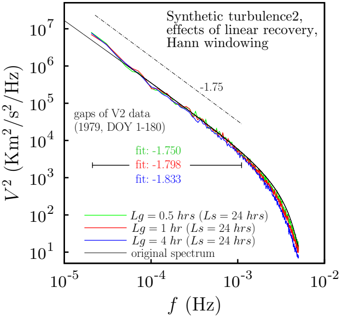
L_s = length of reconstructed segments used to compute spectra;

L_g = maximum length of filled gaps



Effect of interpolation on **Synt 2** data





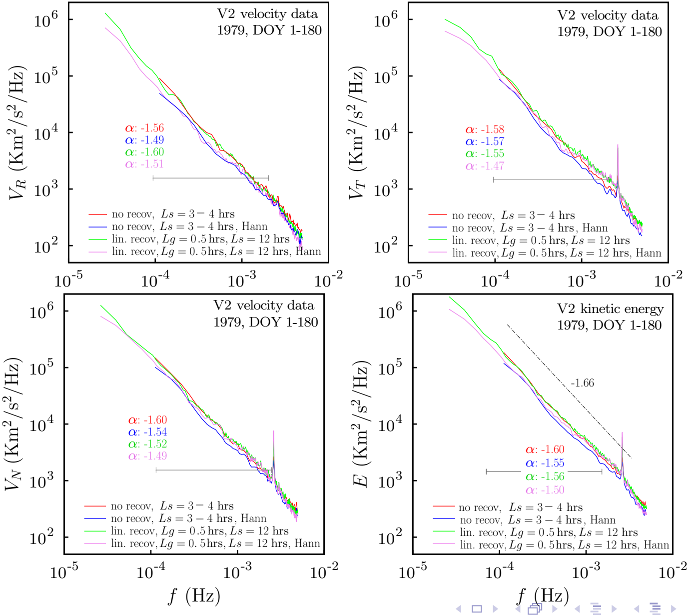
- Effect of segmentation: increase in slope of about 5% in the inertial range .
- Effect of linear interpolation: function of L_g (length of “filled” gaps). This interpolation transfers energy to the low frequences, resulting in an increase (about 6%) in the slope, especially in the high-frequency range ($f > 10^{-3}$Hz).

Effect of interpolation on **Synt 2** data

- Effect of windowing: the Hann window function allows to eliminate spurious energy due to discontinuities ($\approx 1/f$) at the boundary of each segment. The effect is minimal at low wavenumbers. In the high-frequency range, on the one hand a significant increase (up to 23%) of the slope is found to be a function of L_g, on the other hand any change in slope of the real spectrum can be followed.
  Energy correction factor for Hann: 1.63^2

- Without windowing, the segmentation error doesn't allow to represent the correct slope, in the general case (see the analysis on **Synt 2** data). These cases can be recognized by a flattening in the high-frequency range of the spectrum. Averaging long segments helps.

V2 velocity spectra at 5 AU (pre-Jupiter)



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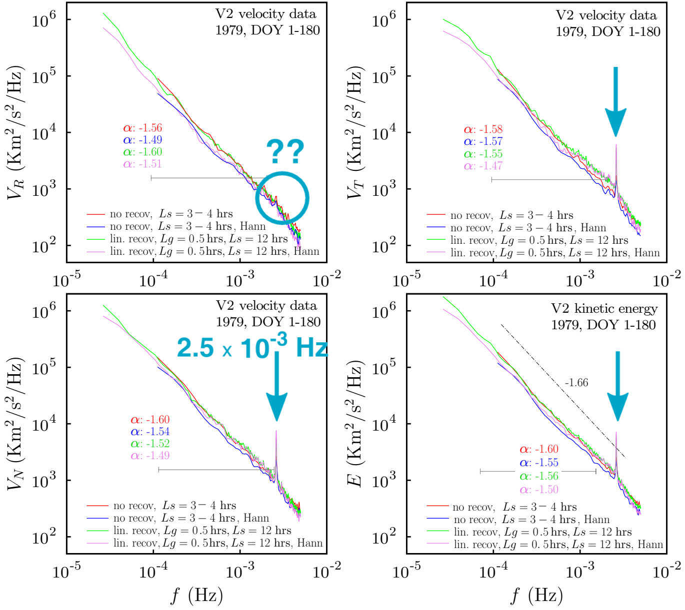
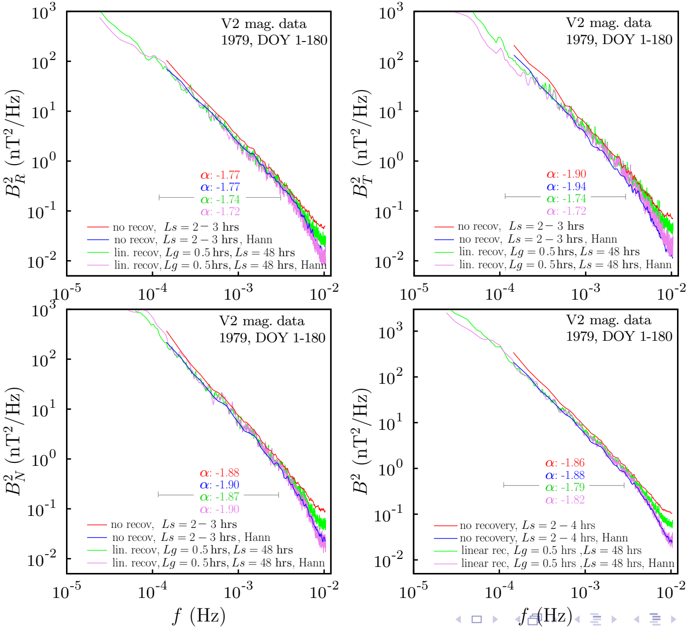
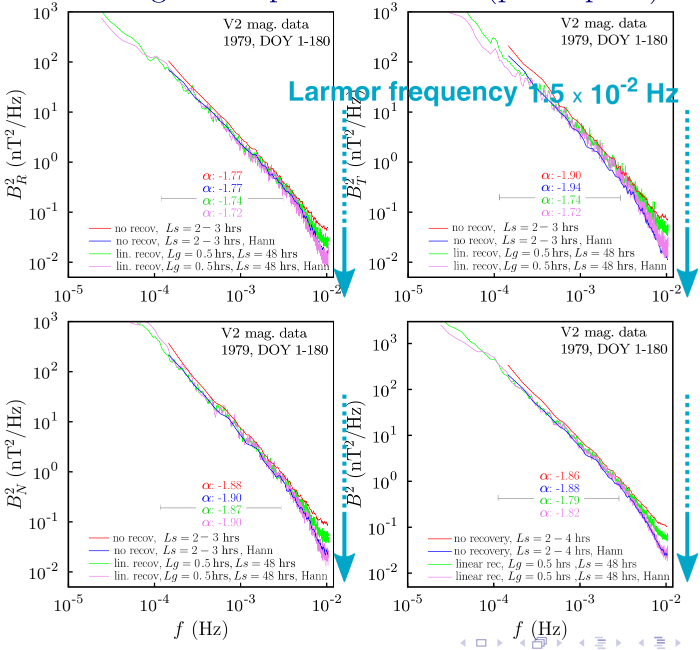


V2 mag. field spectra at 5 AU (pre-Jupiter)



V2 mag. field spectra at 5 AU (pre-Jupiter)



V2 spectra at 5 AU (pre-Jupiter)

Velocity:

- The observed frequency range constitute the inertial range
- All computed exponents ($10^{-4} < f < 2 \cdot 10^{-3}$ Hz) are flatter than the Kolmogorov one:
  $\alpha = -1.53 \pm 0.07$
- Computed slopes may be slightly overestimated
- A peak is located at $f = 0.0026$ Hz for T and N components: is it physical or instrumentation-related? (no relation with f_{ci}, f_{pi}, f^*))

Magnetic field:

- Computed exponents ($10^{-4} < f < 2 \cdot 10^{-3}$) higher lower than the velocity ones:
  $\alpha = -1.81 \pm 0.09$
- Observed steepening for $f > 3 \cdot 10^{-3}$ Hz should not be linked to interpolation issues: the situation recalls that of **Synt 2** case, blue (no recovery) and violet (small gaps filled) give the same result.
- Anisotropy is higher with respect to the velocity field

G.B. Rybicki &W.H. Press prediction

- Minimum variance prediction (interpolation):

  $\boldsymbol{y} = \boldsymbol{s} + \boldsymbol{n}$ irreg. spaced vector data with errors $\boldsymbol{n}$

  $s^* = \sum_{i=1}^{M} d_{*i} y_i + x_*$ s^* =true value at a particular point

  $\hat{s^*} = \mathbf{S}^T [\mathbf{S} + \mathbf{N}]^{-1} \mathbf{y}$ $\hat{s^*}$ =min. variance estimate for s^*

  Assuming stationary process:

  $S_{ij} = \langle s_i s_j \rangle = f(t_i - t_j)$ is the correlation matrix, estimated from data
  $N_{ii} = \langle n_i^2 \rangle$ is the errors diagonal matrix $n_i \rightarrow \infty$ in "new" points

  The min. variance estimation is not, however, a typical realization of the underlying process.

- Minimum variance prediction + Gaussian process

  To obtain a typical realization, a Gaussian process is added to the min. var. estimate:

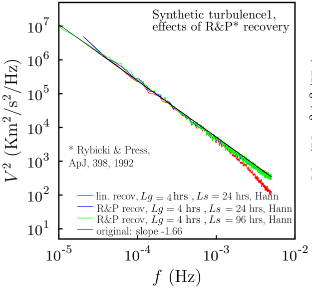
  $s_* = u_* + \hat{s}_*$

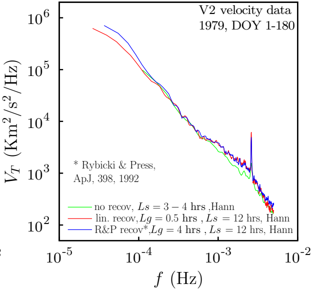
  If realizations constrained to data are desired:

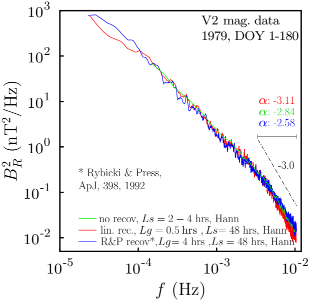
  $\boldsymbol{u} = \boldsymbol{V} diag(\lambda_1^{1/2}, ..., \lambda_M^{1/2}) \boldsymbol{r}$ where

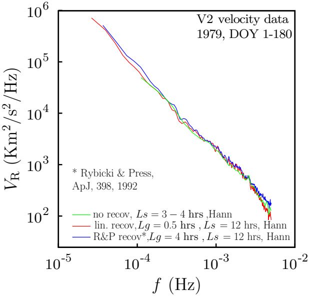
  $\lambda_i = eig(\boldsymbol{Q}), \quad \boldsymbol{Q} = [\boldsymbol{S}^{-1} + \boldsymbol{N}^{-1}]^{-1}, \quad \boldsymbol{r} = rand(\mu = 0, \sigma^2 = 1)$

R&P reconstruction









Final considerations and future development

- V2 data: it is possible to obtain spectra from incomplete data (at least at 5 AU!)
- velocity spectra support the MHD cascade model (Iroshnikov–Kraichnan, -3/2 exponent): -1.53 ± 0.07 exponent
- magnetic field spectra much steeper than velocity ones (-1.81 ± 0.09)
- peak at $f = 2.6 \cdot 10^{-3}$ Hz in V_T and V_N spectra only: a feature of solar wind structure or an instrumentation problem? (note: Larmor frequency one order of magnitude higher)
- Future work:
  - comparison with V1 data (same exponents and peaks?)
  - analysis of the much challenging *Heliosheath* data (V2: 2007-2013, 97% of voids in data; switch to to *compress sensing* reconstruction method from telecommunication engineering.