Solar system turbulence, intermittency and multifractals from in-situ observations at the minimum and maximum of the solar cycle

M. Echim (BIRA-IASB & ISS) and the STORM team

Acknowledgments: *ESA CAA, ESA PSA, ESA UFA, CNES/CNRS AMDA*

Outline

1. Solar wind data bases and data selection at solar minimum and maximum
2. Power spectral densities in the heliosphere from Ulysses, 1999-2001, 2007-2008, Cluster, 2001, 2007-2008, and from Venus Express, 2007-2008
3. Some statistical results, at solar maximum and solar minimum
4. Investigation of intermittency: PDFs, multifractals
5. Summary Conclusions

http://www.storm-fp7.eu

STORM

Solar system plasma Turbulence: Observations, inteRmittency and Multifractals

M. Echim, H Lamy, Y Voitenko - Brussels
E. Yordanova, M André, H. Breuillard - Uppsala/Kiruna
W. Macek, A. Wawrzaszek - Warsaw
G. Consolini, R. Bruno, G. Pallochia, MF Marcucci - Rome
P. Kovacs, A. Koppan - Budapest
G. Voitcu, C Munteanu, E. Teodorescu, C. Negrea – Bucharest
K. Mursula, I. Virtanen, P. Vaisanen - Oulu
Z. Voeroes, Y. Narita, N. Dwivedi, T. Zaqarashvili - Graz
T. Chang - MIT, USA
J. Johnson - Princeton, USA
K-H Glassmeier - Braunschweig

STORM – A Summary

Mission:

From the 5th EU FP7 Call: *"Collaborative proposals in the field of data exploitation are of particular importance since **ESA has supported many science missions, but data analysis has mainly been limited to efforts on a project by project basis, therefore limiting a full exploitation of raw data.** Missions currently in operation produce data sets of potentially immense value for research, and **the funding support from FP7 should add to this value through a more comprehensive interpretation.**"*

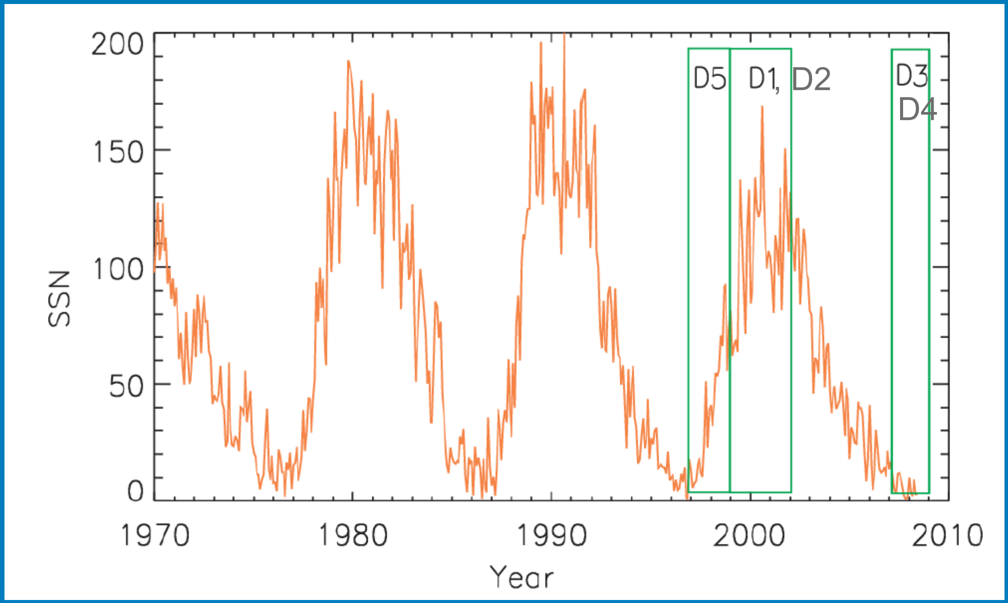
Strategy: Advance the analysis from zero order (PSDs) to higher orders (PDFs, multifractals....); apply the same analysis package on data from multiple spacecraft

.

Objectives (from Grant Agreement 313038/STORM, http://www.storm-fp7.eu)

1. How is the energy transferred between scales in the solar wind and magnetospheric turbulence? Is the process dominated by wave effects or by the interaction of coherent structures ?
2. Which are the mechanisms ensuring the energy dissipation in collisionless solar system plasma turbulence?
3. Which are the sources of intermittency?
4. What are the effects of the solar wind turbulence and intermittency on the turbulence of the planetary magnetosheaths downstream quasi-parallel and quasiperpendicular shocks?
5. Are there any significant changes of the heliospheric turbulence and intermittency from solar maximum to solar minimum ?
6. What is the response of the magnetosphere/ionosphere and of the geomagnetic field to intermittent turbulence in the solar wind? Are there any significant solar cycle trends?

STORM multi-spacecraft data bases, at solar minimum and maximum



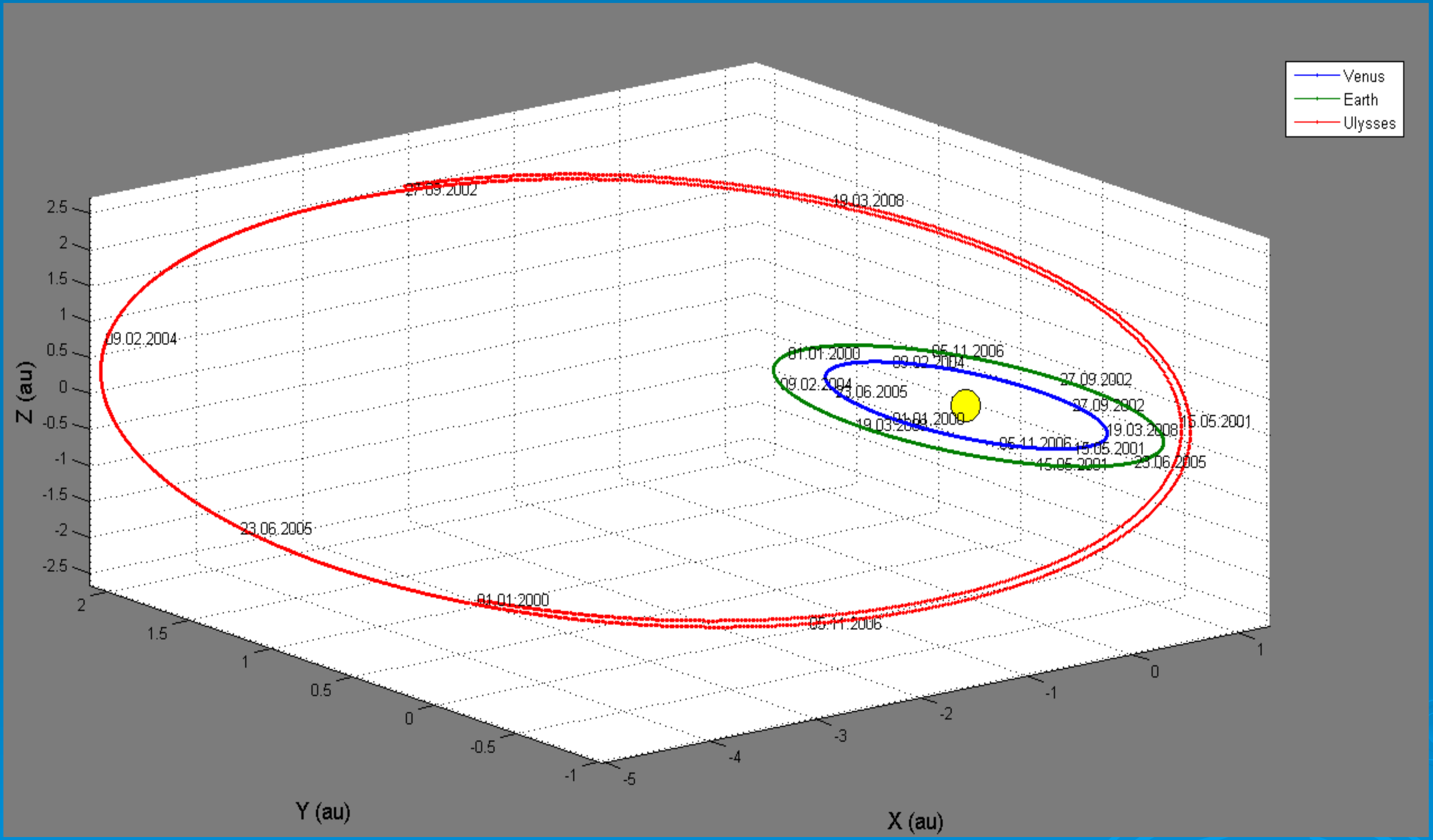
Sunspot number between 1970-2010 and the time intervals selected for the STORM databases

- STORM solar wind databases:
  - D1 (solar max), D3 (deep minimum), D5 (minimum and ascending phase)
- STORM planetary databases:
  - D2 (solar max), D4 (deep minimum)
- Data bases contain processed data for selected time intervals, downloaded from CAA, PSA, UFA or directly from the PI. They also include the analysis results: PSD spectra, PDFs, Multrifractal spectra

- **<u>Solar Wind data:</u>**
  - ULYSSES (1995 - 2008),
  - Cluster (2000-) – multi-point mission
  - Venus Express (2005 -)

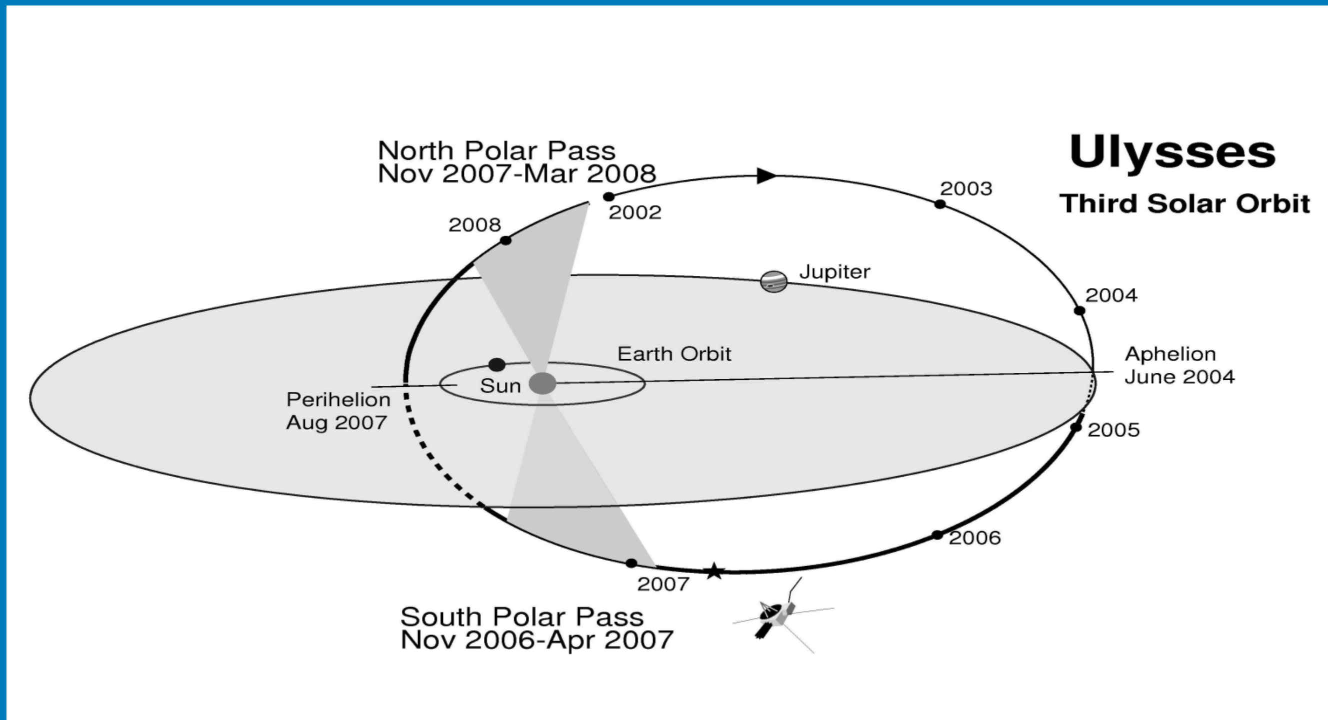
- **<u>Planetary plasma data</u>**:
  - Earth: Cluster (multi-point mission)
  - Venus: Venus Express
  - Mars: MGS
  - Saturn: Cassini
  - Comets: Giotto (maybe Rosetta)

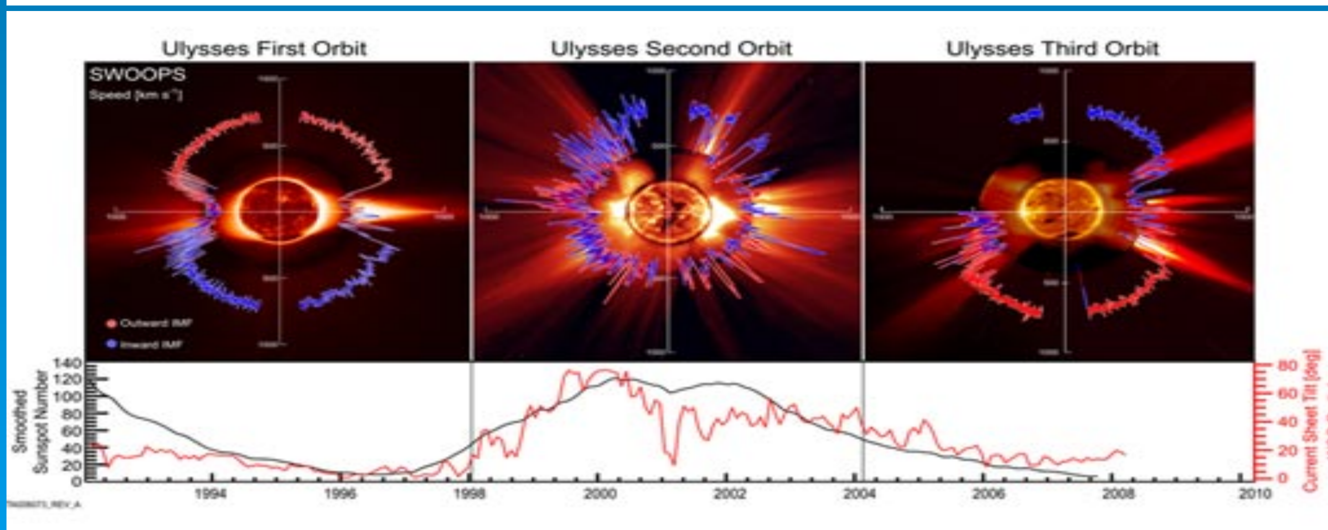
STORM core satellite missions



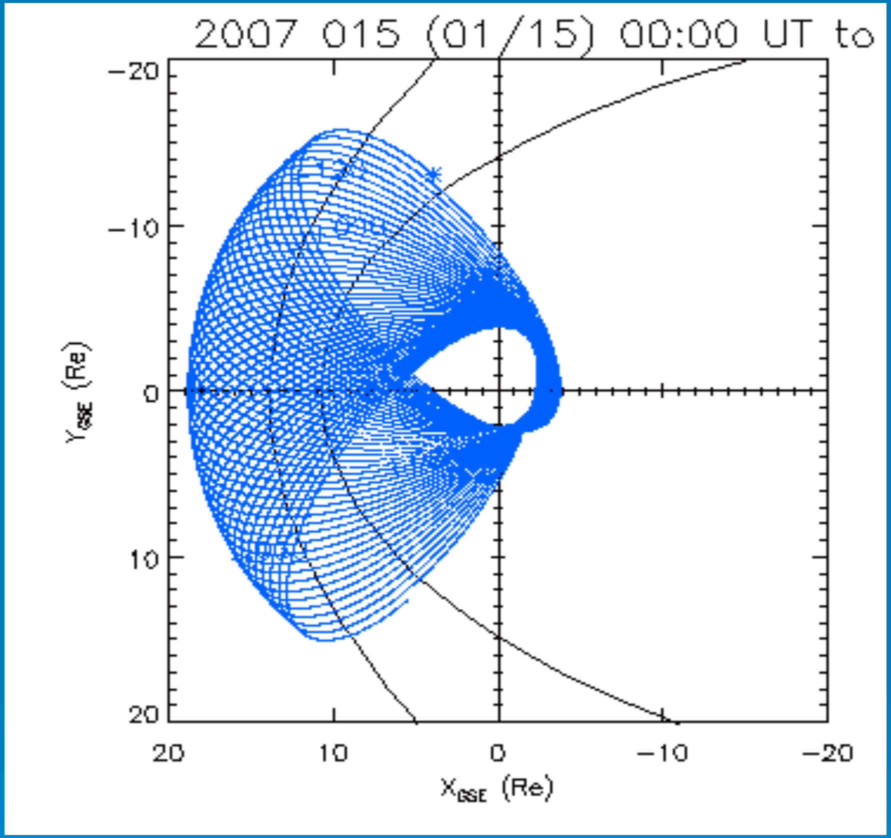
Relative positions of the Earth, Venus and of the Ulysses spacecraft between 2000 and 2008

STORM core missions – ULYSSES



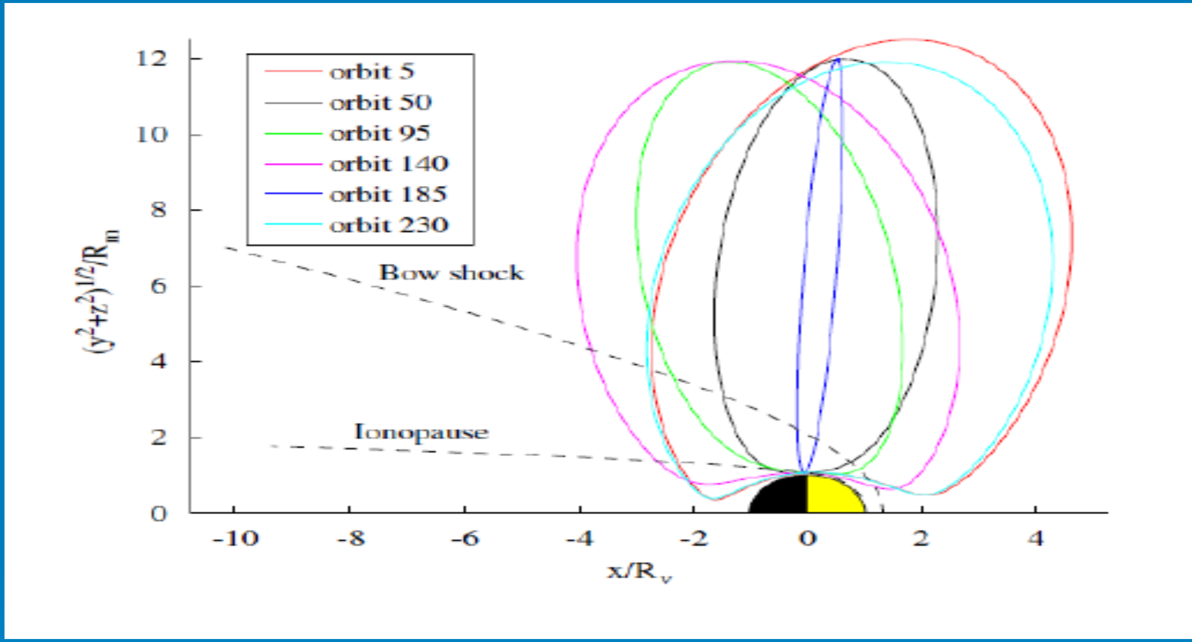


STORM core missions – Cluster

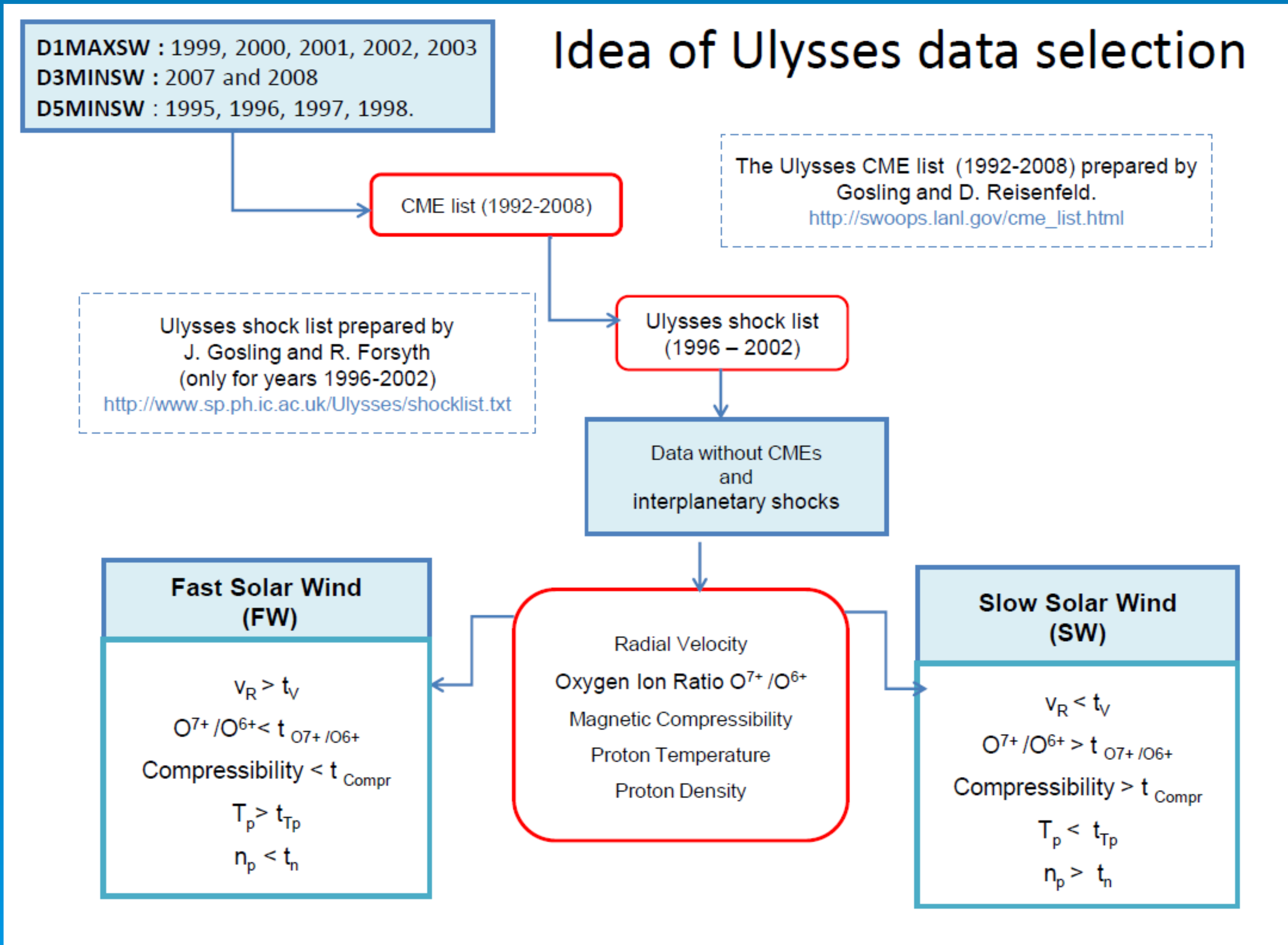


- **<u>Solar Wind data:</u>**
  - Cluster (2000-), seasonal sweeping of the solar wind;
  - Different geometries: quasi-perpendicular, quasi-parallel
  - Unprecedented resolution for plasma measurements in the solar wind

STORM core missions – Venus Express



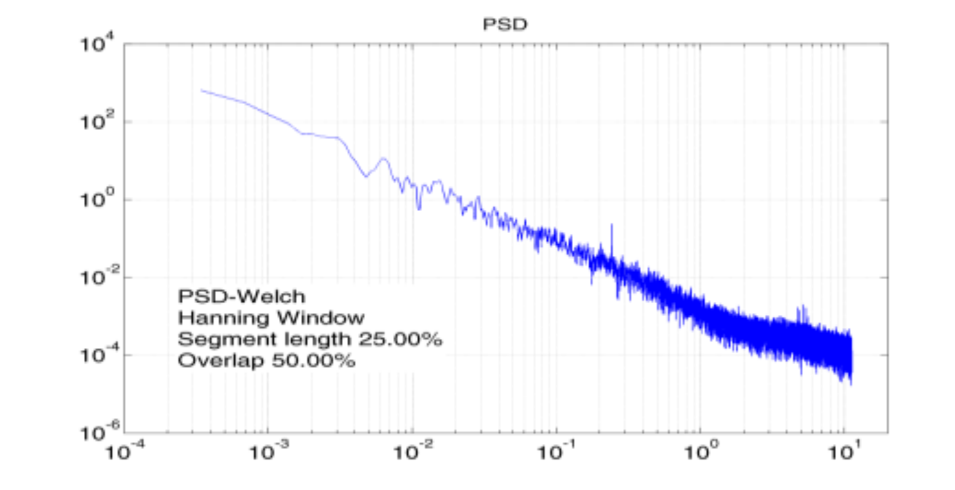
- **<u>Solar wind data</u>**:
  - Venus: Venus Express (2005-2014)
  - True solar wind monitor at 0.72; low resolution plasma data; “noisy” magnetic field records
  - Unique point of observation



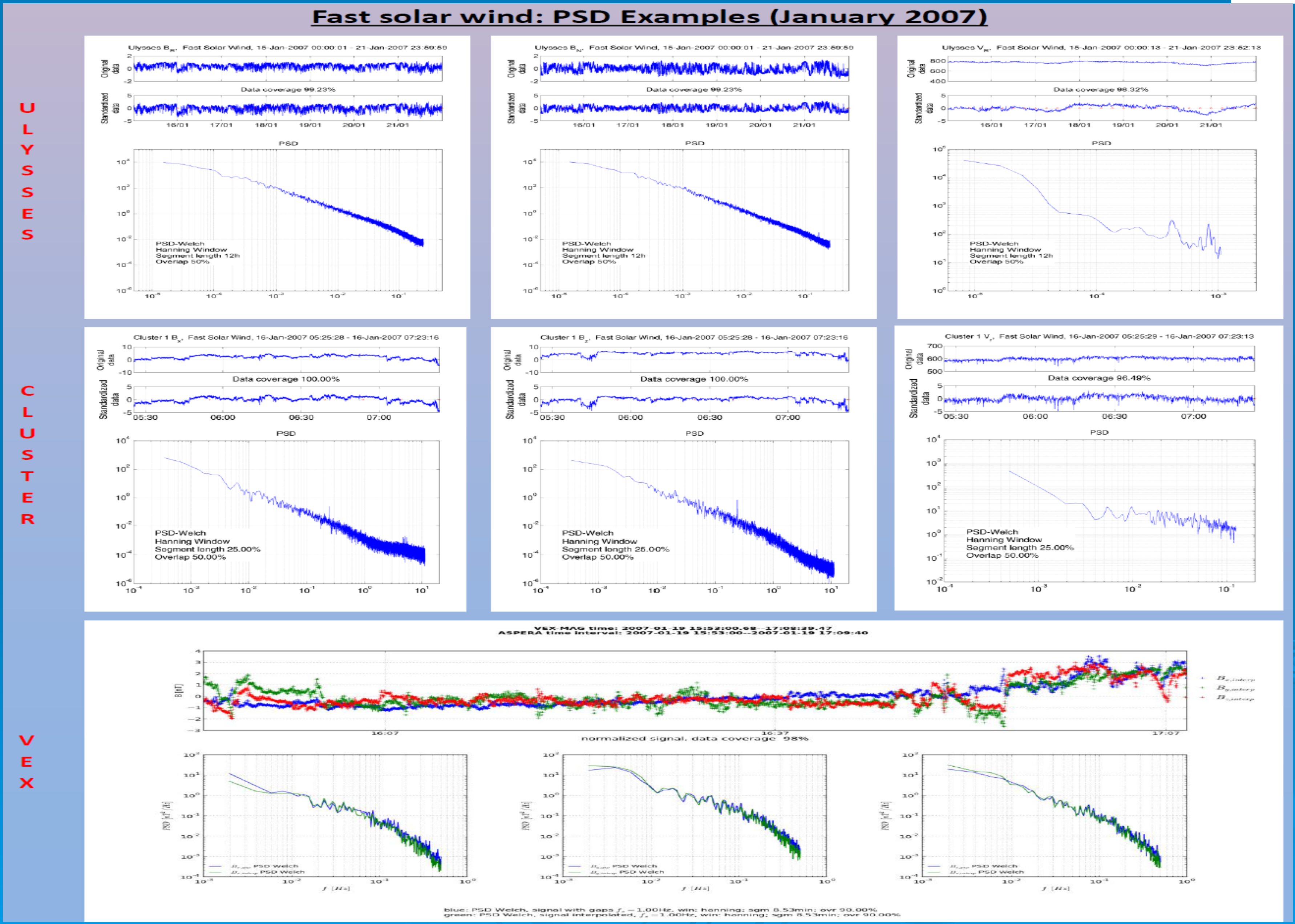
Prepared by A. Wawrsaszek et al.

STORM PSD calculations: what are we looking for ?

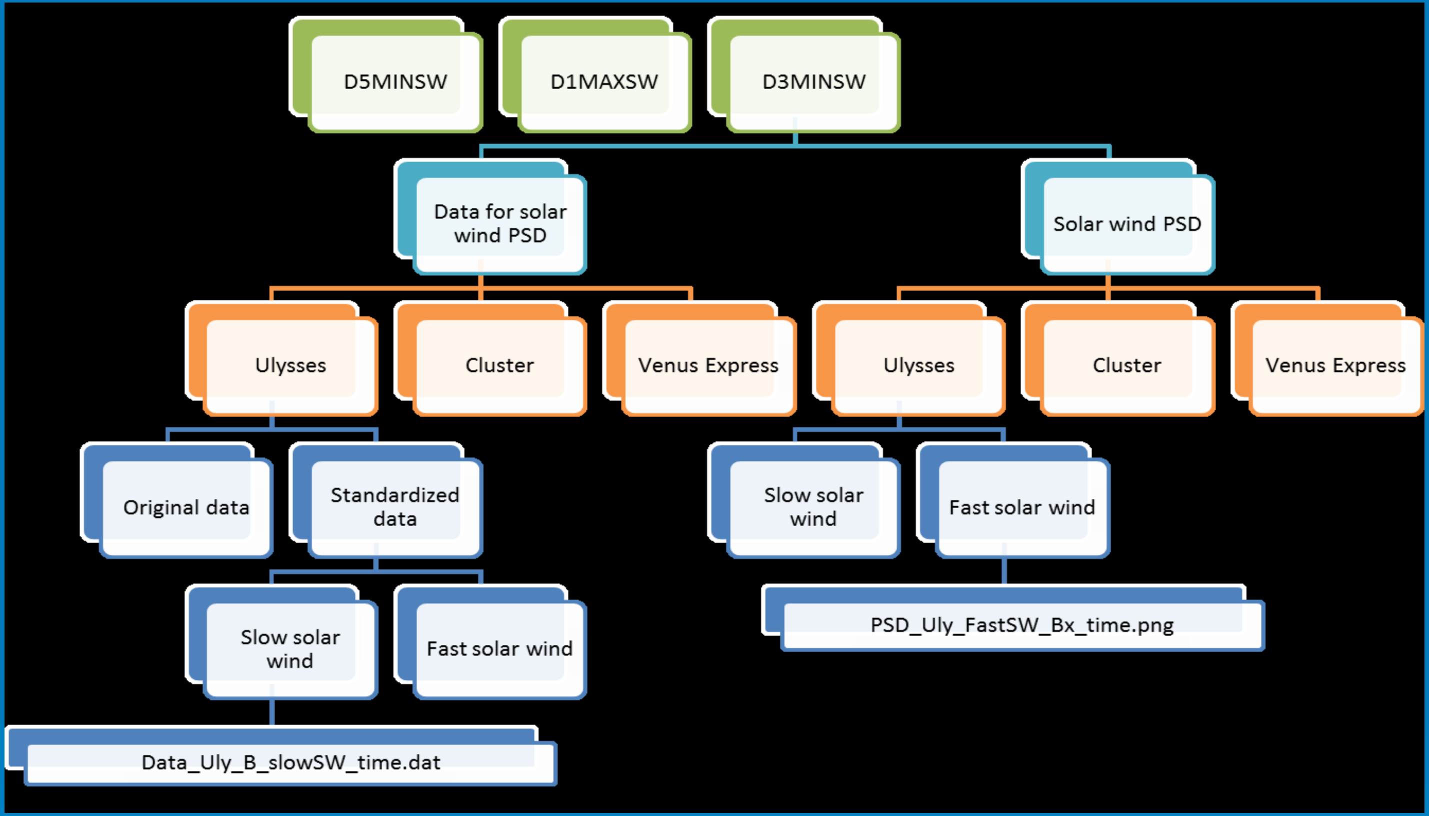
- Inertial range (power law, energy cascade, turbulence models)
- Spectral breaks (transition from convection to inertial, from inertial to dissipation, dissipation models for plasma turbulence, phase transitions ?, non-calibrated data ?, gaps/interpolation ?, flickering noise ?)
- Spectral indices:
  - "$f^{-5/3}$", classical, self-similar, neutral turbulence, why observed in the solar wind ?
  - "$f^{-3/2}$" classical, is the equivalent of the "5/3" index for MHD plasma (Iroshnikov-Kraichnan, 3 wave interaction, critical balance)
  - "f^{-2}" classical, is the equivalent of the "3/2" index corrected for the magnetic anisotropy (correction by Godreich and Shridhar, 1992, but also power law resulting from critical dynamics, Chang, 2004)



Examples of PSD from the three core mission spacecraft



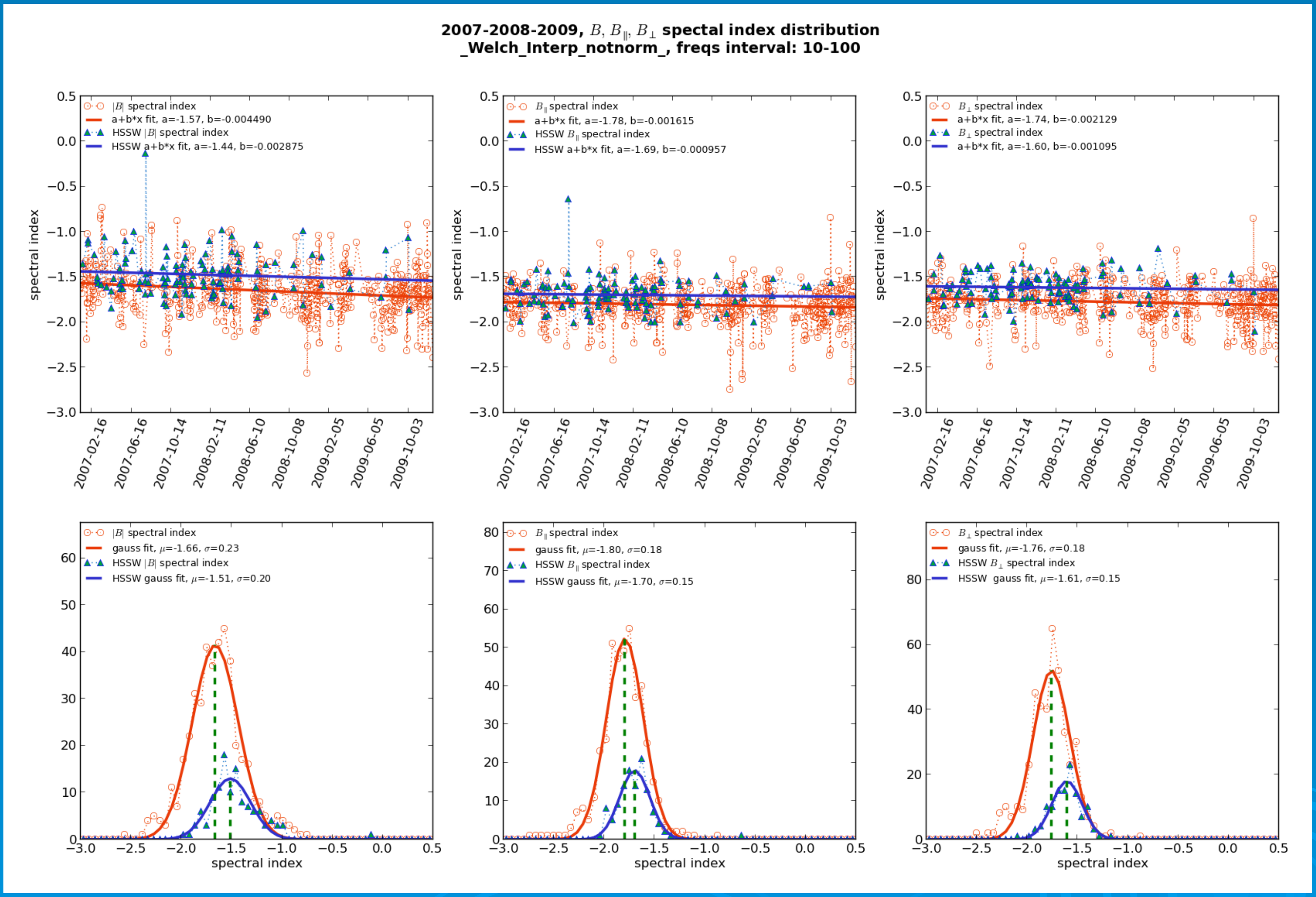
STORM solar wind PSD data base.



http://www.storm-fp7.eu **Structure of the data base (682 spectra).**

- **ULYSSES** - 135 PSDs: 27 PSDs in D5MINSW (12 fast wind, 15 slow wind), 59 PSDs in D1MAXSW (33 fast wind, 26 slow wind) and 49 PSDs in D3MINSW (45 fast wind, 4 slow wind).
- **Cluster** - 173 PSDs : D1MAXSW: 22 PSDs from Cluster 1 data (1 fast wind, 21 slow wind) and 20 PSDs from Cluster 3 data (all slow wind). D3MINSW: 75 PSDs from Cluster 1 data (18 fast wind, 57 slow wind) and 54 PSDs from Cluster 3 data (7 fast wind, 47 slow wind).
- **VEX** : 374 PSD spectra all in D3MINSW (183 for 2007 and 191 for 2008) of which 110 PSD spectra correspond to fast wind (64 in 2007 and 46 in 2008).

PSD analysis of magnetic field at 0.72 AU



Statistical analysis of the spectral index of the parallel and perpendicular component of the magnetic field measured by VEX, 2007-2009 (Teodorescu et al., ApJL, 2015).

Probability distribution functions (PDFs)

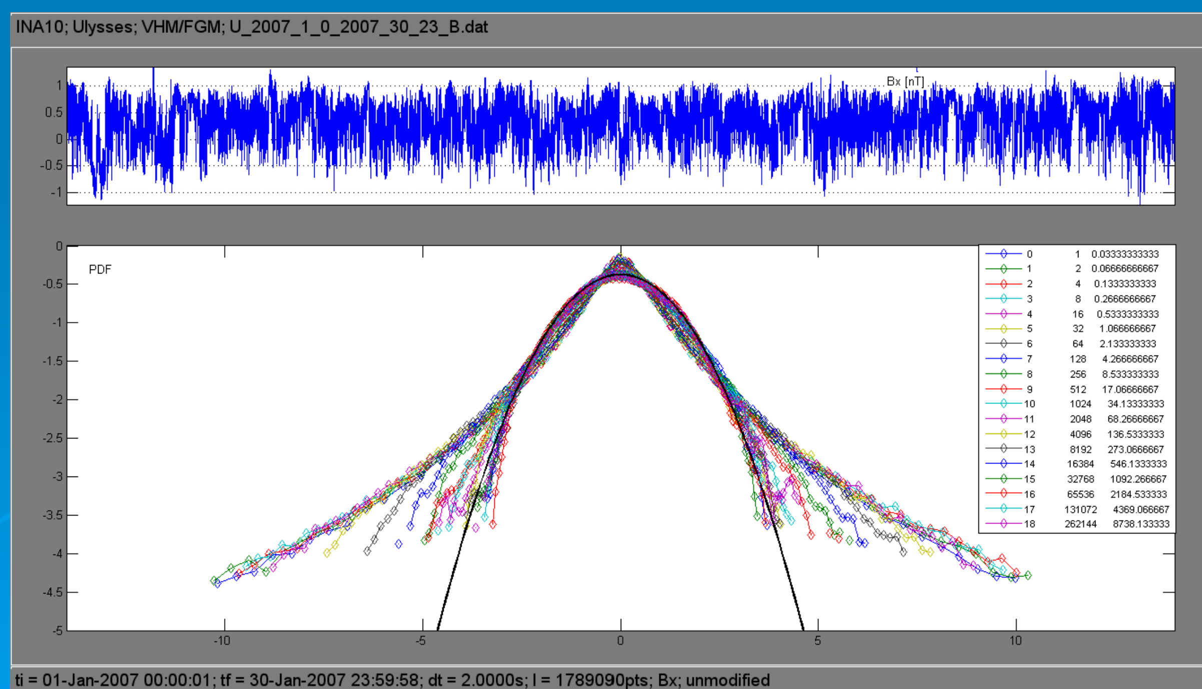
- PDF = histogram of the fluctuating field P(t)

$$P(t, t) = P(t+t) - P(t)$$

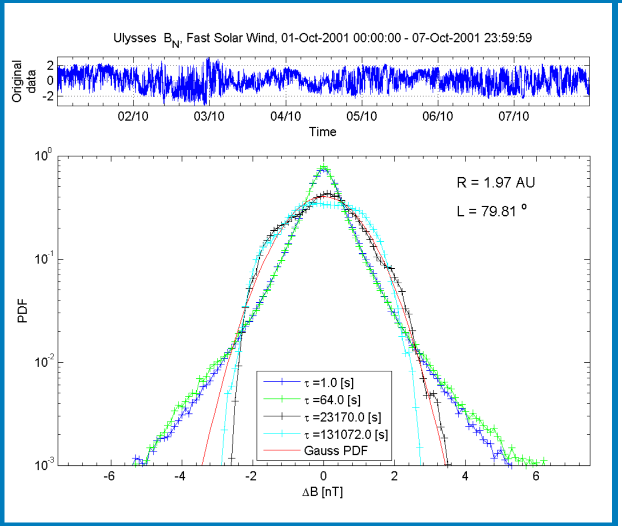
for a given value t of the temporal scale. ($P = B_x, B_y, B_z$, |B| or B^2)

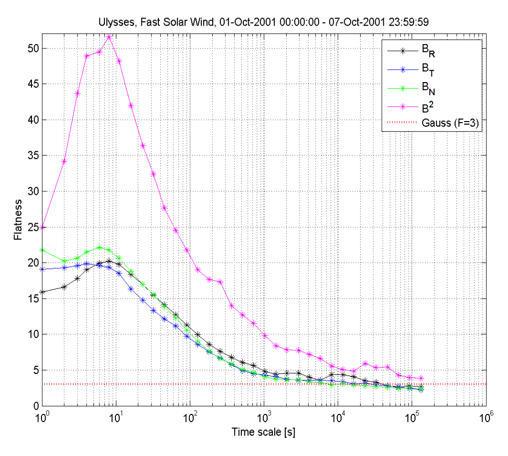
- Intermittency is associated with increasing departure of PDFs from gaussianity and absence of rescaling at all scales when the scale t decreases; indicates presence and interactions of coherent structures.

PDFs of Bx in the solar wind from Ulysses, fast wind

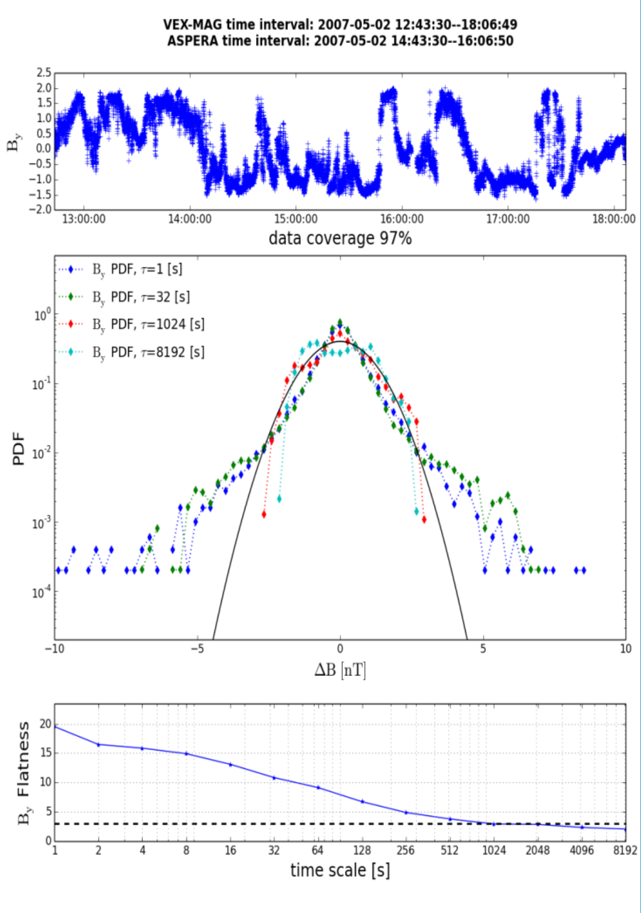


Solar wind PDFs from Ulysses, Venus Express and Cluster

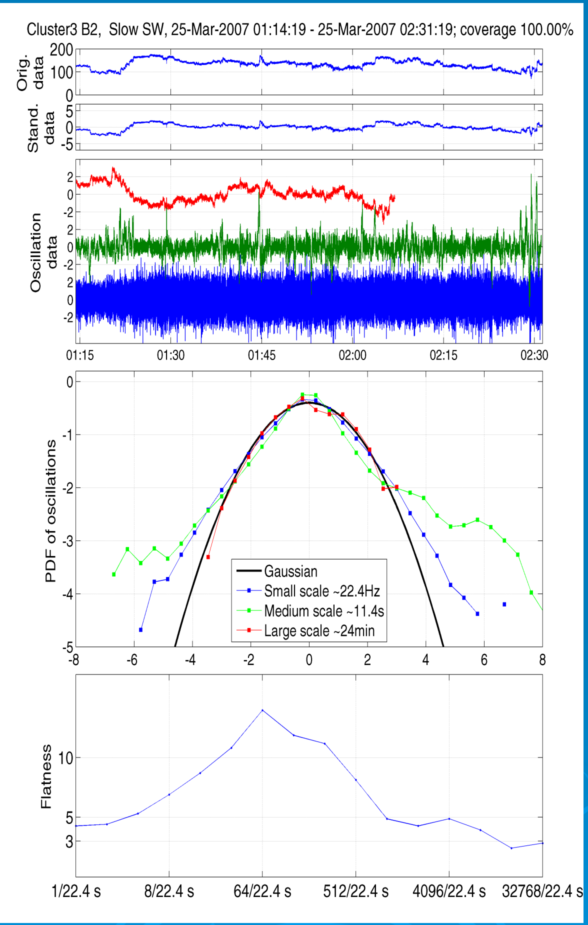




ULYSSES

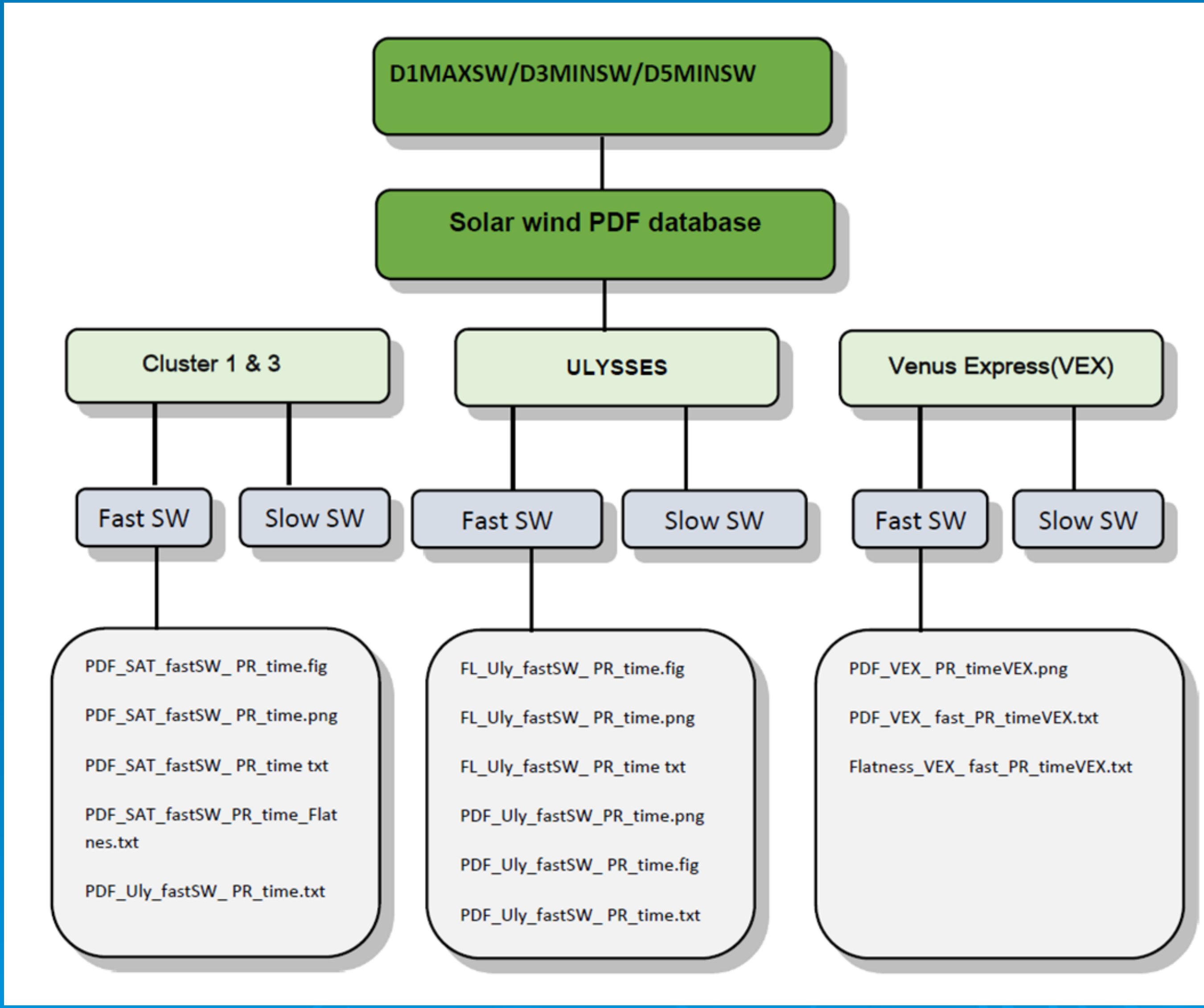


VENUS EXPRESS



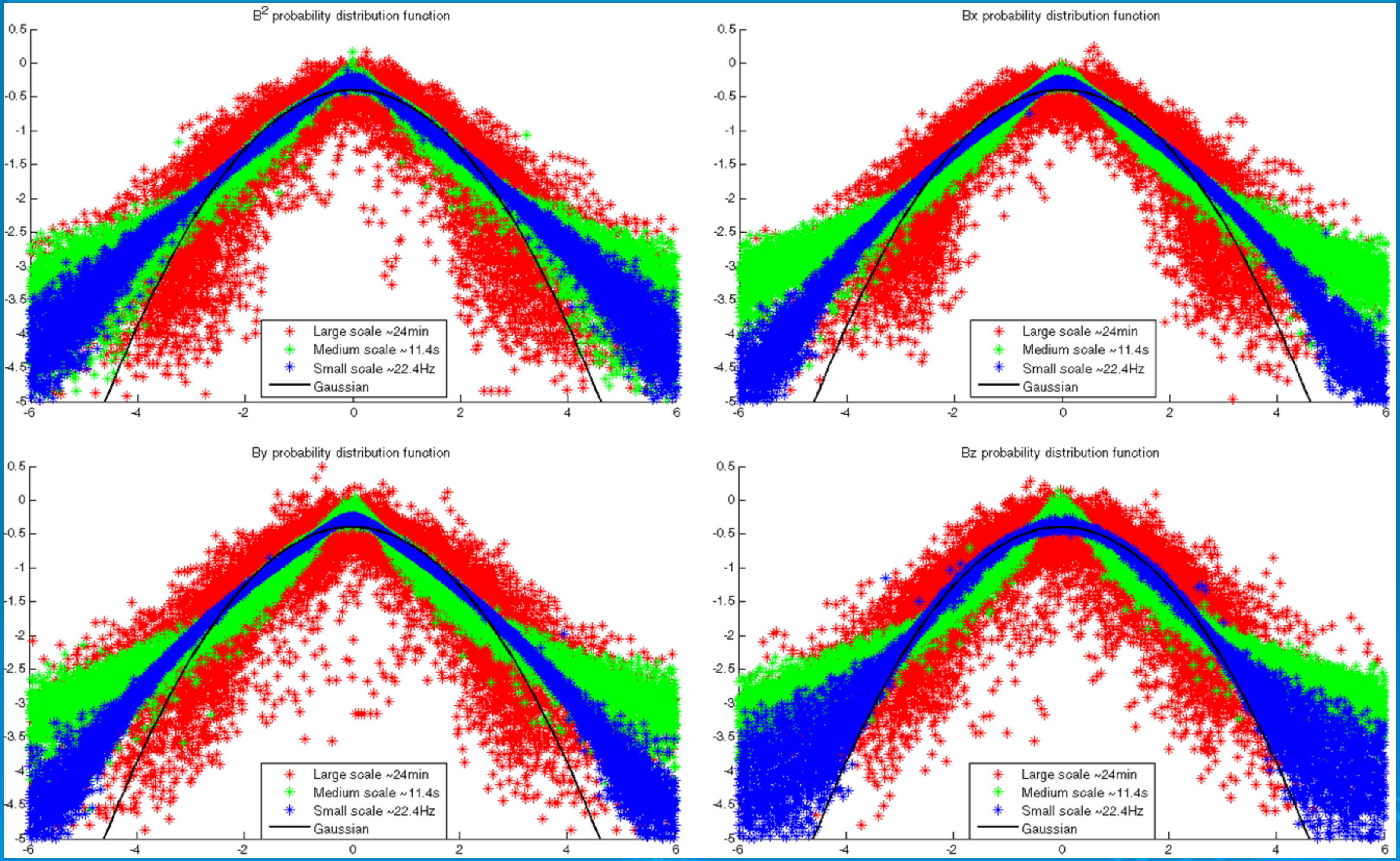
CLUSTER

Solar wind PDFs from Ulysses, Venus Express and Cluster



Structure of the PDFs data base from STORM

Solar wind PDFs from Ulysses, Venus Express and Cluster



Superposition of PDFs from Cluster in the solar wind (2001-2013), from Vaisanen et al., 2015

Multifractal analysis

- The intermittent behaviour is analyzed from the higher order moments of the PDFs : **<u>the structure function (SF)</u>**

$$S_q\left(\delta B^2,\tau\right)=\int_0^{\delta B^2_{\max}}\left(\delta B^2\right)^q P\left(\delta B^2,\tau\right)d\delta B^2=\left\langle \left|B^2\left(x_i+\tau\right)-B^2\left(x_i\right)\right|^q\right\rangle$$

- For each SF S_q, we associate a fractal exponent ξ_q for a range of scales [illegible]

$$\xi_q = d\left(\log S_q\left(\delta B^2,\tau\right)\right)/d\left(\log\tau\right)$$

- If $\xi_q = \xi_1 q$, the fractal properties of the fluctuating series are fully described by the value of ξ_1 : mono-fractal/self-similar fluctuations. For intermittent turbulence → ξ_q is a non-linear function of q : multifractal case

- SFs can be evaluated for any positive values of q but will generally diverge for q < 0

Multifractal analysis – Partition Function

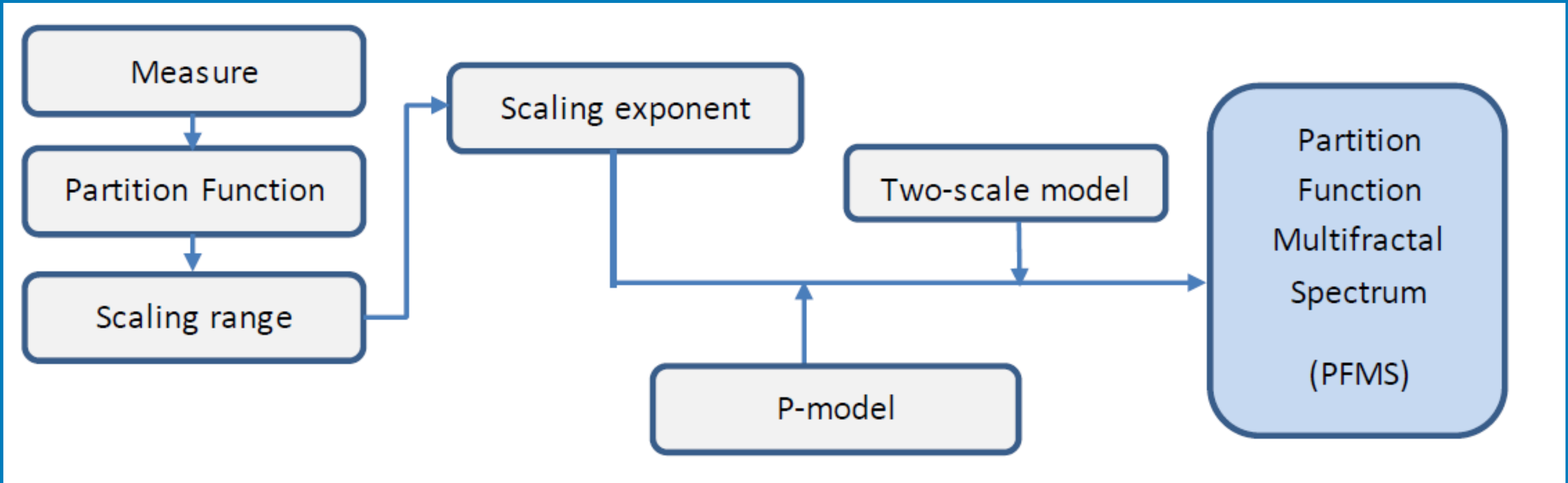
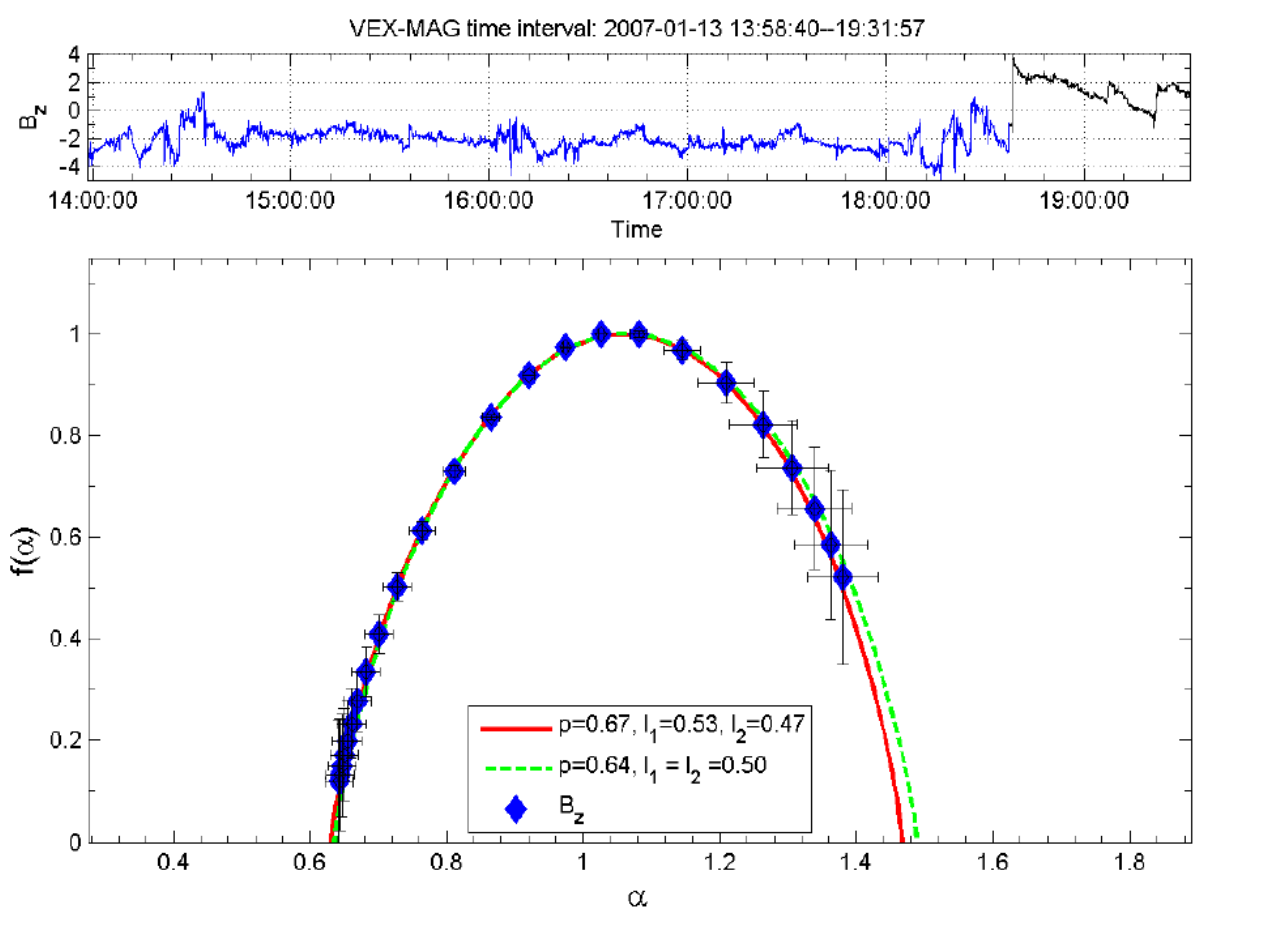


Diagram illustrating the data analysis procedure for the Partition Function Multifraactal Analyis (Wawraszek et al, STORM D2.3 Report)

Multifractal analysis – Partition Function



Multifractal spectrum of solar wind turbulence from Venus Express B-field data.

Multifractal analysis - ROMA

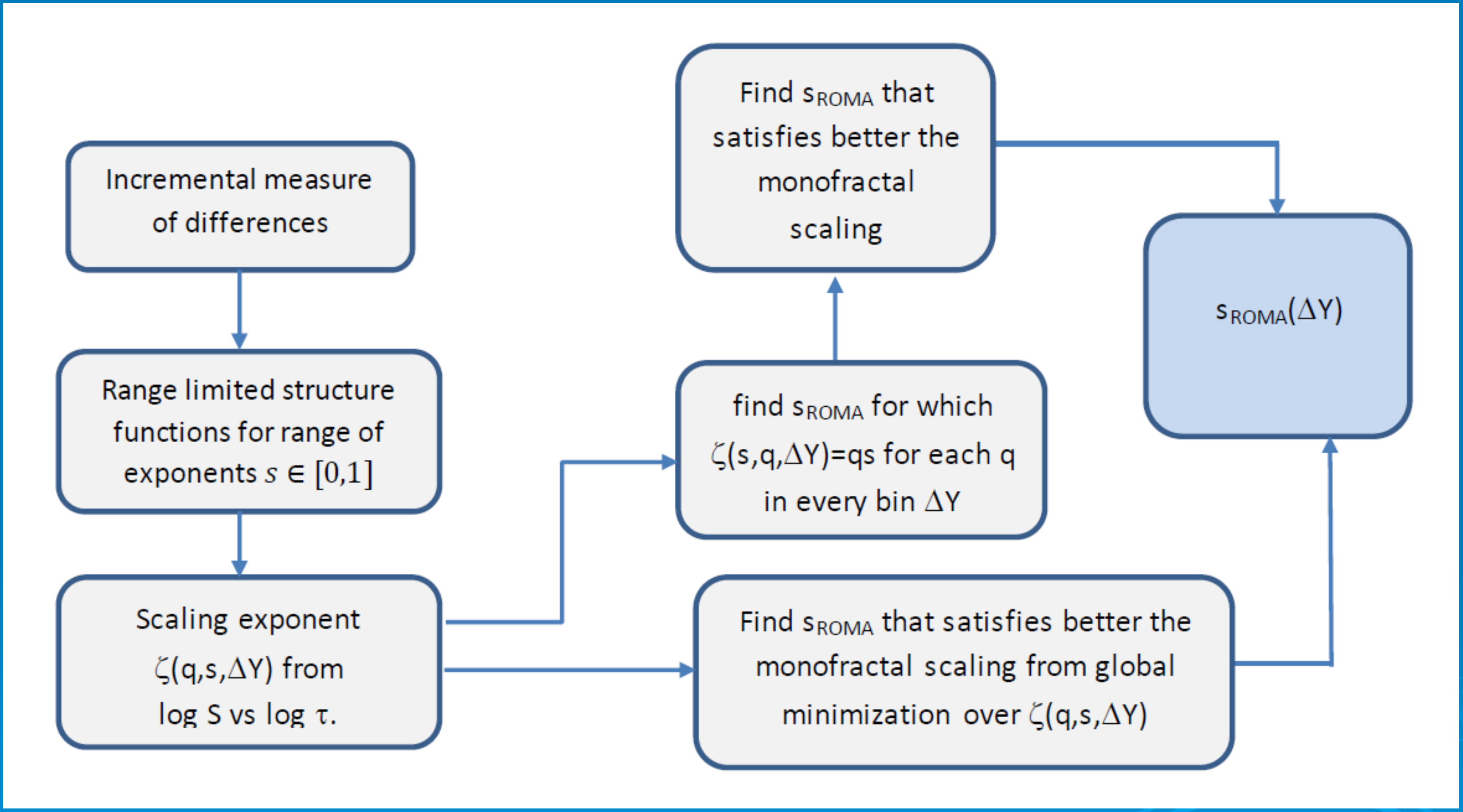
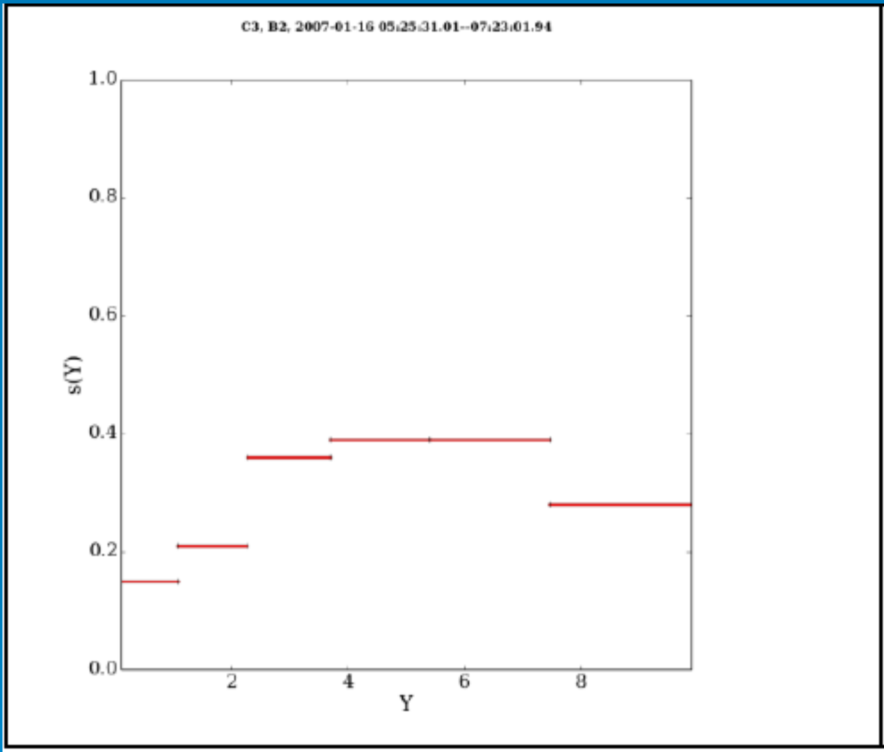
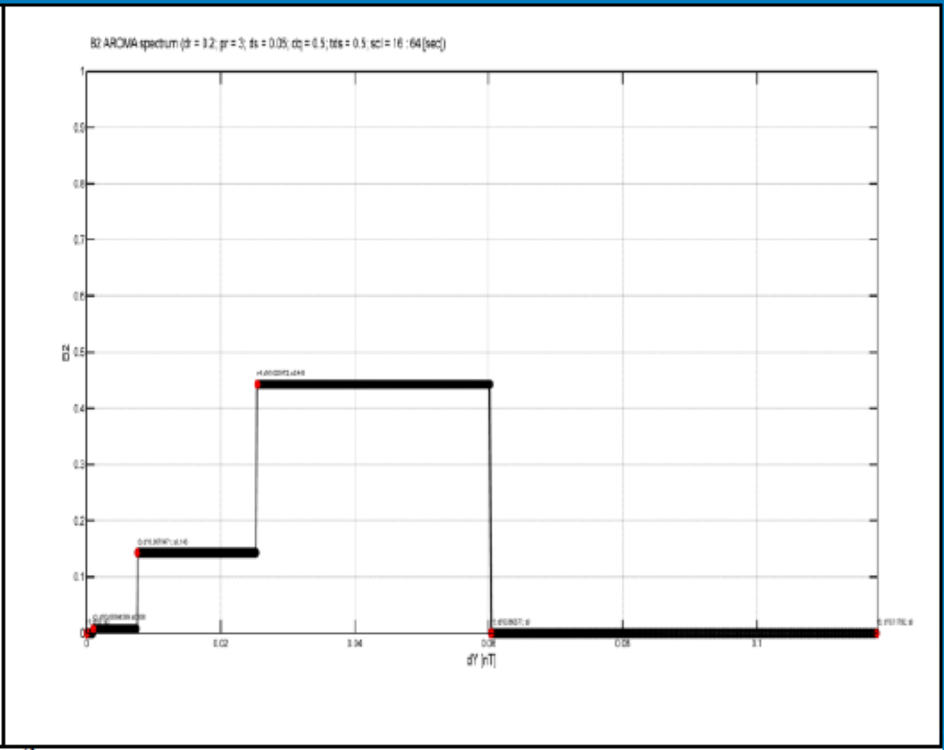


Diagram illustrating the data analysis procedure for the Rank Ordered Multifractal Analysis (Echim et al, STORM D2.3 Report)

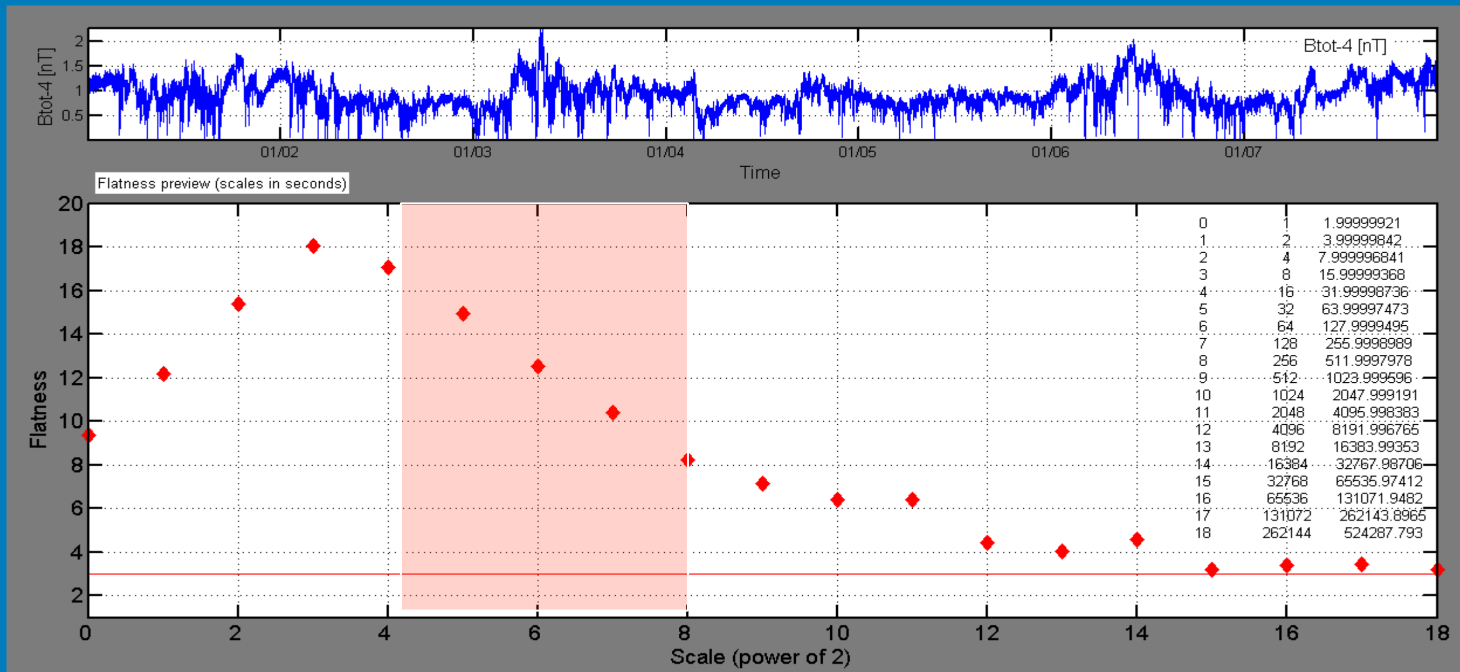
Multifractal analysis - ROMA

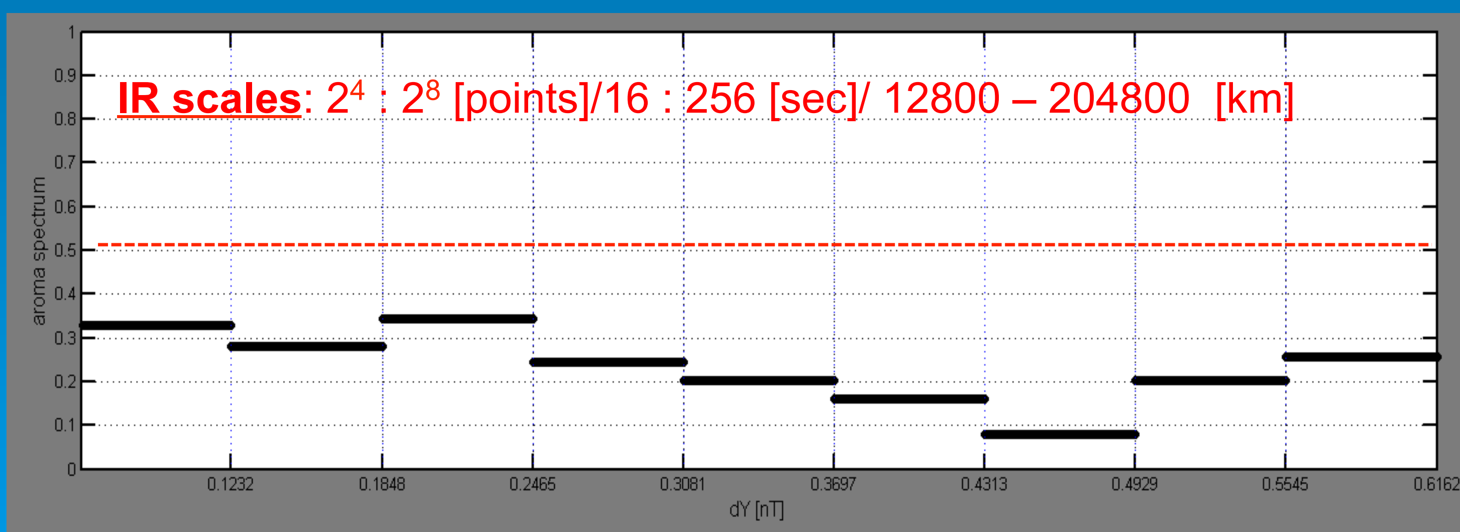




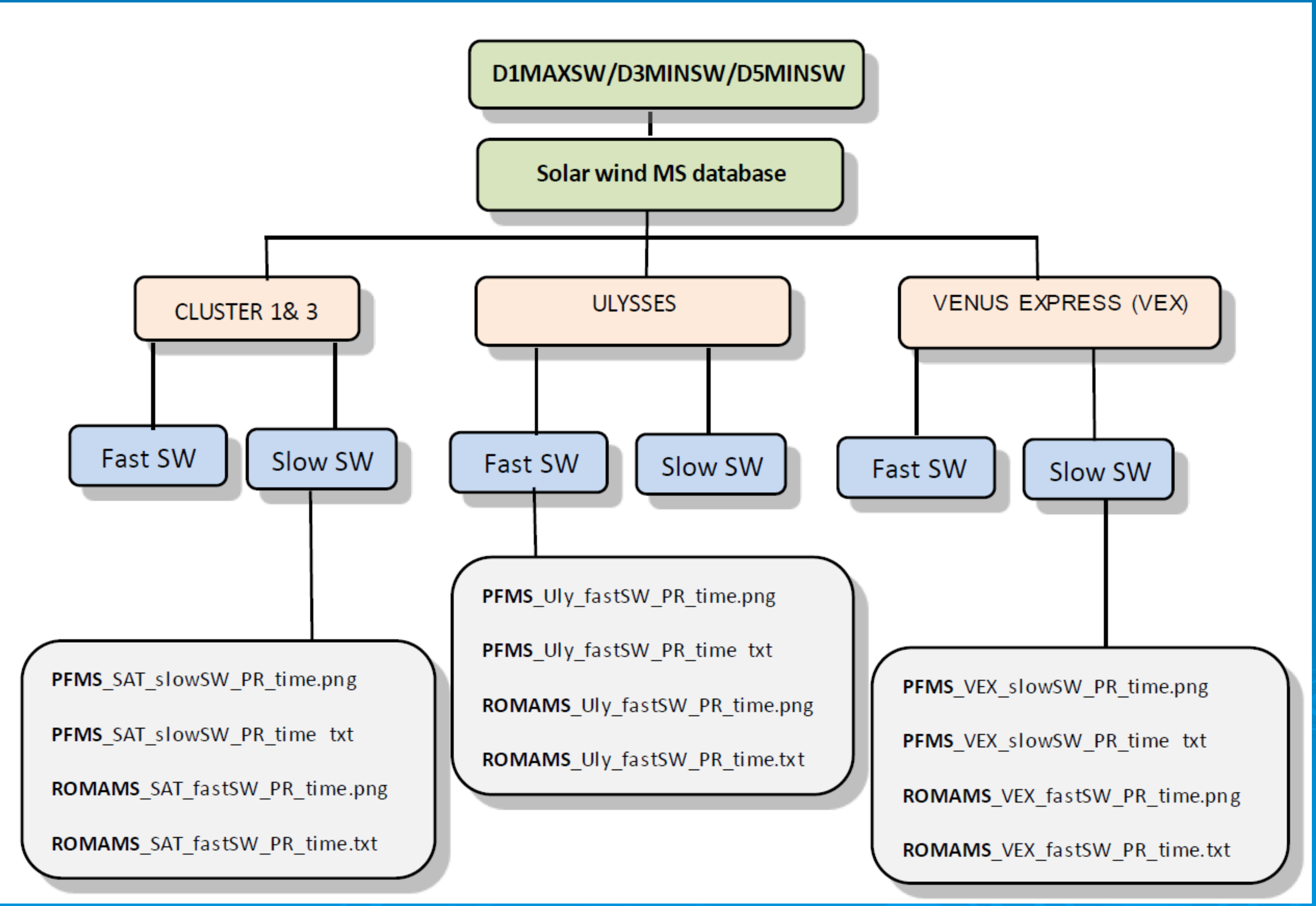
(Left) ROMA spectrum ffor B^2 fluctuations from Cluster in the solar wind. (Right) ROMA for B2 fluctuations from Ulysses.

ROMA spectrum: Ulysses 01 – 07/01/2007



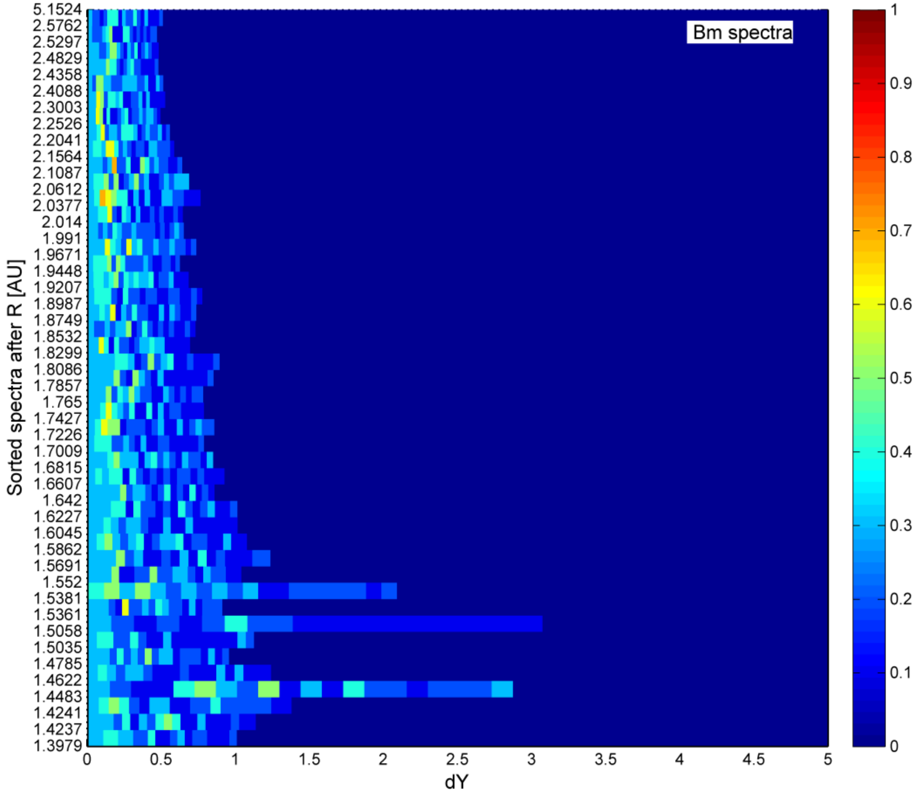


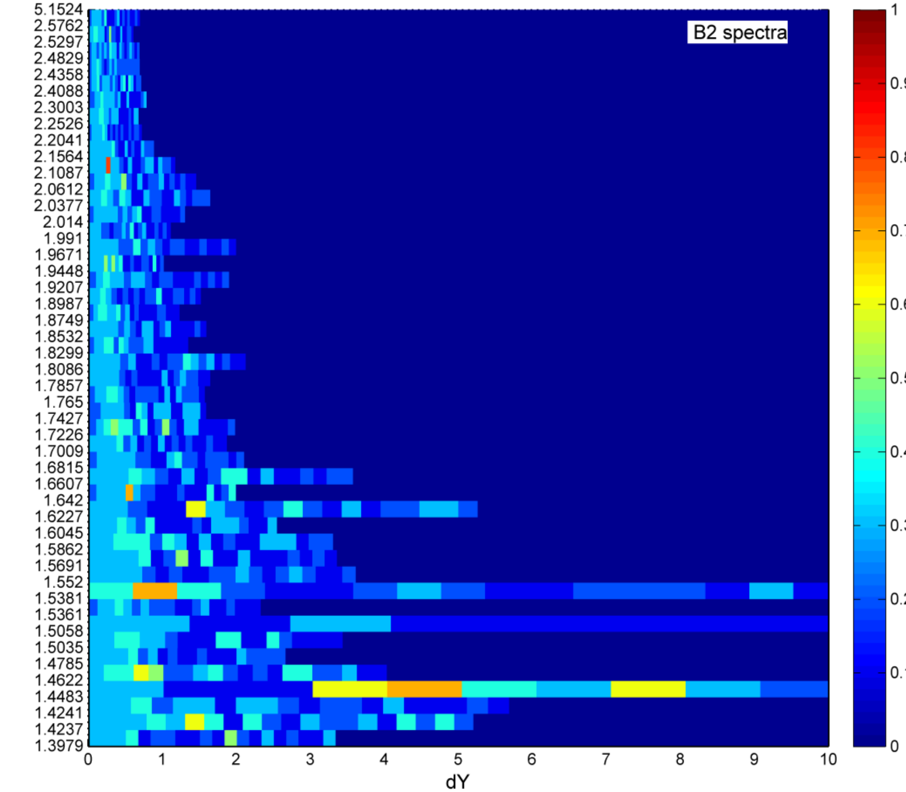
Multifractal analysis



Structure of the STORM multifractal analysis database.

ROMA spectrum: Ulysses solar min, 2007 - 2008

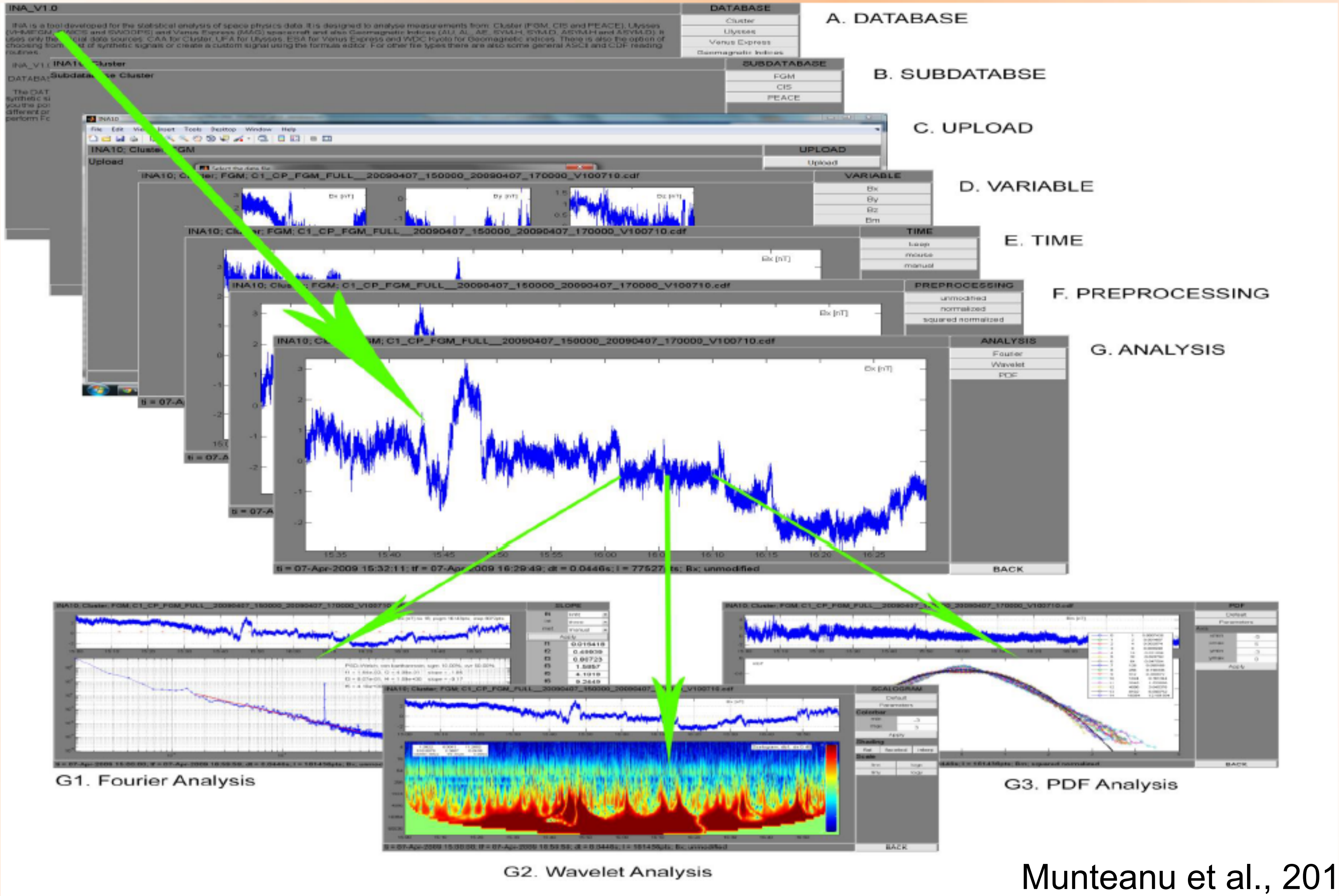




Radial evolution of intermittency based on ROMA spectrum of |B|, 2007 – 2008.

Radial evolution of intermittency based on ROMA spectrum of B^2, 2007 – 2008.

Integrated Nonlinear Analysis library - (INA)



Munteanu et al., 2014

STORM web page: http://www.storm-fp7.eu

SEVENTH FRAMEWORK PROGRAMME

STORM FP7

STORM - Solar system plasma Turbulence: Observations, inteRmittency and Multifractals

Home | STORM Consortium | Science Objectives | Targeted Databases | Research | Data Analysis Tools | Publications

Main Menu

- Home
- STORM Consortium
- Science Objectives
- Targeted Databases
- Research
- Data Analysis Tools
- Publications

Login Form

User Name

Password

Remember Me

Log in

Forgot your password?

Solar system plasma Turbulence: Observations, inteRmittency and Multifractals

In this project we investigate solar system plasma turbulence from in-situ data gathered by automated platforms launched by the European Space Agency (ESA) and NASA. We investigate how the features of turbulence and intermittency vary with the solar activity and estimate the corresponding impact. We use electromagnetic field and plasma data provided by a core of three ESA spacecraft, Ulysses, Venus Express and the Cluster quartet, in coherence with data from other missions like ESA's Giotto and Rosetta, NASA's THEMIS, Cassini and Mars Global Surveyor. Complementary to the satellite databases we study the fluctuations of the geomagnetic field observed on ground. A package of advanced nonlinear analysis methods will be applied on the selected data sets. Power Spectral Densities (PSD) and Probability Distribution Functions (PDF) will be computed first. In a next step we apply five higher-order methods of analysis: (i) the partition function multifractal analysis, (ii) the Rank Ordered Multifractal analysis, (iii) the wave telescope, (iv) the multi-spacecraft methods for anisotropy (v) the discriminating statistics. The targeted physical processes are: the turbulent transfer of energy and dissipation, the intermittency and multifractals, the anisotropy, and non-linearity of the solar system plasma turbulence. The Consortium includes European experts with valuable achievements in space plasma turbulence and complexity, as well as in satellite data analysis. The members of the Consortium are principal or co-investigators of several experiments on-board the selected missions. Two American experts agreed to collaborate and will increase the links with major space actors like the USA. The project responds to the Objectives of the Call by its international, multi-disciplinary dimension, the large number of targeted space missions and databases and the associated analysis methods, and the ambitious scientific objectives that are expected to have a significant impact.

News

STORM Annual Meeting - Graz, November 25-26, 2013

Read more...

STORM Kick-off meeting - Space Pole Uccle, February 20-21, 2013

Read more...

Conclusions, Perspectives

- Solar wind science
  - Selection of relevant data for solar minimum and solar maximum and compilation of the relevant event data bases;
  - Application of the spectral analysis package to reveal the statistical properties of the solar wind turbulence at various distances and latitudes in the solar wind, at solar minimum and maximum
  - Radial profile of the inertial range: on construction
  - Radial dependence of spectral properties: on construction
  - Application of the higher order analysis package:
    - PDFs – done
    - multifractals - ongoing