Deliverable D2.2

Catalog of Probability Density Functions (PDFs) in the solar wind

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1. Introduction

This deliverable is the product of the STORM Work Package 2 “Turbulence, Intermittency and Multifractals in the solar wind, at solar max and solar min” (TIMSW). This work package is devoted to the analysis of intermittent turbulence in the solar wind and a quantitative description of turbulence, of its inertial range and the properties of the energy transfer. As stated in the Description of Work of the Grant Agreement, the data bases to be used are provided by the core mission, Ulysses, Cluster and Venus Express, and, when available, also by Giotto (at earlier dates), Rosetta, Cassini. The project largely satisfies the objectives of this deliverable as **we produced 4317 Probability Density Functions (PDFs) for the three core missions (Ulysses, Cluster, Venus Express)**, an unprecedented, to our knowledge, effort to investigate the intermittency of the solar wind plasma turbulence.

In a previous phase the collaborative work of the STORM consortium provided a selection of relevant solar wind data intervals from Venus Express, Ulysses and Cluster (Virtanen et al., 2014). Other spacecraft data were not considered at this stage of the project since they did not fulfil all the data selection criteria. The data selection procedure was described in the previous report and will not be elaborated again here. We only remind that solar wind time intervals at solar minimum and solar maximum were defined for the Ulysses, Cluster and Venus Express data bases. These time intervals were further divided into two groups corresponding to “pure” fast and “pure” slow solar wind. This refining of data selection is necessary in order to understand if and how the properties of turbulence are different for solar wind emerging from different solar sources.

The procedure for identifying the type of the wind is more elaborated in the case of Ulysses since the SWICS ion spectrometer enables checking of the O^{5+}/O^{6+} ion ratio and this criterion, that describes in fact the solar origin (streamer belt or coronal holes) of the wind, was checked together with other four additional data selection criteria (see the Report on Deliverable D2.1, Virtanne et al., 2014, also on http://www.storm-fp7.eu). The type of the wind, fast or slow, intersected by VEX and Cluster was assigned based on a single criterion defined as a function of the solar wind speed. A description of the magnetic field and plasma measurements by Ulysses, Venus Express and Cluster is given in the previous report of this workpackage (see http://www.storm-fp7.eu). The data is organized in three data collections, for the different phases of the solar cycle 23:

1. D1MAXSW (includes data at solar maximum from Ulysses 1999 – 2001 and Cluster 2000-2001),
2. D3MINSW (includes data at solar minimum from Ulysses, Cluster, Venus Express 2007-2008),
3. D5MINSW (includes data from solar minimum from Ulysses 1997-1998).

The data and the results of the PSD and PDF results, including the PSD and PDF catalogues, are available from the password protected section of the webpage, http://www.storm-fp7.eu.

At this stage of the project we performed a higher order analysis of the selected data sets in order to provide additional information about the spatio-temporal scales relevant for the turbulent fluctuations for which we already computed the spectral properties. We computed the Probability Distribution Functions of magnetic field fluctuations, and in some cases of velocity fluctuations, and evaluated also some of the higher order moments in order to estimate the intermittent features of

solar wind turbulence and their scaling properties. The procedure to compute the PDFs and the structure of the catalogues are described in the following sections.

2. Analysis of PDFs in the Solar Wind

We constructed an incremental measure of turbulent fluctuation based on differences over a range of scales τ (Burlaga, 1991; Marsch and Tu, 1994; Sorriso-Valvo et al., 1999; Bruno et al., 2001, 2003; Voeroes et al., 2002). Thus for a measured parameter Q provided by in-situ satellite measurements (where Q is a magnetic field or plasma velocity component, or magnitude) we define a statistical ensemble of differences by computing the difference:

$$\Delta Q^{(\tau)}(t_i, \tau) = Q(t_i + j\delta) - Q(t_i), \quad \text{for } i=1,N-j\delta \tag{1}$$

in each point of the time series for the scale τ=jδ, where δ is the time resolution of the measurements and N is the total number of samples in the time series. The definition (1) introduces the scale τ as a parameter of the analysis.

The scales selected for this study follow the incremental rule generally used in turbulence studies, i.e. they are distributed over several octaves with j in equation (1) taking values in the range $2^0,2^1,2^2,\ldots,2^P$, thus the window length increases from the 1 point to 2, 4, 8, … 2^P points.

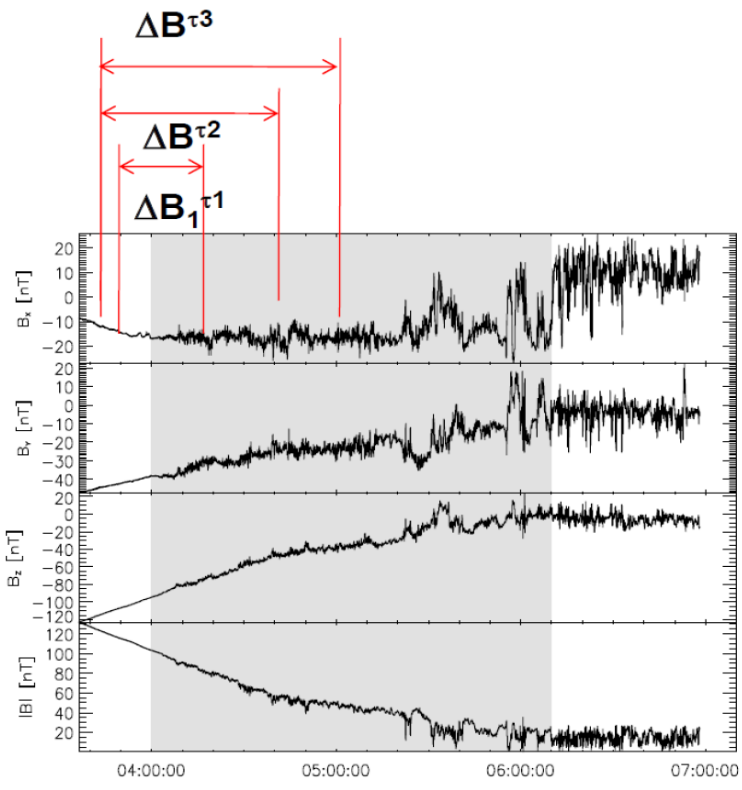


Figure 1. Illustration of the sliding window procedure to construct the incremental measure of fluctuations. In this example three windows of three different lengths (τ1, τ2, τ3) sweeps Cluster magnetic field data and thus provide three ensembles of fluctuations corresponding to the three scales. The normalized histograms of the resulting ensembles of fluctuations provide the probability density functions of the respective variable (figure adapted from Echim et al., 2007).

The sliding window of length τ is moved by one point to compute the difference defined in Eq. (1) across the time series and the results are collected in a statistical ensemble of differences, $(\Delta Q^{(\tau)})$, corresponding to the scale τ. The fact that consequent instances of the sliding window overlap over a number of points raises some questions regarding the statistical independence of the differences. Nevertheless, this is a "compromise" to increase the number of samples and therefore to achieve better statistics. Otherwise, even with high resolution data, it would be virtually impossible to construct statistical ensembles of fluctuations for ranges of large scales in solar system plasmas with one-point measurements.

We compute the histogram of the statistical ensemble of fluctuations, $(\Delta Q^{(\tau)})$ against a number of bins, N_B, and then we normalize the histograms such that the resulting product is a density function. The procedure is repeated for each scale τ. and the Probability Density Function, $P(\Delta Q,\tau)$ is obtained for the range of considered scales.

The deliverable D2.2 is linked to the science questions related to the occurrence of intermittency in the solar wind turbulence and its qualitative and quantitative description – a key issue of the magnetohydrodynamic turbulence of astrophysical flows.

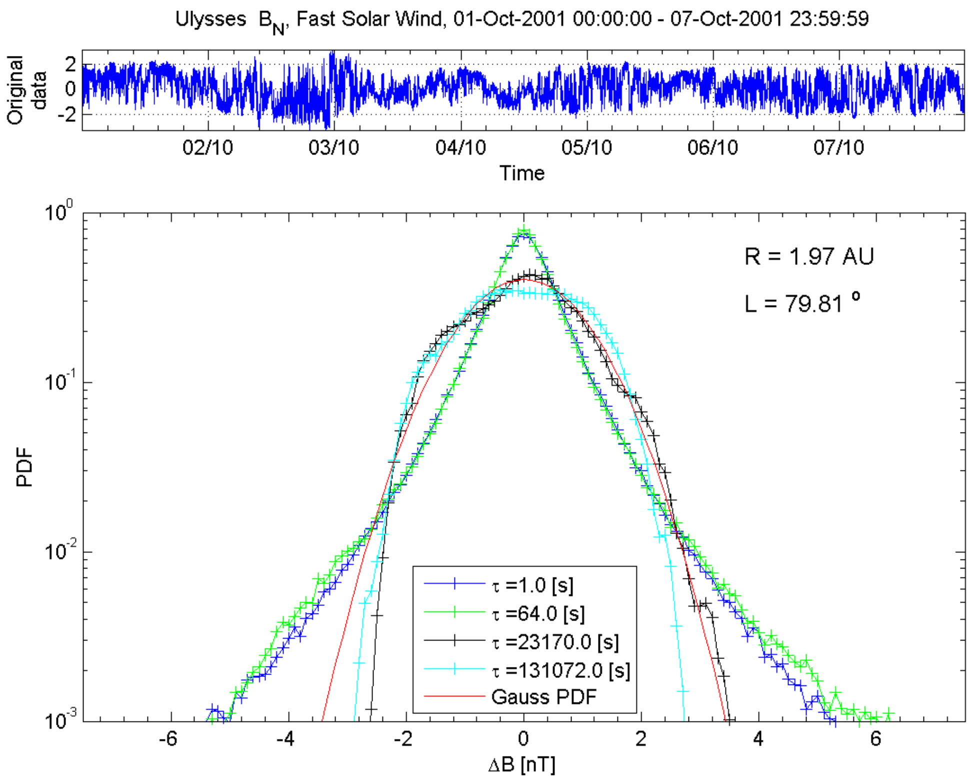


Figure 2. Example of Probability Density Functions computed for 4 different scales for the BN component of the solar wind magnetic field measured by Ulysses. The PDFs corresponding to different scales are color coded. Similar figures are produced in the data base for each analyzed time intervals of Ulysses data.

The PDFs themselves already give information about the presence of intermittency, like the scale dependent non-Gaussianity (observable in the example shown in figure 2), although this is rather qualitative and lefts some ambiguity: the intermittency is perhaps present but how strong is it ?

From the heritage of neutral fluids turbulence studies (Sreenevisan and Antonia, 1997) additional methods to quantify intermittency were adopted for space plasma turbulence (Voeroes et al, 2002; Bruno et al., 2003). The moments of the PDFs and particularly the fourth order one (the kurtosis) provide a more quantitative description of intermittency. The flatness is defined as:

$$F = \frac{\langle \Delta P(t,\tau)^4 \rangle}{(\langle \Delta P(t,\tau)^2 \rangle)^2} \quad (2)$$

The flatness is equal to 3 for fluctuations that follow a normal distribution (Gaussian). Thus the departure of the flatness from this value is a quantitative measure of the "strength" of intermittency for the corresponding scale. For each scale for which the PDFs were computed we also compute their flatness (2). An example of scale dependence of the flatness for Ulysses magnetic field records is illustrated in figure 3.

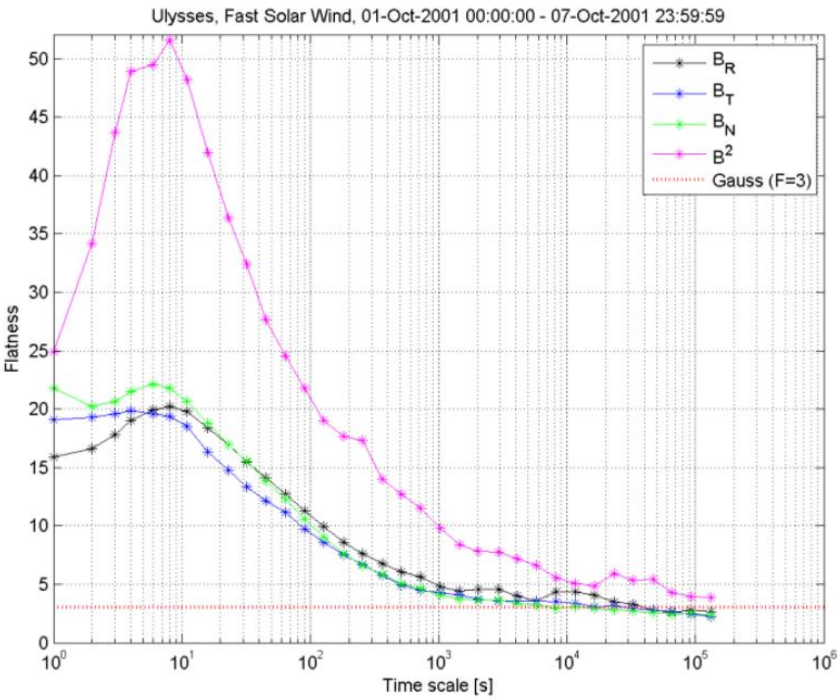


Figure 3. Example of Flatness values computed for magnetic field components (B_R, B_T, B_N), and the square of the total field (B^2) measured by Ulysses on Oct 01-07, 2001. The corresponding PDFs are illustrated in Figure 2. Similar figures are produced in the data base for each analyzed time intervals of Ulysses data.

The main goal of STORM is to perform a thorough survey and analysis of data at solar minimum and maximum. Therefore the procedure outlined above has been applied systematically on all data sets selected during the previous stage of the project. In the following we describe the specific analysis for each of the core missions, Ulysses, Cluster and Venus Express.

3 Ulysses PDFs and Flatness

The Probability Density Functions and the flatness were computed for all the time intervals already analyzed and included in the databases of Power Spectral Densities (Virtanen et al., 2014). In this way the description of turbulent properties of magnetic field fluctuations are enriched with higher order analyses that complement the traditional spectral description. The PDFs and the Flatness were

computed for each component of the magnetic field provided by the Ulysses magnetometer (Balogh et al., 1992) in the RTN system, B_R, B_N, B_T, and also for the square of the magnetic field, a measure of the magnetic field energy, as indicated in Table 1.

Table 1. Interplanetary magnetic field (IMF) parameters selected for calculation of PDF from Ulysses Final Archive database.

Parameters	**Instrument**	**Data resolution**
Radial component of vector magnetic field in nT	VHM-FGM (Vector Helium Magnetometer / Flux Gate Magnetometer)	original res.: 1 s, 2 s
Transverse component of vector magnetic field in nT	VHM-FGM	original res.: 1 s, 2 s
Normal component of vector magnetic field in nT	VHM-FGM	original res.: 1 s, 2 s
Scalar magnitude of magnetic field in nT	VHM-FGM	original res.: 1 s, 2 s

Table 2: Number of samples selected for calculation of PDF from Ulysses database.

	D1MAXSW	**D3MINSW**	**D5MINSW**
Slow solar wind	26	4	15
Fast solar wind	33	45	12

The entire list of Ulysses data intervals for which the PDFs and flatness are computed is given in the Appendix 1 of this report.

Thus we have analyzed 135 time intervals of Ulysses data, of which 45 for “pure” slow solar wind and 90 for “pure” fast solar wind. The distribution between the three databases and implicitely between the three phases of the solar cycle is given in table 2.

We have computed a total number of 540 PDFs for Ulysses, distributed as follows:

1. 156 PDFs and respectively 116 PDFs for fast and respectively slow wind at solar max, 1999-2001,
2. 24 PDFs and respectively 48 PDFs for fast and respectively slow solar wind at minimum, 1997-1998
3. 180 PDFs and respectively 16 PDFs for fast and respectively slow solar wind at minimum, 2007-2008

All the PDFs (and the corresponding flatness values) are stored in the data base and have been also included in six Annexes of this report. The names are self explanatory:

D2.2_PDFs_Flatness_D1MAXSW_ULYSSES_SLOW.pdf,
D2.2_PDFs_Flatness_D1MAXSW_ULYSSES_FAST.pdf,
D2.2_PDFs_Flatness_D3MINSW_ULYSSES_SLOW.pdf,
D2.2_PDFs_Flatness_D3MINSW_ULYSSES_FAST.pdf,
D2.2_PDFs_Flatness_D5MINSW_ULYSSES_FAST.pdf,
D2.2_PDFs_Flatness_D3MINSW_ULYSSES_SLOW.pdf

PDFs

For each set of PDFs computed for Ulysses magnetic field data we include in the data base a picture file in PNG format that evidences the relevant scale behavior of the PDFs, separately for each component, together with information about the position of the spacecraft (radial distance and heliospheric latitude) and an illustration of the analyzed time series. An example is shown in Figure 1. In order to be coherent within STORM the graphical (picture) files were named following the standard convention adopted by the STORM Consortium.

Flatness

For each scale defined to compute the PDFs we also compute the flatness with (2). The results are organized following the same procedure as for the PDFs: one graphical file is produced to illustrate the flatness for all the components of the magnetic field measured by Ulysses and all scales. An ASCII file stores the values for further analysis. The format of the files follows the same rules as for the PDFs

4. Venus Express PDFs and Flatness in the solar wind

We have computed the PDFs and the flatness for 575 time intervals of magnetic field records provided by the MAG magnetometer (Zhang et al., 2006) in the solar wind at 0.72 AU, close to the spacecraft apogee, between 2007 and 2008.Venus Express contributes only to the D3MINSW. A full list of these time intervals is added in the Appendix 3. The distribution as a function of the type of wind evaluated based on the velocity measurements provided by ASPERA plasma analyzer (Barabash et al., 2007) is given in Table 3. Since VEX continuously exit in the solar wind its contribution to the solar wind package is consistent. Nevertheless the magnetic noise on board the spacecraft raises difficult calibration problems. Magnetic field data were available from ESA Planetary Science Archive database, ASPERA data are available from the French AMDA database (Automated Mutli-Dataset Analysis, http://amda.cdpp.eu/) We analyzed magnetic field data at a resolution of 1 Hz; MAG-VEX data is also available at 32 H and we did some preliminary tests not discussed at this stage of the project. A summary of the analyzed data and intervals is given in Tables 3 and 4.

Table 3: Number of samples selected for calculation of PDF from Venus Express database.

	2007	2008
Fast Solar Wind	103	71
Slow Solar Wind	185	116

Table 4. Interplanetary magnetic field (IMF) parameters selected for calculation of PDFs from Venus Express data.

Parameters	**Instrument**	**Data resolution**
B_{X_VSO}	MAG-VEX (Three Axis Flux Gate Magnetometer)	original res.: 1 Hz (partially available at 32 Hz)
B_{Y_VSO}	MAG-VEX (Three Axis Flux Gate Magnetometer)	original res.: 1 Hz (partially available at 32 Hz)
B_{Z_VSO}	MAG-VEX (Three Axis Flux Gate Magnetometer)	original res.: 1 Hz (partially available at 32 Hz)
B, Scalar magnitude of magnetic field in nT	MAG-VEX (Three Axis Flux Gate Magnetometer)	original res.: 1 Hz (partially available at 32 Hz)
B^2, Square root of the magnetic field intensity	MAG-VEX (Three Axis Flux Gate Magnetometer)	original res.: 1 Hz (partially available at 32 Hz)

The PDFs and the flatness are computed with the sliding window procedure described by (1) and (2) applied on each component of the magnetic field, but also on the magnitude and its square. The field is preprocessed by subtracting the average and by dividing by the standard deviation. An example is shown in Figure 6.

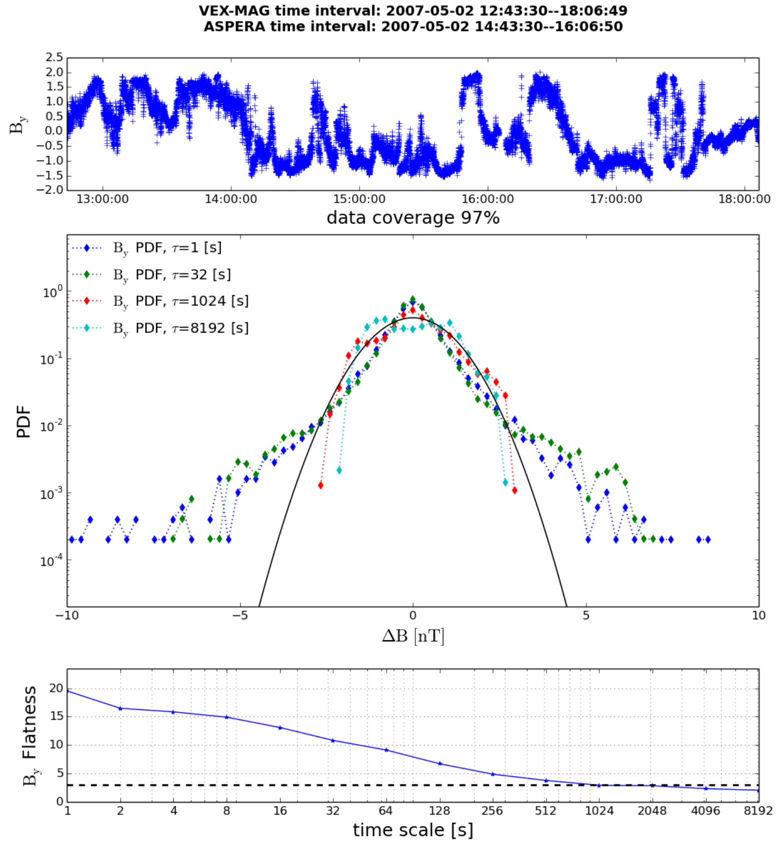


Figure 6. The upper panel shows the analyzed data, the B_{Y_VSO} component of the solar wind magnetic field measured by Venus Express on 2 of February 2007. The signal was standardized by subtracting the average and dividing by the variance. The middle panel shows the Probability Density Functions computed for 4 different scales. The PDFs corresponding to different scales are color coded. Similar figures are produced in the data base for each analyzed time intervals of Venus Express data.

We have computed a total number of 2935 PDFs for Venus Express (this amount cumulates the PDFs for all components): 1500 PDFs for data recorded in 2007 of which 515 and respectively 985 for fast and respectively slow wind, and 1435 PDFs for data recorded in 2008 (of which 355 PDFs for fast wind). For each analyzed variable we produce a graphical file similar to figure 6 that illustrates the PDFs for four relevant scales and the flatness for all the scales considered in the analysis. The PDFs for all scales and the flatness are also stored in a data file saved in ASCII. The file format and file name convention for Venus Express PDFs and Flatness are given below and follows the same principles defined for Ulysses.

The graphical images of the PDFs are attached in two Annexes to this report:

D2.2_PDFs_Flatness_D3MINSW_2007_VEX_FAST.pdf

D2.2_PDFs_Flatness_D3MINSW_2007_VEX_SLOW.pdf

D2.2_PDFs_Flatness_D3MINSW_2008_VEX.pdf

In order to be coherent with the output of the PDF analysis of the other missions we also produced a graphical file where we plot all the values of flatness for all the analyzed signals ((B_{X_VSO}, B_{Y_VSO}, B_{Z_VSO} $|B_{\_VSO}|$ and $|B_{\_VSO}|^2$). An example is shown in Figure 7.

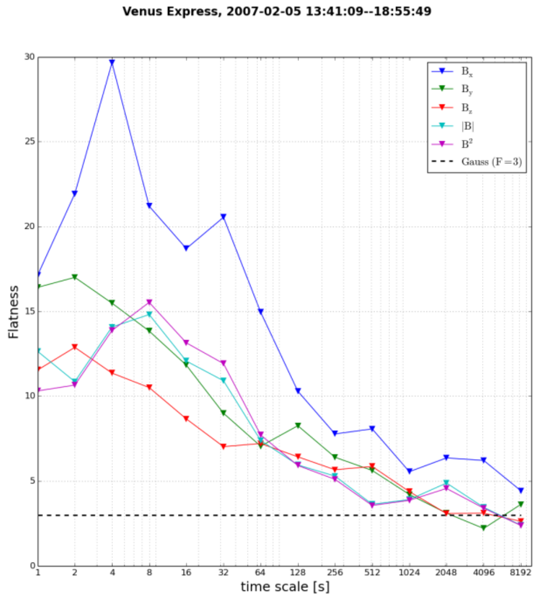


Figure 7. Example of Flatness values computed for magnetic field components (B_R, B_T, B_N), the total field and the square of the total field (B^2) measured by Venus Express on 05/02/2007. The corresponding PDFs are illustrated in Figure 6. Similar figures are produced in the data base for each analyzed time intervals of Venus Express data.

5. Cluster PDFs and Flatness in the solar wind

Due to the seasonal changes of the orbit compared to the Sun-Earth axis, Cluster spend longer time intervals n the solar wind only during several months per year (in spring). Nevertheless, due to the highly eccentric orbit the spacecraft have the potential to probe the solar wind in regions where the planetary ion effect is minimum. A search of such intervals has been done during a previous phase of the project and a number of orbits have been selected (Virtanen et al., 2014). The full list of selected time intervals is given in Appendix 2.

We have computed the PDFs and the flatness for a total of 176 time intervals, of which 101 time intervals of magnetic field data (Balogh et al., 1997) from Cluster 1, and 75 time intervals of magnetic field data from Cluster 3, in 2001 and respectively 2007-2008. Due to the high resolution and availability of plasma moments provided by the Cluster ion spectrometer CIS (Rème et al., 1997) we have been able to compute some preliminary PDFs of the plasma bulk velocity, although the limited number of samples reveals only the central part of these PDFs. Cluster is the only mission that enables this type of analysis. We used the maximum available resolution of FGM and CIS. A summary of the analyzed Cluster data and the distribution among fast and slow wind is given in tables 5 and 6.

Table 5: Number of samples selected for calculation of PDF Cluster database.

		D1MAXSW	D3MINSW
Magnetic field	**Slow solar wind**	41 (211 + 202)	20 (13 + 7)
	Fast solar wind	1 (1 + 0)	103 (59 + 45)
Plasma Bulk Velocity	**Slow solar wind**	41 (21 + 20)	20 (13 + 7)
	Fast solar wind	1 (1 + 0)	103 (59 + 45)

Table 6. Interplanetary magnetic field (IMF) and plasma parameters selected to compute PDFs from Cluster data.

Parameters	**Instrument**	**Data resolution**
B_{X_GSE}	Cluster FGM (Three Axis Flux Gate Magnetometer)	original res.:5 and/or 22 Hz
B_{Y_GSE}	Cluster FGM (Three Axis Flux Gate Magnetometer)	original res.: 5 and/or 22 Hz
B_{Z_GSE}	Cluster FGM (Three Axis Flux Gate Magnetometer)	original res.: 5 and/or 22 Hz

1 From Cluster 1

2 From Cluster 2

B^2, Square root of the magnetic field intensity	Cluster FGM (Three Axis Flux Gate Magnetometer)	original res.: 5 and/or 22 Hz
V, the plasma bulk speed	Cluster Ion Spectrometer	0.25 Hz

The PDFs and the flatness for Cluster data are computed with the sliding window procedure described by (1) and (2) applied on each component of the magnetic field, but also on the square of the magnetic field intensity and the plasma bulk speed. The time series are preprocessed by subtracting the average and by dividing to the standard deviation. An example is shown in Figure 8.

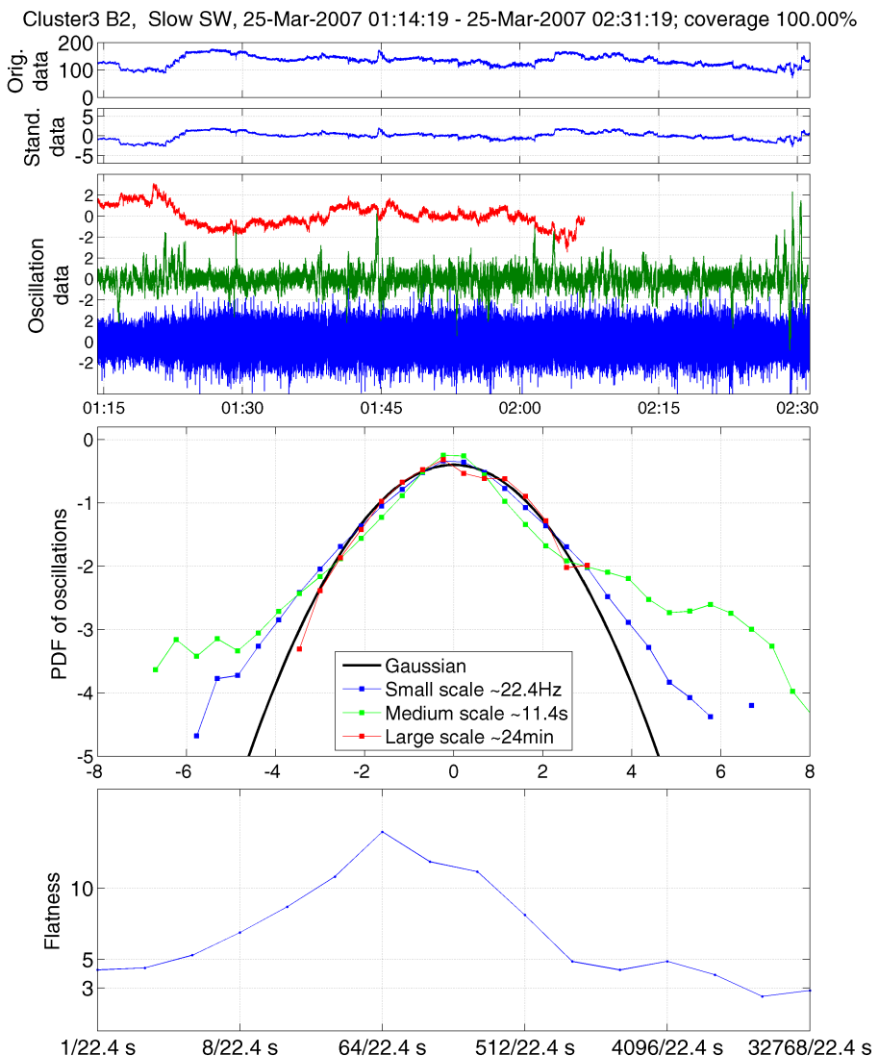
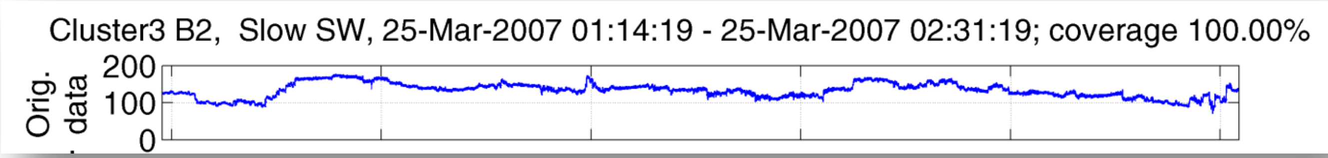


Figure 6. The upper panel shows the analyzed data, the B_{X_GSE} component of the solar wind magnetic field measured by Cluster on 15 of March 2001. The signal was standardized by subtracting the average and dividing by the variance; both the original and the standardized signals are shown. The middle panel shows the Probability Density Functions computed for 4 different scales (and the reference Gaussian profile in black). The PDFs corresponding to different scales are color coded. The lower panel shows the flatness computed with (2). Similar figures are produced in the data base for each analyzed time intervals of Cluster data.

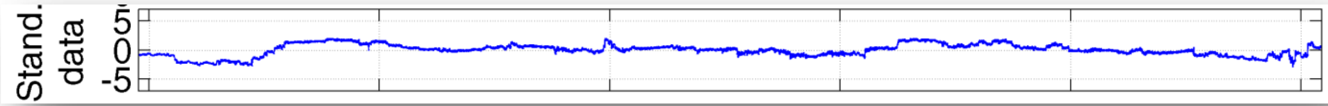
The final .png-pictures are structured as in figure 6. The structure of the pictures file is explained below.

Original data



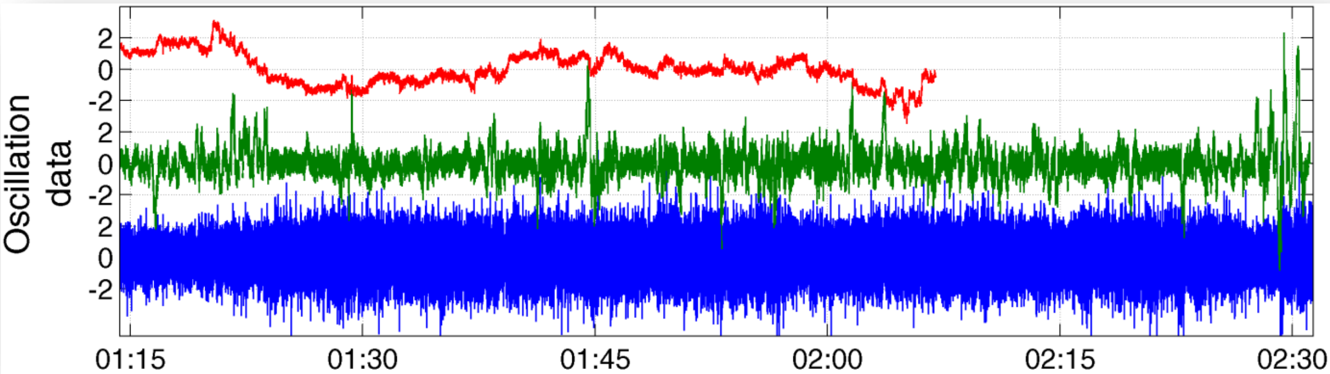
The first plot contains the original raw time series of the interval. Above the original data is also some additional info: The satellite, the solar wind type, the time interval and the data coverage. To produce a picture, a coverage of >80% is required from the script.

1. Detrended and standardized data



By detrending, removing the mean and dividing by variance we get the standardized data from the original data. Data gaps are treated individually: each difference (1) that implies a missing data point is disregarded

Oscillation data

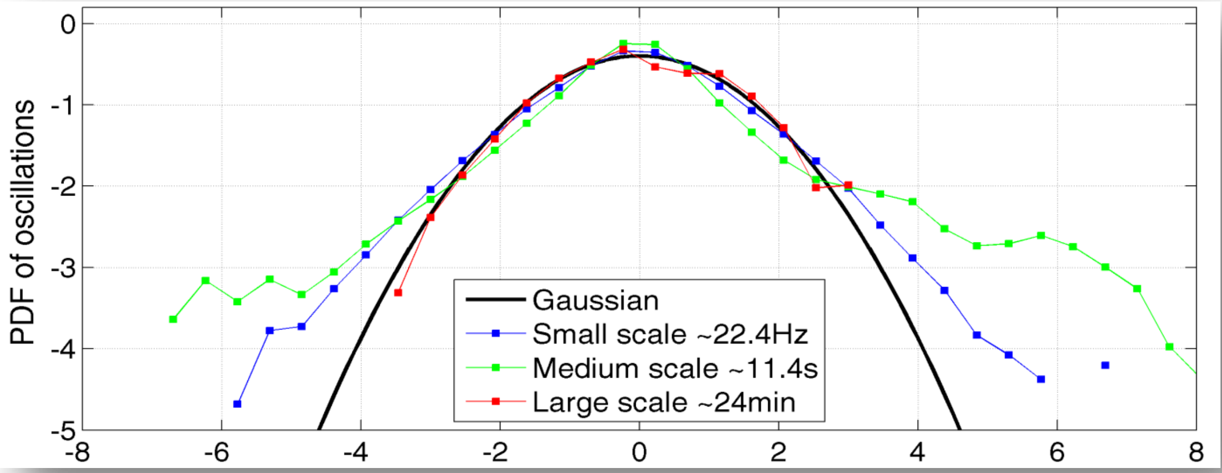


From the standardized data we calculate the oscillation data for three different scales. For each scale we calculate the difference of two points separated by the scale length. The third plots contains all these oscillation fields for the three scales (red = largest, green = medium and blue = smallest). This plot also contains the time vectors as the x-axis that also corresponds to the first two plots. For the oscillations, each time vector corresponds to the start point of the difference calculation.

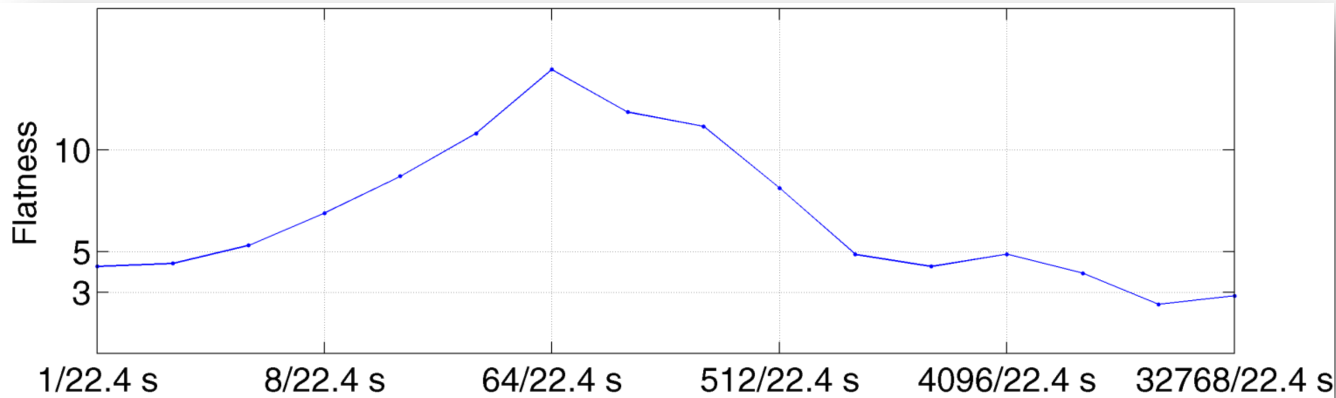
Data type (Instrument)	Smallest scale (blue) = resolution	Medium scale (green)	Largest scale (red)
Magnetic field (FGM)	2^0 = 1 (22.4Hz)	2^8 = 256 (~11s)	2^15 = 32768 (~24min)
Velocity (CIS)	2^0 = 1 (4s)	2^4 = 16 (~1min)	2^8 = 256 (~17min)

Probability density function

The probability density function of the oscillations is calculated by taking a histogram of the oscillation data values. These are plotted in a logarithmic scale. For reference, a Gaussian histogram is plotted too. The binning is fixed from -9 to 9 with 40 bins.



Flatness



The fifth picture contains the flatness (=kurtosis) calculated for all scales. These also included scales that are not shown in the other plots. Flatness is the fourth moment of the distribution for the oscillating field, and is defined by (2).

We produced a total number of 842 PDFs for Cluster, of which 206 PDFs are included in the database D1MAXSW at solar maximum (2001) and 636 PDFs are included in the D3MINSW database at solar minimum (2007-2008), 104 PDFs for fast wind and 532 for slow solar wind. At this stage of the analysis the stationarity of the data is just preliminary investigated. For each PDF computed with Cluster data we create four files:

1. The graphical file in compressed format (PNG)

2. The script file in native Matlab language to produce the graphical file(.fig)

3. The PDF data file that includes the PDFs for all the scales considered in the analysis

4. The Flatness data file that includes the values of F from (2) for all considered scales.

The graphical files are stored individually in the databases but are also included in the Annexes of this report:

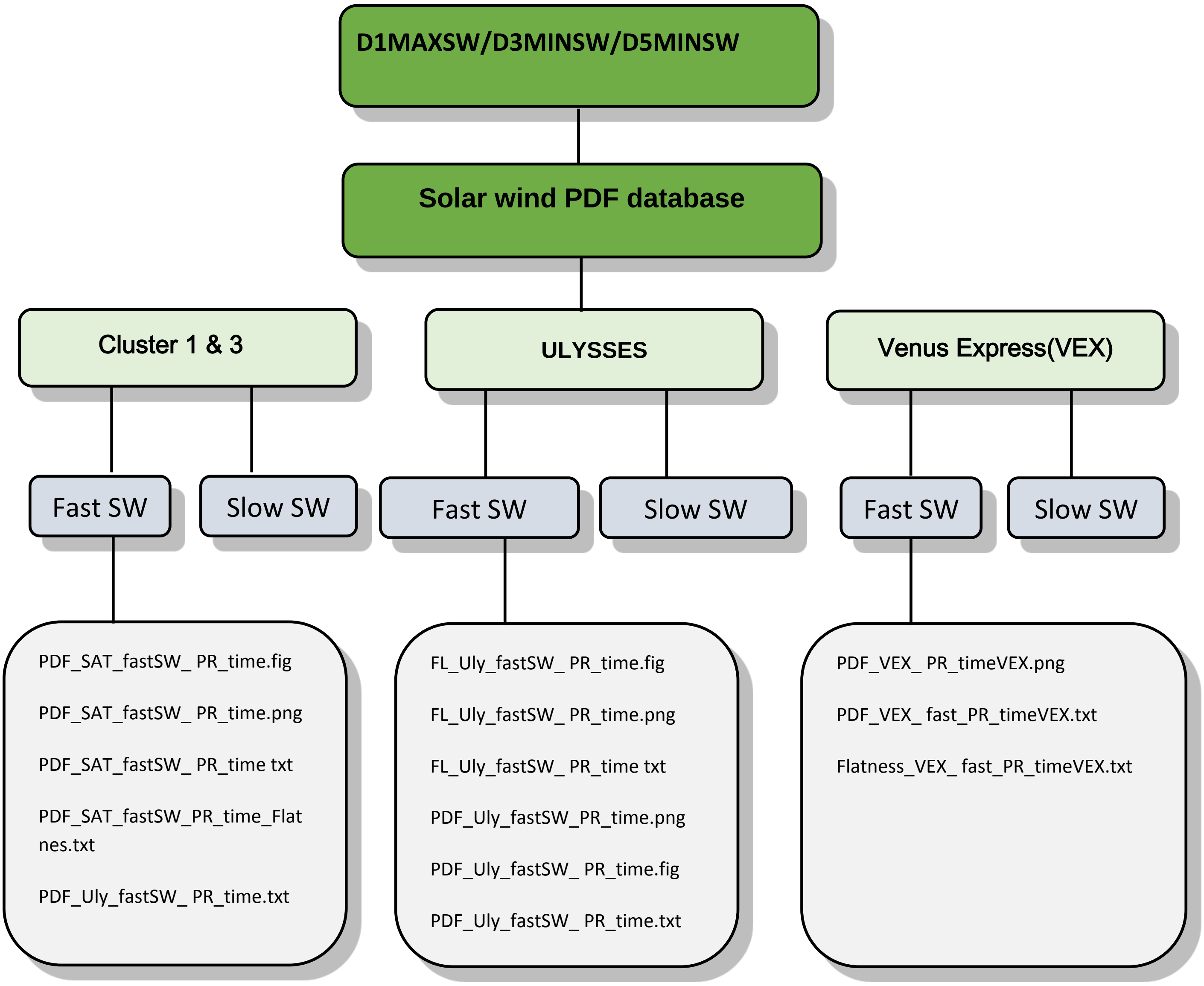
D2.2_PDFs_D3MINSW_CLUSTER_FAST.pdf

D2.2_PDFs_D3MINSW_CLUSTER_SLOW.pdf

D2.2_PDFs_D1MAXSW_CLUSTER.pdf

The file format and file name convention for Cluster PDFs and Flatness are given below and follows the same principles defined for Ulysses.

Block Diagram of the deliverable Database.



where

SAT: C1 or C3

PR: B_{X_GSE}, B_{Y_GSE}, B_{Z_GSE}, B^2 (Cluster), BR, BT, BN, B^2, (Ulysses), B_{X_VSO}, B_{Y_VSO}, B_{Z_VSO},B, B^2 (VEX)

time: yy_mm_dd_hh-yy_mm_dd_hh

timeVEX: YYYY-MM-DD_HHMMSS-HHMMSS

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