PSP Data Analysis Guide

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Contents

This report guides through the use of a basic analysis tool for the data provided by Parker Solar Probe (PSP). A shorthand guide for the instruments and data is also included, in the form of a summary of the official instrument user guides. In-depth information about the instruments and the data can be found from official instrument papers and user guides, which are linked in the end of the report.

1 Analysis program `psp_plot.py`

`psp_plot.py` uses PySPEDAS, a python conversion of the popular SPEDAS framework available for the IDL programming language. PySPEDAS looks up and downloads data from CDAWeb on the basis of parameters such as time and instrument. The program can be configured to plot data from any of the *in-situ* instruments onboard PSP: Solar Wind Electrons Alphas & Protons (SWEAP); Electromagnetic Fields Investigation (FIELDS) and Integrated Science Investigation of the Sun (IS⊙IS). Please refer to part 2 for information about these instruments and their data. Not all data products provided by these instruments are available for plotting in the program, but the most used ones are.

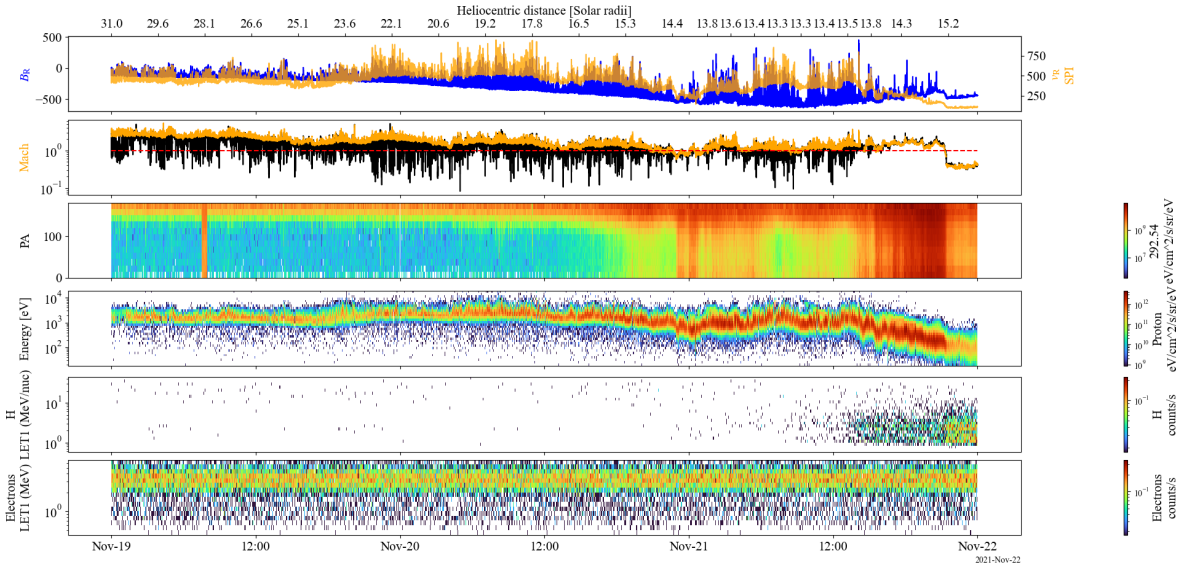

Figure 1: Running the program with pre-set options for the time period 2021-11-19 – 2021-11-22 and PAD electron energy 300 should yield this set of graphs.

1.1 Required non-standard packages

The table below lists all the non-standard packages and versions (at the time of development) used in the plotting program.

Python 3.11.4

Package	Classes	Version
`PySpedas`		`1.5.16`
`hyperlink`		`21.0.0`
`NumPy`		`1.26.4`
`SciPy`	`.interpolate`	`1.14.0`
`matplotlib`	`.colors, .pyplot`	`3.9.1`

1.2 Usage

The user is expected to check the data-availability at CDAWeb inventory before using the program; all data products have more or less gaps in them and these might generate errors in the code. The program is run with the command `python3 psp_plot.py` in the terminal while in the directory in which the program file is saved. The program then asks the user for a "start" and "end" date input. These should be entered separately and formatted as YYYY-MM-DD. If the user wishes to plot electron pitch angle distributions, then the program requests an (approximate) electron energy far which the distribution is plotted to. Dictionary `KeyError` -glitches may sometimes occur when running the program; rerunning will most likely fix them.

In order to change the plottable variables, the user must toggle between True/False values in the beginning of the source code of the program. At least one plottable variable must be toggled "True" in order for the program to run. In the source code, the first set of options (spanning rows 20-35) control the data products provided by the FIELDS and SWEAP instrument suites. The last four options are quality flags, whose values indicate the liability of the data at given times. Each instrument has its own set of values for the flags; these are explained in latter parts of this report and official data user guides.

The heliocentric distance -variable is always plotted at the top of the uppermost plot, whatever variable it happens to be. It is important to note that the heliocentric distance is only calibrated to the uppermost plot, which means that panning and zooming on any other subplot won't scale the distance ticks accordingly.

The density variable will, by default, try to plot both the proton density (measured by either SWEAP SPAN-I or SPC instruments; more about these in part 2.2) and electron density (which is determined by FIELDS' QTN or SQTN measurements; see part 2.1). As electron density data is only available for encounter periods it might not be available at desired time period, in which case it will only plot the proton density. The program will likewise try and find electron density data for calculating the Alfvén speed and Alfvén mach number, if they are opted.

The following options (between rows 44 and 67) deals with plotting variables from the IS⊙IS instrument suite. The first options toggle the different instruments (for details see part 2.3) and respective quality flags, and the latter options toggle different atomic elements which the suite is able to differentiate from the solar wind. Some quality flags, especially for EPI-Lo, forces the PySPEDAS routine to load support data, which makes running the program somewhat slower. EPI-Lo data files are generally way larger than other instruments' files, making them much slower to download in comparison. The data products provided by IS⊙IS are quite convoluted when compared to other instruments onboard PSP: The data is not as processed and leaves more responsibility to the user when interpreting and using the data. IS⊙IS data products also include lots of supplementary data. When using IS⊙IS products the program will often notify of missing variables. These variables are however not used in this program, and the notifications can therefore be ignored unless they generate errors.

IS⊙IS heavy ion (heavier than He) data are currently (as of 8.2024) only available in counts or as counts per second; Ion flux variables have been defined for only H, electron and He variables, but these are not used in the program. Future data releases might include heavy ion flux variables. The program thus only deals with count rate spectograms of different elements, ranging from protons and electrons to nickel. Heavy elements Na, S, Ar, Ca, Cr and Ni are only available for EPI-Hi, while electrons, protons, He, C, N, O, Ne, Mg, Al, Si and Fe are available to both EPI-Hi and EPI-Lo.

For high energy energetic particles, i.e. when using data from EPI-Hi, the count rates are sums of the A and B directions (see subsection 2.3.2). C direction is unused in this version of the program. As for low energy energetic particles, when using EPI-Lo data, the count rates are averaged over the 80 "look directions", which span approximately half of the sky on the ram-side (see subsection 2.3.1). EPI-Lo electron data is averaged over the 8 wedges.

Rows 70 to 72 span three additional options. The first option toggles whether the RTN -components of the magnetic field B are normalized to au values. When `True`, the magnetic field is expressed as

$$B_{\text{norm}} = \text{flux density}\,[\text{nT}] \cdot (\text{heliocentric distance}\,[\text{au}])^2 .$$

If `False`: B = flux density [nT]. The second option toggles between one minute encounter data and one hour cruise data for the EPI-Hi instruments. While `True`, one minute data is downloaded and plotted. Encounter data is however only available for encounter periods, which means that the program will run into an error if the selected time period is not within the encounter period. One hour cruise data is generally available for almost the whole revolution. The third option toggles between SWEAP's SPAN-I and SPC instruments for proton velocity and density data. While `True`, SPAN-I is used. Whether to use SPAN-I or SPC is up to the user; see part 2.2 for information. Data for heliocentric distance and proton energy distribution is picked from SPAN-I in both cases, since SPC doesn't include those products.

Finally at rows 75 to 78 the user can alter the cosmetics of the plot. `hspace` controls the vertical space between eventual subplots. However because of technical limitations, this parameter can not be used to join the subplots altogheter.

2 PSP in-situ instruments

PSP carries four instrument suites: Solar Wind Electrons Alphas & Protons (SWEAP); Electromagnetic Fields Investigation (FIELDS), Integrated Science Investigation of the Sun (IS⊙IS) and Wide-field Imager for the Solar Probe (WISPR). A summary of the data user guides of SWEAP, FIELDS and IS⊙IS are presented below, along with brief descriptions of the instruments themselves. WISPR is an optical telescope and it is not regarded in this guide.

PSP is sometimes referred to as the Solar Probe Plus (SPP) in some of the instrument papers, as it is its previous designation before being renamned Parker Solar Probe.

2.1 FIELDS

The FIELDS-instrument measures fluctuations in the magnetic and electric fields, plasma wave spectra and radio emissions, among other things. The FIELDS suite is mostly used for magnetic flux density and electron density measurements in `psp_plot.py`.

The electron density is used as a supplement to the proton density measured by SPC or SPAN-I. These instruments might, depending on the circumstances described in part 2.2, only measure the partial distribution of the proton population of the solar wind and coronal plasma. This would result in a lower measured density, and consequently lead to uncertainties in the calculated Alfvén speeds.

The electron density is determined by quasi-thermal noise (QTN) spectroscopy measured by the Radio Frequency Spectrometer (RFS) and Low Frequency Spectrometer (LFR) instruments. QTN spectroscopy is not compromised by the variations of the direction of incident plasma flow, making it a good reference to the SPC/SPAN-I proton density when assuming low helium abundance and charge neutrality in the plasma. More information about QTN measurements can be found in the FIELDS QTN paper.

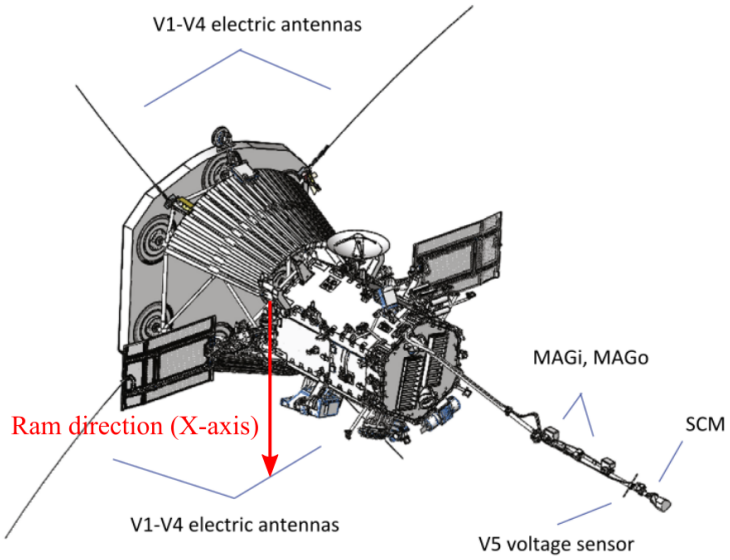

Figure 2: FIELDS suite across PSP, as presented in the FIELDS Instrument Paper. Ram direction is indicated with the red arrow.

2.1.1 FIELDS Quality Flags

The part below is borrowed from the FIELDS data guide -site.

FIELDS quality flags. This is a bitwise variable, meaning that multiple flags can be set for a single time, by adding flag values. Current flagged values are:

1: FIELDS antenna bias sweep,
2: PSP thruster firing,
4: SCM Calibration,
8: PSP rotations for MAG calibration (MAG rolls),
16: FIELDS MAG calibration sequence,
32: SWEAP SPC in electron mode,
64: PSP Solar limb sensor (SLS) test.
128: PSP spacecraft is off umbra pointing (heat shield not pointed sunward).

A value of zero corresponds to no set flags. Not all flags are relevant to all FIELDS data products, refer to notes in the CDF metadata and on the FIELDS SOC website for information on how the various flags impact FIELDS data. Additional flagged items may be added in the future.

2.2 SWEAP

The SWEAP suite measures the bulk of electrons, protons and alpha particles in the solar wind and coronal plasma. The suite consists of a faraday cup, SPC (Solar Probe Cup), and three electrostatic analysers, SPAN-A , SPAN-B and SPAN-E (Solar Probe Analyzers). SPAN-A and SPAN-B are collectively referred to as SPAN-I. SPAN-A and SPAN-E are located on the ram side of PSP while SPAN-B is on the anti-ram side. SPC is faced sunward, on the anti-ram side of the thermal protection system (TPS) heat shield. Together the fields of view of the four instruments combine to cover almost the whole sky.

The user of SWEAP ion data should be aware of the circumstances from which the data is measured from. As SPC is pointed sunward, and with a 30°half-angle FOV, the whole distribution of the incident solar wind and /or coronal plasma might not be in the field of view of the instrument during some parts of the encounter phases; during encounters the spacecraft's speed can reach up to 200km/s, which is close to that of the speed of coronal plasma flows. SPC data from encounters are often unavailable for this reason, except the first couple of encounters in 2018 and 2019, and the user is instead adviced to use ion plasma data from SPAN-I. SPAN-I, while located on the ram side of the spacecraft, can measure a larger portion of the particle distribution during encounters, especially during latter ones.

The SPC data are either derived as either "moments" or "fits". Moments are derived by direct integration of the measured distribution spectra, while fits are derived by fitting Maxwellian disributions to the measured spectra. SPC data used in this program are derived as moments.

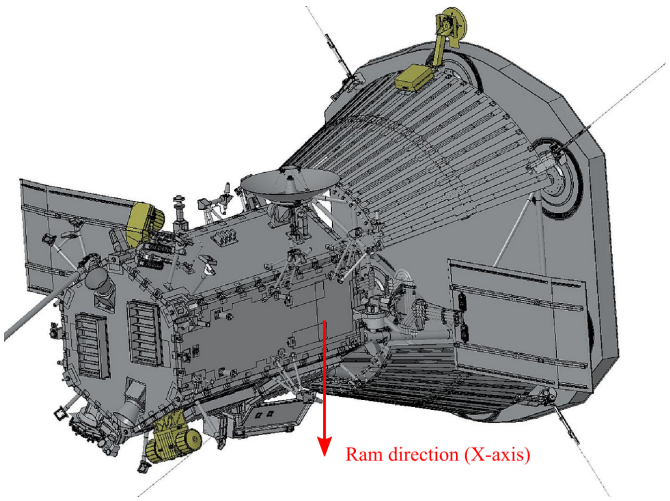

Figure 3: SWEAP instrument suite across PSP (parts in gold), as presented in the SWEAP Instrument Paper. Red arrow indicates the ram direction. The IS⊙IS suite can also be seen on the bottom left of the spacecraft bus.

2.2.1 SWEAP Quality Flags

Following parts are borrowed from the SWEAP Data User Guide.

SPC: "... Efforts have been made to distill all exceptional conditions that can affect normal data analysis into the "GENERAL_FLAG" variable, which can be found in all of the l3i files. In all data quality flags, a value of 0 signifies "good/no condition present"."

SPAN-I: "... Efforts have been made to distill all exceptional conditions that can affect normal data analysis into the "QUALITY_FLAG" variable, which can be found in all of the L2 files. In all data quality flags, a value of 0 signifies that thedata product contains contamination from instrument operations, whereas a value of 1 signifies a good data product."

SPAN-E: "... Of particular note in all data files is the "QUALITY_FLAG" variable, which indicates good or bad data for scientific analysis. A value of "0" indicates the data is "good", whereas a "1" flag indicates data points that are not recommended for scientific analysis, either due to instrument anomaly or calibration checks."

2.3 IS⊙IS

IS⊙IS is an instrument suite for measuring energetic particles (EPs) in the solar wind, above SWEAP's energy range. The suite is also capable of differentiating 18 atomary species in the solar wind. The instrument spans energy ranges of approximately 25keV to 6MeV for electrons, 20KeV to 100MeV for protons and 20keV/nuc to 100MeV/nuc for ions across two instruments: EPI-Lo (Energetic Particle Instrument – Low Energy), for lower energy EPs, and EPI-Hi (Energetic Particle Instrument – High Energy) for higher energy EPs. These are summarized in the following sections.

A living catalog of energetic particle events and enhancements has been made to aid the analysis of energetic particles.

2.3.1 EPI-Lo

The EPI-Lo instrument of the IS⊙IS suite is a time-of-flight (TOF) based mass spectrometer. It measures EPs on the suites lower energy range: Electrons in the range 25-1000 keV, protons 0,04-7 MeV and ions 0,02-2 MeV/nuc. It consists of eight sensor wedges, each with 10 apertures. Together these create the 80 "look directions" of the instrument. The instrument measures roughly half of the sky on the ram side of PSP. More information about the instrument can be found in the IS⊙IS Instrument Paper as well as the IS⊙IS Energetic Particle Data User Guide.

EPI-LO data has different cadences and these vary with instrument channel type and orbit phase. The data used in `psp_plot.py` are of channels C, D and P, all of which combine the TOF and SSD

measurements in order to produce the best certainty and quality of data. TOF-only data is also available, but unused in the program. Channel P has the highest cadence and is exclusively used for protons, while the rest of the ions use either channel C (moderate cadence) or D (slowest cadence of the three). Electron data uses channel E. More details about channel types can be found in the IS⊙IS Data User Guide.

The program averages the ion data over all the 80 look directions. Electron data is averaged over the 8 wedges. The amount of energy bins for the rate spectrograms vary with element type; all bins are often not used and these are neglected in the code. The user must therefore be careful when comparing two spectrograms of different element species.

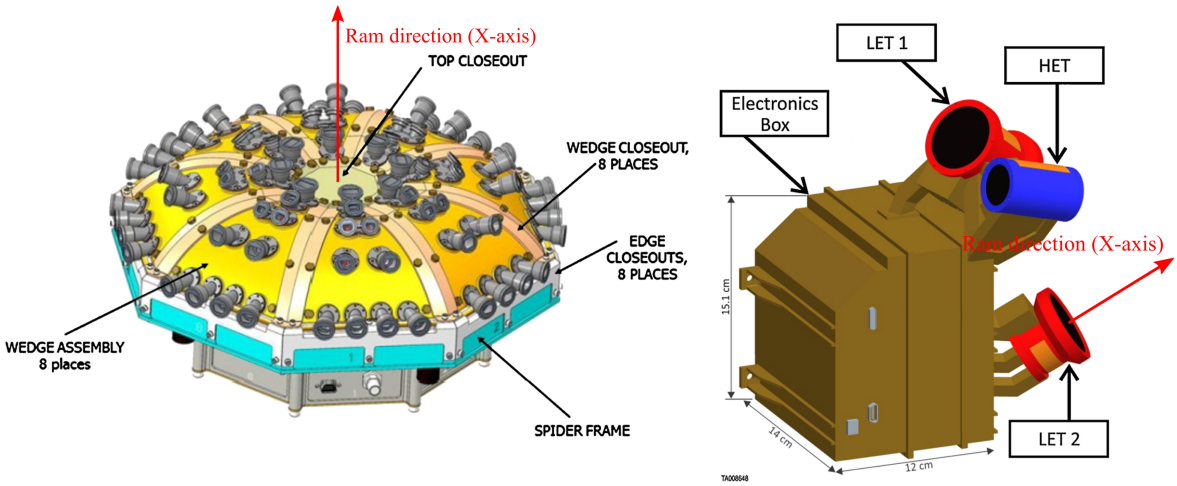

Figure 4: The IS⊙IS instrument suite as presented in IS⊙IS Instrument Paper. Left: EPI-Lo, right EPI-Hi. PSP ram directions have been added as red arrows.

2.3.2 EPI-HI

The IS⊙IS suite is fitted with three high energy telescopes: LET1 (Low Energy Telescope 1), LET2 (Low Energy Telescope 2) and HET (High Energy Telescope). LET1 and LET2 are further divided into three sides: LET1 A, LET1 B and LET2 C. These are often abbreviated LETA, LETB and LETC. HET is similarly divided into HETA and HETB. Letters A, B and C denote different directions on PSP along which these instruments point. A is pointed 45° from the spacecraft Z axis (long axis, approximately along the Sun-PSP line) towards the ram direction (trajectory). This is approximately the Parker Spiral angle at Earth's distance from the Sun. B is the opposite direction of A, and C is pointed in the X direction (ram direction).

2.3.3 IS⊙IS Quality Flags

The part below is borrowed from the IS⊙IS Data Glossary found on the instrument mission page (accessed 30.7.2024):

If the severity is high enough some parts of the data may be omitted as noted below:

Low (1 − 31) there are informational warnings and caveats that are unlikely to affect the scientific validity of the data
Medium (32 − 63) users should take caution when deriving results and contact the instrument team for details, as the data may not be scientifically useful in some cases.
High (64 − 95) affected data are not scientifically useful and are removed from public release
Severe (96 − 127) data are completely invalid, affected fluxes are not calculated

2.4 Links to Home Pages and Articles (accessed Aug 8. 2024)

PSP Mission Paper

CDAWeb
CDAWeb Direct HTTP(S) to Data
CDAWeb Inventory Plots

FIELDS
FIELDS Home Page
FIELDS Instrument Paper
FIELDS QTN paper

SWEAP
SWEAP Home Page
SWEAP Instrument Paper
SPC Instrument Paper
SPAN-I Instrument Paper
SPAN-E Instrument Paper
SWEAP Data User Guide
SPC Data Release Notes
SPAN-I Data Release Notes
SPAN-E Data Release Notes

IS⊙IS
IS⊙IS Home Page
IS⊙IS Science Operations Center
IS⊙IS Instrument Paper
IS⊙IS Energetic Particle Data User Guide
Living Catalog of IS⊙IS Energetic Patrticle Enhancements