PART 1

SPDF DOCUMENTATION FOR ULYSSES-SWOOPS DATA

1. SUMMARY

This document gives a brief description of the SWOOPS instrument (section 2-4.B) and describes Ulysses SWOOPS data provided to the SPDF (sections 5.A-5.B).
Data differ from those previously provided to the ESA archive in that the new set of data is obtained by fitting contours of the distribution function, whereas the old set of data relies on simple numerical integration of velocity-weighted ion distributions over an E/q range (more informations can be found at http://ufa.esac.esa.int/ufa/#data). Data provided to the SPDF are therefore more complete (see section 5.A for a detailed description of the data provided). The contour fitting procedure gives more accurate velocity and temperature and provides also temperature anisotropy. On the other hand, contour fitting of the distribution function depends on the convergence of the data reduction algorithm (see section 5.B) and therefore may display periods with lower resolution data than those on the ESA archive.

2. OVERVIEW OF THE SWOOPS EXPERIMENT

The SWOOPS (Solar Wind Observations Over the Poles of the Sun) experiment has two electrostatic analyzers, one for positive ions and one for electrons. The instrument is fully described in: The Ulysses Solar Wind Plasma Experiment, S. J. Bame, D. J. McComas, B. L. Barraclough, J. L. Phillips, K. J. Sofaly, J. C. Chavez, B. E. Goldstein, and R. K. Sakurai, *Astronomy and Astrophysics Supplement Series*, Ulysses Instruments Special Issue, Vol. 92, No. 2, p.237-265, 1992. The electron and ion analyzers are separate instruments that operate asynchronously. This document describes the positive ion analyzer and the data submitted to the SPDF for that analyzer.

3. INTRODUCTION TO THE SWOOPS ION EXPERIMENT

The SWOOPS ion analyzer measures 3-d velocity-space distributions of positively-charged ions. In its normal solar wind mode, the instrumental energy range is 0.25 to 12 keV/q; active energy tracking allows for fine energy spacing within a smaller range which is ample for characterization of the thermal proton and helium distributions in most cases. The analyzer does not make an explicit ion species determination; separation of protons from doubly-charged helium is enabled by the fact that the two species have similar speeds.

4.A INSTRUMENT OPERATION-SUMMARY

Each spectrum takes 2 minutes to accumulate, but telemetry takes longer. A spectrum is telemetered to the ground in 4 minutes at the highest bit rate; at lower spacecraft bit rates the time is greater. Depending on the mission phase, the data may all be high time resolution, may be partially high time resolution (some 4 minute sampled data, and some 8 minutes sampled data), or may be sampled at rates even slower during certain occasions. Depending on the bit rate, every 9th (highest bit rate) or 5th spectrum (all slower bit rates) is obtained with half the energy resolution of the other spectra.

4.B INSTRUMENT OPERATION-DETAILED DESCRIPTION

The positive ion analyzer is provided with a 200-level high voltage supply to cover a range of ion energies from 255 eV/q to 34.4 keV/q. Level spacings are 2.5%, and are used in a variety of ways.

The normal SWOOPS mode of operation consists of three types of modes, two that deal with protons and alpha particles, and one (not described here) that deals with heavy ions. The two types of measurement modes used for measuring protons and alpha particles are the Search (S) mode and Track (T) mode. The instrument first does a coarse energy scan (S mode) consisting of 40 steps (every 4th step in the lowest 160 of the instrument's 200 available levels). Having located the solar wind flux peak, the instrument then does several T scans in the region around the peak using every other energy step. To obtain increased energy resolution during periods when the solar wind is not changing speed, the instrument was designed so that T scans alternate using the even- and odd-numbered steps of the voltage supply. The data provided to the SPDF are based on individual scans; the alternating even (E) and odd (O) scans have not been combined. During the highest bit rate operation one S scan is followed by eight T scans, at all other data rates one S scan is followed by four T scans. Differences between estimates of solar wind parameters based on lower energy resolution data (S mode) and neighboring T mode data are at times noticeable in plots as S mode outliers in the velocity and temperature values. Generally speaking, the alternating types (O and E) of T mode do not lead to apparent effects in the reduced parameters. However, on rare occasions, during exceptionally cold periods, such as within an Interplanetary Coronal Mass Ejection at distances significantly beyond the orbit of the Earth, an O/E mode alternation in the density and direction of flow is apparent in the reduced data.

5.A DATA DESCRIPTION

The data provided to the SPDF are high resolution (4 minutes and 8 minutes) data of:

- Distribution functions of protons and alpha particles;
- Moments of the distribution functions, that include
    - Number density of protons and alpha particles
    - Particle velocity in the inertial RTN frame
    - Particle temperature parallel and perpendicular to the magnetic field;
- Fit parameters to bi-Maxwellian two-beam distributions.

The magnetic field and the particle velocity are given in RTN coordinates: R is a unit vector pointing from the Sun to the spacecraft; T is Ω x R, where Ω is a unit vector along the Sun's rotation axis; N = R x T. The vector magnetic field was obtained for the time at which the peak of the proton and alpha distribution function was measured, respectively. The particle velocity in RTN coordinates was obtained after rotating the particle velocity from spacecraft to RTN coordinates and then adding the spacecraft velocity.

During periods of spacecraft nutation only the bulk speed and density are reliable, individual velocity components and temperatures are invalid. The beginning of scientifically useful SWOOPS data is at Day 322, 00:59 of 1990; at that time the spacecraft was already nutating and nutation ceased as of Day 351, 22:00, 1990.

There are small systematic uncertainties in the velocity components. These are due to such effects as uncertainty in the accuracy of alignment on the spacecraft, relatively wide angular bins, variation in gains between channeltrons, etc. The velocity component data should not be used for studies of large scale, long term, solar wind deflection. The data are generally suitable for all other studies.

5.B DATA REDUCTION

The SWOOPS ion instrument is a spherical-section curved-plate electrostatic analyzer. Particle arrival directions are measured in spacecraft coordinates of azimuth (scanned by spacecraft rotation) and elevation (determined by the detector number) angles. The spacecraft spin axis was oriented toward the Earth. The energy/charge (E/q) resolution was ~2.5% while the azimuth (φ) and elevation (θ) resolutions were both ~5.6^{o}.

The number of counts in each E/q-φ-θ bin were examined to determine the peak of the proton and alpha particle distribution, respectively, and the vector magnetic field (in spacecraft coordinates) was obtained for the time at which the peak was measured. A “coarse” 2-dimensional matrix was then formed by rotating the data into a coordinate system with axes parallel and perpendicular to the field direction. Note that gyrotropy is assumed in making that transformation. The resolution of the matrix is “coarse” because the vector velocity assigned to each bin was taken to be at the center of the bin. In reality, the counts in each bin were probably not smoothly distributed in velocity space over the bin, but were weighted toward the part of the bin nearest the center of the peak of the velocity distribution. The “coarse” distribution would thus yield values for the density and temperature that were higher than the true values. A correction for that effect was accomplished by fitting contours to the coarse distribution, breaking each bin or pixel into subpixels, and then using the contours and the calibrated angular responses to distribute the counts among the subpixels. New contours were then computed and the process was continued until it converged. More details about this deconvolution of the angular data are given in the appendix of a paper by Neugebauer, M., et al., Ion distributions in large magnetic holes in the fast solar wind, *J. Geophys. Res.,* 106, 5635, 2001.

This procedure generated the matrix of velocity distribution functions of protons and alpha-particles parallel and perpendicular to the simultaneously measured magnetic field. The matrix provided is the log10 of the distribution function and it has dimensions 50x25 (in column-major order). The fluid moments are obtained by numerically integrating the distribution functions for protons and alpha particles.

PART 2

EXPLANATION OF THE CDF FILE CONTENT

We provide 3 types of .cdf files for each species (protons and alphas) per year. This document lists the physical quantities contained in each .cdf file and the corresponding metadata. The relevant information regarding caveats and data reduction summarized in Part 1 is included as metadata of the appropriate file or physical quantity.

1. Matrix (distribution function)

Description (global metadata)

The SWOOPS (Solar Wind Observations Over the Poles of the Sun) ion instrument is a spherical-section curved-plate electrostatic analyzer. Particle arrival directions are measured in spacecraft coordinates of azimuth (scanned by spacecraft rotation) and elevation (determined by the detector number) angles. The spacecraft spin axis was oriented toward the Earth. The energy/charge (E/q) resolution was ~2.5% while the azimuth (φ) and elevation (θ) resolutions were both ~5.6^{o}. A description of the SWOOPS is given in a paper by S. J. Bame, D. J. McComas, B. L. Barraclough, J. L. Phillips, K. J. Sofaly, J. C. Chavez, B. E. Goldstein, and R. K. Sakurai, Astronomy and Astrophysics Supplement Series, Ulysses Instruments Special Issue, Vol. 92, No. 2, p.237-265, 1992. The number of counts in each E/q-φ-θ bin were examined to determine the peak of the proton and alpha particle distribution, respectively, and the vector magnetic field (in spacecraft coordinates) was obtained for the time at which the peak was measured. A “coarse” 2-dimensional matrix was then formed by rotating the data into a coordinate system with axes parallel and perpendicular to the field direction. Note that gyrotropy is assumed in making that transformation. The resolution of the matrix is “coarse” because the vector velocity assigned to each bin was taken to be at the center of the bin. In reality, the counts in each bin were probably not smoothly distributed in velocity space over the bin, but were weighted toward the part of the bin nearest the center of the peak of the velocity distribution. The “coarse” distribution would thus yield values for the density and temperature that were higher than the true values. A correction for that effect was accomplished by fitting contours to the coarse distribution, breaking each bin or pixel into subpixels, and then using the contours and the calibrated angular responses to distribute the counts among the subpixels. New contours were then computed and the process was continued until it converged. More details about this deconvolution of the angular data are given in the appendix of a paper by Neugebauer, M., et al., Ion distributions in large magnetic holes in the fast solar wind, J. Geophys. Res.,106, 5635, 2001. This procedure generated the matrix of velocity distribution functions of protons and alpha-particles parallel and perpendicular to the simultaneously measured magnetic field.

<u>List of variables</u>
'Epoch': epoch
'heliographicLatitude': heliographic latitude [degrees]
'heliocentricDistance': heliocentric distance [au]
'BR', 'BT', 'BN': magnetic field components in RTN coordinates [nT]
'B_MAG': magnetic field magnitude [nT]
'V_MAG': proton/alpha particle speed in inertial RTN frame of reference [km/s]
'Matrix': log10 of the distribution function in units of s^3km^-3cm^-3. The distribution function is a 50x25 matrix. At fixed time, the independent variables are 'v_par' and 'v_per'.
'v_par': speed in the direction parallel to the magnetic field [km/s]. 'v_par' is a 50 elements array
'v_per': speed in the direction perpendicular to the magnetic field [km/s]. 'v_per' is a 25 elements array

<u>Caveats (single variable metadata)</u>
If at a given time v_par and/or v_per have a smaller number of elements than 50 and 25, respectively, then the undefined array entries of v_par and/or v_per and of the distribution function are set to FILLVAL=-10^30.

2. Moments

<u>Description (global metadata)</u>
This file contains the moments obtained from the distribution functions after deconvolution using the same magnetic field values used to construct the matrices. The vector magnetic field and the particle velocity are given in inertial RTN coordinates. The magnetic field was obtained for the time at which the peak of the proton (and, respectively, alpha particle) distribution function was measured. The particle velocity was obtained after rotating the fluid velocity from spacecraft to RTN coordinates and taking into account the spacecraft velocity.

During periods of spacecraft nutation only the bulk speed and density are reliable, individual velocity components and temperatures are invalid. The beginning of scientifically useful SWOOPS data is at Day 322, 00:59 of 1990; at that time the spacecraft was already nutating; nutation ceased as of Day 351, 22:00, 1990.

There are small systematic uncertainties in the velocity components. These are due to such effects as uncertainty in the accuracy of alignment on the spacecraft, relatively wide angular bins, variation in gains between channeltrons, etc. The velocity component data should not be used for studies of large scale, long term, solar wind deflection. The data are generally suitable for all other studies.

List of variables

‘Epoch’: epoch
‘heliographicLatitude’: heliographic latitude [degrees]
‘heliocentricDistance’: heliocentric distance [au]
‘BR’, ‘BN’, ‘BT’: magnetic field components in inertial RTN coordinates [nT]
‘VR’, ‘VN’, ‘VT’: proton/alpha particle velocity components in inertial RTN coordinates [nT]
‘B_MAG’: magnetic field magnitude [nT]
‘V_MAG’: speed in inertial RTN frame of reference [km/s]
‘dens’: density [cm^(-3)]
‘Tpar’: temperature parallel to the magnetic field [K]
‘Tper’: temperature perpendicular to the magnetic field [K]

3. 2-d fits

Description (global metadata)

This file contains the parameters obtained by fitting data to a bi-maxwellian core-beam distribution. Under normal circumstances, the first (slow) population is the core and the second (fast) population is the beam. When the interplanetary magnetic field is folded back on itself due to turbulence or other processes the relation of the first and second populations to the core and beam, respectively, is reversed (see, e.g, M. Neugebauer and B. E. Goldstein, AIP Conf. Proc. 1539, 46, 2013). The vector magnetic field is given in RTN coordinates and it was obtained for the time at which the peak of the proton (and alpha particle, respectively) distribution function was measured. Only good fits are retained.

List of variables

‘Epoch’: epoch
‘heliographicLatitude’: heliographic latitude [degrees]
‘heliocentricDistance’: heliocentric distance [au]
‘BR’, ‘BN’, ‘BT’: magnetic field components in inertial RTN coordinates [nT]
‘B_MAG’: magnetic field magnitude [nT]
‘Vap’: Magnitude of proton-alpha streaming vector [km/s]
‘Valf’: Alfvén speed [km/s]
‘V_MAG’: proton/alpha particle speed in inertial RTN frame of reference [km/s]
‘dnft1’: density of 1st population [cm^-3]
‘vft1’: speed of 1st population (relative to <Vparallel>) [km/s]
‘wpar1’: thermal parallel speed of 1st population [km/s]
‘wper1’: thermal perpendicular speed of 1st population [km/s]
‘dnft2’: density of 2nd population [cm^-3]
‘vft2’: speed of 2nd population (relative to <Vparallel>) [km/s]

‘wpar2’: thermal parallel speed of 2nd population [km/s]
‘wper2’: thermal perpendicular speed of 2nd population [km/s]
‘anis1’: Tparallel/Tperpendicular for 1st population
‘anis2’: Tparallel/Tperpendicular for 2nd population
‘denrat’: normalized total density

Caveats (single variable metadata)
Data with ‘vft1’>’vft2 are set to FILLVAL=-10^30. The parameter ‘denrat=(dnft1+dnft2)/dens’, where ‘dens’ is the value of the density found in the moments calculation, can be used as a further consistency check (ideally denrat = 1.0).