SWA PAS Calibration Tables
Conversion to Physical Values
and Moments Calculations

May 17, 2020

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Version 1.3, 05/17/2020

Contents

III DOCUMENT CHANGE RECORD

Edition	Revision	Date	Madified pages	Reason to change
1	0	28/05/2019	-	First issue
1	1	23/01/2020	all	Add Energy table
1	2	09 May 2020	9	Correct axis in S/C frame
			8,9	Tables contai Energy instead of V
			9	Yield and Elevation corr. tables
			8	DPU tables
1	3	17 May 2020	10 - 12	Full preliminary package for L2 conversion

1 Introduction

1.1 Context of the project

1.1.1 Solar Orbiter mission

The Solar Orbiter is an ESA mission providing an unprecedented opportunity to discover the fundamental connections between the rapidly varying solar atmosphere and the solar wind, revealing the physical links between the outward transport of solar energy, its manifestations in solar convection, the variations of coronal magnetic fields, and the sources and acceleration of solar wind. Solar Orbiter science payload consists of ten instruments including Solar Wind Analyzer suite (SWA).

- The objective of SWA is to provide the comprehensive in situ measurements of the solar wind to establish the fundamental physical links between the Sun's highly dynamic magnetized atmosphere and the solar wind in all its quiet and disturbed states. SWA provides high time resolution velocity distributions of solar wind electrons and ions, and ion's composition.

1.1.2 SWA Instruments

SWA suite of instrument is under the responsibility of MSSL and is composed by :

- HIS (Heavy Ions Sensor) : responsibility of IRAP and US institutions
- PAS (Proton-Alpha Sensor) : responsibility of IRAP
- EAS (Electron Analyzer System) : responsibility of MSSL
- DPU : responsibility of IFSI

1.1.3 HIS and PAS instruments

PAS

- Will determine the characteristics of the solar wind proton and alpha particle distributions
- Will provide high time resolution solar wind properties like plasma density, plasma bulk velocity and temperature.

HIS

- Will provide critical information on the solar wind composition
- IRAP laboratory will provide the Electrostatic Analyzer (HIS EA) for the HIS sensor, while the "time-of-flight' and detector sections will be provided by US laboratories.

Since HIS EA has the same design as the PAS analyzer, HIS EA and PAS instruments will share some documents from the document tree.

1.2 Scope of the document

The document is based on the final PAS calibration report and the "Calibration Record" information. This document describes the procedure on the transformation of the L1 PAS data (counts) to the L2 data (physical values).

2 Related documents

2.1 Applicable documents

AD	Reference	Ed./Rev.	Date	Title of the document
				To fill

2.2 Reference document

RD	Reference	Ed./Rev.	Date	Title of the document
				To fill

3 Reference frames and bins allocation

Figure 1 shows the Elevation and angle angles and bins in the PAS frame. Figure 2 shows the same in the spacecraft frame. Note the the solar orbiter frame corresponds to the RTN Heliocentric frame most of the time with $X_{RTN} = -X_{SC}$, $Y_{RTN} = -Y_{SC}$.

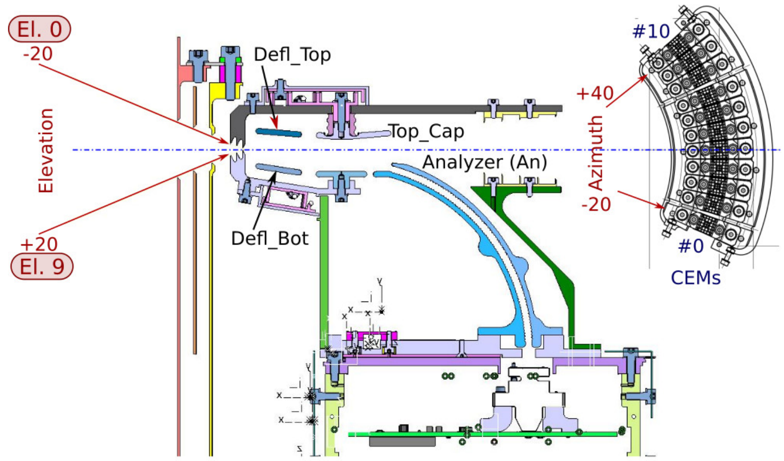

Figure 1: Elevation and azimuth bins and angles in the PAS analyzer frame. The CEMs plane is shown from the Analyzer.

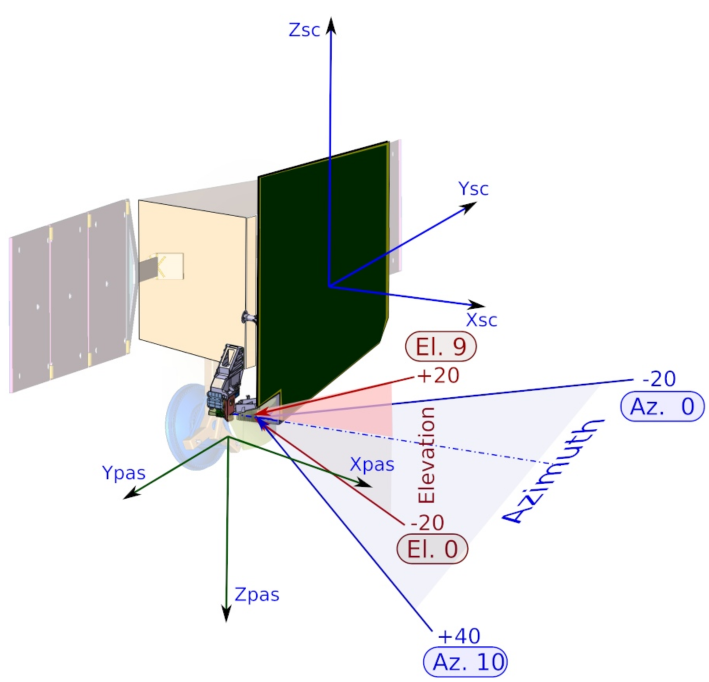

Figure 2: Elevation and azimuth bins in the Solar Orbiter frame.

4 DPU onboard moments tables

Onboard moments calibration record contains files shown in Table 1

Name	Dimensions	Description
PAS_PFM_V_array	96	1D array, MIN - MAX for simple view and onboard moments
PAS_PFM_El_array	9	1D array, MIN - MAX, sin, cos for simple view and onboard moments
PAS_PFM_Az_array	11	1D array, MIN - MAX, sin, cos for simple view and onboard moments
PAS_PFM_CN_array	96x9x11	Conversion factor for **the real** accumulation time

Table 1: Calibration records for DPU

DPU shall process onboard moments calculation as described in Section 6 taking into account that Energy, Elevation and Azimuth arrays are all 1D.

The annex to calibration table are two examples of

5 Onboard Moments Decoding

The decode TM moments values to physical values use rules as follows:

```
Telemetry Density: NT (integer value)

    N  = float(N)/10.0   [cm-3]

Telemetry V: VT  (integer value)

    Vx = float(VTx)                                [km/s]
    Vy =  float(VTy) - 2000.0                      [km/s]
    Vz =  float(VTy) - 2000.0                      [km/s]

Telemetry Pressure tensor: PT (integer value)

    P = 2.0^(Pe-15)*(1.0+Pf/1024.0)*1.0e17/65504.0 [(cm^-1)*(s^-2)]
    here Pe = PT / 1024
    here Pf = (float)PT/1024.0 - (float)Pe
```

Note, that P is the pressure of particles of mass 1 (pressure of particles of mass 1 of number density expressed in cm^{-3} and thermal velocity expressed in $cm \cdot s^{-1}$). Thus to get a physical value (like $J \cdot cm^{-3}$) we have to multiply this value to proton mass and divide to N.

```
To calculate the temperature from the pressure tensor use the formula as follows:
```

$$T[eV] = (P_{XX} + P_{YY} + P_{ZZ})/N \cdot 5.2197 \cdot 10^{-13} \cdot (2/3)$$

6 L1 data conversion and moments calculation

Instrument sampling is expressed as a 3-D array as follows:

$$Count_{ie,iel,iaz}$$

Here:

ie is the energy index [0 .. 95]

iel is the elevation index [0 .. 8]

iaz is the azimuth index [0 .. 10]

Open the files from the PAS CALIBRATION RECORD indicated in Table 2.

Name	Dimensions	Description
PAS_PFM_E_array	96	1D array, MIN - MAX for simple view
PAS_PFM_V_array	96	1D array, V centr. onboard moments ONLY
PAS_PFM_El_array	9	1D array, MIN - MAX, sin, cos for simple view and onboard moments
PAS_PFM_Az_array	11	1D array, MIN - MAX, sin, cos for simple view and onboard moments
PAS_PFM_E_full_array	96x9x11	Energy array
PAS_PFM_GF_array	9x11	Geometrical factor for **the real** accumulation time
PAS_PFM_El_full_array	9x11	Elevation angles
PAS_PFM_CN_array	96x9x11	Conversion factor for **the real** accumulation time
PAS_PFM_AZ_full_array	9x11	Azimuth angles
PAS_PFM_Yeild_array	9x11x9x11	Ghost Count Correction array
PAS_PFM_El_corr_array	96x9	Even-Odd E steps elevation correction
solo_CAL_catalog		Catalog of these files

Table 2: Full Calibration record set

Then do as follows:

1. Read Energies $E_{ie,iel,iz}$in eV from the file PAS_PFM_E_full_array and recalculate it to proton and He++ velocity $V_{ie,iel,iz}$ **in cm/s** as follows:

$$VP_{ie,iel,iaz} = 13.841e5 \times \sqrt{\sqrt{(E^{MIN}_{ie,iel,iaz} \cdot E^{MAX}_{ie,iel,iaz})}}$$

$$VHe_{ie,iel,iaz} = 13.841e5 \times \sqrt{\sqrt{(E^{MIN}_{ie,iel,iaz} \cdot E^{MAX}_{ie,iel,iaz})}/2}$$

2. Read sin $SinElev_{iel,iaz}$ and cos $CosElev_{iel,iaz}$ of the elevation angles from the file PAS_PFM_El_full_array
3. Modify $SinElev_{iel,iaz}$ and cos $CosElev_{iel,iaz}$ according to the table "PAS_PFM_El_corr_array" :

$$SinElev_{iel,iaz} = SinElev_{iel,iaz} + CosElev_{iel,iaz} \cdot \Delta El_{ie}$$

$$CosElev_{iel,iaz} = CosElev_{iel,iaz} - SinElev_{iel,iaz} \cdot \Delta El_{ie}$$

4. Read sin $SinAz_{iel,iaz}$ and cos $CosAz_{iel,iaz}$ of the elevation angles from the file PAS_PFM_AZ_full_array
5. Make the arrays of Vx, Vy, and Vz in the **SPACECRAFT** frame for each energy, elevation, and azimuth as follows

```
VxarrSC(*,iel,iaz) = -Varr*CosElArr(iel)*CosAzArr(iaz) [cm/s]
VyarrSC(*,iel,iaz) =  Varr*CosElArr(iel)*SinAzArr(iaz)
VzarrSC(*,iel,iaz) = -Varr*SinElArr(iel)
```

6. Read the geometrical factor $GV_{iel,iaz}$ array from the file PAS_PFM_GF_array.txt and calculate the proton distribution function value in each Velocity point (see item 4) as follows:

$$DF_{ie,iel,iaz} = Count_{ie,iel,iaz}/(GV_{ie,iel,iaz} \cdot V^4_{ie,iel,iaz}[cm/s])$$

To calculate the moments we do as follows:

1. Read conversion factor from the file PAS_PFM_CN_array.txt
2. Calculate partial density array (number density $[cm^{-3}]$ in each velocity point) as follows:

$$\Delta n_{ie,iel,iaz} = Count_{ie,iel,iaz} \cdot CN_{ie,iel,iaz}$$

3. Calculate number density in $[cm^{-3}]$ as follows:

$$n = \sum_{ie,iel,iaz} \Delta n_{ie,iel,iaz}$$

4. Calculate bulk velocity **in km/s** as follows (X component as example):

$$V_X = (\sum_{ie,iel,iaz} VxarrSC_{ie,iel,iaz} \cdot \Delta n_{ie,iel,iaz})/n$$

5. Calculate pressure tensor for particle mass = 1, the the energy [cm^2/s^2] per cm^3. $[J/cm^3]$ as follows (XY components as an example), here "m" is the particle mass [kg]:

$$P_{XY}[cm^2 s^{-2} cm^{-3}] = \sum_{ie,iel,iaz} (VxarrSC_{ie,iel,iaz} - V_X)(VyarrSC_{ie,iel,iaz} - V_Y)\Delta n_{ie,iel,iaz}$$

$$P_{XY}[J \cdot cm^{-3}] = P_{XY}[cm^2 s^{-2} cm^{-3}] \cdot m[kg] \cdot 10^{-4} \, [J \cdot cm^{-3}] = P_{XY}[cm^2 s^{-2} cm^{-3}] \cdot 1.6726e-31$$

6. Calculate temperatures as follows:

$$T[eV] = (P_{XX}[cm^2 s^{-2} cm^{-3}] + P_{YY} + P_{ZZ})/N \cdot 5.2197 \cdot 10^{-13} \cdot (2/3)$$

7 Software package

7.1 Package contents

Corresponding software package is shown in Table 3.

File	What is it
pas_process.py	main Python module
PAS_moments.py	example how to call moments calculation
PAS_3d_analysis.py	example how to call VDF calculation (needs PLPLOT package)

Table 3: Software package

The package "pas_process.py" contains ALL necessary function. In time of import, the package reads all necessary calibration tables and define corresponding constants. Note that the package applies several several necessary corrections of the raw data before to calculate moments and VDF.

7.2 Package usage

The main package is as follows:

```
import math
import numpy
import pas_process as pas
moments = pas.calcMoments(spectrum3D, sE, sEl, nE, nEl)
N = moments["N"]
Vx = moments["V"][0]
Vy = moments["V"][1]
Vz = moments["V"][2]
T = moments["T"]
Tx = moments["TxTyTz"][0]
Ty = moments["TxTyTz"][1]
Tz = moments["TxTyTz"][2]
Pxx = moments["PxxPyyPzzPzyPxzPyz’’][0]
.... etc ....
vdf = pas.calcVDF(spectrum3D, sE, sEl, nE, nEl) # velocity distribution function
```

“spectrum3D” is the PAS spectrum as it is recorded in L1 CDF file.

“vdf” shape is the same as the shape of the original PAS 3D spectrum.

See examples of the energy spectrum and corresponding VDF is Figure 3 (made by PAS_3d_analysys.py)

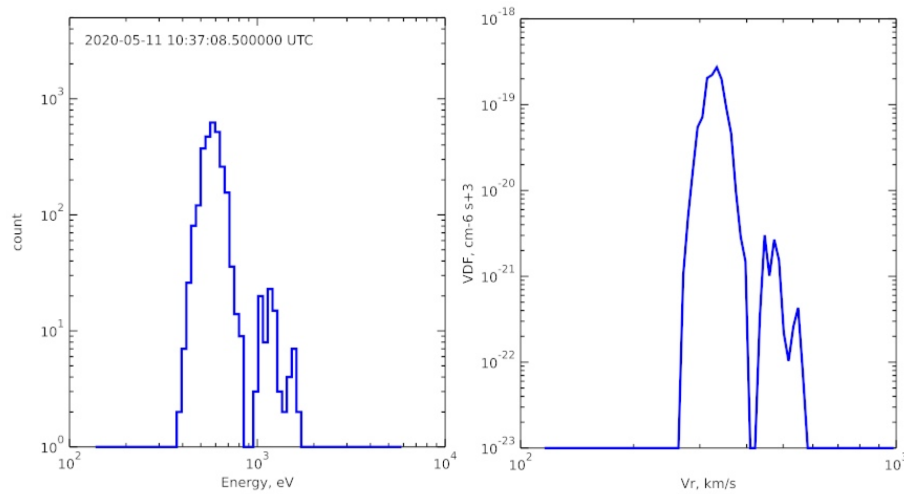

Figure 3: Left: an example of PAS original spectrum. Right: the corresponding VDF

8 Annex

P_origin is the P calculated as a moment flux of unity mass particles

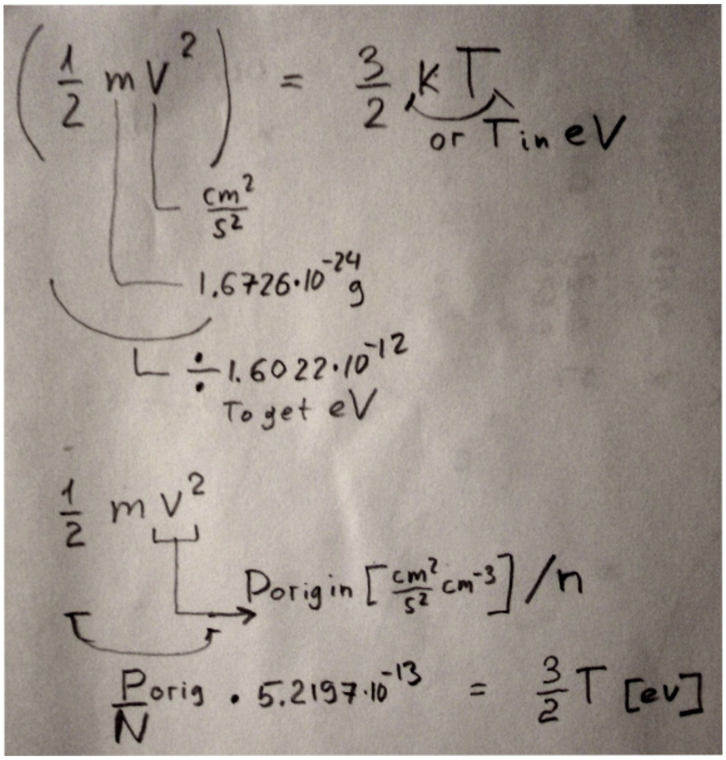

Figure 4: Recalculation of Pressure tensor to Temperature