# 3. Required Instrument Properties (scientific requirements) and general definitions

This section contains the required scientific instrument properties (scientific requirements) that shall be realized by the actual instrument. Also this section defines the position of PAS onboard Solar Orbiter and its frame.

## 3.1. PAS position, reference frame, definitions of angles

The PAS position on the spacecraft is shown in Figure 1 $X_{SC}$ and the $X_{PAS}$ are equivalent and pointed to the Sun. The instant looking direction of one instrument channel is defined by:

The **Azimuthal angle** $\Phi$ is the angle in $X_{PAS} \times Y_{PAS}$ plane from $X_{PAS}$ toward $Y_{PAS}$ corresponding to a rotation around $Z_{PAS}$.

The **Elevation angle** $\theta$ is the angle from $X_{PAS} \times Y_{PAS}$ plane toward $Z_{PAS}$.

Thus the unit direction vector components are as follows:

$$X_{PAS} = \cos(\Theta) \cdot \cos(\Phi)$$

$$Y_{PAS} = \cos(\Theta) \cdot \sin(\Phi)$$

$$Z_{PAS} = \sin(\Theta)$$

**Eq. 1**

$$X_{SC} = \cos(\Theta) \cdot \cos(\Phi)$$

$$Y_{SC} = -\cos(\Theta) \cdot \sin(\Phi)$$

$$Z_{SC} = -\sin(\Theta)$$

**Eq. 2**

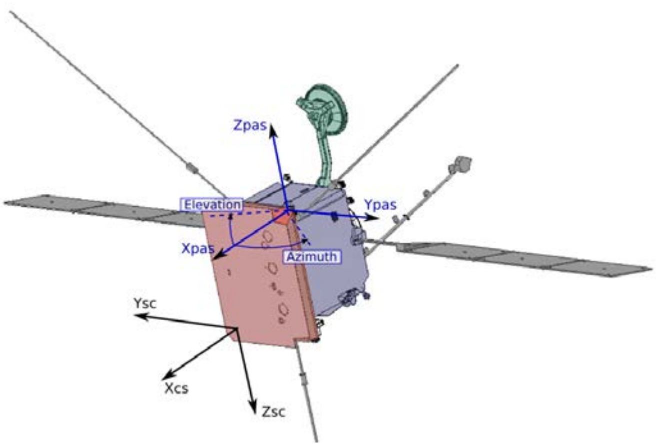


**Figure 1** Position of PAS on S/C. Axis and angles.

PAS alignment requirements are given in Section 5.2.

## 3.2. Instrument Properties

The main properties of the instrument to meet the “Yellow book” requirements and the “Science Performance Report” are shown in Table 1.

| Property | Term | Value | Comments |
|---|---|---|---|
| Energy Range | $[E_{min}, E_{max}]$ | $[0.2 \div 20.0]\ keV$ | Maximal range. It can be less for currently working mode (partial distributions). Defined by HV hardware |
| Physical energy resolution | $\Delta E/E$ | $< 0.055$ | Defined by optics design |
| Binning energy resolution (Energy step factor) | $S_E = E_i/E_{i-1}$ | $< \Delta E/E$ | Interstep factor. Defined by HV control |
| Total number of energy bins | $N_{En}$ | 96 | Maximal value. Measurement modes can use a reduced number of the energy bins (partial distribution). |
| Energy set precision | $\delta E/E$ | $\leq 0.01$ | Defined by HV hardware. |
| Azimuthal range | $[\Phi_{min}, \Phi_{max}]$ | $[-24.0° \div 42.0°]$ | Defined by mechanical design. See Figure Figure 9 |
| Binning azimuthal resolution | $\Delta\Phi$ | $6°$ | Defined by mechanical design. See Figure Figure 3 |
| Azimuthal physical resolution | $\delta\Phi$ | $< \Delta\Phi$ | Defined by ion optics |
| Elevation range | $[\Theta_{min}, \Theta_{max}]$ | $[-22.5° \div 22.5°]$ | Defined by ion optics |
| Binning elevation resolution | $\Delta\Theta$ | $5°$ | Defined by measurement algorithm |
| Physical elevation resolution | $\delta\Theta$ | $< \Delta\Theta$ | Defined by ion optics |
| Analyzer geometrical factor (one azimuthal bin) | $G_I$ | $> 1.0 \cdot 10^{-5}\ cm^2\ sr\ eV\ eV^{-1}$ | Geometrical factor of PAS ion optics |
| Instrument geometrical factor (one azimuthal bin) | $G$ | $> 4.0 \cdot 10^{-6}\ cm^2\ sr\ eV\ eV^{-1}$ | Real instrument geometrical (conversion) factor |
| Nominal time resolution | $T_{Acc}\ Nominal$ | $4\ s$ | Nominal required sampling of 3D full spectrum |
| One sampling maximal time | $T_{Acc}\ Base$ | $1\ s$ | See Section 4 |
| Maximal time resolution | $T_{Acc}\ Burst$ | < 0.1s | Minimal sampling of 2D spectrum |
| Maximal background noise | $B_{max}$ | $0.1\ s^{-1}$ | One detector sector |

Table 1: PAS scientific requirements

**General definitions:**

All terms defined in Table 2 appear in the text of this document as underbar worlds ("xxxxxxxxx").

| Term | Definition |
|---|---|
| Sampling | Snapshot of the Ion distribution function, taken as a result of PAS scanning cycle, and stored in the DPU memory. |
| Full 3D Sampling | Sampling consisting of [96 of energies]x[9 elevation bins]x[11 Azimuths (detectors)] |
| Partial Sampling | Sampling consisting of [less than 96 of energies] AND/OR [less than 9 elevation bins] AND/OR [7 Azimuths (detectors)] |
| SampleTime | Fundamental time constant for PAS. This is the accumulation time of one elevation bin (time when the counter gate is open. |
| Sequencer | A simple controller embedded to the PAS FPGA. It executes a modifiable code that control the process of Sampling. |
| Sequencer Program | A code executed by Sequencer. The program is stored in the DPU memory and should be loaded to the FPGA memory while PAS reset (or switch ON). |
| Ion Optics HVPS | Fast high voltage power supply that produces variable voltages for the Electrostatic Analyzer and Elevation steering Deflector. This HVPS is controlled by the Sequencer. |
| CEM | Channel Electron Multiplier, the low energy particle detector, used in PAS |
| CEM HVPS | HVPS providing the detectors high voltage bias. |
| HK | Housekeping. A system of reading and transmit all non-scientific parameters for instrument relatime characteriszation. |
| Electrostatic Analyzer | Part of Ion optics providing selection of a specified energy of the incident ions. |
| Elevation steering Deflector | Or "Deflector" is a part of the PAS Ion Optics providing elevation steering of the line of sight (selection of the elevation angle) |
| EAIS | Whole Ion Optics Unit. This is an acronym of "**E**nergy **A**nalyzer and **I**on **S**teering system" |
| Electronics box | Box, containing all electronics boards. It provides the mechanical and electrical interfaces to the spacecraft. |
| Maximum Count Position Calculator | Unit able to calculate relatime the position of the maximum of the count in [Energy,Elevation,Detector] matrix. |
| SpaceWire | A standard ESA (IEEE 1355) inter-instrument communication interface that includes a hardware standard and a communication protocol. |
| Static Scheme | DPU and only DPU defines PAS performance that make continuous measurements of the same Sampling. |
| Dynamic Window Scheme | PAS performs one Full 3D Sampling, determines a Partial Sampling parameters and then performs long or short sequence of the Partial Samplings |

**Table 2** Main terms

# 4. Instrument general conception (system requirements)

The general instrument conception includes the sensor ion optics system design and measurement principles. This part contains only the general description and very common requirements. This section also gives necessary definition. Section 5 gives detailed requirements for the ion optics, electronics and measurements algorithms.

**Definition of the SAMPLING:**

The basic objective of PAS is to measure **3D samplings** of the ion velocity distributions. The sampling is done by selecting the energy, elevation angle and azimuth angle of the incident particles and by measuring their flux as the corresponding detector count rate. The energy and the elevation angles are determined by the voltages applied on the ion optics. The azimuthal angle is defined by the detector position. Thus the Sampling is a snapshot of the ion distribution function stored as a matrix of [[Energies]×[Elevations]×[Azimuths]]. We use the underlined word "Sampling" later in the text to designate exactly this notion. The number of the Energies may differ, but never greater than 96. The number of the elevations may also differ but be never greater than 9. The number of azimuths may be either 11 or 7. A Sampling consisting of [96 of energies]x[9 elevation bins]x[11 Azimuths (detectors)] is called Full 3D Sampling. The measuring principles are described in details in Section 4.2.

The instrument conception that fulfills the present measurement scheme is given below:

## 4.1. PAS principles

To meet the declared properties (see Table 1), the general requirements for the raw data product are as follows:

**PAS-R-041-001**: PAS shall produce a Full 3D Sampling of the solar wind ion 3D velocity distribution as a matrix of counts accumulated in a matrix of $[[96\ energy\ bins] \times [11\ azimuthal\ directions] \times [9\ elevation\ directions]]$ for $1\ s$ in the ranges shown in Table 1. The angular bins shall be equivalent (homogenous) and the energy bins shall be equivalent in logarithmic scale.

**PAS-R-041-002**: The solar wind ion differential flux is deduced from the 1s accumulated count matrix as follows:

$$D[cm^{-2}\, s^{-1}\, sr^{-1}\, eV^{-1}] = \frac{count}{G \cdot E} \qquad \textbf{Eq. 3}$$

Here $D$ is the differential flux, $count$ is one bin count accumulated for one second, $E$ is the specific bin energy, and G is the instrument geometrical factor given in Table 1.

To produce such measurements taking into account the extreme thermal and UV flux environments (see SOL-EST-IF-0050 and TEC-EES-03-034/JS) the general requirements for the ion optics design are as follows:

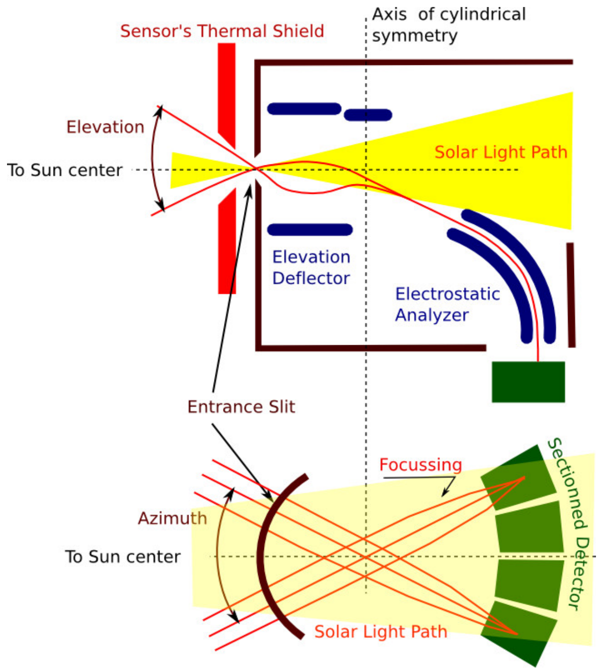


**Figure 2 :** PAS Ion optics (EAIS) principles

**PAS-R-041-003**: The entrance of the sensor (see Figure 2) shall be a slit as small as possible to protect the sensor from the incident photons flux. The vertical size (Z) of this slit shall be large enough to provide the sensor geometrical factor $G_I$ as given in Table 1. The horizontal (YZ plane) slit size shall be large enough to provide the azimuthal range $[\Phi_{min}, \Phi_{max}]$ as it is given in Table 1.

**PAS-R-041-004**: The front side of the EAIS (looking toward the Sun) shall be protected by a local thermal shield. See Figure 2. The thermal shield shall protect any mechanical and electronics part of the sensor against overheating for any steady state spacecraft pointing at Sun-spacecraft distances less than 0.95AU. The thermal shield shall not obstruct the sensor field of view defined by the angular ranges, given in Table 1 and the entrance slit size. The details of the instrument field of view are given in Section 5.2. For any other thermal control requirements see in the dedicated Section 5.3.

**PAS-R-041-005**: Any internal parts of the EAIS shall be out of the direct solar light for any steady-state spacecraft pointing at Sun–spacecraft distances less then 0.95 AU. The size of the corresponding light path is given in Section 5.2. See Figure 2 for understanding.

**PAS-R-041-006**: The Electrostatic Analyzer (Figure 2, a part of EAIS) shall deflect incident positive ions by $90°$ in the plane containing symmetry axis of the sensor, which shall be parallel to Z (Figure 2). This shall provide the focusing of the parallel incident ion beam in a small spot on detector plane. The focusing spot size shall provide the physical azimuthal resolution $\delta\Phi$ given in Table 1. The design of the Electrostatic Analyzer shall provide the $\Delta E/E$ value and $G_I$ value as it is given in Table 1.

**PAS-R-041-007**: An Elevation steering Deflector (a part of EAIS) shall be placed between the entrance slit and the Electrostatic Analyzer. The deflector shall steer the incident ions entering within the elevation range $[\Theta_{min}, \Theta_{max}]$ given in Table 1 toward the analyzer entrance. The steering deflector shall have a cylindrical symmetry around the axis of symmetry of the Electrostatic Analyzer. The design of the deflector shall provide: a) almost equivalent properties of the elevation steering inside the entire azimuthal range $[\Phi_{min}, \Phi_{max}]$, taking into account a finite width of the incident beam (Figure 2, bottom panel); b) the geometrical factor $G_I$ given in Table 1. Later in the text the Elevation Steering Deflector is designated as “Deflector”

**PAS-R-041-008**: A charged particle detector shall be located behind the exit of the Electrostatic Analyzer. The entrance of the detector shall correspond to the azimuthal focal plane of the sensor. The detector shall be divided in 11 equivalent independent sections located according to Figure 3. Each detector section shall represent one azimuthal bin with corresponding angular resolution $\Delta\Phi$ given in Table 1. The edge of the section “0” shall correspond to the “$-24°$” edge of the FOV of the instrument, and the edge of the section “10” shall correspond to the “$+42°$” edge of the FOV. The gaps between detector sections shall be equivalent (homogeneous) if possible and minimized. The detector shall have the maximal ion efficiency within the sensor energy range $[E_{min}, E_{max}]$ given in Table 1. The detector shall work in the counting (one event) mode. The maximal count rate of the detectors 2-6 shall be $> 10^7\ s^{-1}$. The maximal count rate of the detectors 0,1,7-10 shall be $> 10^6\ s^{-1}$.

**PAS-R-041-009** Azimuthal binning: A disposition of the idealized azimuthal bins described in PAS-R-041-008 shall correspond to Figure 3 and Table 4. Any Sampling shall contain data from either full detector set, either from the reduced set of detectors.

**Note:** the position of the center of the individual detector (blue rectangles) differs from the center $Az_i$ of the idealized azimuth bin (sectors at the bottom of . Figure 3).

**PAS-R-041-010** Energy binning: Any Sampling shall contain a subset of full energy bins set defined as follows:

$$\boldsymbol{E_{ie}\,[eV] = 200.0 \cdot 1.0497^{ie}, ie = \{0..95\}} \quad \textbf{Eq. 4}$$

**PAS-R-041-011** Elevation binning: Any Sampling shall contain a subset of full elevation bins set as shown in **Table 3**. See also Figure 5 for clarification.

| Elevation bin, $iel$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Center $\Theta_{iel}$, deg | -20 | -15 | -10 | -5 | 0 | 5 | 10 | 15 | 20 |
| Range $\Theta B_{iel}$, deg | -22.5/-17.5 | -17.5/-12.5 | -12.5/-7.5 | -7.5/-2.5 | -2.5/2.5 | 2.5/7.5 | 7.5/12.5 | 12.5/17.5 | 17.5/22.5 |

**Table 3** Elevation binning

**PAS-R-041-010**: The maximal background count rate $B_{max}$ of one detector section due to the solar UV shall be as it shown in Table 1.

For the detailed detectors system design requirements (include the “reduced set” option) see in sections 5.2 and 5.4.

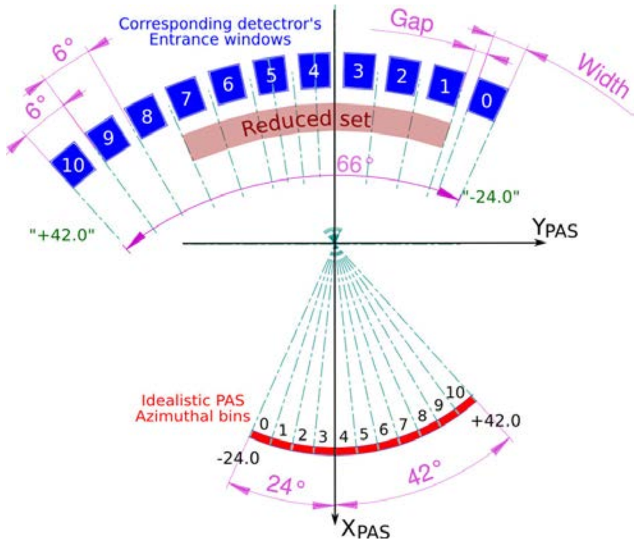


**Figure 3 :** PAS detector angular sectors. Reduced set correspond to the case of Partial Sampling.

| Detector, $iaz$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Part of "Reduced Set" | NO | YES | YES | YES | YES | YES | YES | YES | NO | NO | NO |
| Center $\Phi_{iaz}$, deg | -21 | -15 | -9 | -3 | 3 | 9 | 15 | 21 | 27 | 33 | 39 |
| Range $\Phi B_{iaz}$, deg | -24/-18 | -18/-12 | -12/-6 | -6/0 | 0/6 | 6/12 | 12/18 | 18/24 | 24/30 | 30/36 | 36/42 |

**Table 4**

## 4.2. Measurement Principles

The general diagrams explaining PAS measurement principles are shown in Figure 4 and Figure 5. The corresponding general requirements to the PAS measurement scheme and instrument general design are shown below in this section. The detailed requirements are given in Section 5.7 and 5.8.

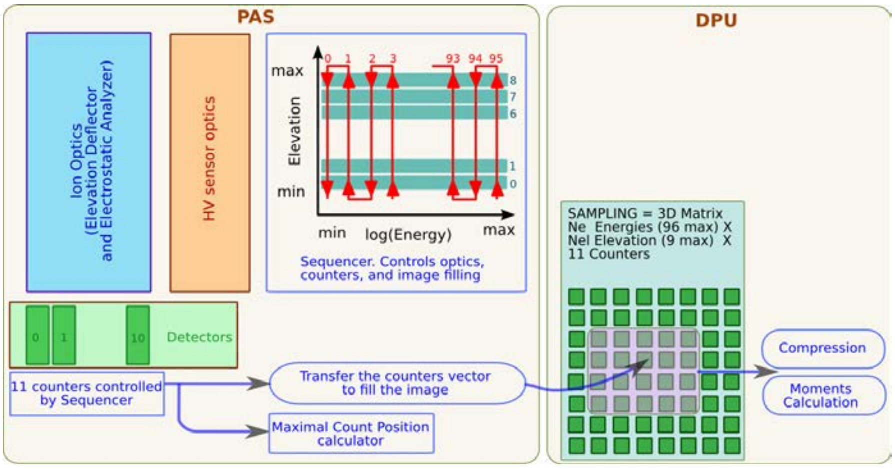


**Figure 4** Block scheme of one Sampling. The real PAS implementation shall contain all presented parts.

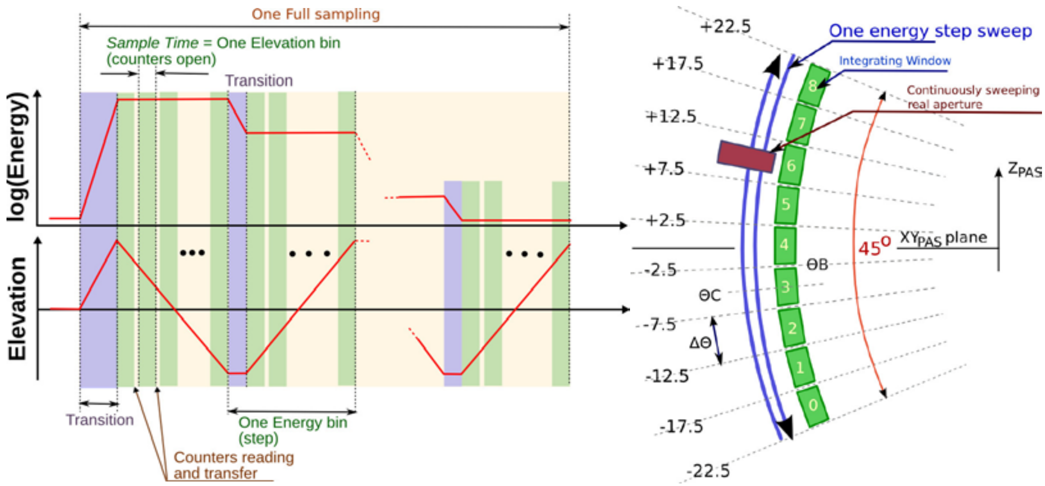


**Figure 5 :** PAS Energy-Elevation scan scheme. PAS has to perform such a scan to complete a Full 3D Sampling. The left panel shows the energy scan (top) waveform and the elevation sweep waveform (bottom). The right panel shows the principle of the elevation sweep binning.

**Definition of the SEQUENCER**.

To execute the Sampling cycle, some digital electronics part are needed control the Ion Optics HVPS and the counters that accumulate the detectors events. This freely reprogrammable controller is called Sequencer (see Figure 4).

**PAS-R-042-011**: To produce a Sampling, the PAS hardware, in a very common sense, shall included at least (see Figure 4):

a) PAS sensor Ion Optics EAIS (see Section 4.1) ;
b) Sensor Optics HVPS: a multichannel fast, high dynamic range high voltage source to provide a variable voltages on the PAS sensor Ion optics electrodes.
c) Sequencer: an electronics device that shall (in general) control the Sensor Optics HV, counters (see below), read the counters data and transmit them toward DPU to perform a

Sampling. This device shall be in-flight reprogrammable.

d) Eleven ion Detectors (see Section 4.1)
e) Eleven event counters controlled by the Sequencer.
f) Maximum Count Position Calculator: a unit capable to calculate relatime the position of the maximum of the count in [Energy,Elevation,Detector] frame.

Other but not least parts of PAS hardware see in Section 5.1

**PAS-R-042-014**: To perform a Sampling the PAS Sequencer shall execute a measurement scheme as follows (see Figure 5):

a) Set a specific energy, starting from the highest one;
b) Make a pseudo-continuous sweep in the elevation range as shown in Figure 5 (right). The extreme sweeping points corresponding to $\Theta = -22.5°$ and to $\Theta = +22.5°$ shall match to the centre of the real physical instrument aperture.
c) During one elevation sweep (for Full 3D Sampling ) Sequencer shall open the counter gate for Sample Time nine times, and command to transfer all counters data to the DPU in order to create 9 (nine) elevation bins in the DPU Sampling matrix as shown in Figure 4. The elevation bins numbering is shown in Figure 5 (right).
d) As soon as the accumulation of one elevation bin is completed, the data of the eleven counters shall be added to the scientific data packet to transmitted to DPU. After that counters shall be reset and be ready to accumulate a new elevation bin.
e) As soon as the accumulation of the 9 elevation bins (Full 3D Sampling case) is completed, Sequencer shall proceed to the next energy step. This subroutine shall be repeated 96 times to complete a Full 3D Sampling.
f) The sequence of elevation sweeps shall be made in UP/DOWN form as it is shown in Figure 5 (left).
**g)** A Full 3D Sampling shall be completed in $T_{Acc}\ Base = 1\ s$ (one second). It means that PAS shall be able to repeat a Full 3D Sampling with 1Hz frequency.

**PAS-R-042-013**: Partial Sampling. The Sequencer shall be capable to perform any part of the Full 3D Sampling with a reduced number of energy steps and/or a reduced number of elevation bins and/or reduced number of detectors (namely 7, see Figure 3). Then the resulting Sampling matrix in DPU shall be a subset of the Full 3D Sampling matrix (Figure 4).

**PAS-R-042-014**: The Sequencer shall be capable to perform two measurement schemes: Static Scheme, and Dynamic Scheme.

# 5. The Detailed PAS requirements (engineering requirements)

The requirements formulated in this section are the results of the system design of PAS ion optics, PAS electronics system design, and PAS FPGA system design. All Engineering requirements are based on the system requirements described in Section 4.

## 5.1. PAS contents requirements (block scheme)

**PAS-R-051-010**: PAS shall be made as a stack of two units:

- EAIS