Abstract. The EPHIN instrument (Electron Proton Helium INstrument) forms a part of the COSTEP experiment (COMprehensive SupraThermal and Energetic Particle Analyzer) within the CEPAC collaboration on board of the SOHO spacecraft (SOlar and Heliospheric Observatory). The EPHIN sensor is a stack of six solid-state detectors surrounded by an anti-coincidence. It measures energy spectra of electrons in the range 250 keV to > 8.7 MeV, and hydrogen and helium isotopes in the range 4 MeV/nuc to > 53 MeV/nuc. In order to improve the isotopic resolution, the first two detectors have been segmented: 5 sectors form a ring enclosing a central segment. This does not only allow to correct the energy-losses for particles with different path-lengths in the detectors, but allows also an estimation of the arrival direction with respect to the sensor axis. For that purpose we developed a method that allows for inferring the angle of incidence and angular distribution for ions. Here we describe the method and apply it to the November, 3, 2011 event. Due to the lack of magnetic field measurements and the restricted view cone of 83°, it is not possible to derive a real pitch angle distribution during this event. However, we can show that the particle distribution is anisotropic for several hours with a symmetry axis that deviates by about 20° from the sensor axis.

1. Introduction
A careful analysis of solar energetic particle (SEP) events allows in principle to derive fundamental information about the acceleration, injection into and propagation in the interplanetary medium. Observation, not only of intensity-time profiles, energy spectra and the elemental and ionic charge composition, but also of the temporal evolution of the pitch angle distribution are determined by the combination of the above mentioned steps. Although often neglected, detailed measurements of the pitch angle distribution are essential and have to be considered by the time the energetic particles have reached the Earth. On a spinning spacecraft a full pitch angle coverage is achieved by dividing a full rotation into several sectors. 3-axis stabilized spacecraft require many sensors or sectored detectors to measure the pitch angle distribution.

1.1. Instrumentation
The NASA/ESA SOlar and Heliospheric Observatory (SOHO) was launched in 1995 and is in orbit about the L1 Lagrangian point since 1996. The scientific payload of the spacecraft consists of several remote and in-situ instruments including the Electron Proton Helium Instrument (EPHIN, Müller-Mellin [1]), a particle telescope with a field of view of about 83° that measures electrons with energies between 0.25 and above 8.4 MeV as well as protons and Helium in the energy range of 4.3 to beyond 53 MeV/nucleon [1].
Figure 1. EPHIN schematics, reproduced from [3].

Figure 2. 1MeV electrons are shown in red, 20MeV protons are shown in blue, secondary gammas in green.

A schematic view of the EPHIN instrument is shown in figure 1. The instrument consists of a stack of six solid-state-detectors (labeled A-F) that are surrounded with a scintillation detector (G), which acts as active anti-coincidence detector. Stopping ions are identified by applying the $dE/dx - E$-method [2]. Since the data rate is limited, energy losses in detectors A-E can only be transmitted for a statistical ensemble of all particles counted by EPHIN that needs to be normalized with respective count rates. A crude separation between electrons, protons and helium has been introduced for different penetration depths, i.e. different coincidences by introducing different energy-loss thresholds in detector A, for details see [1].

In order to improve the isotopic resolution and to decrease the deadtime of the instrument during solar energetic particle events with high count rates, the first two detectors (A and B) consist of six individual sectors (see figure 1, right). Knowing which detector sectors were penetrated can be exploited to reduce the path length uncertainty. Here we show that those sectors can be used to distinguish in a qualitative manner if a particle distribution is anisotropic or not. To decrease the deadtime, at times of high count rates, the outer ring segments are disconnected. This reduces the geometric factor from $5.14 cm^2 sr$ to $0.18 cm^2 sr$ (first two proton and helium channels).

1.2. Data Structures
The EPHIN data are provided as different levels and file formats. Our analysis uses the Level-2 rate and pulse height files. The rate files contain counting rates for individual particle species plus an additional channel for penetrating particles (the integral channel). In addition, the rates are divided according to the energy channel and - in case of protons and helium isotopes - according to trajectory inclination relative to the sensor axis. The energy channels are defined by the penetration depth in the sensor, e.g. the channel P4 predominantly counts protons that stop in the second detector. The inclinations are given by the extension GM, GR and S.

Here P4 GM designates the protons with energy between 4.3 and 7.8 MeV which, when passing detectors A and B, have passed through the central sectors (sectors A0 and B0 as designated in Fig 1). Notice that only particles with trajectories whose inclination $\Theta$ relative to the sensor axis is less then $21^\circ$ fit into this category. The GR group contains rates of trajectories passing through corresponding sectors A1 and B1 or ... or A5 and B5 having $\Theta$ between 0 and
28 degree. Finally, the S rates contain trajectories with Ax, By where \( x \neq y \) and \( \Theta \) between 0 and 42 degree. To improve the isotope separation, for Helium, the S rate has been split into S1 and S23 rates. S1 contains trajectories where either A0 or B0 (but not both at once!) with \( \Theta \in \{0^\circ, \ldots, 34^\circ\} \). S23 contains trajectories with Ax and By where \( x, y \in \{1, \ldots, 5\}; x \neq y \). In total, there are 16 Helium count rates per observation interval.

The pulse height files contain detailed energy deposition per detector and the detector A and B segment information. Number of pulse-height analyzed particles is only a statistical sample. Helium events are given priority (designated with the priority flag).

The pulse height and count rate files are interrelated, as are the developed methods. In most cases we use both to achieve results.

2. Directional response function

To determine the directional response function of the instrument we developed a model based on a GEANT4 [4] Monte Carlo simulation. For this purpose we modeled the instrument and exposed it to an isotropic particle flux. We then modified the sample flux by making it anisotropic by introducing a preferred direction of incidence, defined by angles \( \theta_P \) and \( \phi_P \), and a polar angle distribution relative to the preferred incidence direction \( \cos^n \theta \). In this model, the particle flux contains trajectories defined with \( \theta_T, \phi_T \) relative to the preferred direction of incidence which are selected randomly with the total flux having a polar angle distribution defined by \( n \) (see figure 3).

This has been done systematically for \( \theta_P \in \{0^\circ, 10^\circ, 20^\circ, 30^\circ\}, n \in \{0, 1, 2, 4, 8, 20, 64, 256, 4096\} \) and \( \phi_P \in \{0^\circ, 36^\circ\} \). The value of \( n \) defines how "beamlike" the flux is, as shown in figure 4. An isotropic flux is given by \( n = 0 \). A flux in which all particles have the same direction would have \( n = \infty \), since \( \lim_{n \to \infty} \cos^n(x) = 0 \) for \( x \notin [0, \pm \pi, \ldots] \). This particular set of \( n \)'s defines several intermediate fluxes . \( \theta_P \) modifies the inclination of the preferred incidence direction relative to the sensor axis. \( \phi_P = 0^\circ \) represents a flux with preferred azimuthal direction of incidence parallel to the border of sectors 1 and 5 , while \( \phi_P = 36^\circ \) describes a flux bisecting the first sector (see figure 1).

We assumed that the particles move along straight lines. That is, when a particle deposits energy in a detector, its direction is not changed. Simulation results show that electrons within the measurement range are strongly scattered when interacting with the detector matter (compare electron trajectories shown in red with the one of protons shown in blue in figure 2). Thus the developed method is not applicable to the electron channels, since it does not consider scattering processes. The simulation shows that the change of direction for ions is negligible...
Figure 5. The aperture of 3 virtual detectors is projected onto a spherical surface at infinite distance. The virtual detectors are designated with $g$ (see equation (2)). The lower panels show the $\phi$ and $\theta$ sensitivities of the virtual detectors.

(blue trajectories in figure 2). Simulations have been performed using non-interacting particles (geantinos). The method is an extension of the Monte Carlo determination of geometric factor, as described by Sullivan [5].

Our guiding idea is that separate counters can be viewed as individual particle telescopes.

2.1. The rate data

Figure 5 shows on top the areas covered on the sky by 3 different sector combinations. The lower left panel shows that for $A=0, B=0$ no sensitivity in $\phi$ is found. However, the combinations $A=0, B=4$ and $A=2, B=4$ cover similar $\phi$ ranges with a peak at 230° and 260° respectively. From the right panel it is obvious that all 3 combinations cover different $\theta$ ranges. Thus when combining all sector combinations with $A=0, B \neq 0$, the $\phi$ dependence is lost. The same is true for all sector combination groups found in the rate files. Calculating all different combinations and grouping them accordingly to the EPHIN data gives the result in figure 6. We have also divided the relative intensity by the number of sector combinations within each group.

The next step involved reproducing the EPHIN data products. We used our simulation results to calculate the ratios of the three proton variables and tried to map them to the flux parameters $\theta_P, \phi_P, n$. In figure 6 we see that the sensitivities of the GM and GR groups are very similar. Therefore we combine them in a single count rate $G$. The proton flux is now characterized by only two variables: the countrates $G$ and $S$. We derived a single quantity - the count rate factor
\[ F = \exp \left[ -\frac{G}{S} \right] = \exp \left[ -\frac{GR + GM}{S1 + S23} \right]. \]  

(1)

Figure 6. \( \phi \) and \( \theta \) sensitivity divided by the number of sector combinations per group

Figure 7 shows how \( F \) depends on the simulation parameters \( n, \theta_P \). The simulation showed no significant dependence of \( F \) on the third simulation parameter \( \phi_P \).

For some sets of simulation parameters, \( F \) is unique enough to allow direct mapping. This is the case for areas designated U and W, which correspond to strong particle beams. Areas V and Y have similar \( F \) but correspond to completely different sets of simulation parameters. Finally in the area between U, V and Y we have to use the pulse height data, since no information about \( \theta_P \) or \( n \) can be recovered from the rate data.

2.2. The pulse height analysis (PHA) data

In figure 7, for \( \theta_P = 20^\circ \) we have very similar \( F \) for \( n = 1 \) and \( n = 8 \). Using the detailed information that are available for a statistical sample of all measured events, we can discriminate between such cases. A particle measured in segment \( x \) and \( y \) of detector A and B, respectively, could be assigned to group:

\[ g = 6 \times x + y. \]  

(2)

When grouped in this way, we have defined 36 virtual telescopes. For each of those, a sensitivity matrix \( R_g \) representing the response similar to figure 5 has been generated. Each response matrix holds information about the relative directional acceptability of each virtual telescope. Figure 5 shows for three combinations the sensitive region in the sky and its response function in theta as well as in phi.

This pulse file method can help us in cases were the rate file method leads to ambiguity. If we multiply the response matrix \( R_g \) of each sector combination \( g \) with the actual count rate \( n_g \)
during some observation interval, we get the flux intensity as a function of the azimuthal and polar angles $\phi, \theta$. An example of this procedure can be seen in figure 12. A flux with values of $n$ higher than 2 has to show dominant peaks in the intensity plot. Based on this, we can investigate if the count rate factor $F$ is assigned to area V or Y.

It is sometimes helpful to observe only the $\phi$ profile of a given flux, namely $\sum n_g \cdot \Phi_g$ with the associated poissonian error $\sqrt{\sum n_g \cdot \Phi_g}$. The error is indicated in figures 9-11 by the thickness of the graph. Careful analysis shows that this is an error overestimation, since several of the 36 virtual detectors have similar sensitivity matrices (e.g. GR group) and their count rates could be added together to improve statistics. By fitting a $\cos^n(\phi)$ function within the thick graph of such $\phi$ flux profiles, we can approximately determine $n$.

The final algorithm exploits both data sets. First the count rate factor $F$ is calculated from the rate data. This usually reduces the number of possible simulation parameters $n, \theta_P$ to which the data can be mapped. Then, the phi flux profile is reconstructed from the PHA data and finally $n$ is approximated. After crossreferencing the results, we are able to characterize the incident flux. This is successful in cases with good statistics, i.e. high count rates. Sometimes the observation interval has to be increased at the cost of resolution. If pulse height analysis was available for all events, we would have to work only with the PHA data.

3. Application

3.1. SEP event of 3th of November, 2011

As an example we analyzed the proton flux of the SEP November 3th 2011 event (measured with EPHIN on 04.11.2011). This event has been discussed by Gómez-Herrero (see [6]).
Figure 8. EPHIN Proton intensity profile with ACE magnetic field data given using the RTN (Radial Tangential Normal) coordinate system.

Figure 9. A [00:00-03:00]  Figure 10. B [03:00-06:00]  Figure 11. C [06:00-09:00]

8 displays at the bottom the intensity profile of the event. The top shows the local magnetic field at L1 measured by ACE (Advanced Composition Explorer). Measurements with WIND spacecraft (not shown here) indicate very similar magnetic field directions. It is important to note that ACE, SOHO and WIND are all at L1, but not exactly at the same location. Since the field configurations are similar at ACE and WIND, it is plausible to assume, that the magnetic field at SOHO is similar too.

The analysis has been conducted with a three-hour accumulation interval. In that case more than 4000 counts were available for the calculation of the azimuthal angle intensity profile. In table 1 we summarized the measured count rate factor as well as the determined preferred $\theta$ and $n$. This event is remarkable, because the anisotropy is maintained and non-varying over a several hour period. The event has been divided according to measured anisotropy into three parts: A, B and C (see figures 9, 10 and 11). These figures show the relative intensity (arbitrary units) as a function of the azimuthal angle $\phi$. The determination of the flux parameters during the interval C was only possible because both data sets have been used. Results shown in figure 12 show the reconstructed angular distribution. The bluish circles show the ACE magnetic field direction.

Note that our method depends considerably on the assumption that the preferred angle of incidence does not change during a single accumulation interval. The validity of this assumption is supported if the azimuthal intensity plots (figures 9 and 10) show only one dominant peak. Lack of such peaks indicates intervals with nearly isotropic particle flux (figure 11). Shortening of the accumulation interval sometimes removes additional dominant peaks, on cost of the statistics.
Figure 12. Relative angular distribution of the incident proton flux for the 3 periods A, B and C (in arbitrary units). Also shown is the direction of the Sun and the direction of the local magnetic field vector according to ACE. The size of the magnetic field marker indicates the statistical uncertainty of the 3-hour averaged direction. In the lower left figure, $\vec{B}_{ACE}$ is outside the range. Also, the ring distribution in this panel is due to the geometry of the telescope [5].

4. Conclusion and outlook
We have successfully developed a method which enables anisotropy measurements using EPHIN. This is limited to periods where all detector segments are operational. Soon we plan to switch to a new data set in which the electron contamination of proton and helium channels is removed. The developed method serves as a proof of concept: multisector detector stacks can indeed be used to gain information about the angular distribution of the incident particle flux and, if the local magnetic field is known, the determination of the pitch angle distribution. Our method could be used in future for optimizing in-situ particle telescopes.

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