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The influence of in situ pitch-angle cosine coverage on the derivation of solar energetic particle injection and interplanetary transport conditions

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Abstract

Modelization of solar energetic particle (SEP) events aims at revealing the general scenario of SEP injection and interplanetary propagation and relies on in situ measurements of SEP distributions. In this paper, we study to what extent the LEFS60 and LEMS30 electron telescopes of the Electron Proton Alpha Monitor (EPAM) on board the *Advanced Composition Explorer* are able to scan pitch-angle distributions during near-relativistic electron events. We estimate the percentage of the pitch-angle cosine range scanned by both telescopes for a given magnetic field configuration. We obtain that the pitch-angle coverage is always higher for LEFS60 than for LEMS30. Therefore, LEFS60 provides more information of the directional distribution of the observed particles. The aim of the paper is to study the relevance of the coverage when fitting LEFS60 particle measurements in order to infer the solar injection and the interplanetary transport conditions. By studying synthetic electron events, we obtain that at least 70% of the pitch-angle cosine range needs to be scanned by the telescope. Otherwise, multiple scenarios can explain the data.

Keywords: Energetic particles; Monte Carlo simulations; Electron events

1. Introduction

In situ measurements of the pitch-angle distributions of solar energetic particles (SEPs) play an important role in the investigation of the solar particle acceleration and injection mechanisms, and the properties of their subsequent transport through interplanetary space. Modelization of SEP events aims at revealing the general scenario of SEP injection and transport and relies on in situ directional measurements of SEP distributions. Therefore, it is important to understand to what extent the observational data computed by a telescope maps the pitch-angle distributions (PADs) during an SEP event. Only those events observed with high pitch-angle coverage can provide the most conclusive studies about the transport and injection history of SEPs.

Many particle experiments use the rotation of the spacecraft to measure the PADs of SEPs in interplanetary space, because it allows a single detector to scan different directions of space as the spacecraft spins. The swath of space swept out by a detector during a spin is normally divided into nearly equally spaced sectors. The number of counts recorded while scanning each sector together with the measurement of the interplanetary magnetic field (IMF) direction is used to infer the PADs of the particles or derive the anisotropies (Ng, 1985; Sanderson et al., 1985). The number of sectors determines the resolution in sampling

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the directional distribution of the incoming particle population.

In principle, a single detector is not able to provide full information of the three-dimensional SEP distribution. Hence, multiple detectors mounted at different positions with respect to the spin axis are needed, such as in the Low Energy Proton Experiment (DFH) on board *ISEE-3* (Sanderson et al., 1981) or in the three-dimensional Plasma and Energetic Particle Investigation (3DP) experiment on board *Wind* (Lin et al., 1995).

In this paper, we address the question of the role that the pitch-angle coverage of the telescope plays when trying to infer from in situ measurements the injection and transport conditions of SEPs. In Section 2 we explain how to quantify the pitch-angle cosine coverage of a telescope on board a spin-stabilized spacecraft. We focus on the study of two electron telescopes of the Electron Proton Alpha Monitor (EPAM) experiment (Gold et al., 1998) on board the *Advanced Composition Explorer* (*ACE*) spacecraft, i.e. the LEFS60 and LEMS30 telescopes. In Section 3, we assume an injection profile of electrons at the Sun and set the interplanetary transport conditions to simulate synthetic electron events. By taking into account the angular response of the telescope and assuming an IMF configuration we are able to transform the simulated PADs into synthetic sectored intensities and study how spin-averaged intensity profiles change depending on the region of the PAD that the telescope is able to scan. In Section 4, we study the role of the pitch-angle coverage when deconvolving synthetic events. Section 5 summarizes the main conclusions of this work.

2. Pitch-angle cosine coverage

ACE is a spin-stabilized spacecraft orbiting the L1 libration point. The spin axis of the spacecraft points within 20° of the Sun and the spin period is of 12 s (Gold et al., 1998). As the spacecraft spins, the detectors sweep out swaths of space, providing information of the SEP directional distribution. The space scanned by each detector during one rotation is divided into nearly equally spaced sectors.

Of particular interest to this study are the LEFS60 and LEMS30 electron telescopes of the EPAM experiment. The LEFS60 telescope measures near-relativistic (45–312 keV) electrons in four energy channels. The detector has a full-cone opening angle of 53° and points at 60° from the spacecraft spin axis. As the spacecraft spins, the measurements are divided into eight sectors, each 45° wide (Gold et al., 1998). Similarly, the LEMS30 telescope measures near-relativistic (38–315 keV) electrons in four energy channels. The detector has a full-cone opening angle of 51° and points at 30° from the spacecraft spin axis. This telescope provides measurements into four sectors, each 90° wide (Gold et al., 1998).

The directions scanned by each sector and their relative probability can be estimated by calculating the angular response of a sector. Agueda et al. (2008) presented a method to calculate the angular response of the sectors scanned by a detector on board a spin-stabilized spacecraft, such as the sectors scanned by the LEFS60 and LEMS30 detectors. Fig. 1 sketches the solid angle encompassed by the LEFS60 telescope projected onto a sphere and the approximate definition of the sectors. In the spacecraft coordinate system, z is the spacecraft spin axis and the x–y-plane is perpendicular to the spin axis. Note that the directions scanned by a given sector remain constant in the spacecraft coordinate system. The pitch-angle cosine of a particle, μ, is defined as the cosine of the angle α between the particle velocity and the magnetic field vector; $\mu = \cos\alpha$. Then, the pitch-angle cosine of the particles scanned by a sector depend exclusively on the magnetic field vector direction. We define a generic IMF vector in the spacecraft coordinate system given by the unit vector $\overline{B} = (1, \theta_B, \phi_B)$ expressed in spherical coordinates where θ_B is the polar angle and ϕ_B is the clock-angle. As can be seen from Fig. 1, a change in θ_B produces a change in the range of μ swept by the telescope. Whereas a change in ϕ_B, modifies the range of μ scanned by each sector but it does not change the total μ-range scanned by the telescope.

Using the same grid of directions (θ, ϕ) as in Agueda et al. (2008) for the calculation of the angular response function of a sector, we can calculate a matrix of pitch-angle cosines, $\mu_{jk} = \mu(\theta_j, \phi_k, \hat{B})$, for a given orientation of the IMF vector. Here μ_{jk} is a 180×360 matrix since $(\theta_j, \phi_k) \in [j\alpha, (j+1)\alpha] \times [k\alpha, (k+1)\alpha]$, with $\alpha = 1°$ and $j \in [0, 179]$, $k \in [0, 359]$. If R^s_{jk} is the angular response matrix of sector s, we can derive the view boundaries of the sector, that is, the highest and the lowest μ values scanned, by extracting the maximum and the minimum μ values of the μ_{jk} matrix that have a non-zero response. The highest and lowest μ values from all the sectors are then the maximum and the minimum μ values scanned by the telescope.

Using this procedure, we can calculate the view boundaries of the sectors as a function of the magnetic field vector orientation. The right diagram in Fig. 1 shows the view boundaries of the two limiting sectors of the LEFS60 telescope when $\phi_B = 60°$. As a function of θ_B, it shows the highest and lowest μ values scanned by two different sectors which are represented by solid and dotted curves, respectively. When $\theta_B = 0°$ or $\theta_B = 180°$ all sectors scan the same range in μ due to the symmetry of the system.

We define the pitch-angle cosine coverage of the telescope, μ-co, as the percentage of the pitch-angle cosine range scanned by the telescope for a given magnetic field configuration. Thus,

$$\mu\text{-co} = \frac{1}{2}(\mu_{\max} - \mu_{\min}) \times 100\% \tag{1}$$

Note again that the pitch-angle cosine range covered by the telescope only depends on θ_B because the system is symmetric with respect to ϕ. Fig. 2 shows the pitch-angle cosine range covered by the LEFS60 (solid) and the LEMS30 (dashed) telescopes and the μ-co of the telescopes as a func-