A method of pitch angle distribution reconstruction in PAMELA experiment

Malakhov V.V. *, **Mikhailov V.V.** *, **Grishantseva L.A** * *for PAMELA-collaboration*
Moscow Engineering and Physics Institute,RU-115409 Moscow, Russia

***Abstract*. The PAMELA apparatus is installed on board of the Russian satellite Resurs DK-1 in a low Earth orbit with an inclination of about 70 degrees and altitudes between 350 to 600 km. The satellite has 3-axes stabilization with pointing accuracy better than one degree. PAMELA instrument was developed for the study of an antimatter component of cosmic rays in near-earth space in the energy range 80 MeV - 190 GeV for antiprotons and 50 MeV - 270 GeV for positrons. The device is also capable to measure charged particle spectra of protons, electrons and light nuclei, with a large statistic along its orbit. The PAMELA apparatus comprises a time-of-flight system, a magnetic spectrometer, a silicon-tungsten electromagnetic calorimeter, an anticoincidence system, a shower tail catcher scintillator and a neutron detector. Good angular resolution of Pamela's tracking system make it possible to measure direction of particles flight in space with high accuracy. That allows to reconstruct pitch-angular distributions of particles in geomagnetic field (in South Atlantic Anomaly). Angular efficiency of the instrument was calculated by Monte-Carlo modeling. Here it is described a method to reconstruct pitch-angular distribution. This method is very important for analysis of trapped particle in the radiation belt and is uses for data processing in PAMELA-experiment. Pitch-Angular distributions was obtained on boundaries of SAA for proton.**

***Keywords*: Pitch angle, trapped radiation, SAA.**

I. Introduction

Besides the energy spectra, angular distribution of particles at low altitude is needed for study of behaviour of trapped radiation in SAA. It is known that trapped particle fluxes strongly depend on registered direction relative to magnetic field [1]. Unfortunately, most of satellite experiments in the radiation belt does not allow to obtain a direction of registered particles. Therefore it is very important to take direct measurements of particles fluxes for different pitch-angles. For precise calculation of pitch-angle it is necessary to know a particle velocity in the instrument reference frame, a satellite orientation, a vector of the Earth magnetic field in the point of registration and angular efficiency. In this paper method of reconstruction of trapped protons pitch-angle distribution is presented for PAMELA experiment. Distributions for different pitch-angles were obtained on data set collected by the instrument between 15 June 2006 and 31 December 2008

II. The instrument

The PAMELA apparatus is inserted inside a pressurized container attached to the Russian Resurs-DK1 satellite. It was launched from the Bajkonur cosmodrome on 15 June 2006 on board the satellite that was placed into a 70^o inclination quasi-polar orbit, at an altitude varying between 350 km and 615 km. A period of it's rotation is about 90 minutes that corresponds 16 orbits per day. The satellite has 3-axis stabilization with pointing accuracy better then one degree. Besides scientific mission Resurs-DK1 spacecraft comprises a device for picture taking of the Earth surface and periodically makes rotations, that results in orientation changing. The orientation data of instrument is calculated by onboard processor and written in the memory in the form of quaternions with a frequency one time per 30 seconds at the time the standard mode and one time per 0.25 second while a rotations. The quaternions data set fully describes spacecraft orientation in the space with accuracy better then one degree.

PAMELA apparatus comprises the following subdetectors: a time-of-flight system (ToF); a magnetic spectrometer; an anticoincidence system (AC); an electromagnetic imaging calorimeter; a shower tail catcher scintillator and a neutron detector. The magnetic spectrometer is basically composed by a permanent magnet and a silicon tracker. The total height of the spectrometer is 445 mm, with an inner rectangular cavity of 161x131 mm^2. Six equidistant silicon detector planes are inserted inside the magnetic cavity constitute the Silicon Tracker. The measured spatial resolution is about 4 μm [2]. Data from the magnetic spectrometer allow to determine direction of flight in the instrument reference frame with accuracy about 0.2^o.

III. Method of pitch angle reconstruction

SGP4 model [3] was used to obtain the spacecraft position and IGRF2005 model [4] was utilized for calculation of vector of the Earth magnetic field $\overrightarrow{B}$. Direction of magnetic field was given in the local geographical reference frame. For determination particle direction in space the magnetic spectrometer data were taken into account. After recovering a track parameters in the spectrometer we obtained direction of particle velocity in the instrument reference frame as vector

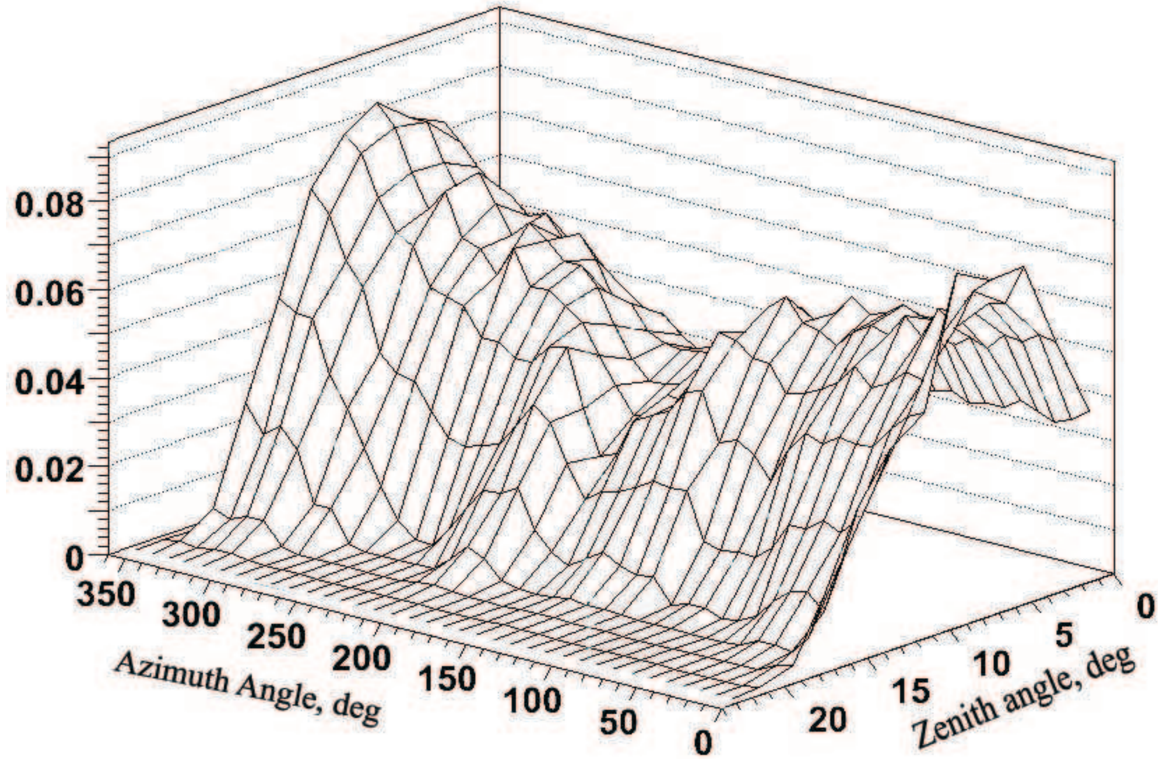

Fig. 1: Angular efficiency.
On Z-axis the angular efficiency coefficient $\varepsilon(\theta,\varphi)$ was built according with equation (3), where θ is zenith-angle, φ is azimuth-angle

$\overrightarrow{\mathbf{P}}=(P_x,P_y,P_z)$.
To calculate pitch angle ψ a rotations of vector $\overrightarrow{\mathbf{P}}$ was necessary according (1).

$$\overrightarrow{P}_{geo} = |\mathbf{I}|\overrightarrow{P}, where|\mathbf{I}| = |\mathbf{C}| * |\mathbf{B}| * |\mathbf{A}| \quad (1)$$

here $|\mathbf{A}|$ is transit matrix from instrument reference frame to inertial one, $|\mathbf{B}|$ is transit matrix from inertial reference frame to Greenwich one [5], $|\mathbf{C}|$ is rotations matrix from Greenwich reference frame to local geographical one.
Pitch angle ψ is defined as scalar product of vectors $\overrightarrow{B}$ and $\overrightarrow{P}_{geo}$ (2):

$$\psi = (\overrightarrow{\mathbf{B}}, \overrightarrow{\mathbf{P}}_{geo}) \quad (2)$$

IV. Angular efficiency estimation

For estimation of angular efficiency of the instrument protons for given directions were simulated by Monte-Carlo method using software developed in PAMELA collaboration based on GEANT 3 code.
Coefficient of angular gathering power was calculated by following formula:

$$\varepsilon = \pi S \Omega N_{reg}/N_{mod} \quad (3)$$

Here S is square of modeled area, Ω is solid angle, N_{reg} is number of registered particles, N_{mod} is number of simulated particles. ε was calculated for rigidity diapazon from 0.5 to 2 GV divided into 100MV bins. An example is shown on Fig.(1) for R=1.4÷1.5GV.

V. Method of proton fluxes calculation for different pitch-angles

The instrument orientation related to $\overrightarrow{B}$ is characterized by two angles - β and ω. β is an angle between $\overrightarrow{B}$ and main-axis of instrument (Z-axis). ω is angle between $\overrightarrow{B}$ and X-axis. Those two angles fully define an orientation of the device related to the magnetic field at every time. To calculate proton fluxes for given pitch angles (ψ_k) data sets of ω and β corresponded to this ψ were divided into *n* and *m* bins accordingly. Proton flux j_ψ(R) for this pitch-angle and fixed rigidity(R) was calculated by following formula:

$$j_\psi(R) = \frac{1}{\Delta R}\sum_{\beta=0}^{n}\sum_{\omega=0}^{m}\frac{N_{\beta\omega\psi}(R)}{T_{\beta\omega\psi}\varepsilon(\theta(\beta,\omega,\psi),\phi(\beta,\omega,\psi),R)} \quad (4)$$

Here $N_{\beta\omega\psi}$(R) is a number of events with instrument orientation (β,ω) and pitch-angles diapason ψ_k. $\varepsilon(\theta(\beta,\omega,\psi),\phi(\beta,\omega,\psi),R)$ is an efficiency depending on ω, ψ and rigidity R, see Fig 1. $T_{\beta\omega\psi}$ is a time of pointing of the instrument in the direction characterized by β,ω and ψ.

VI. Proton spectra and pitch-angle distribution

Resurs-DK1 satellite cross the radiation belt just on boundaries, in SAA area $0.180 \leq B \leq 0.215$G, L-shell$\leq$1.5. Because of zenith pointing the instrument is

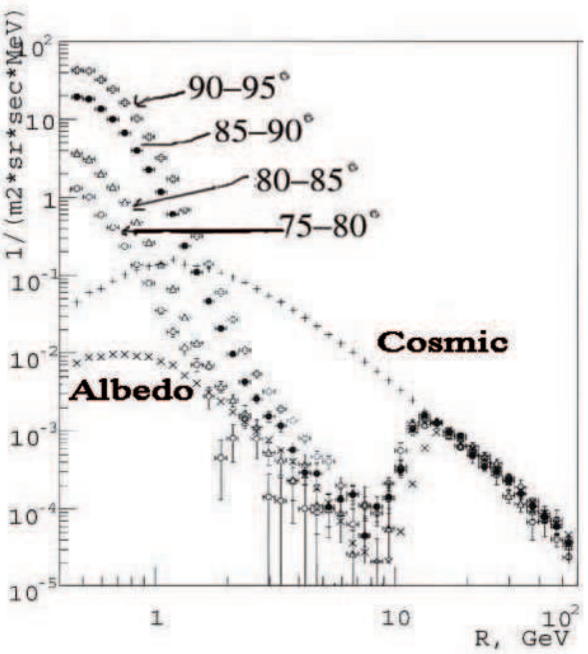

Fig. 2: Proton spectra for different pitch-angles for B<0.216G, L<1.5.
Here cosmic ray protons (daggers), equatorial protons (tilted daggers), trapped protons with pitch angles 70^o - 75^o (balls), 75^o - 80^o (triangulars), 80^o - 85^o (filled balls), 85^o - 90^o(wide diggers) are shown

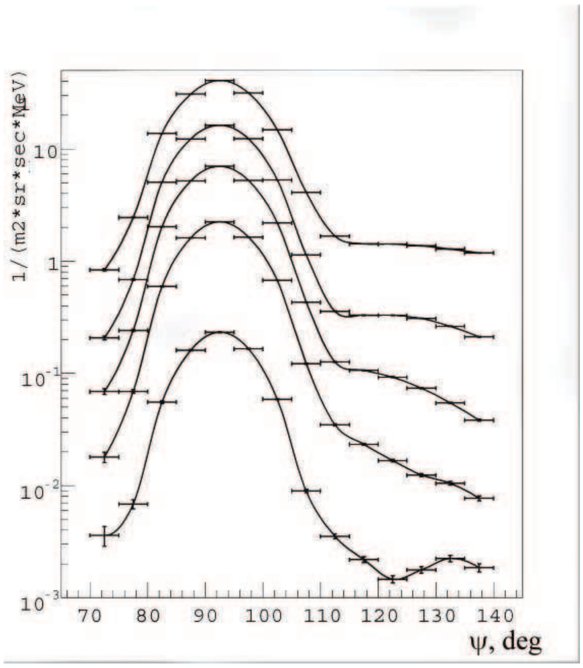

Fig. 3: Pitch angle distribution for B<0.216G, L<1.5
Here protons pitch angle distribution for R=0.5 GV, 0.7 GV, 0.9 GV, 1.25 GV, 1.6 GV are shown top-down correspondingly

able to register particles just in interval of pitch-angle from 70^o to 150^o at that region. For protons separation a data of ToF, magnetic spectrometer and calorimeter were used [2]. Pitch angles for each events was calculated by formula 2. Then pitch-angle interval was divided into 14 bins from 70^o to 140^o with 5 degrees step. Proton spectra were calculated for each bin according 4. Figure 2 shows result of spectra calculations for pitch angles between 70^o to 95^o. Proton cosmic rays spectra in the polar region and albedo spectra in the equatorial one are shown for comparison. At high energy all spectra coincide as it is expected.
Protons pitch angular distribution for rigidities close to 90^o up to $\sim$2 GV were obtained. For example, on figure 3 pitch angular distributions for rigidities R=0.5, 0.7, 0.9, 1.25, 1.6 are shown. It's possible to see that pitch angle distributions peak close to 90^o up to $\sim$1 GeV.

VII. Conclusion

The method of pitch-angular distribution reconstruction was developed for Pamela experiment and presented here. It is based on a satellite orientation data and a particle trajectory in the magnetic spectrometer. Developed method allows to reconstruct fluxes of trapped particles e.g. protons, in the radiation belt for chosen pitch-angles.

VIII. Acknowledgments

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References

[1] J.G.Roederer, Dinamics of geomagnetical trapped radiation, W. 1970
[2] Picozza, P., Galper A.M., Castellini G., .et.al., Pamela - a payload antimatter matter exploration and light-nuclei astrophysics, *Astroparticle physics,27*, 296, 2007
[3] http://www.celestrak.com/
[4] http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html
[5] Gorbatenko S.A. et.al. Flight mechanics. - M.: Mashinostroenie, 1969, in Russian