The X-ray polarimeter of solar flares for the Interhelioprobe mission: a study of the characteristics of the physical model using radioisotope radiation sources

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Abstract. The paper describes the physical model of the PING-P polarimetry unit of the PING-M X-ray polarimeter. The polarimeter is developed jointly by the Ioffe Institute and the Institute of Astrophysics of the Moscow Engineering Physics Institute for the Interhelioprobe mission. The model (PING-P-FM), made by the Ioffe Institute, represents the detector part of the polarimeter. The polarization degree is determined by the measurement of the asymmetry of the scattered radiation field. The device uses active scatterers based on paraterphenyl crystals for detecting the events of Compton scattering. A useful signal is the coincidence of pulses from one of the active scatterers (detector-scatterer) and one detector-receiver of scattered radiation. The polarimetry unit contains 3 detector-scatterers and 6 detector-receivers, thus resulting in 18 measurement channels. The requirements for instrument symmetry and stability of the measuring channels are high. The paper presents the results of an experimental study of the parameters of the measuring channels of the PING-P-FM model and their calibrations at different X-ray energies using Cd-109, Am-241, and Ba-133 isotope sources.

1. Introduction
Hard X-rays from solar flares, being the bremsstrahlung of electrons accelerated in a flare, carry the most direct information about the processes of explosive energy release in solar flares. With an isotropic angular distribution of accelerated electrons, the degree of polarization of hard X-rays does not exceed a few percent [1]. With the existence of anisotropic beams of accelerated electrons, the polarization can reach several tens of percent [2, 3]. Thus, the degree of linear polarization of hard X-ray radiation from solar flares gives unique information about the angular distribution of electrons accelerated in the flare region and, thus, about the mechanism of converting the energy of a magnetic field into other forms of energy. Despite this, there is still a shortage of reliable data in this field of knowledge.

To measure the X-ray polarization from space objects, the asymmetry of the emission of Compton scattered photons was most often used [4–10]. The layout of a polarimeter based on this principle consists of a primary radiation scatterer and detectors measuring the asymmetry of the field of scattered radiation. The greatest polarization dependence is observed when scattering is by an angle close to 90 degrees, so the detectors are usually located on the side of the scatterer.

When measuring stationary sources, it is possible to rotate the instrument around its axis directed towards the source and to obtain a modulated signal in the detectors using the epoch superposition method [4]. The modulation depth and phase allow one to determine the degree and direction of polarization.
When measuring the radiation flux from a nonstationary source such as a solar flare, this experimental approach is unsuitable. Therefore, the solar polarimeter should consist of a scatterer and a number of detectors (at least three) measuring the asymmetry of the field of scattered photons simultaneously. Such a measurement scheme places high demands on the identity of the measuring channels. When the physical differences of the detectors can be taken into account during ground calibration, the drift of energy thresholds in flight can lead to significant measurement errors [8]. The requirements for high stability of energy thresholds are stipulated by the steeply decreasing energy spectrum of radiation, because slight differences in the thresholds lead to significant differences in the counting rates in the detectors.

All solar X-ray polarimeters, except for the PENGUIN-M polarimeter, used scatterers made of beryllium [5–10]. In a number of instruments for the correction of instrument asymmetry, a rotary mechanism was used, providing measurements in two different positions [7, 9].

In the PING-M device [11], as well as in the PENGUIN-M device, active scatterers are used. That means, the scatterers are at the same time detectors for Compton recoil electrons. The receiving detectors register X-ray photons scattered at angles close to 90 degrees. A useful signal is the coincidence of pulses in one of the detectors-scatterers (DR) and one of the detectors-receivers (DP)\(^1\).

The useful event has two characteristics: the energy of the Compton electron, registered in the DR, and the energy of the scattered photon, registered in the DP.

The use of active scatterers allows to solve the problem of the strong influence of the instability of the energy thresholds of detectors registering scattered radiation on the measurement results. At Compton scattering at a right angle, the energy of the recoil electron depends on energy of the primary photon. Thus, if a certain lower energy threshold for the registration of recoil electrons is set for DR, then in the double coincidence mode only photons with energies higher than some will be recorded in DP. In this case, the photon spectrum recorded in the DP will be cut off from the side of low energies. This energy cutoff is determined by the threshold of the DR and is the same for all DP’s. Even if the energy threshold in the DR changes slightly, the cutoff energy will change in all the DP’s equally and the instrument symmetry will not be broken.

2. Construction of the PING-P-FM physical model

The PING-P-FM unit includes:
- three detector-scatterers (DR1…DR3) with Ø35×30 mm paraterphenyl crystals and Hamamatsu R3886A photomultipliers;
- six detector-receivers (DP1…DP6) with CsI(Tl) Ø45×5 mm crystals and Hamamatsu R10131-01 photomultipliers;
- preamplifiers and high-voltage power supplies.

The layout of the detectors is shown in Figure 1.

The information obtained from the physical model represents the one- and two-dimensional pulse height spectra recorded by the detectors. As a result, we obtain the following data:
- 256-channel amplitude spectra of single pulses from each of the detectors;
- the spectra of double coincidences of the signals from each DR with each DP (total of 18 double two-dimensional spectra) with subdivision into 40×40 amplitude channels in the energy range: 0 to 36 keV plus one integral channel (> 36 keV) for DR; 0 to 496 keV plus one integral channel (> 496 keV) for DP.

\(^1\) DR and DP are transliterated Russian abbreviations for Detector-Rasseivatel and Detector-Priyomnik.
3. Equalization of the energy scales of detectors
Calibration and adjustment of the energy scales of the detectors – both scatterers and receivers – was carried out using the Cd-109 radioisotope source. Calibration of the detector-scatterers is performed by the 22 keV line, and detector-receivers – by the 88 keV line. Gain adjustment in the signal transmission paths is carried out by varying the high voltage at the photomultipliers.

The estimation of the line position was obtained by approximation of the pulse height spectrum by the Gauss function. Examples of such an approximation are presented in Table 1. The results of the approximation are the parameters of the peak: $A$ is the average amplitude (expressed by the number of channels), $R$ is the energy resolution, $S$ is the peak area.

Table 1. Characteristics of the PING-P-FM detectors.

| Parameter | Detector-scatterers, line 22 keV | Detector-receivers, line 88 keV |
|-----------|----------------------------------|---------------------------------|
|           | DR1 | DR2 | DR3 | DP1 | DP2 | DP3 | DP4 | DP5 | DP6 |
| $A$       | 66.6| 66.7| 66.7| 44.2| 44.3| 43.8| 44.1| 43.7| 44.2|
| $R,\%$    | 44  | 43  | 43  | 26  | 24  | 27  | 23  | 24  | 23  |
| $S$       | 54200| 52830| 58010| 26530| 28750| 26790| 25040| 26940| 31850|

4. Energy dependence of detector parameters
The dependence of the amplitude of the pulses and the resolution on the energy was studied for detector-receivers using three radioactive sources: Am-241, Ba-133 and Cd-109. Before measurements, the gain in the detectors was equalized at the 88 keV line. The average pulse amplitude and energy resolution were determined by Gaussian approximation of the peaks in the pulse-height spectrum. The results are shown on Figure 2.

5. The instrument asymmetry
In this experiment, double coincidence spectra from Cd-109 and Am-241 sources were recorded. From these spectra, counting rates were calculated for groups of channels which can be attributed to a
Figure 2. Average pulse amplitude (A) and energy resolution (R, in percent) for detector-receivers as function of photon energy (E).

specific spectral line of incident radiation. Figure 3 shows an example of the spectra with selected areas.

The degree of symmetry of the polarimeter can be characterized by the following values. Eighteen pairs of detectors (DR-DP), available in the device, are divided into three groups. Detectors belonging to the same group are located at the same distance from each other: near, middle and far pairs. Ideally,

Figure 3. Examples of double coincidence spectra and areas selected for count rate summation. Left panel: for photon energies 22 keV (bottom spot) and 88 keV (upper spot). Right panel: for 59.5 keV. Horizontal scale is the amplitude of the signal in the detector-receiver, vertical scale – in the detector-scatterer (channel grid is uneven).
the counting rate of double coincidences from a non-polarized source should be equal in pairs of
detectors of the same group.

Measurements at energies of 22, 59.5 and 88 keV showed that the differences in count rates of
different pairs of the same group reach as much as 16%. On the other hand, the relative count rate
deviations of different detector pairs are qualitatively similar for all energies. Thus, for polarimetric
measurements, it is necessary to introduce correction factors that equalize the sensitivities of the
registration channels.

Channel sensitivity can be expressed as

\[ N_{ij} = P_i \cdot W_j \cdot \Omega_{ij}, \]  

where \( P_i \) is the registration efficiency of DR(i), \( W_j \) is efficiency of DP(j), \( \Omega_{ij} \) – geometric factor, i and j
are the numbers of DR(i) and DP(j), respectively. Turning to the relative (to the average) values and
taking into account that the corrections to the above parameters are small values, we can write in a
linear approximation:

\[ \delta n_{ij} = \delta p_i + \delta w_j + \delta \Omega_{ij}, \]  

where \( \delta n_{ij}, \delta p_i, \delta w_j, \delta \Omega_{ij} \) are correction factors to relative values of channel sensitivities, efficiency of
DR’s, efficiency of DP’s, and geometric factors, respectively. The geometric factors are not
independent variables, since they are determined by a smaller number of geometric parameters. The
values of \( \delta n_{ij} \) are determined by experiment. Corrections to the detector efficiencies and geometric
factors were found using the least square method. It means minimizing the sum over all i’s and j’s of
squares of differences between the calculated and measured values of \( \delta n_{ij} \). The obtained values
allowed us to equalize the sensitivity of the channels with an accuracy of 1–2%, which corresponds to
the statistical accuracy of the measurements.

6. Registration efficiency
The probability of registering a single pulse in the detector-scatterer per 1 incident photon is 24% at
the 22 keV line. This value is determined based on the activity of the source and the observed count
rate.

The probabilities of registering double coincidences and the effective area of the polarimeter for
different X-ray lines are given in Table 2.

| Pairs of detectors | Registration probability, % |
|-------------------|---------------------------|
|                   | 22 keV | 59.5 keV | 88 keV |
| Near              | 0.39   | 3.61     | 4.4    |
| Middle            | 0.12   | 1.22     | 1.3    |
| Far               | 0.03   | 0.46     | 0.4    |
| Sum               | 0.54   | 5.29     | 6.1    |
| Effective area, cm² | 0.16   | 1.5      | 1.8    |

7. Conclusion
The studies of the physical model confirmed the practical possibility of the polarimeter operation
of the proposed geometry with an active scatterer in double coincidence mode, in the energy range
above \( \approx 20 \) keV. Such a low limit of registration is achieved thanks to use of paraterphenyl crystals
with high light output as a scatterer.

The characteristics of the polarimeter detectors are determined, the linearity of the energy scale is
proven for detector-receivers (CsI) over the working energy range. An effective procedure has been
developed for the symmetrization of measurement channels in the double coincidence mode.
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