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Review

Charged Particle Monitor on the Astrosat Mission

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Abstract. Charged Particle Monitor (CPM) on-board the Astrosat satellite is an instrument designed to detect the flux of charged particles at the satellite location. A Cesium Iodide Thallium (CsI(Tl)) crystal is used with a Kapton window to detect protons with energies greater than 1 MeV. The ground calibration of CPM was done using gamma-rays from radioactive sources and protons from particle accelerators. Based on the ground calibration results, energy deposition above 1 MeV are accepted and particle counts are recorded. It is found that CPM counts are steady and the signal for the onset and exit of South Atlantic Anomaly (SAA) region are generated in a very reliable and stable manner.

Keywords. Scintillation detector—photodiode—high-energy proton—South Atlantic Anomaly.

1. Introduction

Satellites in the Low Earth Orbit (LEO) pass through the trapped radiation belts of the South Atlantic Anomaly (SAA). In this region, the particle environment can change very drastically within a few tens of seconds. A model for the SAA can be created from data accumulated by previous missions, but that does not account for variable influences like solar flares. Previous studies indicate a significant drift rate of the SAA region (Badhwar 1997; Ginet *et al.* 2007).

The charged particles (mostly consisting of protons) cause adverse effects like the saturation of the detectors, detector dead-time (after SAA), aging of the detectors, etc. Hence, in SAA region, most of the X-ray detectors need to be switched off. To optimize the operation time of the detectors, this region needs to be monitored and the entry and exit times of the satellite in the SAA region need to be estimated accurately.

Astrosat is a multi-wavelength observatory which was launched on 2015 September 28 in a LEO with an altitude of 650 km and an inclination of 6°. Primary instruments of Astrosat include the Soft X-ray Telescope (SXT), three Large Area X-ray Proportional Counters (LAXPCs), the Cadmium-Zinc-Telluride Imager (CZTI), the Ultra-Violet Imaging Telescope (UVIT) and the Scanning Sky Monitor (SSM) (Singh *et al.* 2014). Many of these instruments are sensitive to charged particles in the SAA region. With low source counts of X-ray sources, it is desirable that the observation time of each instrument is maximized. For better optimization, a monitor for particle count rate, called Charged Particle Monitor (CPM), has been installed as an auxiliary payload on the Astrosat satellite.

In previous missions, to alleviate the problem of particle bombardment, particle monitors were incorporated alongside the primary instruments. Rossi X-ray Timing Explorer (RXTE) included a particle monitor with the High Energy X-Ray Timing Experiment (HEXTE) (Rothschild *et al.* 1998) and BeppoSAX mission with Phoswich Detection System (PDS) (Frontera *et al.* 1997). Both particle monitors used plastic scintillators coupled with a Photo-Multiplier Tube (PMT). In both cases, the particle monitor sent a signal to reduce the voltage of the PMT connected to the Phoswich detector when the satellite was in the SAA region.

CPM in Astrosat is designed to measure the count rate of charged particles at the satellite location. It is sensitive to protons above 1 MeV. The following sections detail the device design, electronics and calibration procedure used on ground and in-flight for the assessment of the device.

2. Detector design

For CPM, we use the basic design parameters of the charge particle monitor onboard the RXTE satellite (Rothschild *et al.* 1998). A scintillation detector for detecting area 1 cm^2 provides a typical count rate of about 1 s^{-1} outside the SAA region, increasing (in a typical e-folding time of 40 s) to several hundred counts per second in the SAA region. Outside the SAA region the background is mostly protons, and the electron component increases in the SAA region and it changes with position and solar activity (Koshiishi 2014). Further, the proton spectrum is flat up to 20 MeV and falls off sharply thereafter (Koshiishi 2014). Hence for the CPM, we chose a particle detector of similar area, lower energy threshold of 1 MeV (so that the integral counts will not change more than 10% with a factor of 2 uncertainty in the threshold). It is estimated that gamma-ray bursts and solar flares can give a measurable count rate (>10 counts/s) above 0.5 MeV in very rare cases (occurring at a rate of less than once per year). The time-scale for detecting the entry and exit of SAA is kept large enough to ignore such rare events.

Scintillation detectors combined with a photo-diode are used for the detection of high energy particles. They are preferred over standard photo-multiplier tube (used in HEXTE particle monitor; Rothschild *et al.* 1998) for their compactness and stability in gain (Murray & Meyer 1961). A 10 mm cube of Cesium Iodide Thallium activated (CsI(TI)) crystal (wavelength = 550 nm) with teflon reflective material is coupled to the same area window of a Si-PIN diode. CsI(Tl) detector has sufficient sensitivity for charge particle detection and it is very rugged to use. This photo-diode has a broadband response in the visible spectrum (average efficiency of ∼50%) with high sensitivity, low dark current and good energy resolution. To achieve the lower energy threshold requirement, the top side of the detector is covered with a very thin sheet (25.4 μm) of Kapton. The Kapton window, along with a protective 10 μm teflon tape gives an effective low-energy threshold of about 1.2 MeV[1] . The Kapton window gives adequate protection and also gives a reasonable low energy threshold. The electronic threshold is programmable and has been kept at 0.5 MeV. CsI crystal has higher detection probability for gamma-rays (Murray & Meyer 1961), which has been used in the calibration of the device.

2.1 *Electronic design*

When a proton strikes the detector, it causes ionization, thereby resulting in a bunch of photons, the total number of which is proportional to the energy of the incident proton. The photo-diode converts these photons into an electrical signal by generating a voltage proportional to the number of photons. Since the photodiode output impedance is high and signal level is around a few millivolts, a low noise Charge Sensitive Pre-Amplifier (CSPA) is used to process the signal. The CSPA is placed just behind the photo-diode to reduce noise. The CsI(Tl) crystal, along with Si-PIN photo-diode and CSPA, are all combined into a small compact module.

The output of the CSPA can be connected to a Multi-Channel Analyser (MCA) in the lab to get the required spectral information. In the flight model, the output of the CSPA is connected to a comparator. The comparator takes another input from the Low-Level Discriminator (LLD) circuit. If the signal from the CSPA is higher than the LLD signal, the comparator sends a pulse to the gating circuit. The level of LLD is programmable from ground. The event pulse generated from the comparator is passed through a free running 16-bit counter. This counter is gated at 5 s intervals, at which it sends the accumulated counts to the processing circuit. The gating time of 5 s is also programmable from ground.

The count rate is transmitted through telemetry to the ground station. It is also made available to onboard experiments in a serial format. This count rate is compared with a preset value, which is programmable from ground. Whenever the count rate is greater than the preset value, an output is activated. This output is deactivated whenever the count rate goes below the preset value. To avoid false triggering, the output is activated/de-activated only after confirmation of 3 successive count rates exceeding the set value. These SAA

[1] Based on the standard range calculations as given in http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

Table 1. Design specifications of CPM.

Scintillator	CsI(Tl)
Size	10 mm × 10 mm × 10 mm
Light collector	Photodiode with CSPA
Electronic low energy threshold	0.5 MeV
Window	25.4 μ Kapton
Window threshold	1.2 MeV
Field-of-View	2π Steradians
Gating time	5 s (1 s 100 s))
LLD	1 MeV (programmable)
Count rate threshold	3 counts/s (programmable)
User output	Serialized count rates and SAA signal

warning outputs are available for the other onboard experiments. The design specifications of CPM have been summarized in Table 1. The interval of 15 s being one-third of the e-folding time of the SAA (Rothschild *et al.* 1998) causes only a small increase in the counts to which payload instruments are exposed to. The payload instruments can also use a hard boundary in case of CPM trigger failure.

3. Ground calibration

The CPM, by design, is sensitive to protons above about 1 MeV and it provides the count of the number of protons it detects above this energy. It was found that the number of particle counts in the laboratory is very low and it is extremely difficult to test the detector with a beam of charge particles at every stage of the experiment. Hence we evolved the following strategy for ground calibration. Since the detector is sensitive to any ionizing radiation, the response of the detector to protons and gamma-rays are established first for the engineering model. For further versions of the package (qualification and flight models), tests are carried out using gamma rays of known energies from radioactive sources. Further, a method was established to extract the gain of the system using only the count outputs. At every stage of testing, response for gamma-rays are measured to understand the behaviour of the detector.

Spectral analysis of gamma-ray sources were done to determine the stability of the detector as well as the response of the detector in various operational conditions. The output of the CPM is the number of events with energy greater than the LLD. As the output of the device does not have direct energy information, different methods were used to get energy information. An MCA was used only for the engineering model (EM). For qualification and flight models (QM & FM) integral spectrum was obtained by varying the LLD, which was later differentiated to get the actual spectrum. The spectrum obtained from the MCA is shown in Fig. 1(a), while the differentiated spectrum in shown in Fig. 1(b).

The calibration included illumination of the device with radioactive sources and determining the peak position in the differentiated spectrum by fitting a Gaussian function. The position of the peak and the Full Width at Half Maximum (FWHM) was used for the calibration of the device. To observe the response of the detector, testing was done for different sources, and to see the effect of particles on the detector, protons of different energies were bombarded on the detector. Further experiments tested the stability of the detector by observing for different time durations and in different environmental conditions.

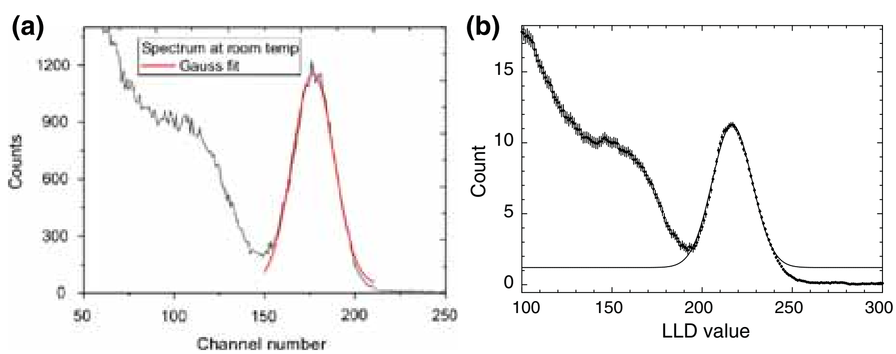

Figure 1. Spectrum of radioactive source ^{137}Cs obtained from CPM. (**a**) A Multi Channel Analyser (MCA) was used to obtain the spectral information in the Engineering Model (EM). (**b**) Spectrum for further models was obtained by changing the LLD levels and reading the counts above it. The integral spectrum thus obtained was differentiated to get the spectrum.

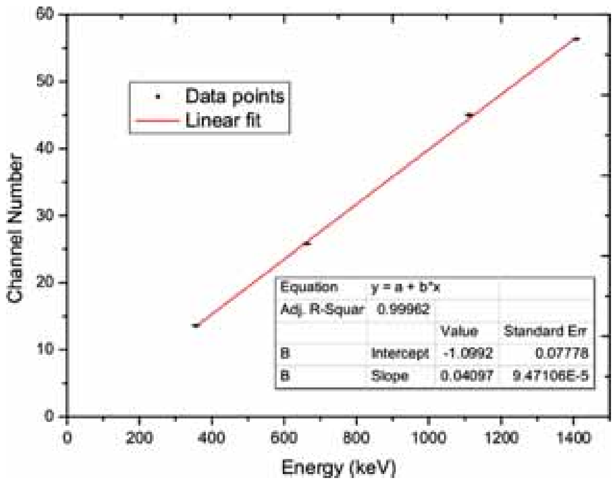

Figure 2. Linearity in the peak position for different gamma ray sources (linear regression coefficient R^2 of 0.9955).

3.1 *Linearity in gamma ray response*

The detector was tested with different radioactive sources to observe the response of the device. The gamma rays produced by these sources are close to the expected energy threshold of the detector and can thus characterize the detector performance at those energies. The sources used were ^{133}Ba, ^{137}Cs and ^{152}Eu. The peak position followed an increasing trend and was fitted with a linear function. Figure 2 shows the fitting function and its parameters. MCA channel 1024 corresponded to 10 V. On converting energy from the fitting, the detector gain works out to around 1.20 mV/keV.

3.2 *Linearity in high-energy particle response*

Since the CPM is supposed to detect charged particles, the testing of the device was also done using proton beams. Proton beams of energy 15, 17 and 18 MeV were generated in BARC-TIFR Pelletron facility. The proton beams for lower energy were not used as at lower energies the beam is not well defined and it was difficult to make controlled experiments. The available proton incidence rate was around 10^{10} counts/s and the expected count rate in deep SAA is only 10^3 counts/s. Thus the mounting was done off-axis to reduce the incident event rate. The observed energy of the beam was less due to attenuation by the air column, black paper, teflon and mylar covering of the detector. The combined effect of these blacking materials were estimated and the resultant proton energy impinging on the detector was calculated. The observed peak height is plotted against the estimated proton energy in

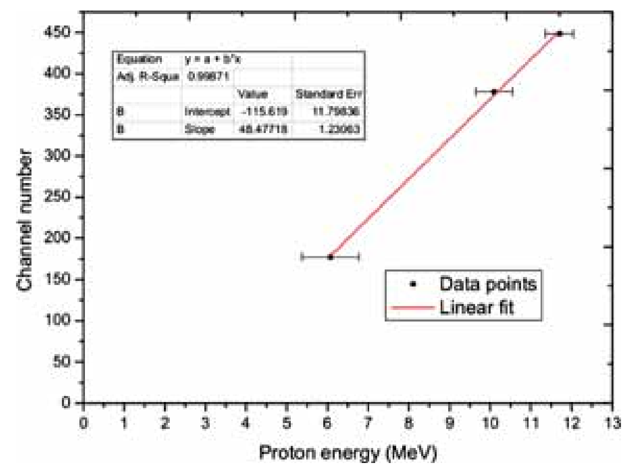

Figure 3. Linearity in the peak position for proton beams (linear regression coefficient R^2 of 0.9994).

Table 2. Variation of peak position with exposure time.

	Data Set 1		Data Set 2	
Real time (s)	Peak channel	FWHM	Peak channel	FWHM
10	170	–	184	–
100	168	24	188	27
500	171	31	187	34
1000	169	32	186	35
5000	168	33	187	34
10000	168	33	187	34
20000	167	32	188	35

Fig. 3. A linear fit is found between these two quantities.

In the MCA, 1024 channel corresponds to 10 V. From the slope of the linear fit (48.477), the conversion rate is 0.47 mV/keV. This value is lower than photon response as the light output of CsI (Tl) is lower for the protons as compared to photons (Murray & Meyer 1961). This in turn reduces the pulse height which leads to reduction in energy to channel conversion rate.

3.3 *Variation with time*

The detector was kept in the presence of a source for varying durations of time to test the effect of long exposure of radiation on the crystal and it was observed that the peak position was consistent across the readings. The data from the experiment is reported in Table 2. As can be seen from the table, for a day's observation, the values do not vary much. We did find, however, some

Table 3. Variation of peak position with environment.

Environment	Peak position	FWHM
−10°C	158	51
0°C	157	54
10°C	171	35
20°C	172	32
30°C	167	40
40°C	150	67
Room temperature (16°C)	177	27

difference in the two sets of observation (taken on 2010 October 25 and 2010 November 30, respectively). On closer inspection of experimental set up, it was found that shielding is an important parameter and the difference could be explained due to the proper shielding by a copper cover. Subsequent tests were performed by appropriate shielding.

3.4 *Variation with environment*

Testing at different environmental conditions was done in a thermo-vacuum chamber. The temperature was varied from −10°C to 40°C. The data from the experiment is tabulated in Table 3. The detector shows degradation at the extreme conditions, but is stable at the ambient conditions. This variation was attributed to the combined effect of crystal performance and amplifier gain variation. Hence, extreme care was taken to keep the detector at the optimum range of temperature during the onboard operations.

4. Onboard performance

The CPM started its operation on 29 September 2015 during the satellite's 19th orbit. The count rates from the CPM were available immediately through telemetry. The count rates for most part of the orbit, outside the SAA region, varied from 0.4 to 1 count/s. The orbit of the satellite is inclined at 6 degrees, due to which the satellite periodically passes through the SAA region. Since each satellite orbit traces a different ground path, the duration of the time spent in SAA region varies across the day. The region of SAA through which the satellite passes is non uniform in nature and thus, over the course of a day, the counts in CPM vary as shown in Fig. 4. The maximum counts detected by CPM is ∼400 counts/s, which occur when the satellite passes through the deep SAA region.

The primary purpose of the CPM is to detect the regions of high particle region in the SAA and send a signal to the devices onboard Astrosat to switch off their respective HV. To get an idea of the shape of the SAA region at the altitude of Astrosat, the counts were plotted with the latitude and longitude of the satellite. Due to the orbital variation, the region of SAA that the satellite passes through varies across days as well.

Contour maps of the SAA region were created using data corresponding to a month. Figure 5 shows the

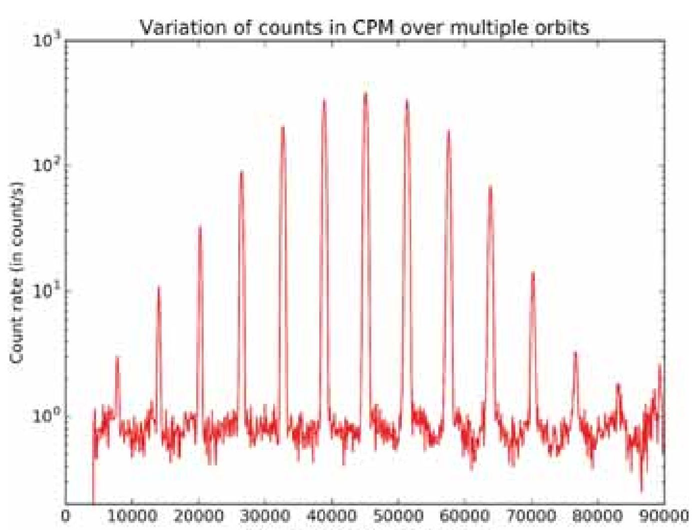

Figure 4. Light curve of count as observed by CPM. In the light curve the recurring peaks denote the section of SAA region traversed in an orbit. The highest peak denotes when the satellite ventured deepest into the SAA region. Varying peak height is caused due to the shift of the region of SAA sampled by successive orbits of the satellite.

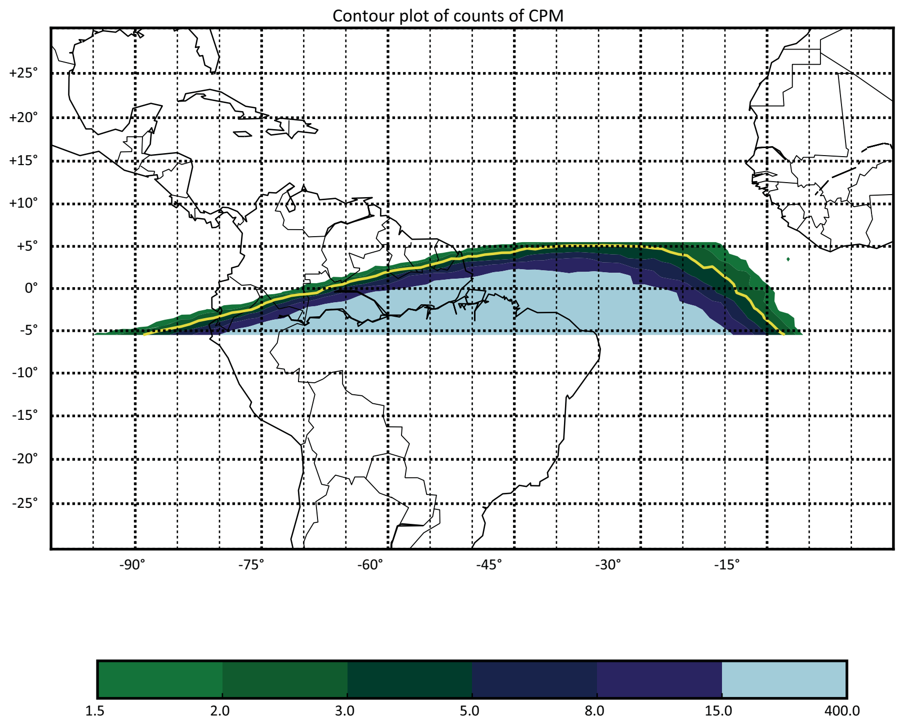

Figure 5. Contour maps of SAA region. CPM count rate data for a month was spatially binned and contour maps were generated. The contour maps show variation of count rates from ∼1 in non-SAA region to 280 counts/s on an average while the peak value reaches 400 counts/s. The boundary for SAA used in Astrosat is 3 counts/s which is shown as a yellow line in the figure. The counts less than 1.5 counts/s have not been shown for clarity of the image.

contour map for the month of November 2015. The threshold kept for Astrosat instruments is 3 counts/s, which has been shown as the yellow line.

5. Conclusions

The ground calibration successfully established the stability of CPM and the onboard testing has demonstrated the capability of CPM as a monitor of the SAA region. The CPM can successfully demarcate the SAA boundary based on the primary instrument requirement. Based on the CPM data, a hard boundary for the SAA region can be used in case CPM trigger fails to alert the instruments.

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