Space weather observations with four SREM radiation monitors

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Abstract—The ESA Standard Radiation Environment Monitor (SREM) is a particle detector developed with the main purpose of permanent monitoring of the space radiation environment and providing alerts of radiation related hazards to the spacecraft and its payload. Four SREM instruments are launched onboard of PROBA-I, ROSETTA, INTEGRAL and recently GIOVE-B satellites. SREM offers fair spectral and directional sensitivity thus allowing for precise quantitative studies of the radiation environment in the Solar system. This includes Sun transient events like Solar Energetic Particles with their propagation through the interplanetary space, long-term measurements of Cosmic Ray fluxes, as well as dynamic mapping of the Van Allen radiation belts.

1. INTRODUCTION

SPACE weather is an environmental concept that refers to the dynamic conditions in the space contiguous to Earth, interplanetary, and interstellar space. Wide variety of physical phenomena influences space weather. This includes Solar events like Coronal Mass Ejections (CME) and Solar flares, Galactic Cosmic Rays (GCR), energization of the Van Allen radiation belts, geomagnetic storms, ionospheric disturbances, geomagnetically induced currents at Earth's surface, etc. [1].

Space weather has impact on several areas generally related to the spacecraft operation and functioning of the ground-based communication systems. Geomagnetic storms, due to increased solar activity can potentially blind sensors aboard spacecraft, or interfere with on-board electronics. An understanding of space environmental conditions is also important in designing shielding and life support systems for manned spacecrafts. In addition, there is justified concern that geomagnetic storms may expose conventional aircraft flying at high latitudes to increased amounts of radiation.

The standard radiation environment monitor (SREM) is a particle detector developed for satellite applications with the main purpose to provide radiation hazard alerts to the host spacecraft. SREM is capable of measuring fluxes of highly energetic charged particles coming within ±20° of its pointing direction and exhibits fair spectral resolution.

SREM was developed by the Paul Scherrer Institute (PSI) and was manufactured by Contraves Space under a contract with the European Space Agency (ESA). Ten SREM units have been produced. Four of them are in operation onboard of PROBA-I, INTEGRAL, ROSETTA and GIOVE-B satellites. Two additional units are scheduled for launch onboard of HERSCHEL and PLANCK satellites in 2009.

Multiple, individually calibrated radiation monitors provide the unique possibility of mapping the radiation environment and comparing in-flight data for the same time periods in different regions of the magnetosphere. In addition, verification of the space radiation models (i.e. AP-8 [2] and AE-8 [3]) and cross-calibration of instruments is possible.

2. THE SREM INSTRUMENT

The SREM instrument comprises two detector systems. One system is a single silicon diode detector D3, Model EG&G Ortec Ultra T4-013-025-500 with the area of 25 mm^2 and the entrance window of 0.7 mm aluminum. This system has energy thresholds of ~0.5 MeV for electrons and of ~8 MeV for protons. The second system consists of two silicon diodes (detector D1, model EG&G Ortec Ultra T4-013-025-500 with the area of 25 mm^2 and detector D2, model EG&G Ortec Ultra T4-013-050-500 with area of 50 mm^2) in telescopic arrangement. The entrance window of this system consists of 0.5 mm aluminum and 0.7 mm brass, resulting in proton and electron thresholds of 20 MeV and 1.5 MeV, respectively. Two layers of 0.5 mm thick aluminum and 0.7 mm thick tantalum separate the two diodes resulting in high electron

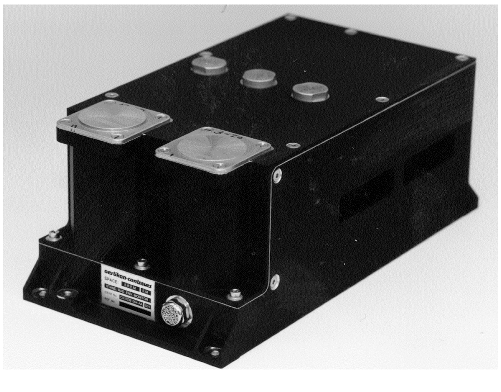

Fig. 1. The SREM instrument

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suppression when used in coincidence. Both detector systems have directional sensitivity of ±20° defined by conical openings.

Detected events are binned in 15 channels with different energy threshold levels set by discriminators. Any two of the channels can be used to raise an alarm flag when the count rates exceed a pre-programmed threshold. The detector electronics is capable of processing a detection rate of 100 kHz with dead-time correction below 20%.

The SREM instrument is shown on Figure 1. It utilizes a single box housing of 96×122×217 mm^3 and weighs 2.5 kg. The box contains two detector systems along with the analog and digital front-end electronics, a power supply, a TTC-B-01 Telemetry and Telecommand interface protocol and protective shielding. The interface can be adapted to any spacecraft system. Total power consumption of the SREM instrument is approximately 2 W.

For each SREM unit, the energy dependent response functions of all 15 SREM channels are determined by individual calibration measurements at the Proton Irradiation Facility, (PIF) of the Paul Scherrer Institut (PSI) [4]. In addition, the instrument and the host spacecraft are simulated with the GEANT3 and GEANT4 [5] Monte Carlo simulation codes to accurately determine the response functions to electrons at energies between 0.3 and 15 MeV and to protons in the 8 to 800-MeV energy range.

Three additional counters are assigned to each detector for dead-time correction pulser. Events detected by the telescopic detector system are divided into 10 bins, (including four proton coincidence bins) and one heavy ion bin. SREM is incapable of discriminating between various heavy ion particle types and identifies particles as heavy ions, in one bin only, if the deposited energy in D2 is higher than 9 MeV. The D3 detector is sensitive to electrons with energies from 0.5 MeV. In addition, it is also sensitive to protons and thus proper deconvolution procedures must be applied to obtain particle spectra in mixed environments. All SREM counters along with their sensitivity limits to protons and electrons are listed in Table I.

TABLE I
CHARACTERISTICS OF SREM CHANNELS

scaler ID	logic	particle	discriminator level (MeV)	energy range (MeV) protons	electrons
TC1	D1	proton	0.085	24 – inf	1.6 – inf
S12	D1	proton	0.25	24 – inf	1.6 – inf
S13	D1	proton	0.60	24 – inf	1.7 – inf
S14	D1	proton	2.0	24 – 46	5.6 – inf
S15	D1	proton	3.0	24 – 34	n/a
TC2	D2	proton	0.085	47 – inf	1.2 – inf
S25	D2	ions	9.0	90 – 143	n/a
C1	D1*D2	coinc. p.	0.6, 2.0	47 – 64	n/a
C2	D1*D2	coinc. p.	0.6, 1.1	57 – 190	n/a
C3	D1*D2	coinc. p.	0.6, 0.6	76 – 280	n/a
C4	D1*D2	coinc. p.	0.085, 0.6	130 – inf	3.2 – inf
TC3	D3	electron	0.085	11 – inf	0.4 – inf
S32	D3	electron	0.25	11 – inf	0.5 – inf
S33	D3	proton	0.75	11 – inf	0.8 – inf
S34	D3	proton	2.0	11 – inf	2.3 – inf
PL1	D1	dead time			
PL2	D2	dead time			
PL3	D3	dead time			

3. SREM ONBOARD PROBA1

The PRoject for OnBoard Autonomy (PROBA) [6] is a true micro satellite with only 94 kg of weight and dimensions of 800×600×600 mm^3. PROBA-I was launched on 22 Oct 2001 as a piggyback payload on the India's Polar Satellite Launch Vehicle and has fully autonomous capabilities – i.e. it operates virtually unaided. The satellite operates on a Lower Earth (LEO), Sun synchronous orbit with a period of 97 minutes, apogee of 640 km, perigee of 570 km and inclination of 97 degrees.

The path of PROBA-I covers the polar horns, where energetic electrons of the outer Van Allen radiation belt reach low attitudes, the South Atlantic Anomaly (SAA) where energetic protons of the inner radiation belt contribute to the enhanced particle fluxes, the polar and equatorial regions with average and low particle fluxes, respectively. PROBA-I is also exposed to energetic particles from the sun during energetic events, and to cosmic rays. Such full-Earth coverage allows the collection of important environment-specific radiation data.

All SREM channels readings during five consecutive PROBA-I revolutions are depicted on Figure 2. SAA and polar horns are easily identifiable by the increased count rates in the proton and electron counters, respectively. Figure 3 shows the particle counts in different energy bins of detectors D1 and D3 with respect to the scalers energy threshold at several locations during the satellite trajectory – SAA, polar horns, poles and equator. To date, the spectral unfolding method used for SREM data measurements is a simple conversion factor (SCF) [7]. It is based on the mean of the integral transform of the response function within a certain energy range. This simplified method has the main disadvantages of not proper accounting of the incident particle spectra and inability to unfold particle spectra in mixed environment; therefore detectors count rates rather than protons and electrons fluxes

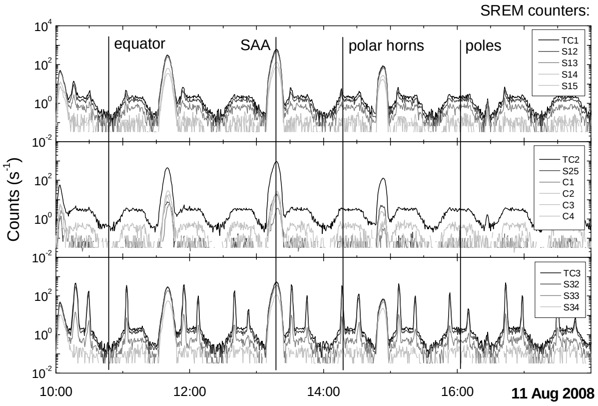

Fig. 2. Five PROBA-I revolutions including passage through SAA and polar horns

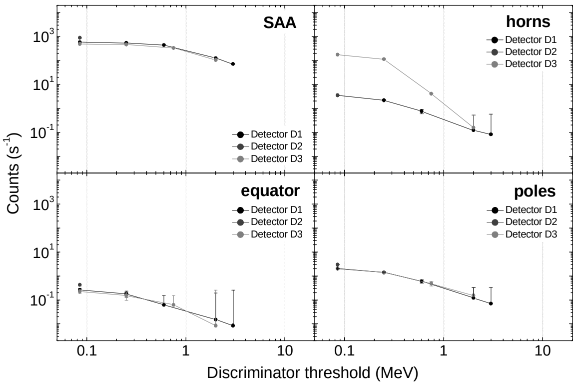

Fig. 3. Spectral components of the radiation environment at several locations along the PROBA-I orbit

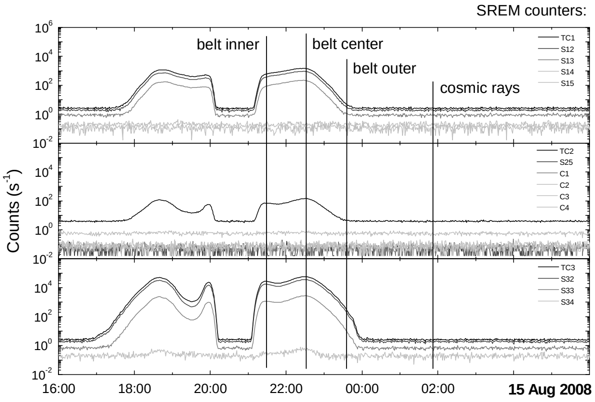

Fig. 4. Double INTEGRAL passage through the outer electron belt

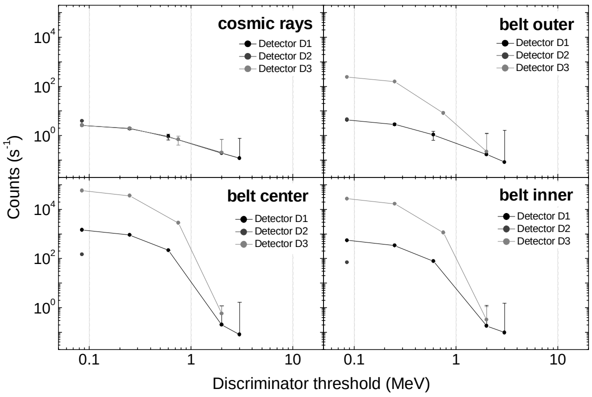

Fig. 5. Spectral components of the radiation environment at several locations along the INTEGRAL orbit

are presented. The statistical errors estimates shown are related to the number of counts. It should be noted that in one specie-dominated environment, electron and proton fluxes correlate to a reasonable extent with the readings of detectors D3 and D1, respectively.

The SREM data from PROBA-I satellite clearly illustrates the dominant amount of electrons in the polar horns of the outer electron belt and mixed high-density environment of both electrons and protons in the SAA. Lower counts are observed within the Earth's equatorial and polar regions. The polar region shows readings very similar to cosmic rays measured by INTEGRAL (see Figure 5).

4. SREM ONBOARD INTEGRAL

The INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) [8] is the first space observatory that can observe simultaneously objects in gamma rays, X-rays and visible light. It is an impressive spacecraft of 5 m height and 4 t overall weight of which 2 t of payload. INTEGRAL was launched on 17 October 2002 by the Proton rocket launcher from Baikonur, Kazakhstan. The satellite operates on a geosynchronous Highly Eccentric Orbit (HEO) with revolution period of 72 hours, apogee of 155 000 km, perigee of 9 000 km and inclination of 51.6 degrees.

INTEGRAL crosses twice the outer electron radiation belt close to its orbit perigee, thus allowing detailed dynamic studies of the radiation belt environment. The rest of the orbit covers the interplanetary space where cosmic rays, solar protons as well as energetic solar and Jovian electrons are encountered.

Figure 4 shows the readings of the IREM (the SREM onboard INTEGRAL) channels along a perigee double electron belt passage of the INTEGRAL satellite. The asymmetrical readings during the two belt passages clearly demonstrate the dynamic behavior of the belt due to the influence of solar wind. Detector readings of D1 (counters TC1, S12, S13, S14 and S15), D2 (counter TC2) and D3 (counters TC3, S32, S33 and S34) in respect to the counters discriminator level for several specific locations are shown on Figure 5. These locations include the inner/upper part of the belt, the center of the belt, the outer/lower of the belt and outside of the belt where cosmic rays particles are detected. A dominant electron species content is expected in the outer belt locations, thus demonstrating the fault of direct D1 detector readings in distinguishing high-energetic electrons from protons. More sophisticated unfolding methods for conversion of SREM channel counts to particle-specific fluxes need to be developed in the future for rectification of this drawback.

5. SREM ONBOARD ROSETTA

Rosetta is an interplanetary mission from ESA intended to meet and study the 67P/Churyumov-Gerasimenko (C-G) comet [9]. The mission was launched as flight 158 on 2 March 2004 by the Ariane-5G rocket from Kourou, French Guiana and is scheduled for rendezvous with the C-G comet in 2014. The spacecraft consists of the Rosetta space probe and the Philae lander that will be deployed on the comet's surface.

During the long cruise to its target Rosetta is scheduled for several planet swing-bys – three times around the Earth in 2005, 2007 and 2009, and once around Mars in 2007. In addition, the mission will take advantage of the trajectory crossing twice the main asteroids belt to perform two asteroid fly-bys. During the orbiting around the C-G comet period, Rosetta will reach the closest point to the Sun in its orbit allowing for the consequent increase of activity to be measured.

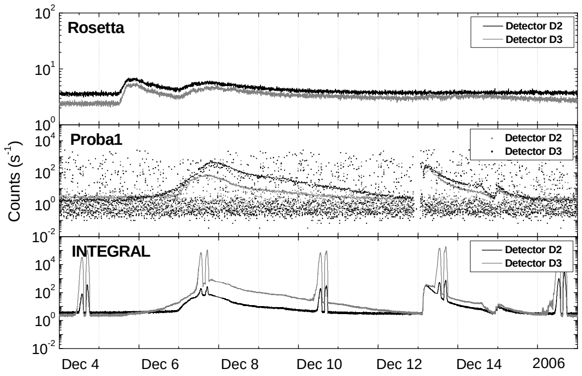

Fig. 6. Solar particle event from 6 Dec 2006 as observed by SREM onboard Rosetta, Proba1 and Integral

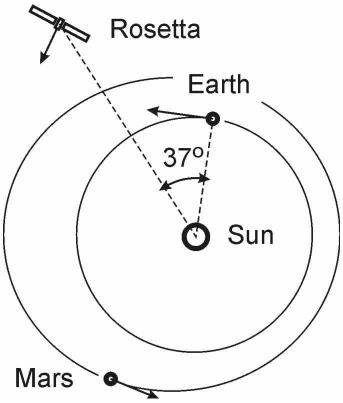

Fig. 7. Positions of Rosetta, Earth, Mars and Sun on 5 Dec 2006 in the ecliptic plane seen from the north celestial pole

Figure 6 shows SREM total counts of D2 and D3 from ROSETTA, PROBA-I and INTEGRAL during several solar particle events starting on 5 December 2006 and proceeding on the following days. The total counter TC1 of ROSETTA SREM experienced temporal problems therefore D1 readings are excluded. The location of ROSETTA at that time is 306 million km away from Earth, approaching Mars for a swing-by and 37 degrees away from the Earth in respect to the Sun. The locations of ROSETTA, Earth, Sun and Mars in ecliptic plane seen from the north celestial pole are illustrated on Fig. 7. The readings of SREM onboard ROSETTA demonstrate slight increase in the flux of Sun energetic particles starting on 5 December 2006 around 11:45. This event correlates with a moderate Solar Flare event no. 6120521 registered by RHESSI satellite datacenter on 5 December 2006 with starting time around 10:30 [10]. The time until the flux reaches its maximum around 5 hours. The same event is observed by the lower threshold channels of INTEGRAL and PROBA satellites around Earth, with much longer transition time of 55 hours, reaching its maximum around 19:30 on 7 December 2006. Possibly, this sun event was CME correlated with Solar Flare no. 6120521 with higher energetic particles ejected in the direction of ROSETTA and lower energetic tail directed to the Earth. Electron fluxes around Earth of energy >1.2 MeV remained above cosmic ray background until 13 December, more than 7 days after the event.

The total counters of D2 on SREMs of INTEGRAL and PROBA-I register moderate increase in the particle flux due to subsequent event starting around 23:00 on 6 December and reaching its peak around 18:30 on 7 December. Slight increase in the SREM onboard ROSETTA readings starting around 00:00 on 7 December is correlated with this data. 1-hour delay between the readings corresponds to the longer distance between the Sun and ROSETTA. This event is not correlated with any of the reported Solar Flare events by RHESSI datacenter. Proton fluxes of energy >27 MeV remained above cosmic ray background until 10 December.

Further, a harsh increase in the readings of PROBA-I and INTEGRAL appears around 3:30 on 13 December, which is well correlated with Solar Flare no. 6121305 observed by RHESSI around 2:28 on 13 December. This flare of class X3.4 was one of the largest during the period of solar activity minimum and caused disruption on the global positioning system (GPS) and shortwave (HF) radio communications [11,12]. The flare was followed by high energetic CME that caused severe Geomagnetic storms. Enhanced energetic particle fluxes around Earth remained for about three days after the event.

6. SREM ONBOARD GIOVE-B

The second Galileo In-Orbit Validation Element (GIOVE-B) part of the future ESA Galileo positioning system was launched on 27 April 2008 aboard Soyuz-FG/Fregat rocket launcher from Baikonur, Kazakhstan. GIOVE-B carries three atomic clocks: two rubidium standards and the first space-qualified passive hydrogen maser. It is a 530 kg spacecraft and is positioned at Middle Earth Orbit (MEO) of 22 300 km.

The path of GIOVE-B crosses the outer electron radiation belt. Figure 8 shows the total counts of SREM detectors D1, D2 and D3 during GIOVE-B single passage through the outer electron radiation belt. Since no significant proton presence is expected, the readings are interpreted as D3 representing the electron flux of energy higher than 0.5 MeV, D1 representing the electron flux of energy higher than 2.0 MeV and D2 representing the electron flux of energy higher than 2.8 MeV.

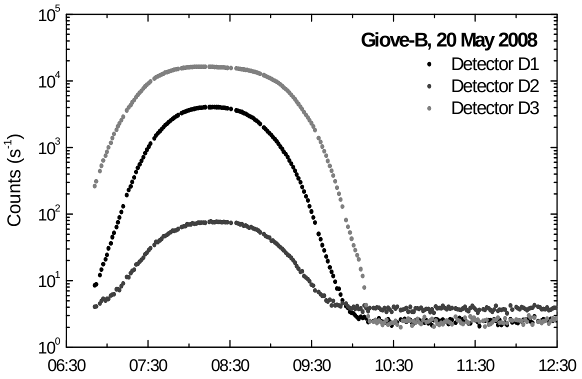

Fig. 8. Giove-B single passage through the outer electron belt

7. CONCLUSIONS

The unique fleet of nearly identical, individually calibrated SREM instruments at various locations in the Solar system provides the opportunity of dynamic mapping of the Space Weather and forecasting of radiation level with short downlink delays of space radiation data. This is a key to the improved understanding of the radiation environment and its effects.

More sophisticated methods for particle spectra unfolding out of the SREM channel count readings need to be evaluated in order to extract the maximum of useful information necessary for more precise flux and spectral interpretation of the data.

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