The ESA Standard Radiation Environment Monitor Program First Results From PROBA-I and INTEGRAL

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***Abstract*—The main characteristics of the European Space Agency (ESA) Standard Radiation Environment Monitor (SREM) are outlined. First SREM results from the Project for On-Board Autonomy-I (PROBA-I) and INTEGRAL spacecraft are presented.**

***Index Terms*—AE8, AP8, electron, ESA, GAIA, GSTB-V2, Herschel, integral, IREM, Planck, PROBA-I, proton, radiation, radiation environment, radiation monitor, rosetta, space instrument, spectrum, SREM, STRV1-c.**

I. INTRODUCTION

THE standard radiation environment monitor (SREM) is a particle detector developed for satellite applications. It measures high-energy electrons and protons of the space environment with a $\pm 20^{\circ}$ angular resolution, spectral information and provides the host spacecraft with radiation information. SREM was developed and manufactured by Contraves Space in cooperation with Paul Scherrer Institute under a development contract of the European Space Agency.

SREM is the second generation of instruments in a programme, which was established by ESA's European Research and Technology Centre (ESTEC) to:

- provide minimum intrusive radiation detectors for space applications;
- provide radiation hazard alarm function to instruments on board spacecraft;
- assist in investigation activities related to possible radiation related anomalies observed on spacecraft;
- assist in in-flight Technology Demonstration Activities.

The design goals are low weight, small dimensions, low power consumption, combined with the ability to provide particle species and spectral information. In total 10-SREMs have been manufactured of which nine are assigned to specific ESA missions, with the first SREM flown on QinetiQ's (UK) Space Technology Research Vehicle 1-c (STRV1-c) microsatellite. Besides providing important radiation environment data to their corresponding spacecraft operators, the combined data collected by all SREM will provide results augmenting current space radiation models (i.e., AP-8 and AE-8 [1], [2]). This paper describes the SREM instrument, presents the first SREM results from PROBA-I and INTEGRAL missions, and finally gives an outline of the future radiation monitor instruments.

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II. SREM INSTRUMENT

The SREM consists of three detectors (D1, D2, and D3) in two detector heads configurations. One system is a single silicon diode detector (D3). The main entrance window is covered with 0.7 mm aluminum, which defines the lower energy threshold for electrons to ~ 0.5 MeV and for protons to $\sim$ 10 MeV. The other system uses two silicon diodes (detectors D1/D2) arranged in a telescope configuration. The main entrance of this detector is covered with 2 mm aluminum giving a proton and electron threshold of 20 and 1.5 MeV, respectively. A 1.7-mm-thick aluminum and 0.7–mm-thick tantalum layer separate the two diodes of the telescope configuration.

The telescope detector allows measurement of the high-energy proton fluxes with enhanced energy resolution. In addition, the shielding between the two diodes in the telescope prevents the passage of electrons. However, protons with energies greater than ~ 39 MeV go through. Thus, using the two diodes in coincidence gives pure proton count rates allowing subtraction of the proton contribution from the electron channels. A total of 15 discriminator levels are available to bin the energy of the detected events. Any two of the levels can be used to raise an alarm flag when the count rates exceed a programmable threshold. This alarm signal can then be used to control the operation of the spacecraft and its instruments. The detector electronics is capable of processing a detection rate of 100 kHz with dead-time correction below 20%.

The SREM is contained in a single box of $20 \times 12 \times 10$ cm^3 and weighs 2.6 kg (see Fig. 1). The box contains the detector systems with the analog and digital front-end electronics, a power supply, and a TTC-B-01 telemetry and Telecommand interface protocol. By virtue of a modular buildup, the interface can be adapted to any spacecraft system. The power consumption is approximately 2.5 W.

An essential input for the interpretation of the detection rates, in terms of particle fluxes, are the energy dependent

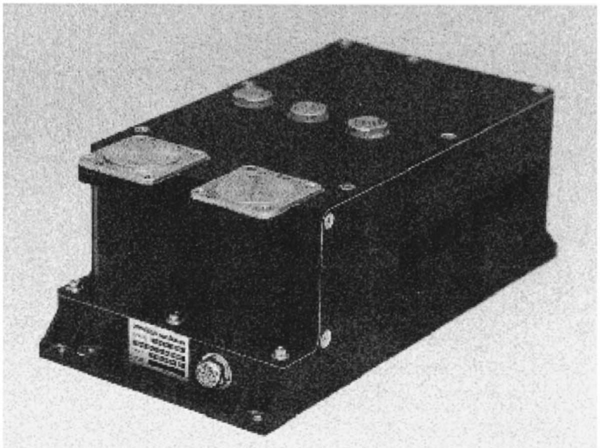

Fig. 1. Picture of SREM \FM.

response functions. Therefore, prior to launch, the instruments are fully calibrated at the Proton Irradiation Facility, (PIF) of Paul Scherrer Institut (PSI) [3]. In addition, the instrument and the host spacecraft are simulated with the Geometry and Tracking (GEANT) 3.21 and GEANT4 particle transport codes to accurately determine the response functions to electrons at energies between 0.3 and 15 MeV and to protons in the 8–800-MeV range.

In addition to 15 energy bins, three counters are assigned to detector one to three dead-time correction values, respectively. Table I lists all SREM counters.

As explained earlier, the D1/D2 configuration measures protons from approximately 20 MeV to infinity. Events detected by this configuration 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 their deposited energy in D2 is higher than 9 MeV. The D3 sensor is sensitive to electrons with energies from 0.5 MeV. In addition, it is also sensitive to protons and proper deconvolution procedure must be applied to obtain particle spectra in mixed environments.

III. First SREM Data From PROBA-I

On 22 October 2001, the second SREM instrument was launched aboard the ESA microsatellite project for on-board autonomy (PROBA-I [4]) by an Antrix/ISRO PSLV-C3 rocket from Sriharikota, India. The satellite reached its foreseen Sun-synchronous, initially 680 km low Earth orbit (LEO) with an inclination of 97.9°, and a period of approximately 97 min. During the commissioning phase the SREM proved to operate nominally and has successfully generated data for approximately 2 years.

The path of PROBA-I covers the polar horns, where energetic electrons of the outer radiation belt are transported to low altitudes, as well as the South Atlantic Anomaly (SAA) with its enhanced particle fluxes. PROBA-I is also exposed to energetic particles from the sun during energetic events, and to cosmic rays. The full-Earth coverage enables important radiation environment-specific measurements.

TABLE I

List of SREM Counters. The Energy in the Last two Columns is Given in MeV. "C.Proton" Indicates Coincidence Proton Channel

NR	BIN	LOGIC	PARTICLE	E Min.	E Max.
1	TC1	D1	proton	20	Inf.
2	S12	D1	proton	20	550
3	S13	D1	proton	20	120
4	S14	D1	proton	20	27
5	S15	D1	proton	20	34
6	TC2	D2	proton	39	Inf.
7	S25	D2	Ions	150	185
8	C1	D1*D2	c.proton	40	50
9	C2	D1*D2	c.proton	50	70
10	C3	D1*D2	c.proton	70	120
11	C4	D1*D2	c.proton	130	Inf.
12	TC3	D3	electron	0.5	Inf.
13	S32	D3	electron	0.55	2.3
14	S33	D3	proton	11	90
15	S34	D3	proton	11	30
16	PL1	D1	Dead Time		
17	Pl2	D2	Dead Time		
18	PL3	D3	Dead Time		

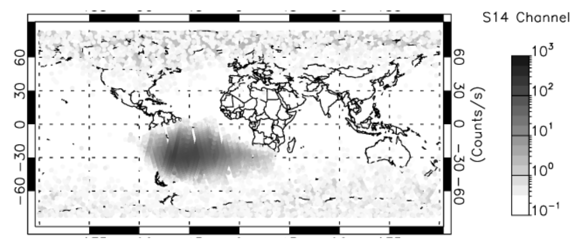

Fig. 2. SREM (PROBA-I) proton data clearly illustrating the increased proton flux in the South Atlantic Anomaly region.

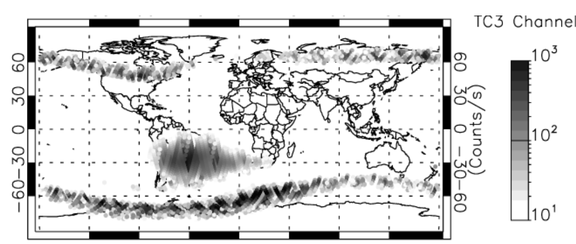

Fig. 3. SREM (PROBA-I) TC3 electron channel with proton contamination. The data clearly illustrates the increased particle flux in the South Atlantic Anomaly and polar horns.

The SREM is located on PROBA-I such that the instrument view cone ($\pm 20°$) is directed toward the wake. Fig. 2 shows the S14 channel (p^+ with energy > 20 MeV) counts measured by SREM aboard PROBA-I. These data have been collected by SREM from January 2002 over a period of three months. The data clearly illustrate the increased proton flux in the SAA. Fig. 3 shows the counts from the TC3 channel (e^- with an energy > 500 keV and p^+ with an energy > 11 MeV) measured by SREM aboard PROBA-1. These data have been collected in the same period as the data in Fig. 2. In addition to the SAA, the data clearly illustrate the increased electron flux from the outer electron belt in the polar horns.

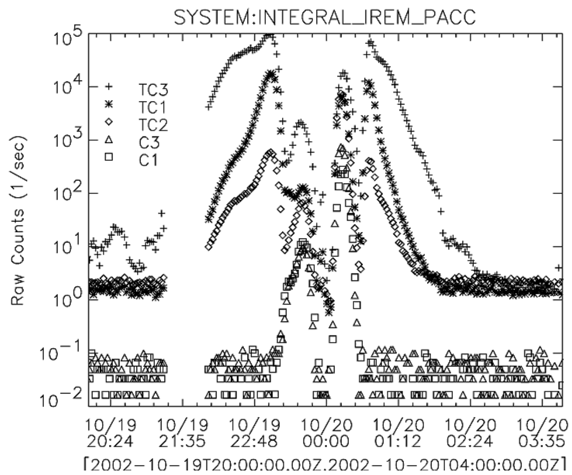

Fig. 4. First in-orbit data in various counters of the SREM on INTEGRAL. The peaks correspond to the inbound and outbound passes of the orbit through Earth's radiation belts.

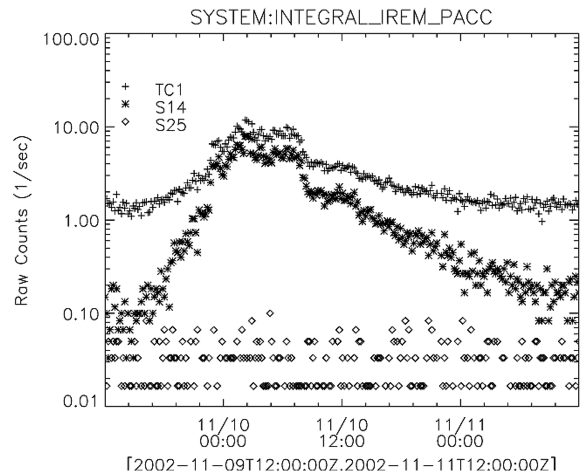

Fig. 5. TC1, S14, and S25 (e^-, p^+ and ion) data for the INTEGRAL SREM. The data covers 9 November to 11 November and show a small solar proton event.

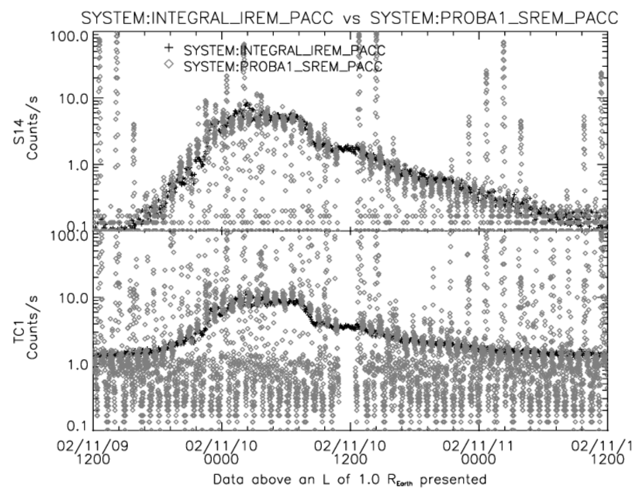

Fig. 6. Illustrates in the lower panel the TC1 channel and in the upper panel the S14 data for the PROBA—I SREM (gray diamonds) and INTEGRAL SREM (black pluses). The data covers 9 November to 11 November and shows a small solar proton event.

IV. First SREM Data From INTEGRAL

The ESA International Gamma-Ray Astrophysics Laboratory (INTEGRAL [5]) was launched 17 October 2002 onto a highly eccentric 72-h period orbit with a perigee of 9000 km and apogee of 155 000 km, and an inclination of 51.6°. The launcher employed was a Russian Proton rocket. With this orbit, the IREM (an SREM unit specifically modified for INTEGRAL) samples both the dynamic outer electron belt and the interplanetary environment where cosmic rays, solar proton events, as well as energetic solar and Jovian electrons are encountered. The planned mission lifetime of INTEGRAL is two years, with a possible extension for up to 5 years, such that the declining phase of the Solar Cycle can be covered. Fig. 4 illustrates the first data acquired by SREM on INTEGRAL, a perigee passage through the outer electron belt, the inner electron belt and the proton belt. The data from SREM will support the INTEGRAL science investigations and will be used together with other instrument data to improve the understanding of the radiation environment and its effects [6].

V. Comparing PROBA-I/INTEGRAL Data

A significant advantage of flying multiple radiation monitors is the possibility of mapping the radiation environment and comparing in-flight data for the same time periods in different regions of the magnetosphere and for cross-calibration purposes. The case is illustrated by investigating the PROBA-I and INTEGRAL data for a small solar proton event observed in the period 9 November 2002 until 11 November 2003.

Fig. 5 illustrates the TC1, S14 and S25 counts measured by the INTEGRAL SREM over a 2-d period. During its 72-h orbit the INTEGRAL Spacecraft is located outside the radiation belts, in the interplanetary space, for approximately 70% of its flight, measuring the radiation environment (i.e., solar protons) not significantly affected by Earth's magnetic field. Fig. 5 illustrates the quiet proton environment on 9 November with the proton environment gradually increasing from end of 9 November until a plateau is reached in the morning of 10 November. The increased proton count rates are maintained until approximately the end of 10 November and slowly return to the "quiescent" level on the beginning of 11 November. During this entire period, the INTEGRAL spacecraft was not subjected to significant geomagnetic shielding.

Fig. 6 shows the INTEGRAL-SREM data TC1 and S14 channels superimposed with the PROBA-I-SREM data of the same time period. The PROBA-I-SREM data are not as "smooth" as the INTEGRAL-SREM data as they also include effects of geomagnetic shielding and the passages of the trapped proton belts (the spikes that exceed the count rate of the proton event) as the spacecraft passes through the SAA. In Fig. 7, the data have been filtered to exclude points with an L-Shell below 8 $\mathrm{R_{Earth}}$, which effectively removes from the PROBA-I-SREM data the effects of geomagnetic shielding and the passes of the SAA and selects only the data of solar origin. The result shows a close masutch between the data from the two detectors throughout the event.

The above observation is further strengthened by Figs. 8 and 9 illustrating the world map orbit trace of the INTEGRAL and PROBA-I spacecraft, respectively. Superposed on the orbit trace

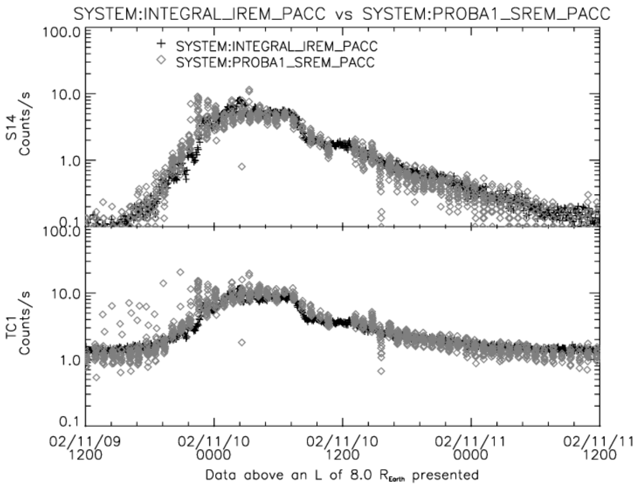

Fig. 7. As in Fig. 6, but only the data points which exceed an L-shell of 8, i.e., outside of the radiation belts and insignificant geomagnetic shielding.

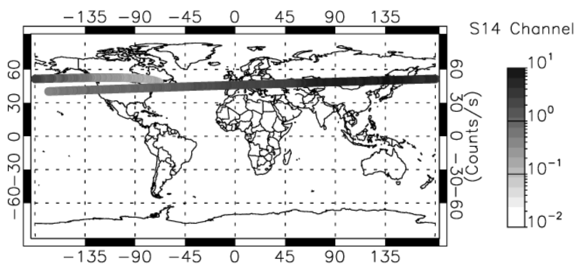

Fig. 8. INTEGRAL SREM S14 Scalar counter for the period from 9 November 2002 to 11 November 2002 on a world map.

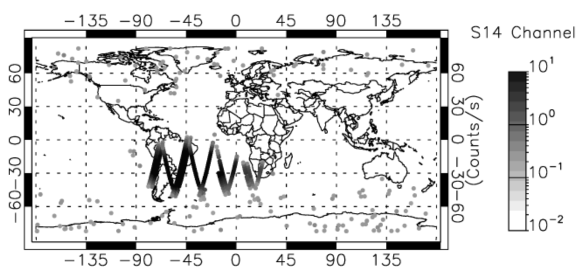

Fig. 9. PROBA-I SREM S14 scalar counts from 6 and 7 November, 2002 on a world map.

lines is the color-coded S14 scalar proton intensity. In Fig. 8 the increased proton counts are shaded.

Interestingly, Fig. 9 illustrates that the higher proton counts are observed in the polar horn regions. Observe, also the familiar increased proton counts in the SAA region.

For comparison, Fig. 10 illustrates a quiescent period of three days immediately prior to 10 November solar proton event. Notice the lower proton counts in the polar horns compared to the counts presented in Fig. 9 and the largely unchanged state of the SAA.

The close match between the PROBA-I and INTEGRAL instruments is further demonstrated in Fig. 11 during the prompt solar proton event, which occurred at the end of May 2003. The disturbed state of the magnetosphere on the 28–29th, where a geomagnetic K_p index [7] (a measurement of the disturbance

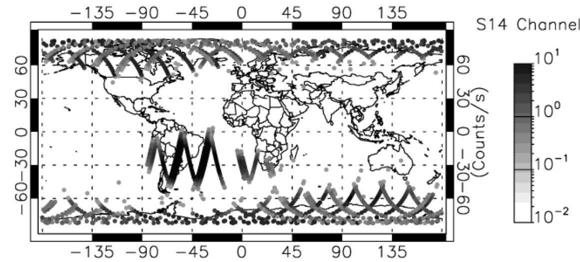

Fig. 10. PROBA-I SREM S14 scalar counts from 9 to 11 November, 2002 on a world map.

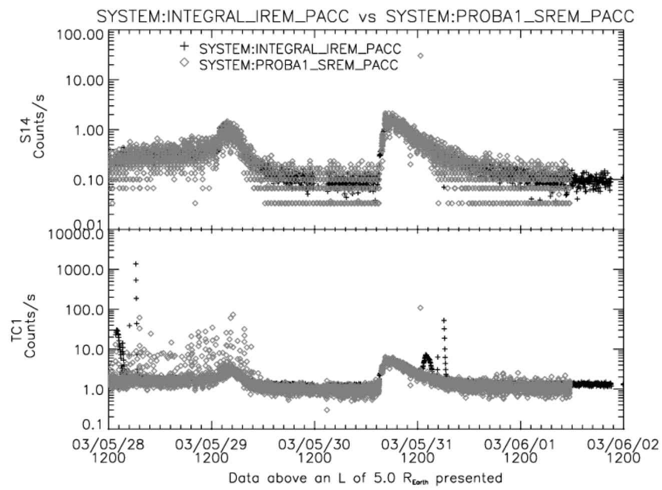

Fig. 11. PROBA-I (gray diamonds) and INTEGRAL (black pluses) TC1 (lower panel) and S14 (upper panel) channels above an L-shell of 5 for the recent solar proton event and geomagnetic storm at the end of May 2003. The passage of PROBA-I through the polar horns (outer electron belt) appears as "noise" exceeding 3 counts/s in the TC1 data prior to 21:00 on the 29th. The passage of INTEGRAL through the outer electron belt is similarly seen as the spikes centered about 16:00 on the 28th and the 31st of May.

in the geomagnetic field ranging from 1 to 8) of 8 was reached, is depicted by the dramatic decrease in the counts registered in the outer electron belt by the PROBA-I TC1 channel (seen as "noise" prior to the 30th). This depletion of the outer electron belt is also seen in the outer edge by the lower counts during the INTEGRAL perigee passage, where the INTEGRAL TC1 count rate dropped by more than an order of magnitude during this storm. During such periods of high activity, the magnetic field can be intensively modified. The high L-shells can open to the interplanetary medium and the particles trapped on these shells can be lost from the belts as the particles cross the magnetopause and enter the interplanetary medium [8].

Plotting the data from the two satellites in geomagnetic B-L space shows the coverage of the radiation belts provided by the satellites. Fig. 12 shows the trapped proton belts as measured by the S14 proton channel during the first quarter of 2003. The two satellites encounter the extremes of the belts, PROBA-I at high B, and INTEGRAL at low B values, but neither of the two satellites' orbits cover the middle region. Similarly for the electron belts, Fig. 13 shows the TC3 electron counts from the two satellites over the same period. The PROBA-I satellite encounters both the inner and outer belts and the slot region, while the INTEGRAL satellite encounters only the outer belt (at approximately 4Re).

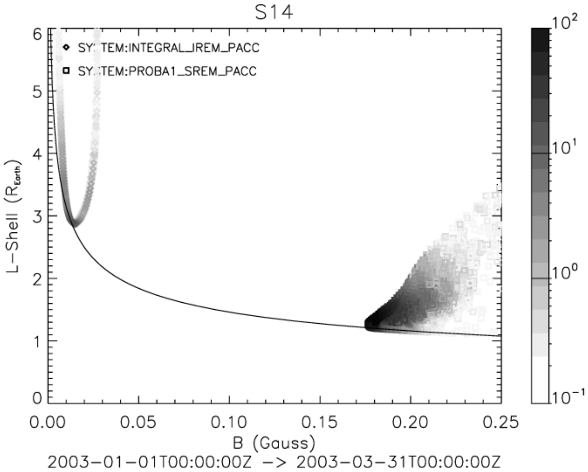

Fig. 12. Counts from the S14 proton channel ($20 < E < 27$ MeV) from both INTEGRAL-SREM (loop on the left) and PROBA-I-SREM in B-L space. The solid line represents the geomagnetic equator (the minimum L-Shell for a given dipole magnetic field strength).

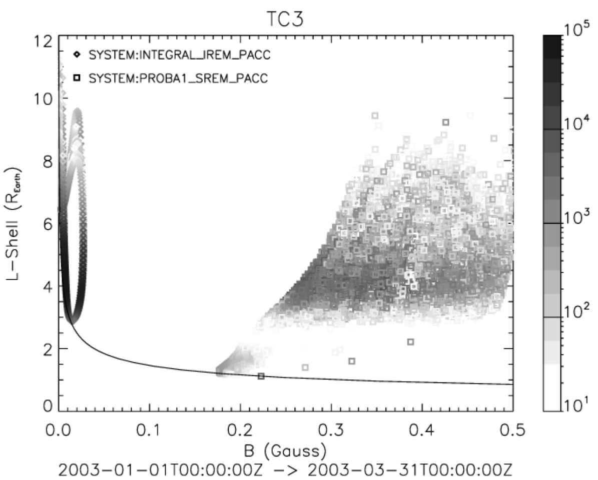

Fig. 13. Counts from the TC3 electron channel ($E > 500$ keV) from both INTEGRAL-SREM (loop on the left) and PROBA-I-SREM in B-L space. The solid line represents the geomagnetic equator (the minimum L shell for a given dipole magnetic field strength).

While it is possible to interpolate between the two regions, it is preferable to have as data coverage that is as complete as possible for modeling purposes.

VI. Discussion

The results from the first SREM missions on PROBA-I and INTEGRAL indicate that the instrument concept is beneficial to spacecraft design by providing greater understanding of particle depletions and enhancement and adding data to model databases and the spacecraft's operation by providing on-board hazard alarm functions to mitigate the risk of radiation damage to sensitive components. SREMs are providing invaluable radiation environment data that are employed to augment current radiation environment models. Additionally, SREM has proven to provide radiation hazard alarm functions to scientific instruments on-board INTEGRAL enabling counter measures to be initiated to extend their nominal life. The advantages of flying multiple well calibrated SREMs have also been highlighted both in terms of verifying events observed by a single unit and also in terms of the possibility of shedding light on particle transport phenomenon. Data from the solar proton event of 9 November 2002 and the magnetospheric disturbance resulting in the depletion of the outer electron belt at the end of May 2003 have been presented for both PROBA-I and INTEGRAL with good agreement shown between the two datasets.

The SREM project has proven successful and endorsed by a number of ESA mission project managers traditionally unfamiliar with the benefits of flying radiation monitors on spacecraft. To nourish the momentum gained and to accommodate for the requirements of smaller spacecraft, ESA has initiated several new activities to develop miniaturized radiation monitors. The principal activity is based on the SREM and aims to develop an instrument with equal or superior functionality but having smaller size, lower mass, and lower power consumption than the SREM. This may be achieved by utilizing novel technologies, such as new packaging techniques, etc.

A second ESA activity initiated for developing miniaturised radiation monitors aims at pursuing new particle detection principles. It is intended to develop instruments that are an order of magnitude smaller, lighter and less power consuming than current instruments. The first version of these instruments, based on scintillating crystals, will detect electrons, protons and heavy ions whilst providing a coarse energy spectrum. A trial version of this instrument has already been developed and is flying on PROBA-I. Early test results indicate that the instrument is operational. The specifications for this instrument are $10 \times 10 \times 3$ cm^3, 325 g and a power consumption of only 0.5 W. Further volume, mass and power reductions are foreseen for the final flight versions.

The ultimate aim of these activities is to develop a network of complementary monitors providing continuous and long-term measurement of the radiation levels in the near Earth as well as in the interplanetary space.

TABLE II
PLANNED SREM MISSIONS

Mission	Launch Year	Orbit
Rosetta	**2004**	**Interplanetary**
GSTB-V2	**2005**	**24,000km**
Herschel	**2007**	**L2**
Planck	**2007**	**L2**
GAIA	**2010**	**L2**

VII. Current and Future SREM Missions

In addition to the PROBA-I and INTEGRAL SREM units, seven units were manufactured under a batch procurement activity by the Agency and are planned to be flown on various ESA science and technology missions in the following years. Table II lists the confirmed SREM mission to date.

The next SREM mission is a flight on the ROSETTA [7] spacecraft (SREM spare flight models assigned to the

ROSETTA and GSTB-V2 missions). This mission is particularly interesting as, during the hibernation phase of the Rosetta (lasting 10 yr), the SREM will be one of the few (probably the only) active instrument and taking measurements. In addition to providing environmental data, SREM is assigned to providing alarm functions to several of the Rosetta scientific instruments and accumulated total dose data requested by the power subsystem responsible for solar cell degradation evaluation purposes. Thus, as for the INTEGRAL, SREM fulfills two important functions of being an essential part of the mission safety system and general space weather data-collecting device.

An SREM flight on Galileo-Sat Test Bed (GSTB)-V2 is greatly anticipated and desirable, as measurements for the harsh radiation environment at this orbit (24,000 km) are limited. The data generated by SREM on the GSTB-V2 will also be used to evaluate the technology flown with respect to the radiation environment. The three L2 mission consisting of Herschel, Planck and GAIA will provide invaluable data from an orbit that has rarely been investigated.

VIII. Summary

The first results from the PROBA-I and INTEGRAL satellites and description of the detectors have been presented. The good agreement between the two datasets for quiet periods and for solar proton events and Magnetospheric disturbances has been demonstrated, subsequently providing a valuable operational tool for on-board hazard warnings to the payloads. The data from orbits of INTEGRAL and PROBA-I provide a unique resource for the understanding of particle depletion and injection events as well as supporting the generation of new radiation belt models. This resource will be further expanded with the flights of SREM detectors on future missions. The ultimate goal of flying radiation monitors is to create a network of complementary monitors providing continuous and long-term measurement of space radiation environment.

Acknowledgment

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