IREM MEASUREMENTS OF THE EXTERNAL RADIATION ENVIRONMENT ALONG THE INTEGRAL ORBIT

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Abstract

The Integral Radiation Environment Monitor (IREM) is flying onboard the INTEGRAL satellite. The Monitor continuously provides information about protons and electrons along the orbit. The INTEGRAL protection scheme enables payload instruments to react instantly. Scientific IREM data are available for further analysis almost without delay.

INTRODUCTION

The IREM is a special version of the ESA Standard Radiation Environment Monitor (SREM) that was developed in partnership between ESA, PSI and Contraves Space AG (Zürich) [1]. The IREM was launched on 17th October 2002 from the Baikonur cosmodrome onboard of the INTEGRAL (ESA International Gamma-Ray Astrophysics Laboratory) mission. The Russian Proton rocket was used as a launcher. The satellite orbit is highly eccentric, 72h long one with a perigee of 9000 km and apogee of 155000 km. Its initial inclination is equal to 51.6°.

The IREM is a space dedicated detector system for real time spacecraft alerting and onboard dosimetry as well as for proton and electron spectroscopy. The INTEGRAL mission is the first one during which the IREM can fulfil its both objectives of being a crucial part of the spacecraft radiation protection system and of working as an autonomous radiation monitoring device. The INTEGRAL orbit allows the IREM to study both the dynamic outer electron belt and the interplanetary environment where cosmic rays, solar proton and electron events, as well as other phenomena like energetic Jovian electrons are encountered – see Fig. 1. The planned mission lifetime of the INTEGRAL is two years and possible extension for up to 5 years might enable covering of the whole declining phase of the Solar Cycle.

The INTEGRAL mission's prime goals are to study sources of intense gamma radiation (e.g. black holes) and to explore rare and powerful events (e.g. supernova explosions). Four main instruments on board allow for observations that cover the whole energy range between visible light and high-energy gamma rays. The spectrometer SPI (Spectrometer on INTEGRAL) measures gamma-ray energies with a very high resolution of few keV (2 keV at 1 MeV). The imager onboard INTEGRAL (IBIS) gives sharp gamma-ray images within a resolution of 30 arcseconds. The Joint European X-Ray Monitor (JEM-X), a so-called imaging micro strip gas counter, provides images in the X-ray energy range of 3 to 35 keV, while the optical camera (OCM) allows for observations of the visible light. All payload instruments strongly rely on the IREM information about the current radiation level and react to it accordingly.

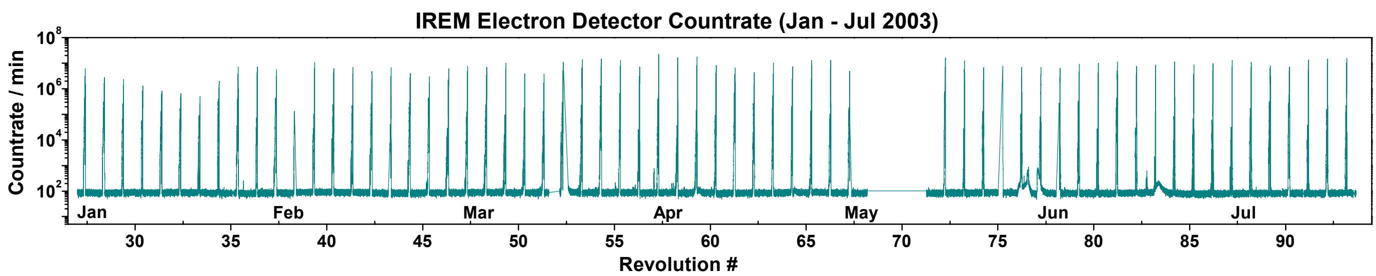

Fig. 1 Typical flow of the counting rates in the IREM detectors. Several orbits starting from Jan 2003 are shown illustrating a representative dynamics along the orbit. Small count rate periods represent cosmic ray background environment while regular peaks indicate crossing through the radiation belts. One can also see increased counts between the belts from the Coronal Mass Ejection emitted protons.

Two similar IREM like monitors are also flying in space – one on onboard of the ESA PROBA [3] micro-satellite and the other one on STRV1-c. The PROBA SREM was launched into space on 22nd October 2001 by an Antrix/ISRO PSLV-C3 rocket from Sriharikota, India. The satellite reached its sun-synchronous Low Earth Orbit (LEO) with an inclination of 97.9°, and a period of approximately 97 minutes. Since the commissioning, the SREM operates nominally and provides data for already more than one year. (The other SREM operated successfully until the communication with the mission was lost due to an antenna receiver malfunctioning.)

INSTRUMENT FEATURES

Three standard Silicon Surface Barrier Detectors are used as IREM sensors. In order to assure good energy resolution and provide directionality of incoming radiation, two sensors are arranged in a telescope. Both the single detector and the telescope are embedded in a bi-metallic shielding of Tantalum (inner) and Aluminium (outer). All pulses are pre-amplified and analysed by a set of fifteen fast comparators – ten for single events, four for coincidences and one is left as a heavy ion channel. Their levels are optimised to get the best spectral shape information for the detected particles in a covered energy range. The low energy detection thresholds for protons and electrons are ca. 9 MeV and 0.5 Mev respectively (defined by the Aluminium entrance windows). Although electrons and lower energy protons enter the detector through conical collimators with ±20° opening, higher energy particles can enter the detector from any direction. It was taken into account by Monte Carlo simulations where the detector response was generated including not only the IREM itself but the whole satellite as well. The level of response alteration depends on the satellite mass and its distribution as well as on location of the monitor [4].

There are two different operation modes of the IREM: The Standard- (SOM) and the Integral-Operation Mode (IOM). Both operation modes have their own sets of telecommands to interact with the spacecraft. The mode can be changed anytime by sending a corresponding telecommand. After reset or restart the SOM is invoked first. It enables to perform data acquisition measurements and checking IREM status and health as well as reading measured data that are already saved in the monitor memory. There are also low-level functions like reading/writing of the monitor Register Bank or patching program memory. In the IOM the IREM behaves in a more autonomous way. After its initialization it continuously performs radiation measurements and health checking. It also periodically executes radiation monitoring/alerting functions without any assistance from the spacecraft. Duration of the measurements and housekeeping verification frequency can be set via proper telecommand.

INTEGRAL RADIATION ALERTS

Every eight seconds the IREM passes to the spacecraft a fifteen words long Transfer Data Block (TDB). It is used to inform the spacecraft about current radiation environment as well as about the IREM status. In addition, the TDB contains the scientific and housekeeping data for further downloaded to the ground. The radiation watching and alerting tasks for the Integral mission are accomplished in the following way. Three TDB words contain counting rates from pre-selected, dead time corrected IREM scalers. These count rate data are further distributed via the Integral Broadcast Packet Bus to the payload instruments. It enables them for prompt reaction to the current level of radiation environment. One BCP scaler is responsible for monitoring of the proton flux, the other one is mostly sensitive to electrons, while the third one provides information about a deep dose deposition. Through appropriate choice of the scalers, one can adjust their sensitivity and energy threshold for detection of protons and electrons. The dose counter originates from sampling of the dead time in a deeply shielded rear detector of the telescope. The counters data for BCP comes from events accumulated over 10 sec long measurements. Thus, the TDB is updated with the new radiation information averaged over such a period of time.

The mission provides threefold protection against high radiation events. During radiation belt passages, the corresponding flag is generated in the Broadcast Packet informing instruments about potential hazards. Currently and per default the flag is set for all Integral altitudes below 60'000 km. It was however already observed that the elevated electron fluxes also occurred at ca. 80'000 km heights, specially during the spring equinox. To protect instruments against such incidences, one utilises three, BCP transmitted, IREM counters for protons, electrons and dose rates. As each instrument has its specific radiation sensitivity and tolerance level, it is left for the instruments themselves to initiate the most proper action – see Fig.2 and Table 1.

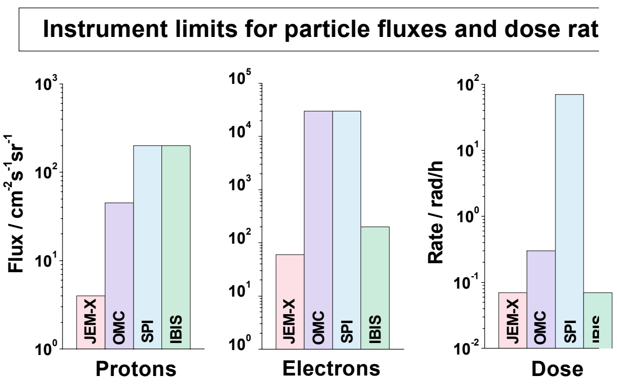

Fig 2. Limits of Integral payload instruments put on dose rates as well as proton, electron fluxes to enter the safe operation mode.

This way, their operating modes are always adapted to particular radiation environment and spacecraft status. Moreover, permanent watch of the radiation level allows gaining an extra observing time for the scientific observations. It was estimated that using real data instead of fixed, altitude based radiation flags may give about 5% more observing time per orbit.

In addition to radiation warning signals from both spacecraft/ground-station and the IREM, all payload devices have an independent safeguard. It relies on their own detector's counting rates and sends the instrument into a protected mode in case when counting rates are above preset limits. While entering of the safe mode is automated, the exit from it depends on the instrument and may be programmed or manual, executed from the ground station. The table below illustrates different requirements and limits posed by the Integral payload apparatus on electron, proton and dose rates from IREM BCP counters.

Table 1: Instrument limits for proton and electron particle fluxes and dose rates.

Instrument	Protons	Deep Dose	Electrons
	[/cm^2/s/sr]	[rad/hour]	[/cm^2/s/sr]
IBIS	2.0E+02	7.0E-02	2.0E+02
SPI	2.0E+02	7.0E+01	3.0E+04
JEM-X	4.0E+00	7.0E-02	6.0E+01
OMC	4.5E+01	3.0E-01	3.0E+04

Values given in the table are given for integrated fluxes of protons with energies ranging from 9 MeV up and for electrons with energies above 0.5 MeV. Protons, in addition to high-energy cosmic rays, also contribute to the deep dose deposition. It can be seen that the range of response thresholds spans over several magnitudes. In addition to the device intrinsic resistance it also reflects an impact of its location on the spacecraft and applied shielding. The most sensitive is the JEM-X proportional counter that goes into the safe mode already when the proton radiation level starts to grow. The next one is the Optical Monitor OMC with its CCDs and readout electronics. Both the IBIS imager and SPI spectrometer are more radiation tolerant but they also enter the protected mode when the proton environment becomes harsher.

RADIATION ENVIRONMENT ALONG THE ORBIT

As the highly elliptical Integral orbit has the Perigee of 9000 km, the satellite spends most of its 72 hours long revolution outside of the Radiation Belt. Most of the time, a practically constant flux of cosmic rays constitutes the mission radiation environment in this region. When the belt is entered the flux of electrons can very quickly rise up by even five orders of magnitude – see Fig. 1. The high narrow peaks exemplify regions of high-energy particle fluxes in the belts. Usually, the passage through the electron belts takes between seven and ten hours depending on the geomagnetic coordinates of the orbit and space weather conditions – see Fig. 3. Electron fluxes may reach up to $1 \bullet 10^7$ /cm^2/sec for energies higher than 0.5 MeV. The peak intensity can vary from orbit to orbit by a factor of three. The proton belt is barely touched by the spacecraft orbit.

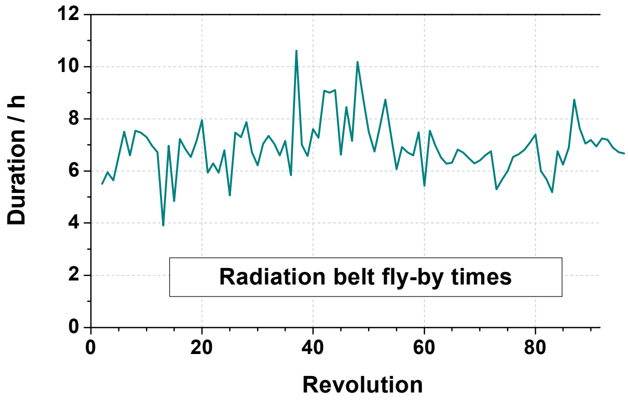

Fig. 3 Typical duration of the radiation belt passage from the Integral launch in October 2003. One can see an increase in variation level and duration during the spring equinox.

Therefore, the intensity of protons reaches only of about $1 \bullet 10^1$ /cm2/sec for energies above 20 MeV. It takes up to 1.5 hours to fly through the elevated proton environment area. The scientific observations are carried out during low radiation periods represented by flat segments between the belt peaks in Fig. 1. Occasionally, a solar coronal mass ejection (CME) can disturb such quiet radiation environment for many hours. Until now, the Integral experienced several such events. They have influence on the radiation level along the orbit and also may strongly interrupt the mission observing time. Long solar event occurred in December 2002 and high levels of radiation were present for almost entire day. Solar protons dominated the particle spectrum – see Fig. 1. As it is clearly shown in Fig. 4, the CMEs can also disturb the whole particle population inside of the belt.

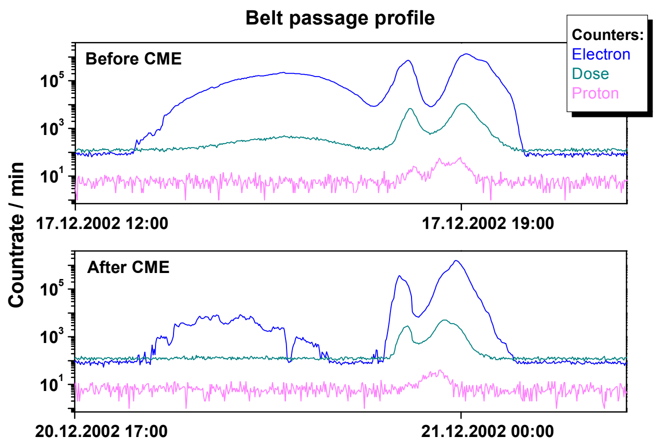

Fig. 4. Comparison of radiation environments inside of the belts for protons and electrons. The data is shown for a quiet period and for a disturbed one, directly after CME occurrence.

One can see that after the CME both the shape and particle intensities inside of the outer electron belt are drastically different. Such a change may last for several days until the previous conditions are restored. In contrary, the intensity and spatial distribution of the Integral scanned fraction of the proton belt remain roughly on similar level as before.

The electron spectra inside of the belts can be fitted with a simple exponential model. The CME's have also an influence on the spectrum hardness – see Fig 5. It is observed that the spectra become harder after the event. The general trend of bigger hardness when closer to perigee is also confirmed.

The comparison between orbital data and latest belt models (AP8, AE8) shows rather good qualitative agreement. Because presently used versions are static only, considerable efforts are initiated to construct dynamic ones.

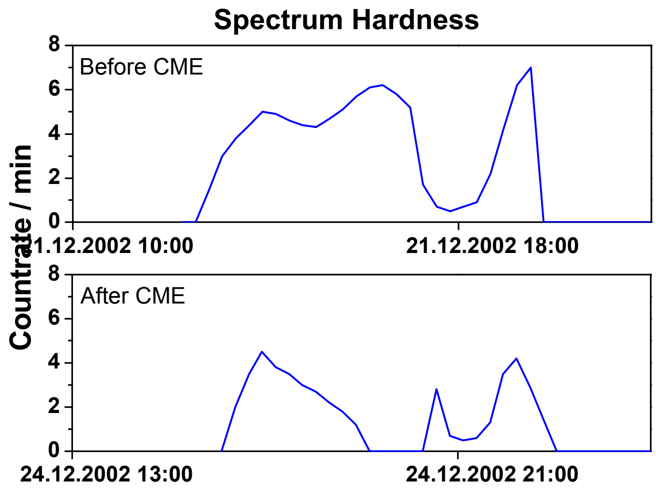

Fig. 3 Variations in the spectrum hardness as a function of the belt penetration depth shown for two periods: before and after the CME.

SUMMARY

The IREM is a replicate of the ESA Standard Radiation Environment Monitor SREM. Its detectors are optimised for measurements of proton and electron fluxes and spectra along of the spacecraft orbit as well as for monitoring of the radiation dose deposition. The monitor software is adapted to the Integral mission specific requirements with respect to the radiation protection scheme. The IREM was the first instrument onboard to be switched on after the lift-off. After a short commissioning phase it began its nominal operation. Its basic task is to warn spacecraft payload instruments against high levels of radiation. This function is realized by sending periodic broadcast packets informing about current levels of proton and electron fluxes as well as about deep dose deposition rates. Each instrument has its own response method depending on individual radiation hardness. Continuous radiation monitoring makes it also possible to increase the mission observing time as the scientific program do not rely on the fixed altitude position after passing through the high particle flux regions of the belts.

In addition, the IREM measures proton and electron spectra along the orbit and stores them as a scientific data. They are subsequently downloaded to the Integral Science Data Center (Versouix, CH) for further analysis. The data are usually available on ground for further analysis after few hours only. This fast access to the current radiation environment allows to use IREM as a part of the space weather network that monitors in a quasi-real time the radiation conditions around the Earth.

Most of the time the radiation environment is calm and consist of the cosmic rays. During passes through the belt, one can observe high variability in both particle intensity and their spectral hardness. Seasonal variations were particularly strongly visible during the spring months when the radiation belt boarders extended well above 80'000 km. This time was also characterized by large intensity variations. The IREM also detects CME events. It was seen that several CMEs observed until now may powerfully influence the electron belt features. Until now the IREM detected about five such events.

Successful performance of the IREM onboard of the Integral demonstrates its ability to operate as both a mission fitted real time radiation monitor and a simple spectroscopic device for particle environment measurements and space weather studies. It proves the ESA initiated concept of developing and using radiation monitors onboard of its spacecrafts.

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