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Letter to the Editor

Radiation environment along the *INTEGRAL*★ orbit measured with the IREM monitor

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Abstract. The *INTEGRAL* Radiation Environment Monitor (IREM) is a payload supporting instrument on board the *INTEGRAL* satellite. The monitor continually measures electron and proton fluxes along the orbit and provides this information to the spacecraft on board data handler. The mission alert system broadcasts it to the payload instruments enabling them to react accordingly to the current radiation level. Additionally, the IREM conducts its autonomous research mapping the Earth radiation environment for the space weather program. Its scientific data are available for further analysis almost without delay.

Key words. plasmas – radiation mechanisms: general – atmospheric effects – instrumentation: detectors – sun: flares – gamma rays: observations

1. Introduction

The *INTEGRAL* Radiation Environment Monitor (IREM) is a space dedicated detector assembly for both dosimetry and on board electron and proton spectroscopy. It is an adapted version of the Standard Radiation Environment Monitor (SREM) developed in partnership between European Space Agency (ESA), PSI and Contraves Space AG (Zürich) (Contraves 1996). Ten identical instruments were manufactured and calibrated for the ESA space program. Three monitors are by now in space (on board *STRV*, on board *PROBA* and on board *INTEGRAL*) and the rest have already been assigned to the forthcoming scientific missions. As it is well illustrated by *XMM-Newton*, *CHANDRA* or *INTEGRAL* itself, an autonomous radiation monitoring is of great importance for the spacecraft operations as well as for the lifetime and health of its instruments and devices. Having a reliable radiation monitor on board can help optimizing the mission observing time, react quickly to elevated radiation levels (by providing indications as to when safety measures must be applied for the most sensitive devices) or support in tracing the spacecraft anomalies.

The *INTEGRAL* (Winkler 2003) mission's prime goals are studies of intense gamma radiation sources and explorations of rare and powerful events. Four very sensitive payload instruments allow for observations in the range 3 keV to 10 MeV. In addition, an optical monitor (500–850 nm) allows observation in the *V* band. In order to maximize uninterrupted observing time and protect vulnerable equipment from hazardous radiation the satellite's orbit extends from 10 000 to 153 000 km. It allows spending almost 90% of its 72 hours long revolution outside of the Earth's radiation belts (altitude above 40 000 km). The IREM is responsible for the radiation monitoring on board and its key function on *INTEGRAL* is a continuous checking of the radiation environment to alert the spacecraft when high radiation levels are met. The payload instruments rely on such information and react accordingly entering, if necessary, a special safe mode in which they are protected from possible radiation damages.

The IREM was switched on only 10 hours after the launch (2002 October the 17th) and after a short commissioning phase it began its routine operation. During the *INTEGRAL* mission it can achieve its two objectives: being a vital part of the spacecraft radiation protection system and functioning as an autonomous radiation monitoring device. The mission highly elliptical orbit allows IREM to probe 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. With the planned mission lifetime of up to 5 years the IREM will be able to cover the whole declining phase of the current Solar cycle.

We will briefly characterize below the main features of the monitor, including its calibration and response modeling (Hajdas et al. 2002) and present its first measurements of the external radiation environment along the *INTEGRAL* orbit.

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★ Based on observations with *INTEGRAL*, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA.

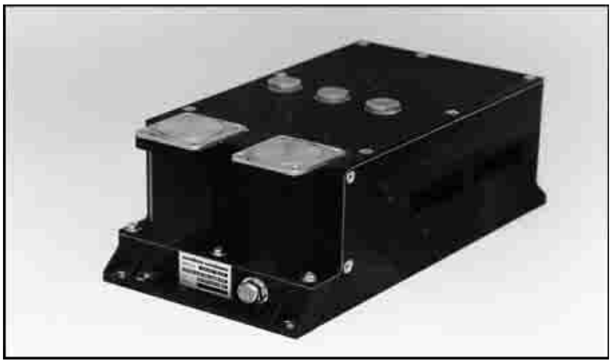

Fig. 1. The *INTEGRAL* Radiation Environment Monitor.

2. Instrument characteristics

The IREM (Fig. 1) utilizes three standard Silicon Surface Barrier Detectors; 500 μm thickness, active area 25 (2) and 50 (1) mm^2 – see IREM Users Manual[1] for more details. They are embedded in a bi-metallic shielding of tantalum (inner) and aluminum (outer) with 8 g/cm^2 of total thickness. For enhanced resolution in energy and directionality of the incident particles, two of the detectors are arranged in a telescope. All pre-amplified detector pulses are scrutinized by a set of fifteen comparators – ten for single events, four for coincidences and one heavy ion channel. Their levels are optimized to get the most accurate information on the spectral shape of the detected particles. The low energy detection thresholds are: $E^{\rm p}_{\rm thr} \simeq 10$ MeV for protons and $E^{\rm e}_{\rm thr} \simeq 0.5$ MeV for electrons. The heavy ion channel has an energy threshold of ~150 MeV/nucleon. The particles come through the conical front collimators of ±20° opening.

High energy particles ($E_{\rm p} > 100$ MeV) can enter the detector from any direction. Some of them, however, are stopped in the satellite bulk mass before they hit the monitor. Therefore, the full response matrix must take the satellite into account (Hajdas et al. 2002).

3. Calibrations and modeling

IREM calibrations were done using the Proton Irradiation Facility (PIF) (Hajdas et al. 1996) as well as gamma and electron radioactive sources in PSI. It was important to use the same particles and spectra as anticipated during the mission in space. The full data set comprising several initial particle energies (E_0: 8–300 MeV) and incoming angles (θ: 0–180°) provided a reference for the response matrix. Experimental results were compared with fine-tuned computer calculations performed with the help of the GEANT code from CERN using a precise computer model of the monitor. In the next step, IREM responses for both protons and electrons were generated for the whole energy range anticipated in space.

The proton response was calculated for thirty energy bins equally spanned on logarithmic scale between 8 and 800 MeV. The response presented for selected scalers in Fig. 2 (lower panel) shows results integrated over the full 4π angle of incoming particles. The right hand side of the sensitivity curve strongly depends on the extra shielding provided by the satellite. For electrons, the number of bins was only equal to 15 and covered the energy range from 0.3 to 15 MeV. The bins had equal widths on logarithmic scale. Response calculations (also integrated over the full 4π angle) are presented for selected scalers in Fig. 2 (upper panel). The shielding of the monitor stops not only the bremsstrahlung but also electrons coming from outside of the entrance collimators. It implies that their response function is only very weakly affected by the satellite.

[1] E.g. `http://pif.web.psi.ch/irem/IREM_USER_MANUAL_v3.pdf`

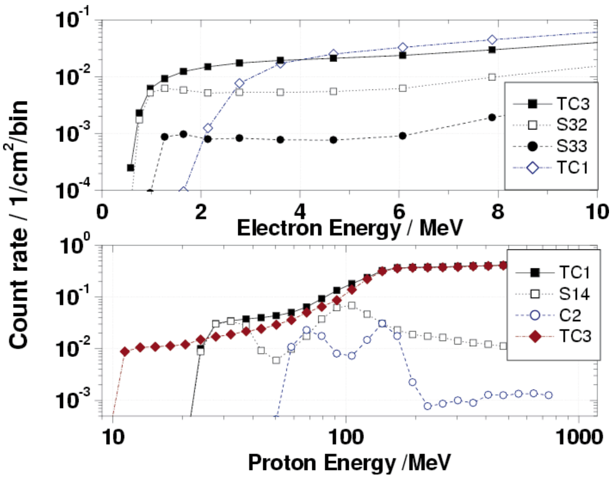

Fig. 2. Proton and electron responses shown for selected scalers as a function of incoming particle energy.

Table 1. Instrument limits for particle fluxes and dose rates.

Instrument	Protons	Deep dose	Electrons
	(cm^{-2} s^{-1} sr^{-1})	(rad hour^{-1})	(cm^{-2} s^{-1} sr^{-1})
IBIS	$2.0 \times 10^{+2}$	7.0×10^{-2}	$2.0 \times 10^{+2}$
SPI	$2.0 \times 10^{+2}$	$7.0 \times 10^{+1}$	$3.0 \times 10^{+4}$
JEM-X	4.0	7.0×10^{-2}	$6.0 \times 10^{+1}$
OMC	$4.5 \times 10^{+1}$	3.0×10^{-1}	$3.0 \times 10^{+4}$

4. IREM performance and alerts

The IREM was the first instrument on board to be switched on after the launch. Its basic task of warning the spacecraft payload instruments when high levels of radiation are met is realized by sending periodic broadcast packets. Every eight seconds the IREM passes to the spacecraft a fifteen words long Transfer Data Block (TDB). Its first five words contain information about the current radiation environment as well as about the IREM status. The rest consists of either the scientific or housekeeping data for further download to the ground. Three TDB words containing radiation data come from pre-selected, dead time corrected IREM scalers. One of them monitors proton flux, the other one is sensitive to electrons, while the third one informs about a deep dose deposition. Each payload instrument has its own response method depending on individual radiation hardness – see Table 1.

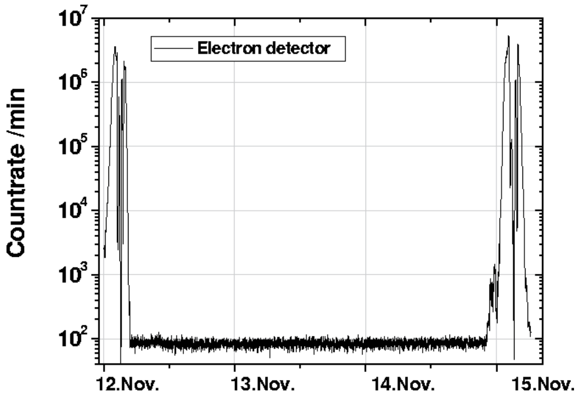

Fig. 3. Typical IREM count rate along the spacecraft orbit measured by the electron detector TC3.

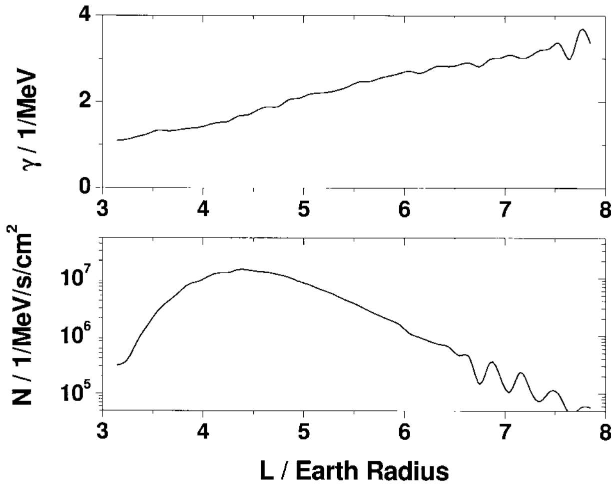

Fig. 4. Electron spectral parameters N and γ shown as a function of the L-parameter inside of the radiation belt.

In addition to radiation warning signals from IREM the mission ground station provides a Radiation Belt alert flag (currently set for descending direction – belt entrance – at 60 000 km and ascending – belt exit – at 40 000 km) and all payload devices have an independent safeguard too.

5. Radiation environment

The orbit of *INTEGRAL* was selected to maximize its uninterrupted scientific observing time and telemetry flow, reducing at the same time its encounter with the Earth's radiation belts to minimum. High energy particles in the belts cause not only an enhanced instrument background but also induce radiation damages and malfunctioning of the spacecraft devices. It may strongly diminish an effective lifetime and data quality of the space observatory. The satellite revolution of 72 hours duration has a perigee of about 10 000 km. The trajectory crosses the whole outer electron belt and just barely touches the inner belt with increased fluxes of protons.

As one can see in Fig. 3, the increase of the count rate inside of the belts may reach 5 orders of magnitude and it is caused by high energy electrons. With an apogee of 153 000 km the mission spends up to 90% of the orbital time in regions dominated only by a fairly constant cosmic rays background (mostly high energy protons with a flux of $\sim$2 cm^{-2} s^{-1}). The IREM used cosmic rays as a cross-check of its detector calibration. The mission observing program is conducted outside the belts. It may, however be interrupted by infrequent solar events.

6. Radiation belts

The spacecraft passage through the belts is characterized by highly variable radiation environment (Bühler & Desorgher 2002) that depends upon geomagnetic coordinates of each particular trajectory. A typical belt crossing takes between seven and ten hours and electron fluxes may reach up to 10^7 cm^{-2} s^{-1} (for energies higher than 0.5 MeV). The maximum flux shows variations from orbit to orbit by a factor of about three. Due to the high perigee value, the IREM observes only a slight increase of the proton flux from the outer edge of the proton belt. Its intensity reaches just about 10 cm^{-2} s^{-1} for energies above 20 MeV. It takes about 1.5 hours to fly through the proton populated area.

The standard coordinate system used to display or analyze radiation belt particle fluxes is making use of the 2 following variables: the magnetic field strength B and the McIlwain L-shell parameter L (McIlwain 1966). For a given satellite position, parameters B and L are computed using the International Geographic Reference Field, IGRF plus an external field model (representing the solar wind influenced parts of the Earth's magnetic field). The IREM electron spectra are usually approximated by an exponential function. The equation below is used to describe the differential electron flux f (cm^{-2} s^{-1} MeV^{-1}) as a function of energy E

$$f(E) = N\mathrm{e}^{-\gamma(E-1.0\mathrm{MeV})}. \quad (1)$$

Parameters N and γ are determined from the measured count rates by a fitting procedure. They depend on the IREM detection system sensitivity and allow to parameterise the electron spectra between 0.5 and 5 MeV. In Fig. 4, the average electron flux normalization parameter N and the spectrum hardness parameter γ are shown as function of L-values, for *INTEGRAL* passages through the outer radiation belt. The data illustrates a period from January 1 to May 1 2003. The spectra are hardest at low L-values i.e. closer to the Earth and soften with increasing values of L while the maximum fluxes are found for $L \simeq 4$–5.

Monitoring of the electron belts boundaries is one of the most important functions of the IREM. In addition to protecting sensitive devices it allows for gaining extra observing slots (up to 3% of observing time per orbit) as the scientific program of the mission is conducted only outside of the belts. Time evolution of the belt entrance and exit limits for the first 81 spacecraft orbits is presented in Fig. 5. Large deviations around the mean value are attributed to both random (like solar flares) and periodic (like its rotation) mechanisms of the solar activity as well as to the sun-earth geomagnetic bond with its seasonal variations.

The radiation environment in space, as measured using on board monitors like the IREM, can be compared with existing models of the belts. The electron AE-8 (Sawyer & Vette 1976)

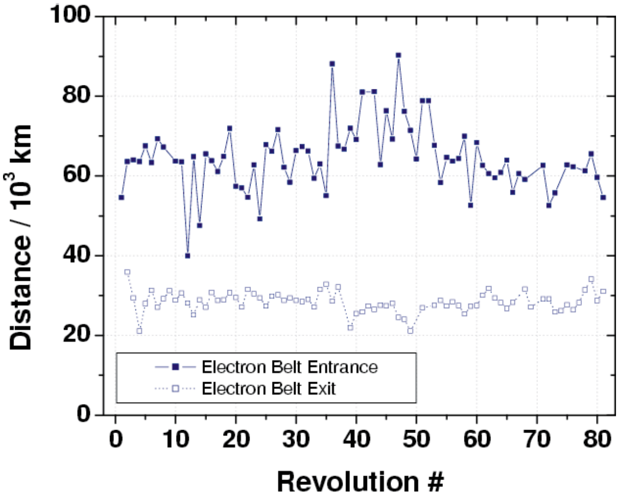

Fig. 5. Position of the electron belt entry and exit regions as a function of the *INTEGRAL* orbit number.

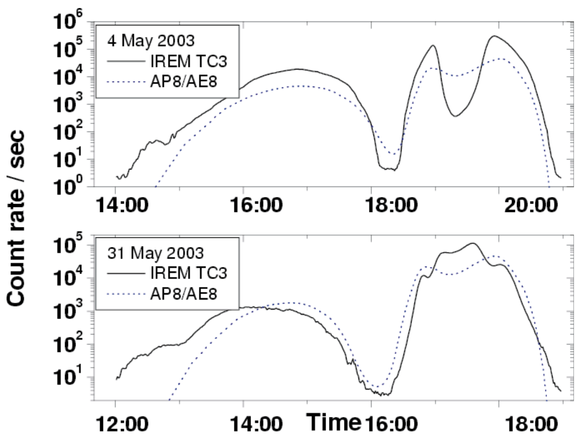

Fig. 6. Comparison of the measured and computed (NASA AP8/AE8 static models) belt profiles for a quiet and post solar event radiation environment.

and proton AP-8 (Vette 1999) NASA belt models are quasi-standards, conventionally used to asses the radiation environment on spacecrafts. They both are static representations of average fluxes of particles trapped in the Earth's radiation belts.

For the proton belt the static approximation is usually qualitatively good enough but this may not be the case for the electron belts as they are highly dynamic (Bühler & Desorgher 2002). This is demonstrated in Fig. 6 where the IREM measured count rates are compared with predictions computed with the AP8/AE8 models. The upper figure shows count rates in the TC3 electron counter (low energy threshold of ~500 keV) for the perigee passage of May 4 2003. Although the measured particle rates are much higher than the predicted ones, both the peak positions and distributions are similar. The lower figure shows an analogous passage (31 May 2003) after a magnetic storm that was initiated by a solar proton event. In this case, neither intensities or peaks nor distributions of measured and predicted environment agree.

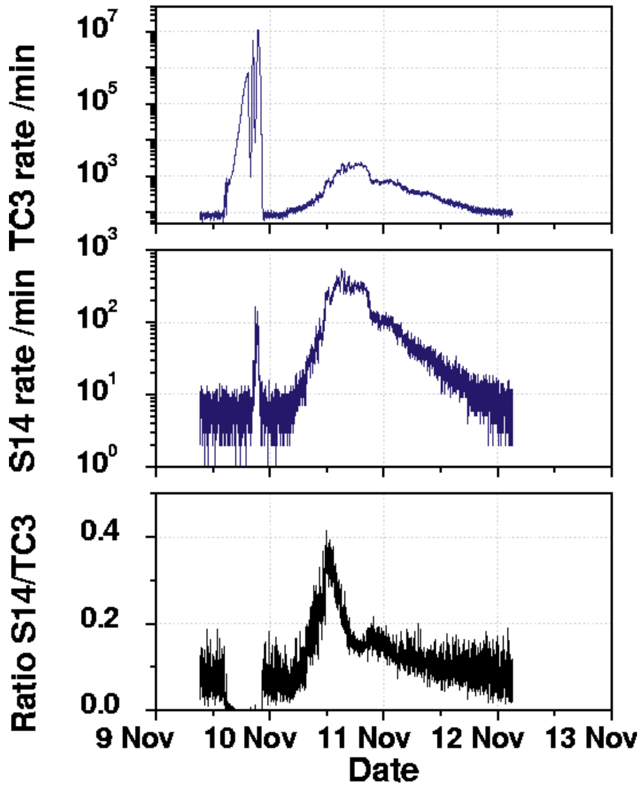

Fig. 7. Particle rates and rates ratio for two scalers with the large solar event of revolution 9 (right peak).

7. Solar events

The time spent outside of the magnetosphere is dominated by cosmic rays and may be occasionally interrupted by particles ejected from the sun during solar events. It is represented by a flat region between the belts peaks as seen in Fig. 3. High energy particle fluxes from coronal mass ejections may have duration from hours to days and can heavily disturb the observation program. Several events of different amplitude and duration have already occurred during the *INTEGRAL* mission reflecting the fact that the Sun is still quite active (maximum part of the Solar cycle). Their long term impact on the radiation belts was already illustrated in Fig. 6 while a light curve of one such solar event itself is shown in Fig. 7 in which one can see an increase of the count rates by more than 100% in scalers TC3 and S14.

In the upper panel of Fig. 7, one could see the contribution of low energy protons (E_p > 10 MeV) to the TC3 count rate (mainly sensitive to electrons E_e > 500 keV) while the middle panel present the higher energy (E_p > 20 MeV) proton count rate from S14. The peak on the left side of both graphs is due to radiation belt particles – electrons in case of TC3 and protons for S14 while the long structure in the middle is made by solar protons. The bottom panel shows the counters ratio in which one sees the evolution of the proton hardness. The peak in the hardness occurred about 5 hours before arrival of the maximum flux.

8. Other instruments

The IREM calibration of count rates was confirmed by other payload instruments during commissioning phase of the mission. For this purpose one used the active shielding BGO detectors of the high energy instruments as well as the CCD chips of the OMC. The verification was performed with highly penetrating cosmic rays and radiation belt particles. Further cross checks are routinely performed using for example the JEM-X and ISGRI data while entering the radiation belt, when the devices are still in their active modes. Such verification revealed very stable performance of all IREM detectors.

9. Summary

The IREM, flying on board *INTEGRAL*, belongs to the ESA Standard SREM monitors that are optimized for detection of protons and electrons and for alerting the spacecraft during high radiation levels. It is specially suited to the *INTEGRAL* payload radiation protection scheme. The IREM permanently monitors an external radiation environment of the satellite and periodically sends broadcast packets with current levels of particle fluxes. Each payload instrument reacts to the IREM message individually.

Most of the spacecraft orbit is characterized by a quasi constant cosmic rays background that may be occasionally disturbed by sporadic CME solar events. When approaching a perigee, the spacecraft passes through the outer electron belt. IREM measurements reveal very dynamic belt environment that shows only a qualitative agreement with the present NASA AP8/AE8 models. Real-time IREM radiation maps allow not only for scientific program optimizing and instrument protection. The data are also used for the space weather global programs and are promptly (i.e. within 2 hours) available for further analysis.

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