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Current Active Detectors for Dosimetry and Spectrometry on the International Space Station

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Abstract
We present a high-level overview of two of the most important radiation detection systems currently flying aboard the International Space Station (ISS), ISS-RAD and Timepix. ISS-RAD is a single, large unit that is capable of detecting both charged and neutral high-energy particles. For most of its first three and a half years of operations onboard Station, ISS-RAD has been periodically moved to different modules, including the USLab, Columbus, JEM, Node2, and Node3. In contrast, the much smaller Timepix-based detectors are deployed in several locations around the station. The first generation of these units were known as REMs, or Radiation Environment Monitors. A second generation has recently been deployed, known as REM-2 units. We will briefly describe the technologies used in these systems and their capabilities.

Overview

The International Space Station (ISS) continues to provide a base for long-term human habitation of space. As such, it is a vital platform for science experiments and engineering demonstrations that will – among other purposes – help NASA select technologies to be used in future journeys into deep space. The ISS orbits the earth every 90 minutes, in an orbit with an inclination of 51.6º and an altitude of about 410 km above sea level. The strength of Earth's magnetic field as seen on ISS varies continuously, as the field varies significantly with latitude, longitude, and altitude. At an altitude of 420 km, field strength varies from about 0.2 to 0.7 Gauss, with the weaker regions of the field permitting almost all galactic cosmic rays (GCRs) to reach low-Earth orbit, while the stronger regions of the field at low latitudes provide substantial shielding against incoming charged particles. In addition to the variations in GCRs, the orbit of the ISS takes it through the South Atlantic Anomaly (SAA) several times each day. The SAA is a region populated by magnetically trapped protons and electrons.

The radiation environment inside ISS at any given moment strongly dependent on its position, giving rise to a dynamic environment that is more complex than the environment in, for example, interplanetary space or the surface of the Moon. For example, in a modestly-shielded part of the ISS, variations in geomagnetic shielding cause the GCR dose rate to vary by a factor of about 5 going from low latitudes (dose rates of ~ 0.05 μGy/minute) to high latitudes (~ 0.25 μGy/minute); dose rates in the SAA can exceed 10 μGy/minute, and can go even higher during Solar Particle Events.

The need for radiation monitoring on the ISS for purposes of crew safety has been apparent from the earliest phases of its development in the 1980's. The Space Radiation Analysis Group

(SRAG) at the NASA Johnson Space Center (JSC) is responsible for this effort. For many years, the principal means of monitoring crew doses was passive dosimetry, such as thermoluminescent dosimeters (most commonly TLD-100), optically stimulated luminescence detectors (OSL), and plastic track detectors (e.g., CR-39). See Zhou et al. (2009) for an overview [1]. These detectors have many useful properties, as well as some drawbacks. A detailed discussion of the pros and cons of passive dosimetry is beyond the scope of this article, but a significant problem with passive detectors is their lack of real-time readout. Passive dosimeters cannot be used as radiation alarms and are unsuitable for expeditions into deep-space destinations, as they would not provide any data prior to being returned to Earth. To satisfy radiation alarm requirements, NASA has long flown Tissue-Equivalent Proportional Counters (TEPCs), which provide real-time data with the added virtue of being sensitive not only to charged particles but also (to a limited extent) to the neutron component of the radiation field inside the ISS. An early version of the TEPC used on the Space Shuttle was described by Badhwar et al. [2]. However, long-term stability of TEPCs is a serious issue, and recent experience with a more ambitious TEPC design flown on ISS [3] has been less than optimal. In the mid-2000's, NASA began investigating other detection technologies that would reduce or eliminate reliance on TEPCs in the future. That undertaking led to the adoption of the ISS-RAD instrument and to Timepix-based detectors, which are the subjects of this article. Timepix systems are likely to be used not only for the remaining lifetime of the ISS, but for exploration missions in the decades to come. In addition, development of personal active dosimeters is well underway. Prototype units have flown on the ISS and have been shown to report dose rates that agree well with those obtained with more established detectors. A brief description of these developments and their implications for future flight will be provided in a separate article.

ISS-RAD

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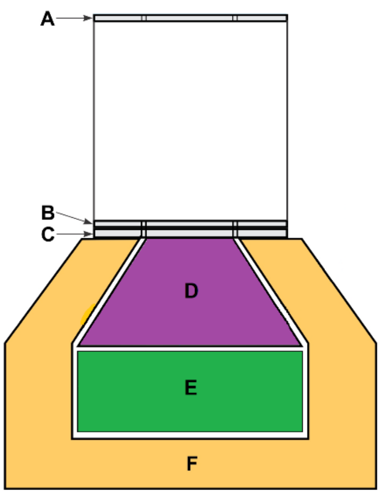

Figure 1. Schematic drawing of the MSL-RAD sensor head, on which the ISS-RAD CPD design is based.

The Radiation Assessment Detector (MSL-RAD) for the Mars Science Laboratory Curiosity Mars rover was proposed and selected in 2004. It is a highly capable instrument, consisting of a combination of silicon diodes and scintillators in a compact, low-mass package (1.5 kg). Detailed descriptions of the instrument and its calibration can be found in the literature [4, 5]. A schematic drawing of the sensor head is shown in Figure 1; the sensor head is coupled to the electronics box, which communicates with the rover computer for commanding, including data transfer and configuration changes. The sensor consists of the A, B, and C planar silicon diodes, each 300 μm thick, and the D, E, and F scintillators. D is made of cesium iodide (CsI) and is an efficient γ-ray detector, as well as being an essential part of the charged-particle telescope. The E and F detectors are plastic scintillators, with F (along with the C detector) providing a nearly hermetic enclosure around D and E. This enables use of D and E as neutral-particle detectors, using simple veto logic: a hit in D and/or E with no other hits in any detectors is considered to have been caused by a γ-ray or a neutron. (E is particularly sensitive to lower-energy neutrons, whereas both D and E are sensitive to higher-energy neutrons.) Work was performed by Koehler et al. to model the response of the system to neutral particles and to invert the deposited energy spectra obtained by D and E into γ-ray and neutron spectra [6]. This design, with a few minor modifications described below, is the basis for the "CPD" half of the ISS-RAD instrument.

Charged Particle Detector (CPD)

The ISS-RAD charged particle detector, or CPD, is nearly identical to the MSL-RAD detector described above. There are two main differences: (1) the D scintillator is made of bismuth germanium oxide (BGO) rather than CsI, owing to concerns about humidity on the ISS (CsI is hygroscopic); (2) the dimensions of the F scintillator were expanded so that, rather than being 1.2 cm thick, it is 1.8 cm thick, giving better resolution of singly-charged particles and improving the efficiency of the veto used for neutral particle detection. Note that the terminology "CPD" is not strictly accurate, since the detector – like MSL-RAD before it – is capable of measuring energetic neutral particles as well as charged particles.

Fast Neutron Detector (FND)

In addition to the neutral-particle measurement capability provided by the CPD, NASA required measurements of neutrons at energies lower than the lower limit of the CPD's sensitivity. A dedicated sensor, the Fast Neutron Detector or FND, was built to meet this requirement, which was driven by two considerations: (1) neutrons in the 0.5 to 10 MeV energy range are abundant in shielded environments in space; and (2) the radiation weighting factors (essentially, estimates of biological effectiveness) of neutrons in this energy range are large. It has been estimated that as much as 30% of the total dose equivalent on the ISS may be attributable to neutrons. It was therefore important to have an instrument capable of making the relevant measurements.

The FND detects neutrons using the "capture-gating" method first developed by Drake and Feldman at the Los Alamos National Laboratory in the 1980's [7]. The concept is as follows. A plastic scintillator is fabricated with boron mixed uniformly throughout. Naturally occurring boron contains 20% of the ^{10}B isotope, which has a large cross section for capturing thermal neutrons. When a "fast" neutron interacts in this scintillator, there is a non-negligible (energy-dependent) probability that it will scatter with a proton in the plastic, transferring some or most of its energy in the process. The first collision or subsequent collisions may cause the neutron to lose nearly all its energy, to the point where it is "thermal" (kinetic energy less than 1 eV) and has a large probability for being captured by a ^{10}B nucleus within a few microseconds of the initial collision. When a capture occurs, the nucleus instantaneously splits into ^{7}Li and ^{4}He, usually accompanied by a γ-ray. These products – particularly the ^{4}He nucleus – produce a characteristic amount of scintillation light. The process overall produces two flashes of scintillation light, the first from the initial collision or collisions that cause the incident neutron to thermalize, and the second from the capture reaction. Although there is still some potential for contamination by other particle types (randomly-arriving γ-rays and/or charged particles with arrival times and amplitudes that fall within the windows for capture decay products), the capture-gating method allows for measurements in the required neutron energy range with powerful discrimination against other particle types.

Common Interface and Data Products

To accommodate the FND, and to provide flexibility in interfacing to various data buses, a new circuit board – the RAD Interface Board, or RIB – was designed to handle the flow of data from both CPD and FND as well as external communications. The RIB can communicate via USB (extensively used in ground testing) and via the MIL-STD-1553 protocol as well as providing the capability to operate from +28 V power (as in the Russian segment of ISS) or +120 V (as in the rest of ISS). RAD provides radiation caution and warning alarms, which requires connection at all times to the ISS 1553 bus. (See https://www.milstd1553.com.) Figure 2 shows two views of the detector, a schematic drawing with the cover not depicted, and a picture taken on ISS after deployment, with the cover installed. The proximity to other pieces of equipment complicates the analysis and interpretation of the data.

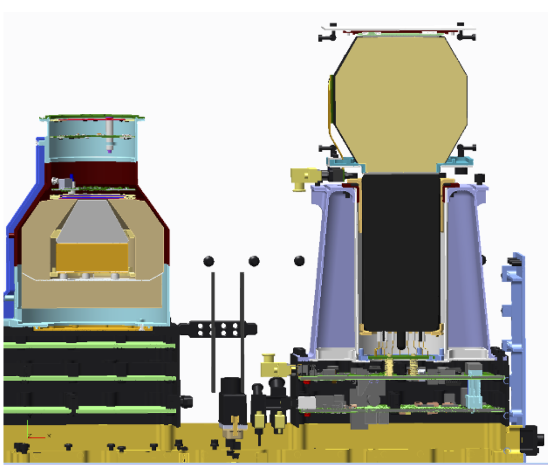

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Figure 2. A CAD drawing of ISS-RAD, which is much larger and more massive than MSL-RAD (9 kg compared to 1.5 kg), is shown at left. At right, RAD is pictured in its initial deployed location aboard ISS in the USLab module. In both images, the CPD is to the left, the FND to the right.

Figure 3 shows a typical display that is available in near-real time to console operators. The science data displayed include the instantaneous and cumulative dose rates measured by the CPD, the instantaneous and cumulative neutron dose equivalent rates measured by the FND, and differential proton fluxes measured by the CPD in three energy bands. These data products all exhibit the same characteristic sensitivity to the orbit phase, with rates varying in a pattern resembling a sinusoid when ISS is outside of the SAA, and spikes during the relatively brief SAA passes. The quasi-sinusoidal patterns seen in the data are due to variations of the geomagnetic field strength as ISS moves through its orbit.

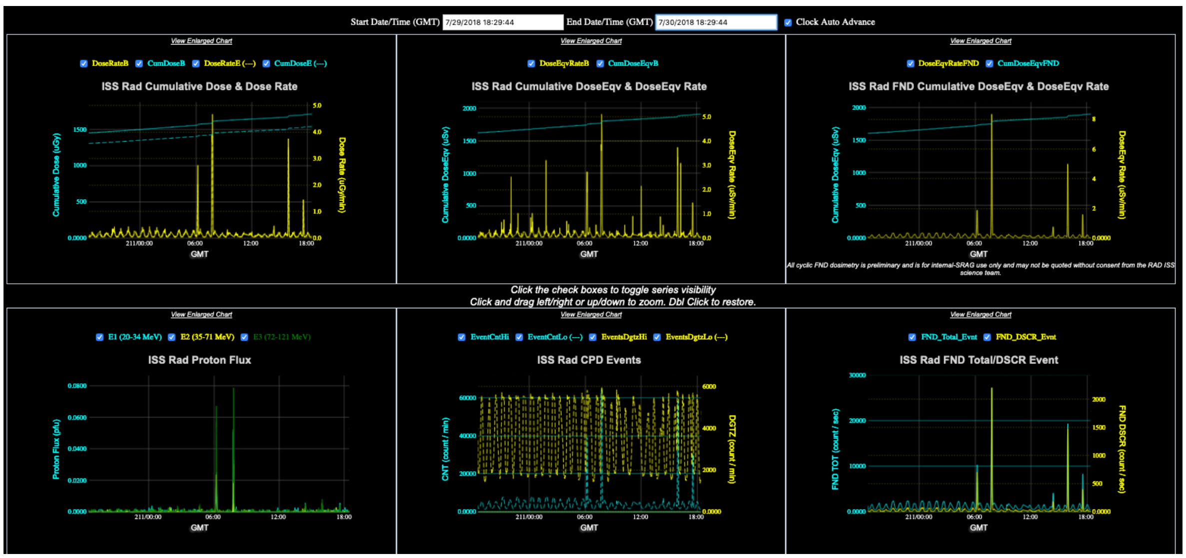

Figure 3. Real-time display of ISS-RAD data products. The plots are typically shown in 24-hour periods with 1-minute time resolution.

Timepix on the ISS

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In 2007, the NASA Johnson Space Center's Space Radiation Analysis Group (SRAG) considered moving forward to the next generation of detectors for use in space radiation dosimetry applications. After assessing the current state of applicable technologies, they decided to examine the Timepix-based devices [8] being designed and produced by the Medipix2 Collaboration [9] based at the European Laboratory for Particle Research (CERN) in Geneva, Switzerland.

After several years of studying and characterizing the Timepix Technology in collaboration with the University of Houston, the first Timepix units were delivered to the International Space Station (ISS) in 2012, and Timepix-based Radiation Environment Monitor (REM) units have been continuously deployed there since then. Timepix-based devices were also deployed as the primary active radiation monitor (known as the *Battery-operated Independent Radiation Detector*, or BIRD) on the first test of the new Orion Capsule on its initial test flight, Exploration Flight Test-1 (EFT-1), in 2014 [10]. At present, the basic radiation monitors planned for use on the upcoming Orion flights are the Timepix-based Hybrid Electronic Radiation Assessor (HERA) units.

The Timepix detector assembly is a hybrid pixel detector consisting of the Timepix detector integrated circuit chip and its associated overlying monolithic 300 or 500 μm thick sensor layer. The Timepix itself is a square chip divided into 256 x 256 (65,536) square pixels, each 55 μm on a side. The sensitive area is about 2 cm^2.

The Timepix is a frame-based device analogous to a camera in that it has an electronic "shutter" that is opened for a specific (adjustable) exposure time, during which any charge collected by the Timepix is recorded. The sensitive element of a Timepix-based system is a solid-state detector, typically silicon, that is mated to the chip via individual solder pads, as illustrated in Figure 4. (Cadmium telluride is sometimes also used as a sensor material.) Each pixel in the chip contains the circuitry needed to convert the amount of charge collected in that pixel into a digital value that is read out when the "shutter" closes. Analysis of the patterns and values of the individual clusters of pixels that are produced by ionization in the sensor allow the identification of the incident particle. One important value that can be measured directly is the linear energy transfer (LET) in silicon created by the incident component of the radiation field. Figure 5 shows an example of one frame from the ISS.

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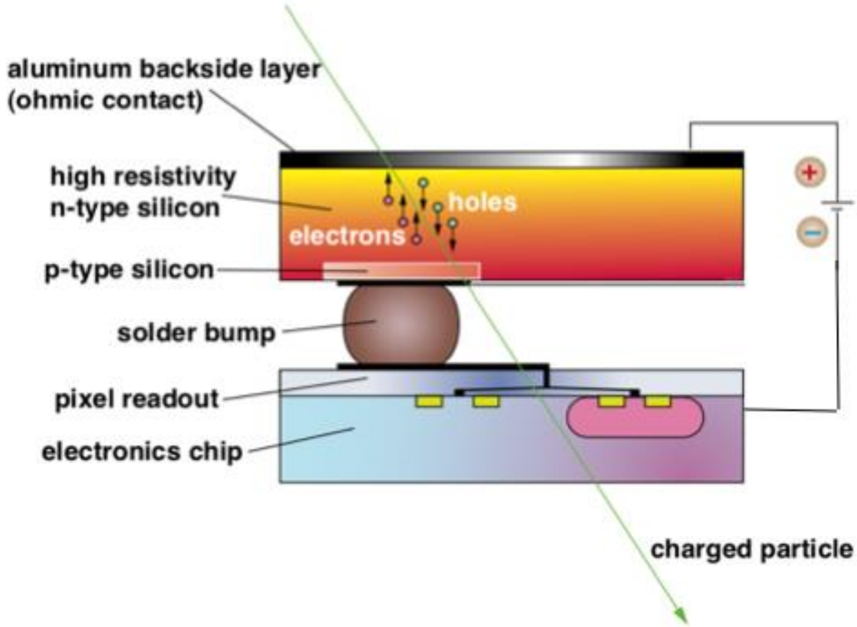

Figure 4. This schematic shows the relative structure of the Timepix chip and its sensor layer with the intervening solder bump. The charges are liberated by the passage of ionizing radiation and drift in the bias-voltage field to be collected by the input to the pixel electronics. Note that the actual sensor layer is 6 to 10 times the 55μm pixel size

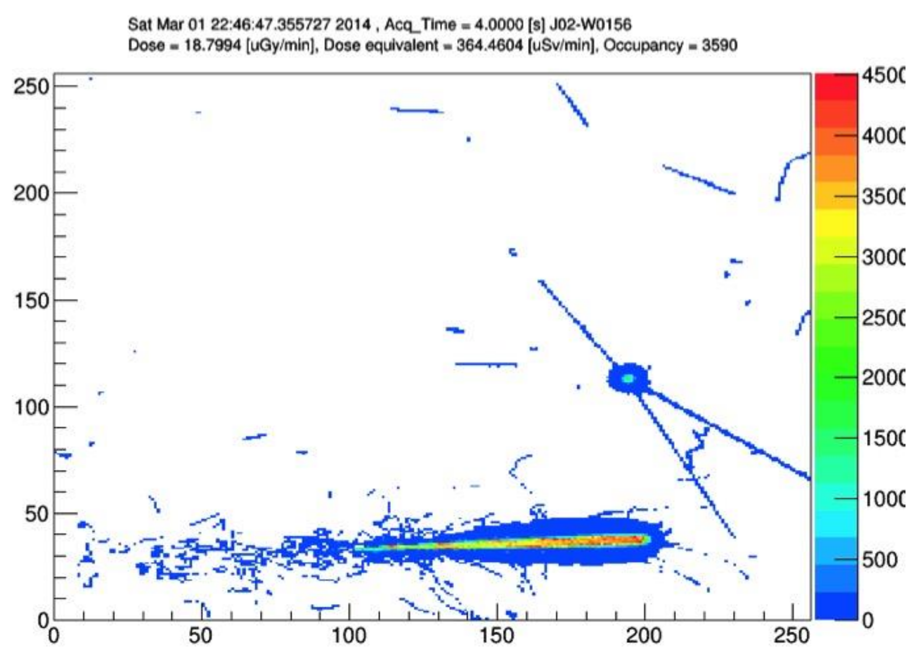

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Figure 5. A Timepix 4-second frame from one of the ISS REM units showing a very rare traversal by a relativistic heavy track, and a separate unassociated interaction with one of the Silicon nuclei in the sensor, against the background of the more normal background.

A considerable number of scientific articles that describe Timepix technology and its uses in greater detail have been published. Interested readers are referred to articles in this non-exhaustive list [11-21].

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