Exploration Systems Radiation Monitoring Requirements

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By

Dr. Ronald Turner

Analytic Services, Inc.
Suite 800
2900 South Quincy Street
Arlington, Virginia

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Acronyms

ALARA	As Low As Reasonably Achievable
APD	Area Passive Dosimeter
AU	Astronomical Unit (distance from the Earth to the Sun)
CARD	Constellation Architecture Requirements Document; CxP 7000
CEQATR	Constellation Program Environmental Qualification and Acceptance Testing Requirements; CxP 70036
CME	Coronal Mass Ejections
CPD	Crew Passive Dosimeter
DRM	Constellation Program Design Reference Missions and Operations Concept: CxP 70007
DSNE	Constellation Program Design Specification for Natural Environments; CxP 70023
EVA	Extra-Vehicular Activity
EVCPDS	Extra Vehicle Charged Particle Directional Spectrometer
GCR	Galactic Cosmic Radiation),
HIDH	Human Integration Design Handbook; NASA/SP-2010-3407
HSIR	Constellation Program Human Systems Integration Requirements; CxP 70024
IMF	Interplanetary Magnetic field
ISS	International Space Station
IVCPDS	Intra Vehicle Charged Particle Directional Spectrometer
LET	Linear Energy Transfer
MeV	Mega-electron Volts: 10^6 electron volts
MORD	Medical Operations Requirements Document; SSP 50260
MOU	Memorandum of Understanding
MS	Mission Systems
NEDD	Constellation Program Natural Environment Definition for Design; CxP 70044
NRC	National Research Council
PEL	Permissible Exposure Limits
PRD	Passive Radiation Dosimeters
RAD	Radiation Assessment Detector
SDO	Solar Dynamics Observatory
SFHSS	Space Flight Human Systems Standard; NASA-STD-3001
SOHO	Solar and Heliospheric Observatory
SPE	Solar Particle Events
SRAG	Space Radiation Analysis Group
STEREO	Solar TErrestrial RElations Observatory
TEPC	Tissue Equivalent Proportional Counter
THREE	The Health Risks of Extraterrestrial Environments
Z	Nuclear charge of an element or ion

Overview of Exploration System Radiation Monitoring Requirements

The threat to human health from exposure to the deep space radiation environment poses one of the most significant challenges to exploration missions beyond low Earth orbit [NRC 2012 and NRC 2008]. NASA's current Permissible Exposure Limits (PEL) could be exceeded within 3 to 6 months in deep space. [Cucinotta, et al., 2011]. Sources of long term radiation exposure include Galactic Cosmic Radiation (GCR), short-term but intense Solar Particle Events (SPEs), and the secondary neutrons generated by interactions between the incident radiation and spacecraft material. There are several articles within the on-line resource "The Health Risks of Extraterrestrial Environments" (THREE[1]) that address radiation risk management strategies [Schimmerling, 2010a, Turner, 2010,]. This article will focus on exploration mission requirements (in this case, specifically human missions away from the protection of the Earth's atmosphere and magnetosphere) to monitor the radiation environment and crew exposure, with emphasis on the types of measurements and instruments needed to support a broader radiation risk management strategy.

The objectives of radiation monitoring for NASA exploration missions is to prevent significant deterministic effects and reducing risks to stochastic effects in compliance with established limits. This includes providing the situation awareness needed to keep radiation exposure "as low as reasonably achievable (ALARA), which is a cornerstone aspect of NASA's radiation risk mitigation policy.

The main elements of terrestrial radiation risk management are time, distance, and shielding: minimize the time of exposure, maximize the distance from the radiation source, and provide adequate shielding to reduce the impact of exposure to radiation emitted by a nearby source. In deep space, the crew is essentially embedded in the source, so distance cannot be a factor; the mission duration is constrained by the destination, by orbital mechanics, and by the mode of space transportation; and shielding, particularly against GCR, is difficult and is constrained by cost. So a different paradigm is needed for deep space radiation risk management. The three analogous foundations of a space radiation strategy include warning, monitoring, and shielding.

- Warning is analogous to the "time" element of terrestrial radiation risk management, since an effective warning system will enable a faster reaction time to elevated levels of the natural radiation environment from solar events, and will thus decrease the direct exposure to episodic severe space radiation, provided an adequate framework exists to recognize the threat of increased radiation and to communicate the warning in an actionable time frame. Or, perhaps as important to operations, a system exists to reliably forecast long periods of very low probability of enhanced radiation, "quiet time" forecasts.
- Monitoring is analogous to the "distance" element of terrestrial radiation risk management, since an effective monitoring system is needed to ensure knowledge of the radiation environment at the astronaut location.
- Shielding plays the same role in both terrestrial and space radiation risk management, as it is the architectural component that is used to reduce the impact of exposure to the unavoidable source. It is complicated compared to the terrestrial counterpart by the high cost to add shielding to space elements and by the highly penetrating nature of space radiation…successive layers of shielding

[1] https://three-jsc.nasa.gov/

[2] The first two-orbit unmanned test flight of Orion, Exploration Flight Test 1 (EFT-1), is scheduled for a launch aboard a Delta IV Heavy rocket in 2014. The first launch with crew would be by the end of 2016 [NASA report to

have limited impact without going to meters of depth. Shielding is divided between different elements of the overall exploration architecture…for example: minimal for spacesuits, more on long-range rovers, and still more on habitats.

This paper will focus on the monitoring requirements, and will consider also monitoring necessary to support adequate, timely, and actionable warning.

Specific Examples for Space Vehicles, Extra-Vehicular Activity (EVA) and Habitats

International Space Station

NASA's radiation monitoring approach to the International Space Station (ISS) provides a starting point for understanding NASA's monitoring requirements for radiation risk management. Note however, that ISS operations have some significant differences from deep space exploration missions. Mission duration for individual crew members can be as short as a few weeks or as long as six months to a year, but at any time the astronauts can abort to Earth. Because of the shielding provided by the Earth's magnetic field, the radiation environment at ISS orbital altitudes is about one third to one half as intense as the deep space environment. In addition to reducing the contribution from Galactic Cosmic Rays, the Earth's magnetosphere also provides substantial protection from Solar Particle Events, with significant exposure limited to short periods at the most northern and southern latitudes. Nonetheless, the radiation environment is monitored extensively within the space station.

There is significant documentation of NASA's radiation monitoring requirements for ISS. The NASA Space Flight Human Systems Standard (SFHSS), NASA-STD-3001 is a two-volume set of NASA Agency-level standards, established by the Office of the Chief Health and Medical Officer, that defines levels of acceptable risks to crew health and performance that result from space flight. Volume 1 of the SFHSS, Crew Health, sets standards related to crew health. Volume 2, Habitability and Environmental Health, defines the environmental, habitability, and human factors standards that are related to environmental health and human-system interfaces during human space flight.

The Human Integration Design Handbook (HIDH), NASA/SP-2010-3407, provides guidance for the crew health, habitability, environment, and human factors design of all NASA human space flight programs and projects. It is a resource for implementing the requirements in the SFHSS, and it provides the data and guidance necessary to derive and implement program-specific requirements that are in compliance with the SFHSS. The scope of the handbook includes all crew operations both inside and outside the spacecraft in space and on lunar and planetary surfaces.

The International Space Station Medical Operations Requirements Document (ISS MORD SSP 50260) defines "the requirements necessary to perform medical operations applicable to the International Space Station (ISS) Program." It covers the medical operations requirements for all phases of ground, flight, and payload/experiment-related activities. In part, it addresses ISS radiation monitoring requirements. It "describes the medical support requirements for ionizing radiation exposure, including common dose limits, radiation monitoring, record-keeping, and management of radiation exposure through "As Low As Reasonably Achievable" (ALARA) practices through all mission phases." [ISS MORD SSP 50260]. According to that document, the ionizing radiation environment is monitored to keep crew doses below legal limits and to avoid unnecessary levels of exposure; to collect and record the data needed to assess crewmembers' exposure; and to enable response to radiation exposure events, such as SPEs.

Very specific monitoring requirements are maintained by the ISS MORD. Crewmembers are required to wear a passive radiation dosimeter at all times during a mission, while inside and outside the vehicle. The passive dosimeters must be changed "frequently" during long missions, and after any potential exposure event.

The ISS area is monitored by both passive and active dosimeters, distributed through the volume of the ISS to determine variation in exposure in different modules or locations. The external radiation environment is monitored to provide input to models of the interior radiation environment, and to support Extra Vehicular Activity (EVA).

Radiation monitors must measure cumulative total dose, the time-resolved Linear Energy Transfer (LET) spectrum or a close approximation, the time-resolved energy- and direction-dependent distribution of charged particles inside and outside the ISS, and the neutron spectrum inside the ISS (but the energy range of neutron monitoring is not specified).

The ISS MORD recognizes the importance of communicating the information collected by the radiation monitors, as it describes recommended time intervals for data down-links.

- Detailed data from time-resolved energy- and direction-dependent charged-particle detector shall be down-linked weekly or more frequently for analysis on a time scale that precludes loss of data or to support contingency evaluation for real-time flight support.
- Dose rate from charged-particle monitoring equipment shall be continuously transferred to the ground for operational evaluation and real-time flight support.
- Time-resolved data from at least one LET monitoring instrument shall be transferred to the ground as required for operational evaluation.
- Detailed time-resolved particle spectra shall be down-linked on a timescale that precludes loss of data.
- Dose rate data characterizing the local radiation environment outside the ISS shall be continuously transferred to the ground for operational evaluation and real-time flight support.

The ISS MORD also requires a crew alarm system, noting that "At least one onboard active instrument shall have the ability to alert the crew when exposure rates exceed a set threshold."

Constellation

The NASA Constellation Program provides another example of NASA's approach to radiation monitoring. The Constellation Program was NASA's response to implement the Vision for Space Exploration announced by President George W. Bush in 2004. The entire Constellation design process was the first instance of a crewed vehicle program in which radiation risk management elements were built into the requirements from the beginning.

The Constellation Program had a series of documents that paralleled the ISS radiation monitoring documents. These requirement documents were prepared and sufficiently mature before the program's cancellation to provide insight into possible requirements for deep space exploration. Note, however, that none of the Constellation Program documents have authority that can be applied to the current Orion Multi-Purpose Crew Vehicle[2] under development by NASA. Formal Orion vehicle design requirements for the deep space variant are not complete, and do not yet include radiation monitoring plans.

The National Research Council (NRC) reviewed NASA's radiation mitigation strategy for the Orion spacecraft (NRC – 2008), and noted "As presented to the committee, the Orion Radiation Protections Plan

[2] The first two-orbit unmanned test flight of Orion, Exploration Flight Test 1 (EFT-1), is scheduled for a launch aboard a Delta IV Heavy rocket in 2014. The first launch with crew would be by the end of 2016 [NASA report to Congress, January 2011]

appears to meet the minimum radiation protection requirements as specified in the NASA radiation protection standards. But any reduction in the requirements outlined in the Orion Radiation Protection Plan may pose potentially unacceptable health consequences." The plan presented to the NRC was consistent with key radiation-related documents in the Constellation program circa 2007, and included:

- CxP 7000 Constellation Architecture Requirements Document (CARD)
- CxP 70007 Design Reference Missions and Operations Concept (DRM)
- CxP 70023 Constellation Program Design Specification for Natural Environments (DSNE)
- CxP 70024 Human Systems Integration Requirements (HSIR)
- CxP 70044 Constellation Natural Environment Definition for Design (NEDD)
- CxP 70036 Constellation Program Environmental Qualification and Acceptance Testing Requirements (CEQATR)

These documents evolved from similar documents used for ISS, particularly the ISS MORD and the Human Integration Design Handbook. The radiation risk management approach was consistent with an overall "risk leveling" philosophy used throughout the Constellation program. According to the CARD, "Space Radiation should be accounted for in the design only to a risk level commensurate with other sources of risk to crew safety." (CARD Section 3.1.3.6.8: Environmental Considerations). The Human Systems Integration Requirements (HSIR) document had the most detailed radiation monitoring "Shall" list of the requirements document. The Ionizing Radiation section closely paralleled the ISS MORD (see Table 1).

3.2.7 Ionizing Radiation
3.2.7.1 Radiation Design Requirements
3.2.7.1.1 Radiation Design Requirements
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3.2.7.5.1 Alerting for Radiation Data

Table 1: Human Systems Integration Requirements (HSIR) Outline for Ionizing Radiation Requirements

In most instances, the HSIR went into more specificity than the ISS MORD. For example, in defining the requirements for Charged Particle Monitoring, the HSIR said:

> "The system shall continuously measure and record the external fluence of particles of $Z<3$, in the energy range 30 to 300 MeV/nucleon and particles of $3 \leq Z \leq 26$, in the energy range 100 to 400 MeV/nucleon and integral fluence measurement at higher energies, as a function of energy and time, from a monitoring location that ensures an unobstructed free space full-angle field of view 1.1345 Radians (65 degrees) or greater." ---HSIR, 3.2.7.2.1 Charged Particle Monitoring

Under "Data Reporting" the HSIR said:

- The system shall display the measured cumulative absorbed dose/minute averaged dose rate to the crew once per minute, with latency less than five minutes
- The system shall display the measured cumulative dose equivalent/minute averaged dose equivalent rate to the crew once per minute, with latency less than five minutes
- The system shall alert the crew, whenever the absorbed dose rate exceeds a pre-flight programmable threshold in the range 0.02 mGy/min to10 mGy/min for 3 consecutive readings.

In addition to examining the detailed radiation monitoring requirements at and within the Orion vehicle (and by extension, to other elements of the Constellation Architecture), the CARD recognized the need for space weather support. Section 4.7.6.2.6, MS (Mission Systems) Architecture Definition, noted the need for space weather services: "The verification shall be considered successful when the inspection shows closure that there is an agreement with Constellation Program and NOAA on the fulfillment of the MOU [memorandum of understanding] and that all of the MS facility and facility systems are ready to support space weather services operations during all mission phases for all flight systems." The MOU with NOAA had not been drafted, and so detailed space weather requirements were not defined.

Radiation Monitoring for Exploration Missions

Given the experience with the space shuttle, with the International Space Station, and with the advanced design state of the Constellation Program, there is significant experience preparing exploration radiation monitoring requirements within NASA, particularly in NASA's Space Radiation Analysis Group (SRAG) at Johnson Space Flight Center (http://srag-nt.jsc.nasa.gov/). There are two classes of radiation monitoring: dosimetry, which measures or indicates the crew members' absorbed dose, and particle flux measurements, which measures or indicates the ionizing particle spectrum within and in the neighborhood of the crew members' vehicles, habitats, or locations when exploring.

Dosimetry (dose and dose rate)

Dosimetry is an essential component of any radiation mitigation strategy. There are two general classes of dosimeters: passive and active. Both classes measure the physical absorbed dose of ionizing radiation, and generally do not provide details of the ionizing radiation properties (individual particle type or energy). Passive dosimeters measure the cumulative absorbed dose over extended periods throughout the mission, while active dosimeters provide near real time dose and dose rate information. Both are needed to support effective radiation risk management strategies. The physics, effectiveness, and limitations of active and passive dosimeters are described in separate THREE articles [Zeitlin, 2012; Benton, 2011; Schimmerling, 2010b]. This article focuses on the applications of dosimeters.

Personal passive dosimeters that stay with the astronauts throughout the mission are needed to provide a record of the crew members' estimated individual cumulative radiation exposure. For long missions (many months), the passive dosimeters should be read and recorded, and either replaced, reset, or returned to continue monitoring exposure. This is needed so that radiation health officials can estimate the impact of exposure or possible future exposure on the crew member, both for the remainder of the mission and for health care concerns for the crew member's life after the mission.

Any specific implement of passive dosimetry, or for that matter, active dosimetry, will be at best a proxy for the actual absorbed dose at any given location within the crew member's body. This is not just because the dosimeters cannot be distributed everywhere one wants to measure, but also because of inherent limitations in what dosimeters can measure. Dosimeters cannot measure the entire range of ionizing particles of concern, at all relevant energies, and they do not measure the biologically effective dose. But generally, techniques such as detailed dosimeter calibration under realistic conditions as well as verification and validation of radiation transport codes used to model realistic shielding and the full range of environmental radiation can – taken together - give high confidence to extrapolating measured dose.

Area passive dosimeters should be located at strategic points throughout the various crewed vehicles and habitats to measure the effectiveness of shielding. They provide essential cues for operational measures involving crew actions to seek refuge (e.g., where to stay or what areas to avoid during an SPE, or how to limit exposure during EVA or a planetary surface sortie).

The effective shielding throughout a vehicle or habitat may change with time. Consumables may be depleted, waste storage may accumulate, modules may be reconfigured or expanded. Maintaining area passive dosimeters and periodically measuring and resetting them through all phases of the mission ensures against over-reliance on extrapolating from a few locations at a few times. For more information about passive radiation detectors, see the THREE articles by Benton, 2011, and Schimmerling, 2010b.

Active dosimeters measure physical absorbed dose over short time periods and can be accessed as needed, perhaps continuously. They should be used as dose-rate monitors at all times, distributed throughout the various vehicles and habitats, but especially near the location of the crew. They should be configured to provide the crew and mission control with steady confirmation of dose rates within allowable ranges, and to provide alerts and warnings when dose or dose rates exceed thresholds.

Active dosimeters are not a replacement for passive dosimeters, but rather a complement to them. While passive detectors provide long-term, perhaps mission-long measurements of exposure, active dosimeters can provide near-real time updates to the radiation environment. Active monitors may be larger than passive dosimeters if they comprehensively measure ionizing radiation sources, and thus carry weight and volume penalties. Or they may be may be smaller than passive monitors but only measure limited components of the radiation environment, for alerts and warnings.

On the space shuttle, NASA provides an operational dosimetry system to monitor individual astronaut exposures, and to monitor the radiation environment [Semones, 2011]. A Crew Passive Dosimeter (CPD) is provided to each astronaut, who is required to wear it through all phases of the mission, including EVAs. Six Passive Radiation Dosimeters (PRDs) are provided for each flight at various locations inside the crew compartment. An Area Passive Dosimeter (APD) and pocket ion chambers are stored in a middeck locker with the Shuttle medical kits. A Tissue Equivalent Proportional Counter (TEPC) is hard-mounted in the middeck for high-altitude (greater than or equal to 205 nautical miles) and/or high-inclination flights (greater than or equal to 50 degrees).

On the ISS, each astronaut wears a Personal Radiation Dosimeter throughout the mission. In addition, there are passive and active radiation monitors throughout the ISS. The active monitors include:

- Intra Vehicle Charged Particle Directional Spectrometer (IVCPDS)
- Extra Vehicle Charged Particle Directional Spectrometer (EVCPDS)
- Tissue Equivalent Proportional Counter (TEPC)

Particle Flux and Spectra (incident flux in the area of the astronauts)

Radiation risk management needs more detailed information about the radiation environment than what can be derived from dosimeters. Radiation transport codes need as input the particle flux by ionizing particle species, energy, and directionality in order to map the external radiation environment to the radiation environment under complex shielding, and inside crew member tissue. Forecasting the immediate threat and attempts to forecast the evolution of an SPE require detailed temporal and spectral information. Finally, future radiation health models may also need details of the ionizing radiation spectrum:

> Hence, an increasing amount of data, theory, and literature support is consistent with the idea that at low particle fluences, as present in space, the dependence of biological effects on radiation

> quality is not well described by LET (Linear Energy Transfer) alone and that, instead, both Z and E must be considered in order to give an adequate description of the three-dimensional track structure, including both the primary particles and delta rays. [NRC 2012].

The need for a comprehensive description of the radiation environment covers a wide range of particle types, energies, flux levels, and reporting timelines. Recall the earlier discussion that in the Constellation program, HSIR sought to measure "particles of Z<3, in the energy range 30 to 300 MeV/nucleon and particles of $3 \leq Z \leq 26$, in the energy range 100 to 400 MeV/nucleon and integral fluence measurement at higher energies." Neutrons, both thermal and up to tens of MeV, should also be monitored under shielding and on planetary/lunar surfaces. It could also be important to monitor energetic electrons, in the energy range of 5 to 50 MeV, as high energy electron flux may serve as a predictor to the evolution of SPEs [Posner, 2006].

There is a wide dynamic range to the flux of ionizing radiation to monitor, from high-Z GCR flux ranging from 10^{-4} /m^2-sec-MeV/nucleon (iron at about 1 GeV) through extreme Solar Particle Event proton flux of greater than 10^9/m^2-sec (>10 MeV protons). For more about the radiation environment, see NRC 2008 and NRC 2012. The types of instruments that can provide these details are discussed in a recent THREE article [Zeitlin, 2012]. As with dosimeters, this article focuses on the application of instruments to measure particle flux and spectra.

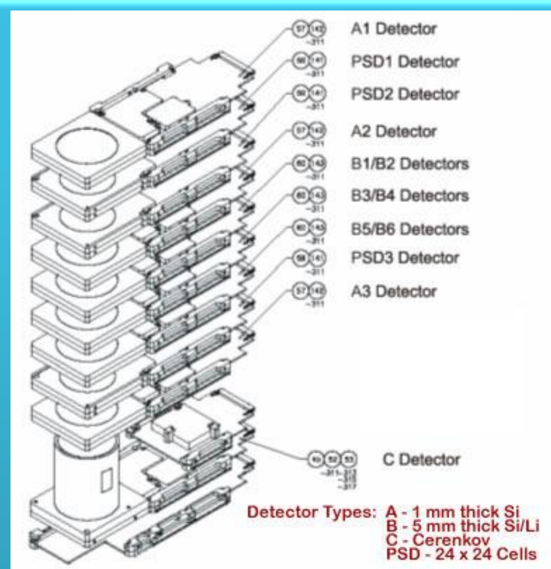
Since the GCR flux varies slowly with time (weeks to months to years) and also does not change significantly between 0.75 and 1.5 AU, there is reduced need to measure its flux near an exploration mission in the inner heliosphere. However, it should be measured somewhere in detail (perhaps near Earth) and monitored at lower temporal/spatial/species resolution near the crew.

SPEs, however, are highly variable in intensity and spectral detail over relatively small displacements in space and time. Therefore, at minimum, the proton flux from ten to several hundred MeV should be measured near the crew, at less than one minute intervals during elevated flux periods and with energy resolution better than ten percent of the energy (<1 MeV near 10 MeV, and <10 MeV at 100 MeV). It is important to measure the high energy tail (a few hundred MeV) of the spectrum, as these are the most penetrating particles, and estimates of the flux extrapolated from measurements near 100 MeV can be off by many orders of magnitude [NRC 2008].

Secondary neutrons are generated as the primary particles penetrate shielding, tissue, the surface of the moon, Mars, or an asteroid, and the atmosphere of Mars. Secondary neutrons can contribute ten to thirty percent of the total dose under shielding [Schimmerling, 2010b]. Secondary neutrons are difficult to measure directly in the range of a few to a few tens of MeV [Benton, et al., 2001], but progress in neutron measurements may help meet this requirement. The neutron contribution on the surface of Mars from atmospheric or surface scattering has not been measured, but some information on the flux from a few to about 100 MeV will be available from the Radiation Assessment Detector (RAD) instrument on Mars Science Laboratory, scheduled to land in the late summer of 2012. [RAD, 2012]

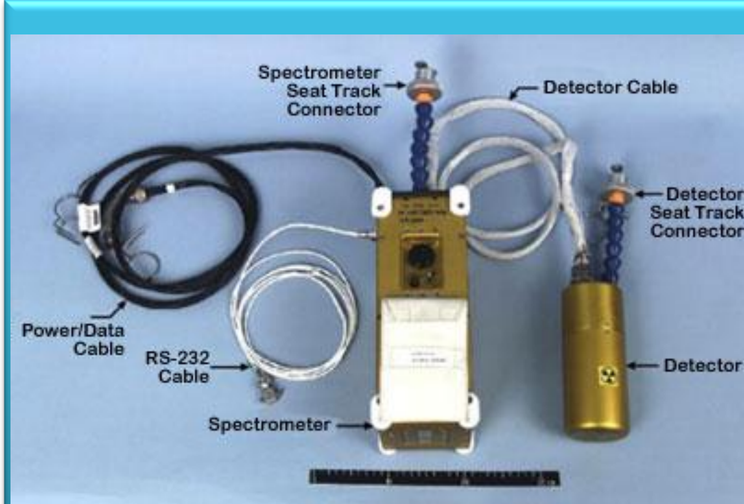
Figure 1 gives more information about the operational radiation monitors on the International Space Station, while Figure 2 is one example of a space radiation monitor that may have wide applicability to future human missions. Other examples can be found in several articles in the THREE library, including: Benton, 2011, Schimmerling, 2010b, and Zeitlin, 2012.

Charged Particle Directional Spectrometer (CPDS). From the NASA Space Radiation Analysis Group website: "The Charged Particle Directional Spectrometer instrument is designed to measure the charge, energy, and direction of a particle that passes through the instrument. There are 13 separate detectors inside the CPDS that are arranged in a stack…. There are four CPDS instruments in use on-board the ISS. The first is the Intra-Vehicular Charged Particle Directional Spectrometer (IV-CPDS)…used inside the ISS with mounting and power options for both the US and Russian segments. The IV-CPDS also performs real-time calculations and displays the average dose rate and other parameters on a small LCD screen on the instrument for use by the astronauts, and sends similar information to Mission Control that allows SRAG personnel to constantly monitor the radiation environment inside the ISS. The remaining three CPDS instruments are mounted outside the ISS in the form of the Extra-Vehicular Charged Particle Directional Spectrometer (EV-CPDS).



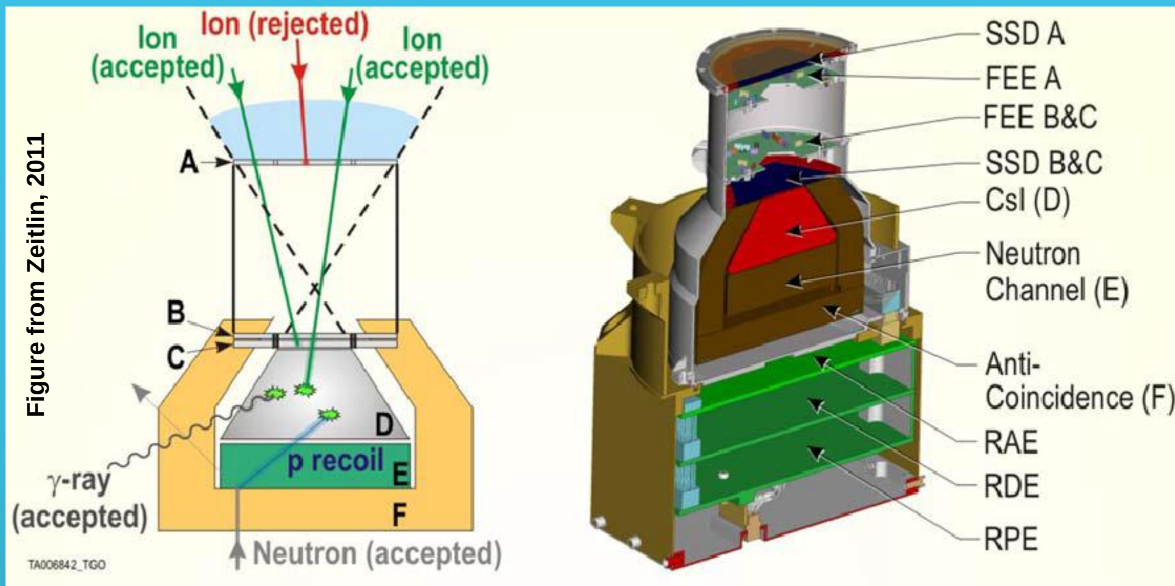
IV-CPDS

EV-CPDS



The TEPC is designed to measure the dose that a small volume of tissue would receive from a wide variety of radiation sources. It simulates a 2µm diameter volume of tissue using a cylindrical detector design. The detector volume is 2 inches in diameter and 2 inches long, and is filled with a very low pressure of propane gas. The gas volume is surrounded by tissue equivalent plastic. The organic molecules in the plastic and gas effectively simulate the cell wall and cell body respectively.

Figure 1: International Space Station Radiation Monitoring Instruments.
From: http://srag-nt.jsc.nasa.gov/SpaceRadiation/How/How.cfm#Equipment



About the Radiation Assessment Detector (RAD)
From: http://msl-scicorner.jpl.nasa.gov/Instruments/RAD/

The RAD instrument consists of a charged particle telescope comprised of three solid-state detectors and a cesium iodide (CsI) calorimeter. An additional BC-432 scintillating plastic channel is used together with the CsI calorimeter and an anti-anticoincidence shield to detect and characterize neutral particles (i.e., neutrons and gamma rays). The outputs of the various photodiodes, used with the CsI and scintillating plastic, and solid-state detectors are converted to digital pulse height discriminated signals for further processing. The digital logic includes an embedded microcontroller to bin and format the data. The RAD particle and energy coverage is shown in the figure below. The RAD instrument is mounted just below the top deck of the rover with the charged particle telescope pointed in the zenith direction.

Figure 2: Radiation Assessment Detector (RAD) Instrument on NASA's Curiosity spacecraft.

Biodosimetry

Another dosimetry approach is to look at changes in the body that can be traced to radiation exposure ("biodosimetry"). A recent review article posted in THREE noted there have been many studies of biodosimetry, most focusing on chromosome aberrations [Brooks, 2012]. In that article, the author concluded that "research on biomarkers of space radiation has provided very good characterization and measurement of the radiation dose delivered during space missions. Still,additional research is required to link these biomarkers to radiation-related changes in cancer risk."

In principle, one could expect biodosimetry to be the ideal dosimeter, providing feedback specific to the astronaut and his/her exposure history. NASA has recognized the value of biodosimetry, and George and Cucinotta, 2011, noted:

> "NASA has implemented a biodosimetry program that utilizes the FISH chromosome painting technique to assess chromosomal aberrations in all US astronauts who participate in long-duration International Space Station (ISS) missions."

However, biodosimetry is "passive" and generally indicates only cumulative exposure: a sample must be taken and assessed periodically. While biodosimetry can provide measures of radiation exposure, its operational limitations include an inability to characterize the nature of the radiation. This limits its usefulness in extrapolating to exposure impacts distinct from the measured end-point, and it is not currently possible to use biomarkers to initiate an "alert" as dose levels increase.

Systems Aspects

Operations Concepts

A collection of dosimeters and radiation detectors does not constitute a radiation monitoring system. Rather, they must be considered elements of a broader system that considers how the data will be used in an operational context. The larger system includes the data collection, the tools that will use the data, the processes and procedures that will lead to actionable responses to radiation exposure (or lack), and the communications systems that connect all of the above.

Details about the operations concept are beyond the scope of this article, but will be touched on here for completeness. Elements of a comprehensive radiation risk management strategy are discussed in [Schimmerling, 2010a, Schimmerling, 2010c, and Turner, 2010]. An overarching strategy must be placed in the context of overall mission risk as well as NASA's legal, moral, and ethical responsibilities to the crew. Radiation exposure limits are developed by NASA and consider recommendations from external advisory bodies such as the National Council on Radiation Protection and Countermeasures. The limits are also responsive to NASA policy directives. The resulting "Permissible Exposure Limits" (PEL) and the need to operationally limit exposure to "As Low as Reasonably Achievable" (ALARA) are codified in the *NASA Space Flight Human Systems Standards*, NASA-STD-3001, Volumes 1 and 2.

These operational limits are then used as the foundation to develop design standards for Exploration mission architectures, as was being applied to the Constellation Program as discussed earlier. In addition, detailed operational "flight rules" must be developed that consider ways to avoid exceeding, or approaching, exposure limits. The key point to consider in the context of radiation monitoring requirements(shielding, monitoring, and warning) is that each element must be consistent with the total radiation risk management system (PELs and ALARA) and they all must work together, while being effectively embedded in the overall mission architecture.

Space Environment Situation Awareness

The "warning" component of a comprehensive radiation monitoring strategy provides alerts and warnings for pending solar storms. For longer term design and development of future space exploration missions, "warning" provides estimates of GCR variability, design-to specifications of "worst case" solar particle events, and probabilities of mission total SPE threat. This section describes the various components of a system, or architecture, that may be employed to produce the space weather data needed for short term SPE and SPE-precursor observations, ultimately to reduce the risk these events pose. This text is similar to a discussion in the THREE article, Turner, 2010.

A comprehensive warning architecture would monitor the Sun, the heliosphere, the near-spacecraft energetic particle environment, the trapped radiation environment (for Earth-orbiting operations) and would have a communications infrastructure complete and robust enough to get the right information to the right users. See Figure 3, from Turner, 2010.

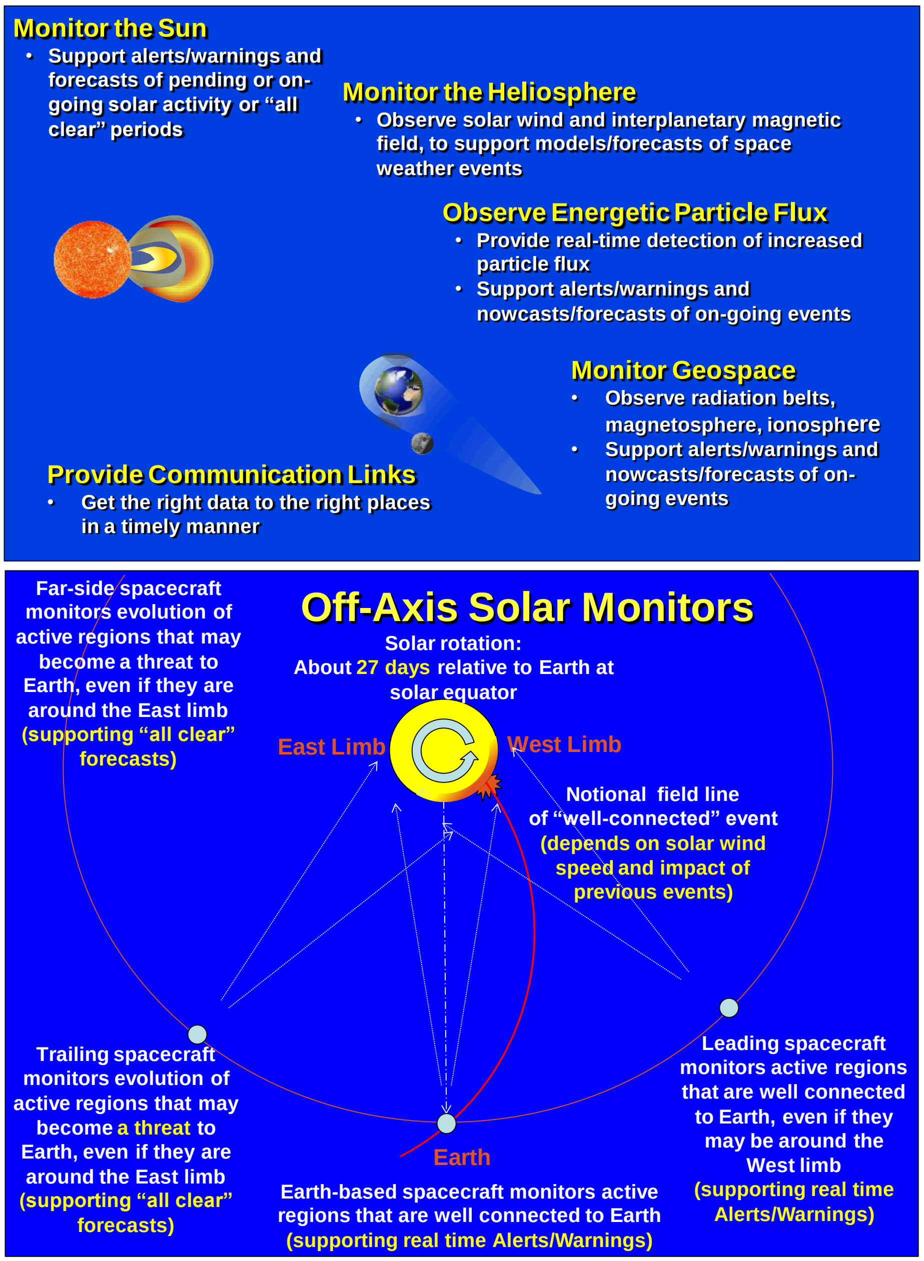


Figure 3: This figure, from Turner, 2010, illustrates the elements of a Space Weather Monitoring Architecture

Direct measurements of *in situ* solar energetic particles via particle monitors and active dosimeters will continue to provide the most important contributions to an SPE risk management strategy. These instruments were described earlier in this report. Measurements at the astronauts' location will be able to confirm that a solar particle event is underway and to provide information about the flux, rate-of-change of flux, and total fluence of the event. In addition, instruments may be needed to measure the relative contribution to the total flux from particles with different energies, from tens of MeV through several hundred MeV. Finally, it may be necessary to identify the flux of high energy, high mass ions that make up an on-going SPE. Additional energetic particle measurements at locations significantly away from the astronauts may also contribute to forecasting the evolution of an on-going event. A variety of instruments are available to provide these measurements, including particle telescopes, solid state detectors, and proportional counters.

Solar monitoring is required to place the forecasts and observations of SPEs into a context of ongoing and potential solar activity. Near-real time observations of solar active regions and emerging Coronal Mass Ejections (CMEs) may provide data useful to predict the occurrence and project the progress of an SPE over a period of hours to days. This can aid in determining, for example, if observed slowly rising flux is likely to continue to rise, or is more likely to decrease before getting to dangerous levels. Additional progress in understanding the physics of CMEs is required to get to a multiday forecast of the probability of a CME eruption and its potential for producing an associated SPE. Equally useful, and more readily attainable in the near term, would be a reliable forecast that there would not be a significant CME/SPE over the next few days (an "All Clear Forecast").

A variety of solar monitoring instruments are needed to support SPE forecasts, from solar surface imagers (observing the Sun in visible, ultraviolet, X-ray, and radio wavelengths) to solar coronagraphs observing the near-Sun heliosphere from a few to a few tens of solar radii. There is an extensive suite of research spacecraft and ground-based facilities providing experience and proof of concept from which to select the appropriate operational instruments for an SPE risk mitigation architecture. NASA's Solar Dynamics Observatory (SDO), The ESA/NASA Solar and Heliospheric Observatory (SOHO), and NASA's Solar TErrestrial RElations Observatory (STEREO) are significant examples. The instrument complement on the twin STEREO spacecraft are illustrative of the kinds of instruments that may be needed to monitor space weather (See figure 4).

The Sun rotates with a period of about 27 days (the rotation rate varies with solar latitude). Among other effects, this leads to a spiral form to the interplanetary magnetic field (IMF) (imagine an overhead snapshot of the water streaming from a rotating water sprinkler). Since high energy particles accelerated by solar storms follow the IMF, active regions that may spawn Earth-impacting storms could be around the leading, west limb of the Sun not visible from Earth. Similarly, evolving active regions rotating toward the Earth are out of view behind the trailing solar east limb. Today operational solar monitors are either in orbit around the Earth or are in the Earth-Sun line at the Lagrange L1 point (about 100 Million km from Earth toward the Sun). Operational solar observations to date are taken from sensors near Earth. A more complete picture of the state of the Sun would involve observations taken away from the Sun-Earth line. Solar activity near or over the west limb may impact the Earth. Active regions that will rotate into a position threatening Earth may be evolving out of sight of the Earth beyond the east limb. NASA's twin STEREO spacecraft are providing proof of concept of the value of off-axis viewing of the Sun, with one spacecraft leading and one trailing Earth at gradually increasing separation.

Heliospheric observations provide information necessary to model or monitor the propagation of solar energetic particles from the source to the astronauts. Density fluctuations from solar emissions and from boundaries between slow and fast solar wind streams affect the shape of the interplanetary magnetic field, along which the energetic particles move. They also affect the strength, structure, and motion of CMEs and the associated shocks that accelerate the energetic particles. The data that may be necessary for SPE propagation models include information on the general state of the solar wind plasma, the interplanetary magnetic field, and local disturbances moving through the inner heliosphere. Both in situ and remote sensing methods may contribute to the characterization of the heliosphere. The in situ instruments are typically small, low-cost sensors with long heritage. Remote sensing techniques include white light observations of interplanetary mass density fluctuations and recently implemented observations of interplanetary radio signals that may provide a measure of CME shock speed.

STEREO Instrument	Role
Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) is a suite of remote sensing instruments consisting of two white light coronagraphs (COR1 and COR2) and an EUV imager (EUVI), collectively referred to as the Sun Centered Imaging Package (SCIP), and a Heliospheric Imager (HI). For details see: http://secchi.lmsal.com/EUVI/DOCUMENTS/howard.pdf	Studies 3-D evolution of coronal mass ejections (from their origin on the sun's surface to their impact at Earth).
PLAsma and SupraThermal Ion and Composition (PLASTIC) Each PLASTIC is a time-of-flight/energy mass spectrometer designed to determine the elemental composition, ionic charge states, and bulk flow parameters of major solar wind ions in the mass range from hydrogen to iron. For details see: Space Science Reviews, Volume 136, Numbers 1-4 (2008), 437-486, DOI: 10.1007/s11214-007-9296-x	Studies coronal-solar wind and solar wind-heliospheric processes
In situ Measurements of Particles and CME Transients (IMPACT) consists of 7 instruments: SWEA (Solar Wind Electron Analyzer); STE (Suprathermal Electron Telescope); MAG (Magnetometer); SEPT (Solar Electron Proton Telescope); SIT (Suprathermal Ion Telescope); LET (Low Energy Telescope); HET (High Energy Telescope) For details see: http://sprg.ssl.berkeley.edu/impact/instruments.html	Measures energetic ions and electrons accelerated in coronal mass ejection shocks and in solar flares
STEREO/WAVES (S/WAVES) The SWAVES experiment includes the following instruments and components: **Radio receivers** (HFR and LFRhi) that measure radio wave intensity, source direction, and angular size in the frequency range of 16 MHz to 40 kHz, corresponding to source distances of about 1 RS to 1 AU; **Low Frequency Receivers** (LFRlo) that make sensitive measurements of radio and plasma waves near the electron plasma frequency at 1 AU (10-40 kHz); **A Fixed Frequency Receiver** (FFR) that measures radio emissions at 50 MHz, at high time resolution, to complement ground-based radioheliograph measurements; **Time Domain Samplers** (TDS) that simultaneously make wideband waveform measurements on 3 electric at one of several commandable sample rates and bandwidths. For details see: http://swaves.gsfc.nasa.gov/swaves_instr.html	Traces the generation and evolution of traveling radio disturbances from the sun to Earth's orbit

Figure 4: NASA STEREO's Solar-observing and heliospheric-monitoring instruments are similar to the instruments that would be included in a comprehensive space weather forecast architecture.

Communication

The communications infrastructure is an often overlooked element of a risk management infrastructure. Typically the discussion about communications focuses on the data link between a satellite and a ground antenna, or a sensor to a mission control center. However, to ensure that all elements of a risk management system work together to provide timely, accurate, accessible, and actionable information, the communications system is much more than the transmission of data (See figure 5).

- Timely: time from collection through delivery to end user must be consistent with operational planning requirements
- Accurate: Observations and subsequent derived products must be reliable, validated, and at appropriate fidelity for operational use
- Accessible: At each step in the process from collection through final action, content should be provided in a suitable format for subsequent processing
- Actionable: The end product must convey actionable options to decision makers via clear and concise instructions provided to the appropriate mission elements

It is important to include these components into the architecture from the outset. There may be a variety of sensors on multiple platforms that provide data to forecast models. Multiple models may be needed to create a clear picture of an evolving radiation environment. Once generated, the environment forecast must then be assessed by mission support in the context of the on-going mission, and risks associated with alternative courses of action must be compared to commensurate risks associated with aborting or delaying planned mission objectives. The delegation of authority at the appropriate level must be clearly understood. The appropriate level of responsibility must then make the call on a specific course of action. This must then be relayed to and understood by the affected mission elements in time to respond. All of these elements require clear lines of communication, backup communication, and procedures should any line of communication fail or not be available for timely transmission. See also, Turner, 2010.

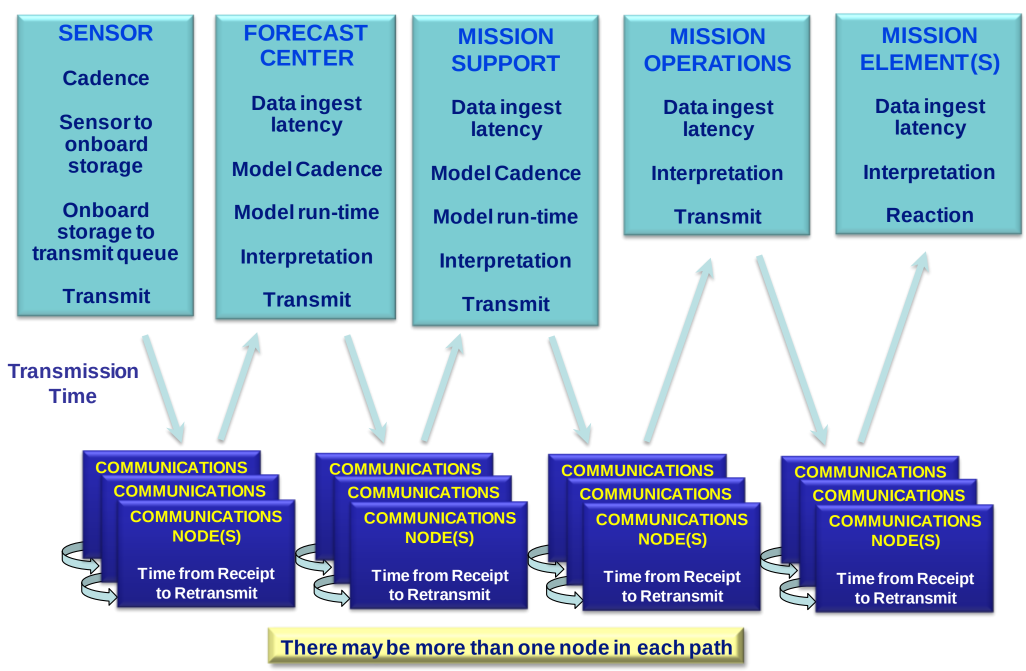


Figure 5: A comprehensive communications architecture considers much more than up-link and down-link antennas (From Turner, 2010).

Conclusion

This article focused on exploration mission requirements to monitor the radiation environment and crew exposure, with emphasis on the types of measurements and instruments that will be needed to support a broader radiation risk management strategy. It was built around a discussion of two of three elements of a radiation risk mitigation strategy: warning, monitoring, and shielding (shielding was not covered in this article). NASA has a history of radiation risk management, from Apollo, Shuttle, and ISS. Radiation monitoring requirements from the ISS and Shuttle had been incorporated into planning the Constellation Program. An effective radiation monitoring approach must be done at the system level, and will include measurements of the radiation environment at the location of the crew (through dosimetry and measurements of ionizing particles flux and spectra) as well as space weather monitoring to provide for alerts, warnings, and the environmental context during elevated periods of radiation exposure. Space weather monitoring may also provide physics-based, high confidence forecasts of all-clear periods. The elements of a radiation monitoring system must be considered in a system context, to include established radiation limits, operations concepts, and the communications infrastructure to tie the elements together.

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