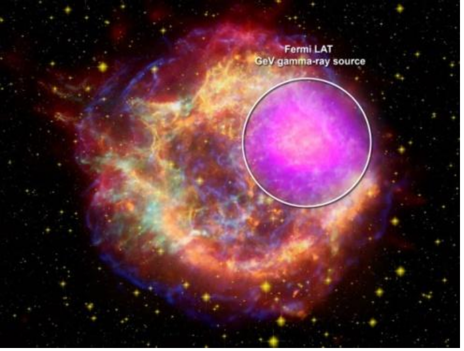

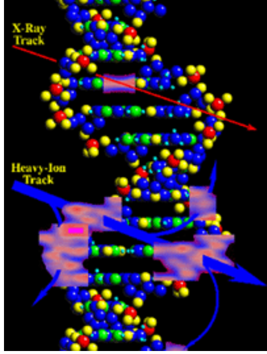

ISS SPACE RADIATION EFFECTS AND EXPERIENCE: UTILIZATION FOR CURRENT AND FUTURE EXPLORATION PROGRAMS

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Workshop on Radiation Measurements for ISS (WRMISS)
Austin, TX
4-6 Sept 2012

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Abstract

In this paper we review the discovery of cosmic ray effects on the performance and reliability of microelectronic systems as well as on human health and safety and the development of the engineering and health science tools used to evaluate and mitigate cosmic ray effects in earth surface, atmospheric flight, and space flight environments based on ISS and Mir experience. This spaceflight experience will be applied to existing and future space programs, especially for deep space exploration. Three twentieth century technological developments, 1) high altitude commercial and military aircraft; 2) manned and unmanned spacecraft; and 3) increasingly complex and sensitive solid state micro-electronics systems, have driven an ongoing evolution of basic cosmic ray science into a set of practical engineering tools (e.g. ground based test methods as well as high energy particle transport and reaction codes) needed to design, test, and verify the safety and reliability of modern complex electronic systems as well as effects on human health and safety. The effects of primary cosmic ray particles, and secondary particle showers produced by nuclear reactions with spacecraft materials, can determine the design and verification processes (as well as the total dollar cost) for manned and unmanned spacecraft avionics systems. Similar considerations apply to commercial and military aircraft operating at high latitudes and altitudes near the atmospheric Pfotzer maximum. Even ground based computational and controls systems can be negatively affected by secondary particle showers at the Earth's surface, especially if the net target area of the sensitive electronic system components is large. Accumulation of both primary cosmic ray and secondary cosmic ray induced particle shower radiation dose is an important health and safety consideration for commercial or military air crews operating at high altitude/latitude and is also one of the most important factors presently limiting manned space flight operations beyond low-Earth orbit (LEO).

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Outline

- **Cosmic Ray Exposure Environments**
  - Earth Surface & Atmosphere
  - Low Earth Orbit (ISS: International Space Station)
  - Interplanetary (Deep Space) Space
- **Cosmic Ray Effects on Contemporary Electronic Technology**
  - Commercial & Military Aircraft Electronics Systems Effects
  - Spacecraft Electronic Systems Effects
  - ISS Experience
- **Cosmic Ray Effects on Human Health & Safety**
  - Commercial & Military Aircraft Environments
  - Manned Spaceflight Environments
  - ISS & MIR Experience
- **Summary & Conclusions**

Cosmic Ray Interactions with Matter

The natural space radiation environment consists primarily of energetic charged particles: GCR, SPEs & Van Allen trapped radiation

Energetic charged particle interactions with target materials: three basic processes

1. Energy loss (dE/dx) by direct ionization/excitation of material along the particle track

- Direct ionization effects – linear energy transfer (LET) – "slowing down"
- Primary cause of single event effects (SEE) in susceptible electronic devices
- Primary cause of total ionizing dose effects in susceptible electronic devices
- Primary cause of human health effects

2. High energy collisions (inelastic/hadronic) triggering nuclear reactions

- Nuclear hadronic reactions initiate secondary particle showers in the target mass
- Further collisions of secondary particles with target nuclei lead to expansion and propagation of the secondary particle shower
- Secondary particles can produce direct ionization and more nuclear reactions

3. Collisions with material nuclei that produce displacement damage

- Displacement of target atoms so as to disrupt crystal structure (solids only – not considered further here, but important for some spacecraft optoelectronics)

Cosmic Ray Effects on Contemporary Electronic Technology

- **Ground-based Computation & Control Systems**
  - **Single event effects (SEEs) caused principally by GCR shower-generated secondary neutrons**
  - **Total Ionizing Dose (TID) effects negligible in the natural environment**
- **Aircraft Electronics Systems**
  - **SEE caused principally by GCR shower generated secondary neutrons & protons**
  - **TID effects negligible in the natural environment**
- **Spacecraft Electronics Systems**
  - **SEEs caused principally by GCR heavy ions, GCR protons, trapped protons, and solar particle events (SPEs)**
    - **Neutrons and other secondary shower particles increasingly important as spacecraft shielding mass increases, especially when the electronic device contains heavy elements (e.g. Pb, Hf & W) impurities**
  - **TID effects are important in specific high-dose-rate natural environments, e.g. planetary radiation belts and/or SPEs**

EFFECTS OF IONIZING RADIATION

ELECTRONICS:

Single Event Effects (SEE) - One particle causes bit-flip, latch-up, burnout, function interrupt & soft errors

Total Ionizing Dose (TID) - An accumulated effect that degrades the device after long-term exposure

Some Radiation Effects on Microelectronics

- **Single-event upset (SEU)** or **transient radiation effects in electronics** are state changes of memory or register bits caused by a single ion interacting with the chip. They do not cause lasting damage to the device, but may cause lasting problems to a system which cannot recover from such an error. In very sensitive devices, a single ion can cause a multiple-bit upsets (MBU) in several adjacent memory cells. SEUs can become **Single-event functional interrupts** (**SEFI**) when they upset control circuits placing the device into an undefined state.

- **Single-event latchup (SEL)** can occur in any chip with a parasitic PNPN structure. A heavy ion or a high-energy proton passing through one of the two inner-transistor junctions can turn on the thyristor-like structure, which then stays “shorted" until the device is power-cycled. As the effect can happen between the power source and substrate, destructively high current can be involved and the part may fail. Bulk CMOS devices are most susceptible.

- **Single-event transient (SET)** happens when the charge collected from an ionization event discharges in the form of a spurious signal traveling through the circuit. This is de facto the effect of an electrostatic discharge.

Some Radiation Effects on Microelectronics

- **Single-event snapback**, similar to SEL but not requiring the PNPN structure, can be induced in N-channel MOS transistors switching large currents, when an ion hits near the drain junction and causes avalanche multiplication of the charge carriers. The transistor then opens and stays opened.

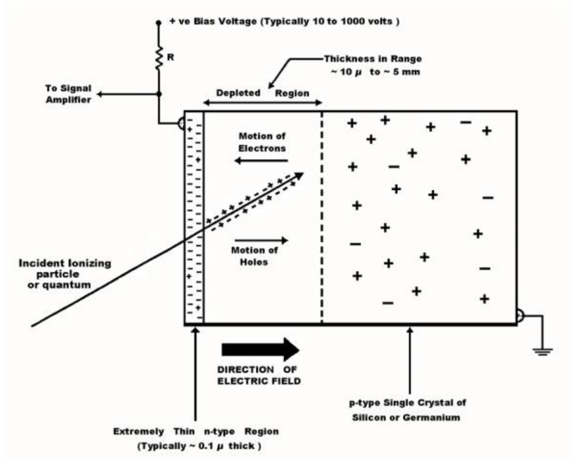
- **Single-event induced burnout (SEB)** may occur in power MOSFETs when the substrate right under the source region gets forward-biased and the drain-source voltage is higher than the breakdown voltage of the parasitic structures. The resulting high current and local overheating then may destroy the device.

- **Single-event gate rupture (SEGR)** was observed in power MOSFETs when a heavy ion hits the gate region while a high voltage is applied to the gate. A local breakdown then happens in the insulating layer of SiO_2, causing local overheat and destruction of the gate region. It can occur even in EEPROM cells during write or erase, when the cells are subjected to a comparatively high voltage.

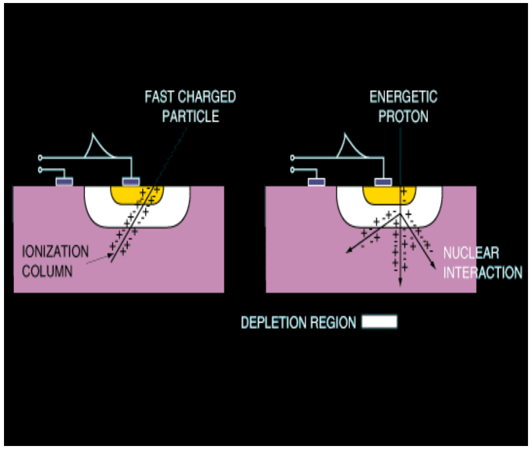
Cosmic Ray Effects on Contemporary Electronic Technology

Solid state electronic devices as charged particle detectors: Single Event Effects (SEE)

Schematics of a solid state charged particle detector (right) and a MOSFET transistor (left) illustrating the particle counting or single event upset process. Direct ionization by CR charged particles and charged particles produced by nuclear reactions in the device can produce counts in the detector and SEE events in the transistor only if the devices are powered, i.e. only if an electric field is applied to force charge collection.



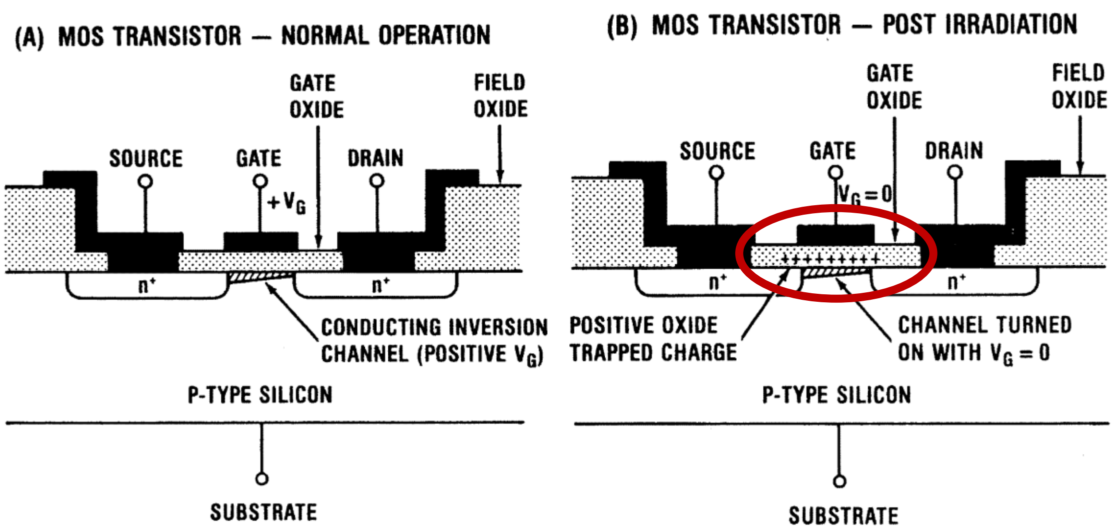
http://nsspi.tamu.edu/nsep/courses/basic-radiation-detection/semiconductor-detectors



Lauriente, M., Vampola, Al. L., "Spacecraft anomalies due to radiation environment in space," NASDA/JAERI 2nd International Workshop on Radiation Effects of Semiconductor Devices for Space Applications, Tokyo, Japan, March 1996.

Solid state electronic devices as charged particle detectors: Total Ionizing Dose (TID) Effects

Schematic of an n-channel MOSFET illustrating radiation-induced charging of the gate oxide: (A) normal operation and (B) post-irradiation. The electrostatic field produced by trapped charge in SiOx layers changes device characteristics. TID damage accumulated even if the device is unpowered.

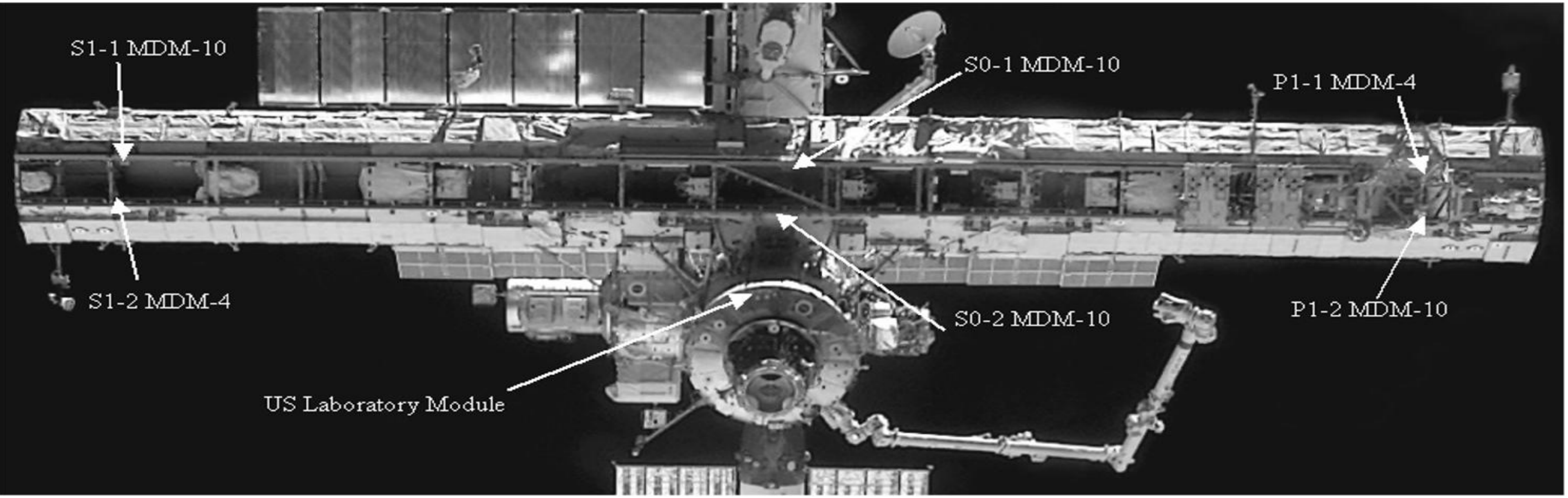


T. R. Oldham, F. B. McLean; "Total Ionizing Dose Effects in MOS Oxides and Devices," IEEE Transactions on Nuclear Science, Vol. 50, No. 3, pp 483-499, June 2003

Spacecraft Electronic Systems

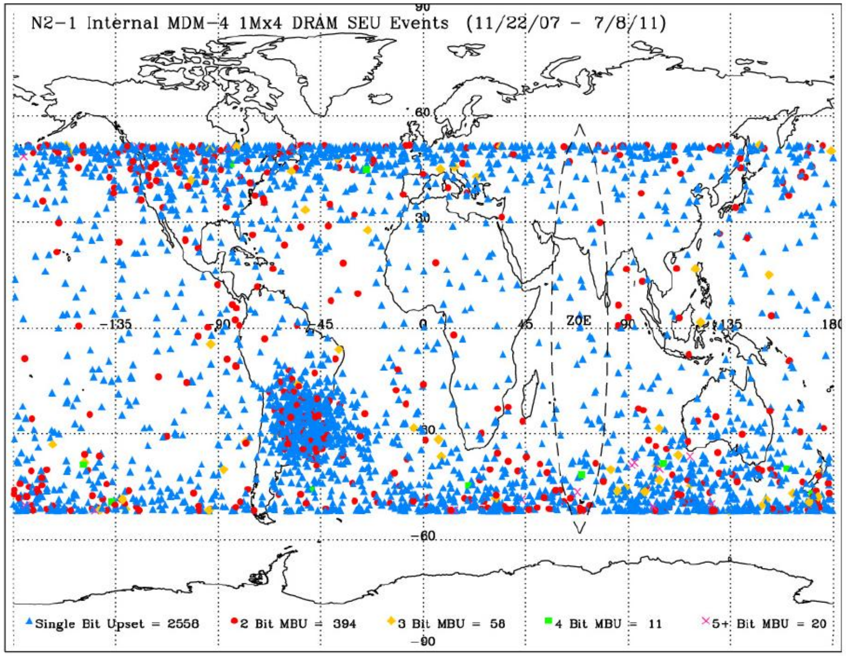
- **The reliability and safety of spacecraft electronic systems are often determined, in practice, by the mission space radiation environment**
  - **SEE rate depends on the primary particle flux and the extent of secondary particle production in spacecraft shielding mass**
  - **TID effects lead to slow degradation of device performance characteristics as dose accumulates during a mission, leading, ultimately, to wear-out like device failure**
- **Mitigating SEE/TID effects in spacecraft electronic systems**
  - **Selection of electronic parts resistant to SEE/TID**
    - **Military Class S parts or equivalent**
    - **Silicon-on-insulator (SOI) device structure for reduce SEU and latch-up sensitivity**
    - **Not always possible – susceptible complex parts may be the only option for the required performance**
  - **Design of robust system architectures**
    - **Triple (or more) module redundancy**
    - **Error detection and correction (EDAC) firmware and software**
    - **Fault detection isolation and recovery (FDIR) software systems**
- **A rigorous component and integrated system test and analysis program is essential to demonstrate the reliability of the spacecraft electronic system before flight**
  Accurate definition of worst-case natural CR and trapped radiation flight environments
  - **Applicable component and system ground based accelerated test methods**
  - **Understanding the relationship between ground based test results and expected on-orbit electronic system failure rates**

EXTERNAL MDM's ON THE ISS INNER TRUSS

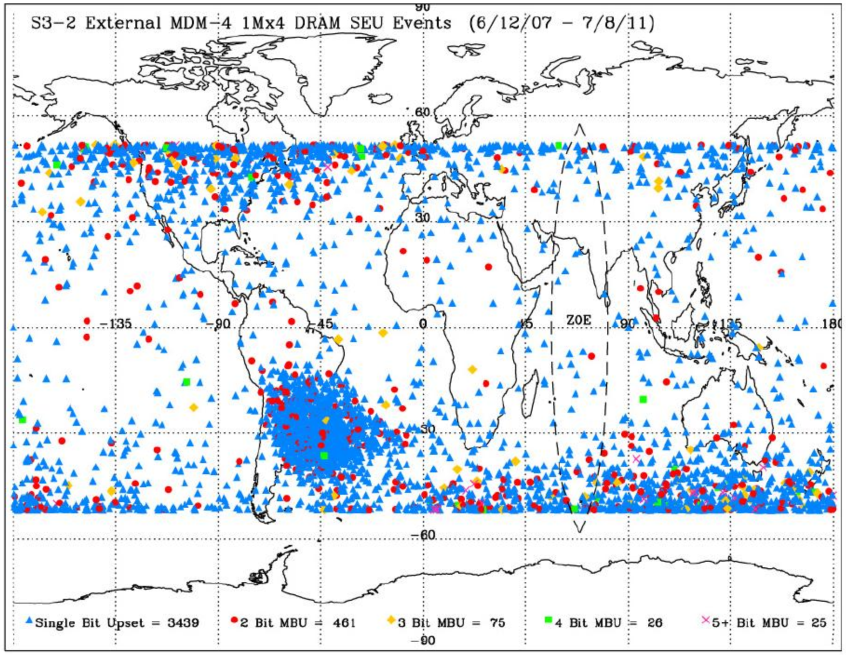


ISS MDM DRAM SINGLE EVENT UPSETS (SEUs)

INTERNAL



EXTERNAL



GCR & trapped proton SEUs detected & corrected by Error Detection And Correction (EDAC) firmware in ISS computer system Dynamic Random Access Memory (DRAM). EDAC operation is part of the nominal system design.

Image Credit: NASA

GCR Exposure Environments: Atmospheric Flight Environments Dominated by Secondary Particles

Earth surface/atmospheric environments

- **1000 grams/cm² air shielding mass at sea level**
- **latitude dependent geomagnetic shielding**
- **GCR secondary particle shower products dominate**

Commercial and military aviation environments

- **Altitude dependent air shielding mass**
- **latitude dependent geomagnetic shielding**
- **Solar cycle modulation of GCR environment**
- **Latitude dependent solar particle event exposure**
- **Pfotzer secondary shower particle maximum at about 20 km altitude (mid latitudes)**
- **Average ISS hourly crew dose rates are on the order of 20 μSv/hr - comparable to commercial aircraft dose rates on polar routes at solar minimum**

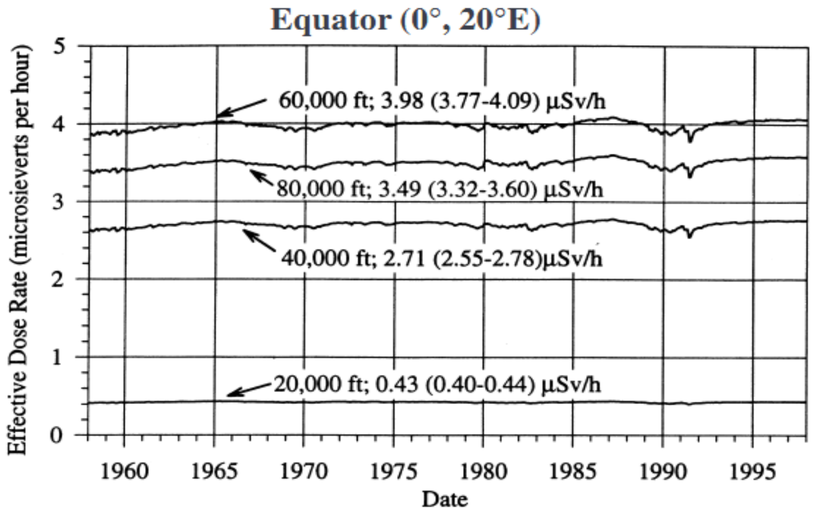
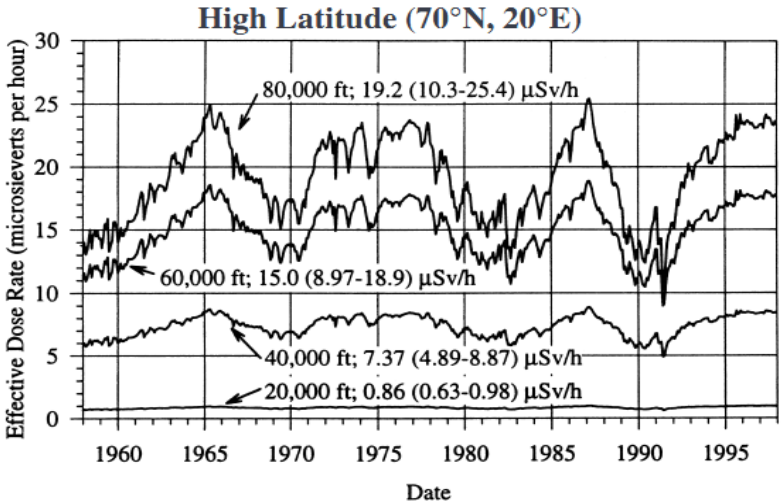


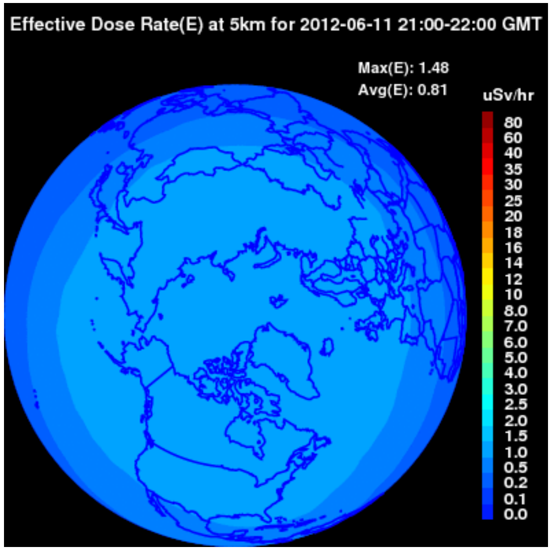
Image Credit -The Boeing Company



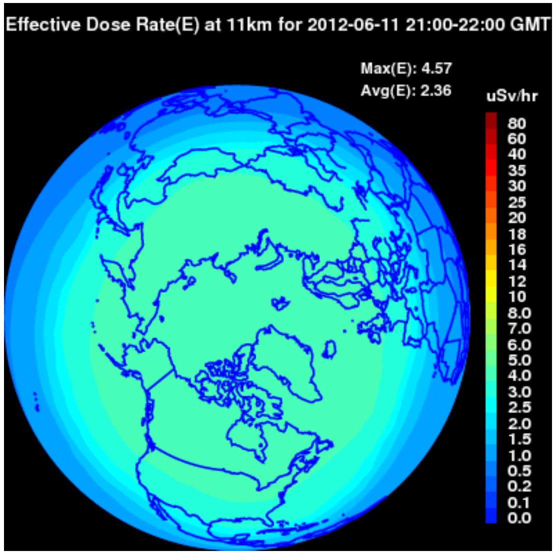
Susan Bailey, "Air Crew Radiation Exposure and Overview," Nuclear News, pp 32-40, January 2000
http://www.ans.org/pubs/magazines/nn/docs/2000-1-3.pdf

GCR Effects – Commercial & Military Aviation Environments
GCR determines the dose rate at high latitude/altitude

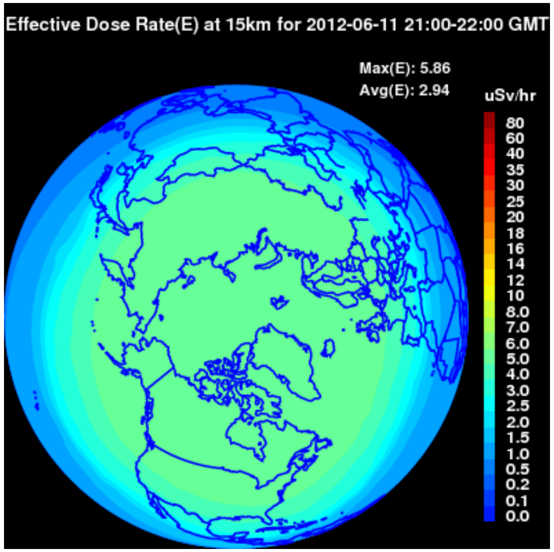
5 km

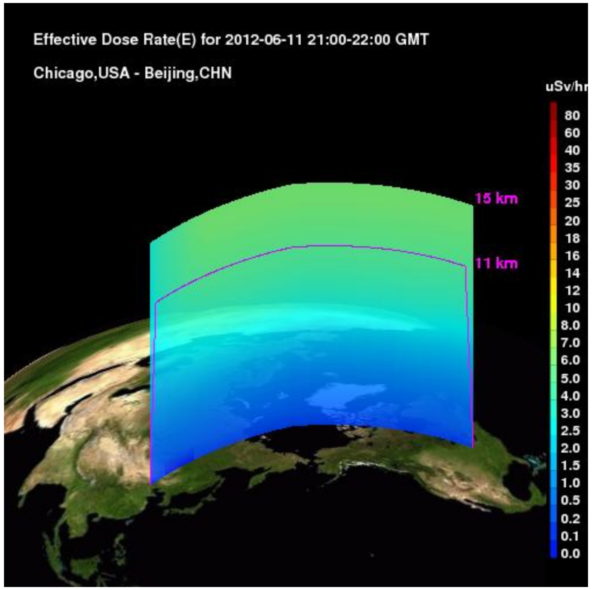


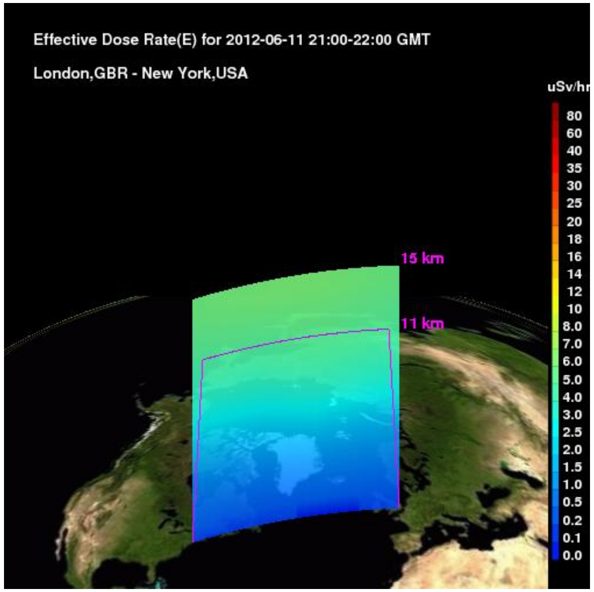
11 km



15 km



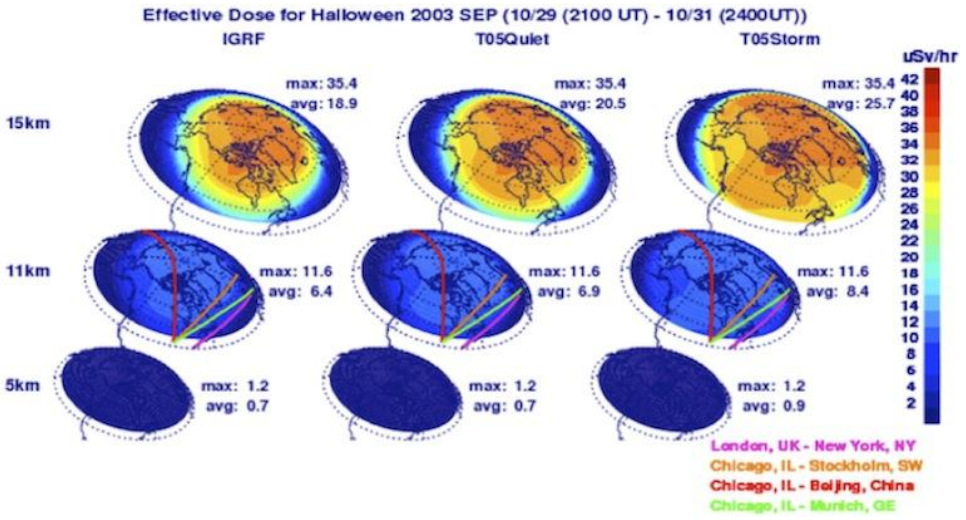


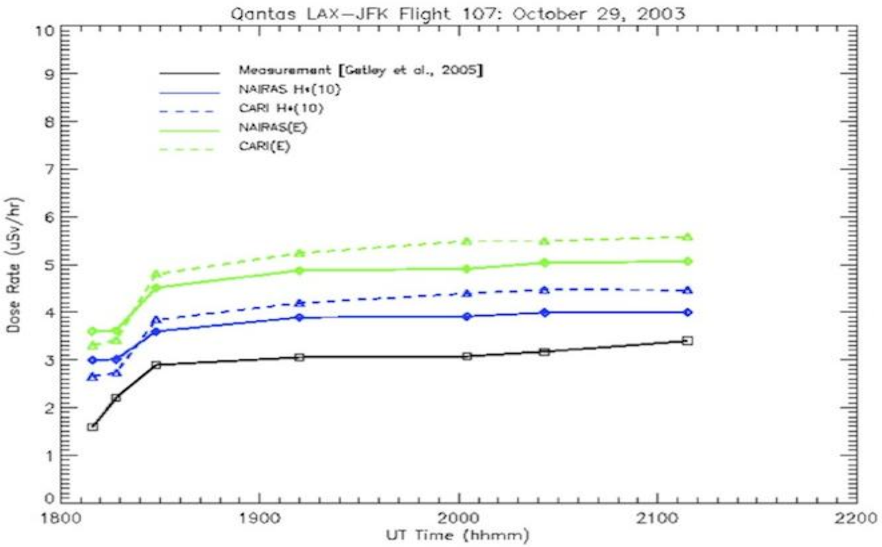


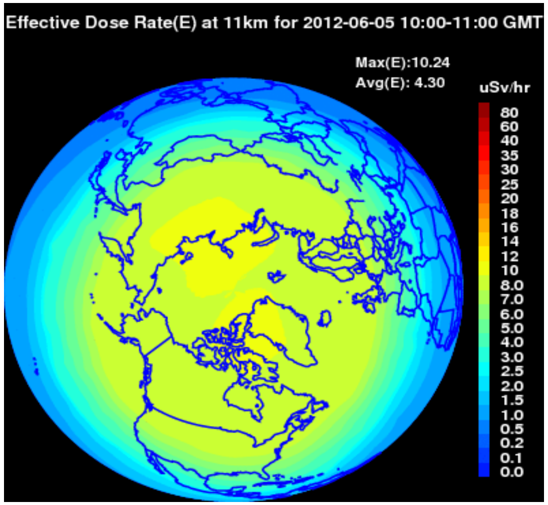
http://sol.spacenvironment.net/~nairas/Dose_Rates.html

GCR Effects - Commercial and Military Aviation Environments: Effect of Solar Particle Events on Aircrew Dose Rates

NAIRAS model - Oct 2003 Geomagnetic Storm and Solar Particle Event Analysis







The figure at right shows the NAIRAS prediction of the radiation exposure quantity related to biological risk - Effective dose rate (uSv/hr). To put the exposure rates into perspective, one chest X-ray is about 100 uSv, and a CT scan is about 8,000 uSv. The exposure rate on ISS ≅ 18-20 μSv/hr.

GCR Effects on Human Health And Safety

Some comparative (earth environment) radiation doses & their effects

2.4 mSv/yr	Typical background radiation experienced by everyone (average 1.5 mSv in Australia, 3 mSv in North America).
Up to 5 mSv/yr	**Typical incremental dose for aircrew in middle latitudes.**
9 mSv/yr	**Exposure by airline crew flying the New York – Tokyo polar route.**
20 mSv/yr	Current limit (averaged) for nuclear industry employees and uranium miners.
50 mSv/yr	Former routine limit for nuclear industry employees. It is also the dose rate which arises from natural background levels in several places in Iran, India and Europe.
50 mSv	Allowable short-term dose for emergency workers (IAEA).
100 mSv	Lowest level at which increase in cancer risk is evident (UNSCEAR). Above this, the probability of cancer occurrence (rather than the severity) is assumed to increase with dose.
250 mSv/yr	**Natural background level at Ramsar in Iran, with no identified health effects.**
350 mSv/lifetime	Criterion for relocating people after Chernobyl accident.
500 mSv	Allowable short-term dose for emergency workers taking life-saving actions (IAEA).
1,000 mSv short-term	**Assumed to be likely to cause a fatal cancer many years later in about 5 of every 100 persons exposed to it. If the normal incidence of fatal cancer were 25%, this dose would increase it to 30%.**
1,000 mSv short-term	**Causes (temporary) radiation sickness (Acute Radiation Syndrome) such as nausea and decreased white blood cell count, but not death. Above this, severity of illness increases with dose.**
5,000 mSv short-term	Would kill about half those receiving it within a month.
10,000 mSv short-term	Fatal within a few weeks.

http://www.world-nuclear.org/info/inf05.html

Biological Effects of Cosmic Radiation: Manned Space Flight Environments

CREW DOSE LIMITS

GUIDELINES

- Code of Federal Regulations
- Crew & Area Dosimetry
- ALARA – “As Low As Reasonably Achievable”
- NASA Flight Rules, e.g., No EVAs in S. Atlantic Anomaly
- Crew Dose Limits

Dose limits (cGy-Eq.) for short-term or career non-cancer effects*

Organ	30-Day Limit	1-Year Limit	Career
Eye (Lens)	100	200	400
Skin	150	300	600
BFO	25	50	---
Heart	25	50	100
CNS	50	100	150

BFO – BLOOD-FORMING ORGAN
CNS – CENTRAL NERVOUS SYSTEM
cGy-Eq. (centi Gray-Equivalent ≅ cSv (centi Sievert)

*NASA STD 3000 (1994) & NCRP Report No. 132 (2000)

- Based on a limit of 3% Radiation Exposure Induced (premature) Death (REID) with 95 % confidence level (Code of Federal Regulations)
- Also, the new Crew Exploration Vehicle (CEV) design objective is 150 mSv/yr, down from historical 500 mSv/yr as driven by uncertainty in the dose-REID relationship in the primary GCR-dominated space radiation environment

Biological Effects of Cosmic Radiation – Manned Space Flight Environments

Spaceflight Radiation Examples - Human Spaceflight Mission Type Radiation Dose:

Assuming 20 to 50 g/cm^2 Al shielding and not including secondary particle shower effects internal to the human body, which can increase effective dose by about 50%

Space Shuttle Mission 41-C (8-day mission orbiting the Earth at 460 km)	**(1984)**	**5.59 mSv**
Apollo 14 (9-day mission to the Moon)	**(1971)**	**11.4 mSv**
Skylab 4 (87-day mission orbiting the Earth at 473 km)	**(1974)**	**178 mSv**
International Space Station (ISS) Mission (up to 6 months orbiting Earth at 353 km)		**160 mSv**
Estimated Mars mission (3 years)		**1200 mSv**

Slow accumulation of whole body dose from GCR (expressed in Sv and including secondary particle showers in the human body) presently limits the duration of manned space operations outside earth's magnetosphere to times on the order of 180 days. The overall programmatic cost of the available active or passive shielding needed to extend that limit is prohibitive at this time.

MITIGATION TECHNIQUES

HUMANS

- PASSIVE SHIELDING (H_2O, POLYETHYLENE [PE], LH)
- INTEGRATE HIGH-HYDROGEN CONTENT MATERIALS IN THE DESIGN
- HEAVILY SHIELDED LOCATIONS WITHIN THE S/C
- "STORM SHELTER"
- for ISS – 1400# HDPE – lined the SM Sleep Stations
- IN-SITU MATERIALS – SURFACE OPS
- ACTIVE SHIELDING – MAGNETIC & ELECTROSTATIC

ELECTRONICS

- INTRINSIC PASSIVE SHIELDING
- BOX LINING - e.g., MITIGATING ALLOY MATERIAL – minimize secondary neutron production
- RAD-HARD DEVICES / RHBD
- ERROR-CORRECTION ("scrub" memory)
- TRIPLE MODULAR REDUNDANCY (TMR) – e.g., Xilinx FPGAs

Summary & Conclusions

- GCR secondary particles, especially neutrons, dominate the effects on electronic systems &human health at high shielding mass
  - Heavily shielded manned spacecraft, e.g., ISS & Mir
  - In massive targets, like the human body, secondary particle showers can contribute on the order of 50% of the total body exposure
- SEE effects on electronic systems can be managed by:
  - Selection of resistant parts; EDAC and FDIR functions & robust/highly redundant system architectures
  - Shielding mass can mitigate electronic system TID and SEE effects from SPE and trapped radiation, but is largely ineffective against GCR
  - Summary of ISS approach and success metrics
- Slow accumulation of whole body dose from GCR presently limits the duration of manned space operations outside earth's magnetosphere to times on the order of 180 days. The overall programmatic cost of the available active or passive shielding needed to extend that limit is prohibitive at this time