The International Space Station Ionizing Radiation Environment: Electronic Systems, Materials, and Shielding Mass Effects


Radiation Technologies Event - NASA JSC: Technology Collaboration Center of Houston, Sept. 21, 2016

Steve Koontz, Ph. D. – ISS System Manager for Space Environments

NASA, Johnson Space Center, Houston, Texas

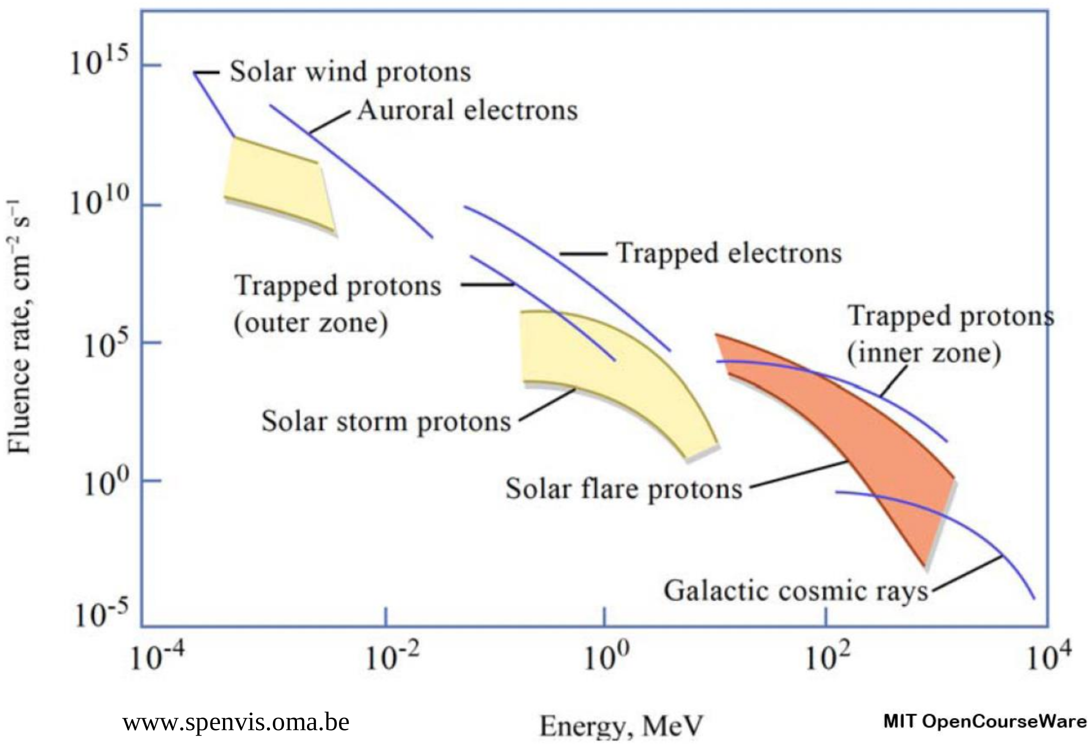
Outline

- **1) Space Radiation: What is it, where is it, and why is it so hard to manage?**
  - The space radiation environment is radically different from Earth surface radiation environments
  - Space radiation effects are determined primarily by highly energetic (often relativistic) charged particles - the term “ray” is an historical misnomer from the early 1900s
    - Galactic cosmic “rays”, solar particle events, and radiation belts - high energy (fast) charged particles and a few high energy photons dominate the environment
- **2) How does space radiation interact with matter (i.e. us and our stuff)**
  - Direct Ionization/Excitation (Particle Tracks) - health effects and microelectronics, materials
  - Nuclear Reactions and Secondary Particle Showers (and more ionization tracks) – health effects and microelectronics
  - Displacement damage – Optoelectronics (solar cells, light emitting diodes, photodiodes etc.
- **3) Space Station Zero - Space Radiation Shielding Specification, Shielding Mass, and Magnetic Shielding in Perspective with humanities oldest spacecraft**
  - Shielding Mass and Magnetic field
  - Shielding performance - Earth Surface Environments
  - Shielding performance - Commercial and Military Aircraft Environments
- **4) International Space Station - Space Radiation Shielding Specification, Shielding Mass, and Magnetic Shielding**
  - Geomagnetic field
  - Spacecraft Shielding Mass
  - Shielding performance - electronic systems - internal and external
  - Shielding performance - surface materials
- **5) Summary and Conclusions**
- **6) Supporting Information and References**
  - A listing of space radiation environment, transport, and analysis/modeling tools and where to obtain them
    - Monte Carlo Simulators – FLUKA and related Monte Carlo codes
    - Boltzmann codes – CRÈME-96, HZETRN 2015
  - **A short bibliography and resource list**

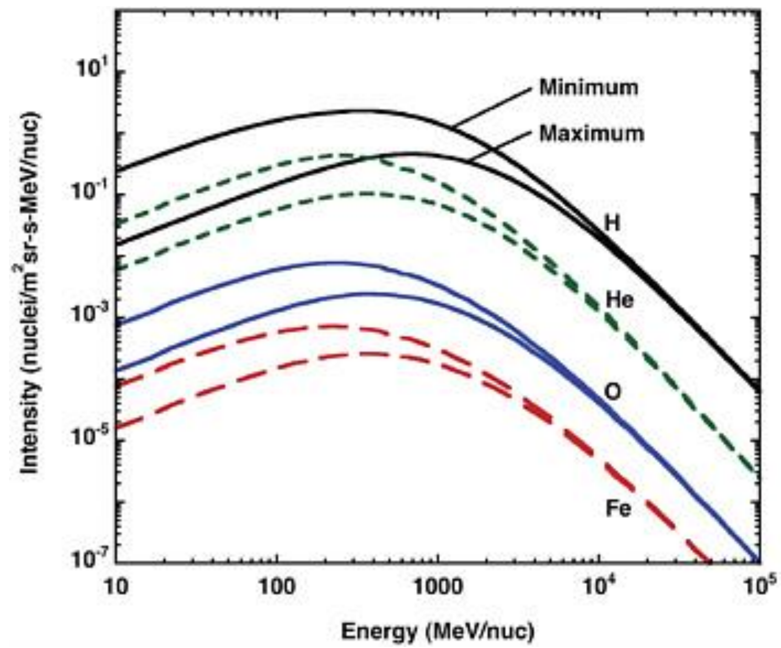
1.0: Space Radiaiton: What is it, where is it, and why is it so hard to manage?

- **Important space radiation characteristics**
  - **Origin** - Where are they from and haw are they formed?
  - **Composition** – Ions, electrons, or photons and of what kind?
  - **Flux and Fluence (abundance)** - how many per square cm per unit time (isotropic in free space except photons)?
  - **Energy Spectrum** - how many particles in each energy interval over the relevant range of values. Energies measured in electron volts (eV) – usually millions (MeV), billions (GeV), and trillions (TeV) of electron volts
- **Galactic cosmic rays (GCR)**
  - Origin - outside the solar system but inside the Milky Way galaxy for the most part (supernovae & other extreme events)
  - Composition **- atomic nuclei (and a few gamma rays) - the all elements of the periodic table are represented**
    - 87% protons, 12% He nuclei, 1% heavier nuclei, smaller flux of energetic gamma ray photons
  - Flux and fluence (abundance) - about **0.1/(cm^2 sec)** at the top of earth's atmosphere and about **0.5/(cm^2 sec)** in interplanetary space (geomagnetic shielding) - GCR flux modulated significantly by the 11 year solar cycle
  - Energy spectrum - Most energetic charged particle population – most are relativistic or ultra-relativistic, traveling very close to the speed of light - Most in the energy range between **100 MeV to 100 GeV and greater**
- **Solar particle events**
  - Origin - solar flares and coronal mass ejections (these can also produce high fluxes of of X-rays that can damage spacecraft surface materials)
  - Composition - **mostly protons/electrons with small percentage of heavier ions**
  - Flux and fluence - **10^3 to 10^4 protons/(cm^{2}sec)** at **E > 100MeV** - SPEs are of short duration – 2 to 3 days typically
  - Energy and spectrum - **10 MeV to 1 GeV**
- **Trapped Radiation – confined to planetary radiation belts**
  - Origin – Uncertain at this time – some contribution from decay of neutrons produced by GCR interactions with Erth's atmosphere and some from capture of solar particle event protons and electrons
  - Composition – **Protons and electrons for the most part**
  - Flux and fluence - **up to 10^5 per cm^2/sec**
  - Energy and spectrum – **10 MeV to 100 MeV**

What kind , how much, when and where



Synoptic view of integral particle fluence rate of space radiation versus upper boundary of particle energy (Wilson, J.W., 1978. Environmental geophysics and SPS shielding. Lawrence Berkeley Laboratory Report LBL-8581, pp 33-116.



R.A. Mewaldt, California Institute of Technology.

Solar cycle modulation of galactic cosmic rays in the interplanetary environment. The Earth's geomagnetic field further reduces GCR flux in LEO in a latitude dependent manner

2.0: How does space radiation interact with matter?

(that is with us, our stuff, and our shielding materials)

Energetic charged particle interactions with target materials:
Three basic physical processes

1. Energy loss (dE/dx) by direct ionization/excitation of material along the particle track (The Electromagnetic Force – collision with electrons)

- 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
- Damage to some spacecraft materials

2. High energy collisions (inelastic/hadronic) triggering nuclear reactions (The Strong or Nuclear Force – collision with atomic nuclei)

- 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 (The Electromagnetic Force again – collision with nuclei without nuclear reaction)

- Displacement of target atoms so as to disrupt crystal structure (solids materials only – important for spacecraft optoelectronics, i.e. PV power systems)

The Electromagnetic Force - Direct ionization & excitation (electromagnetic force) of target substance

- **High speed charged particles decelerate by losing energy to target substance electrons during columbic collisions leaving an ionization/excitation damage track**
  - Nuclear collisions make little contribution to deceleration except at the lowest kinetic energies near end of track (displacement damage) but are the cause of secondary particle showers and limit the distance traveled by very high energy primary CR particles
  - http://pdg.lbl.gov/2010/reviews/rpp2010-rev-passage-particles-matter.pdf
- **dE/dx is the rate of energy transfer: keV/micron or MeV-cm^2/mg in a particular target substance**
  - Linear and nearly constant over most of the particle range - **hence the term linear energy transfer (LET)**
  - Nonlinear near end of track – most of the energy is deposited near the end of track in the "Brag Peak"; basis of accelerator hadron therapy for certain cancers
  - http://tvdg10.phy.bnl.gov/LETCalc.html Brookhaven National Laboratory on-line LET and range calculator
- **Quantified by the relativistic Bethe-Bloch equation**

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$

Projectile (space radiation particle) dependencies

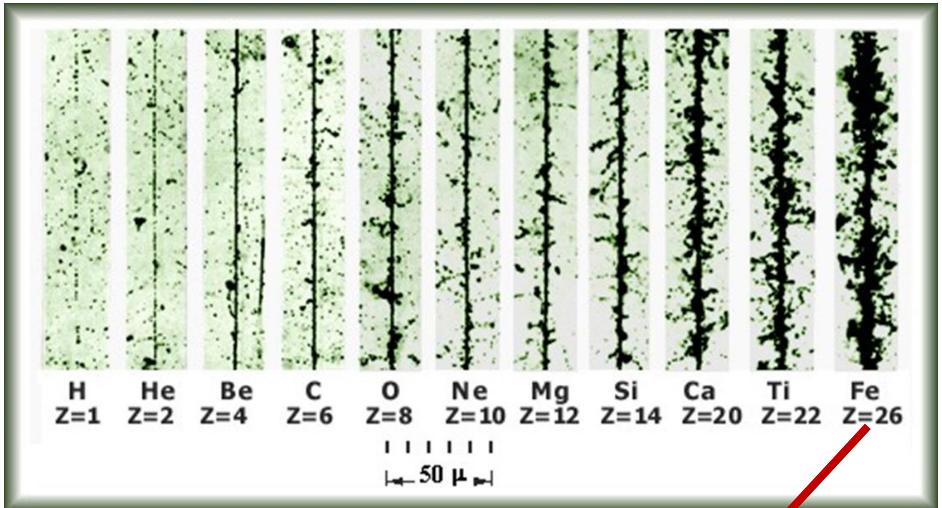
$\beta = v / c$; v = velocity of the particle; E = energy of the particle; x = distance travelled by the particle in the target; c = speed of light; z = particle charge; ε_0 = vacuum permittivity

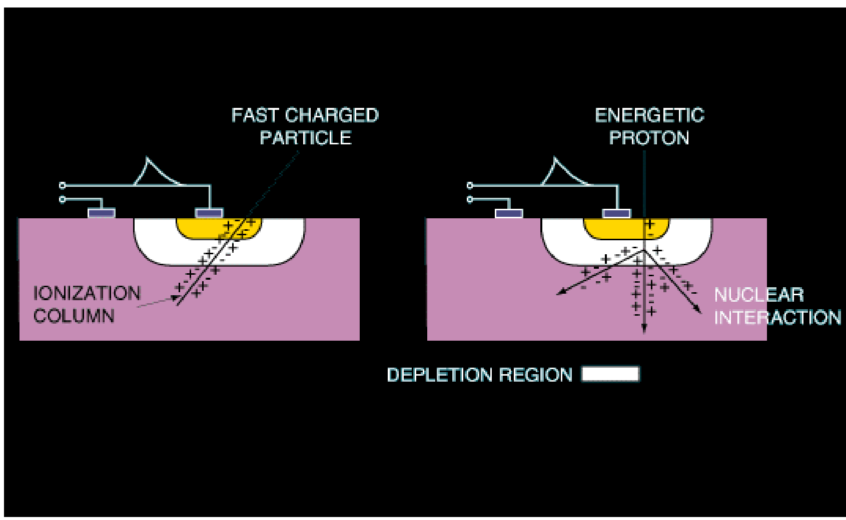
Target substance dependencies

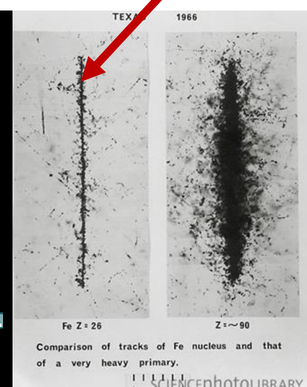
I = mean excitation potential of the target = 10eV(Z), n = electron density of the target = $(N_A\ Z\ \rho)/A\ M_\mu$; ρ = density of the target; Z = target atomic number; A = target atomic mass number; N_A = Avogadro number; and M_u = Molar mass constant = 1 in Si units; e = charge of the electron; m_e = rest mass of the electron

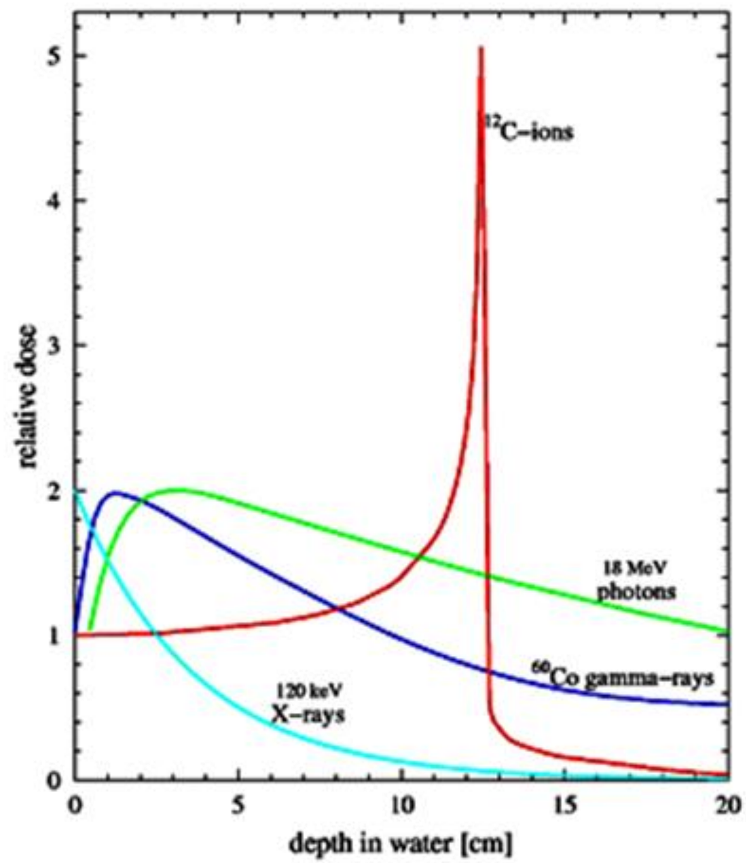
The Electromagnetic Force - Direct ionization & excitation (electromagnetic force) of target substance

Powell Fowler Perkins/Science Photo Library





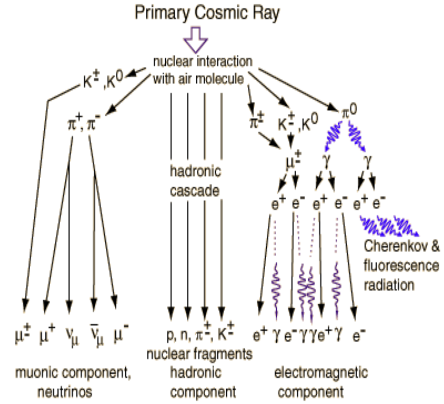




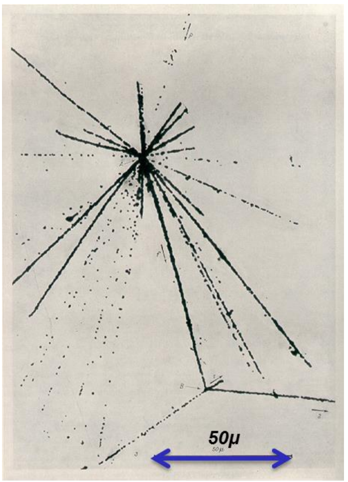
Single event upset (SEU) in a MOS/CMOS Field effect transistor.
The space radiation single event environment is an important consideration for spacecraft and aircraft reliability. The figure on the right should read high energy proton <u>or neutron</u>

The Strong Force - Nuclear Reactions and Secondary Particle Showers

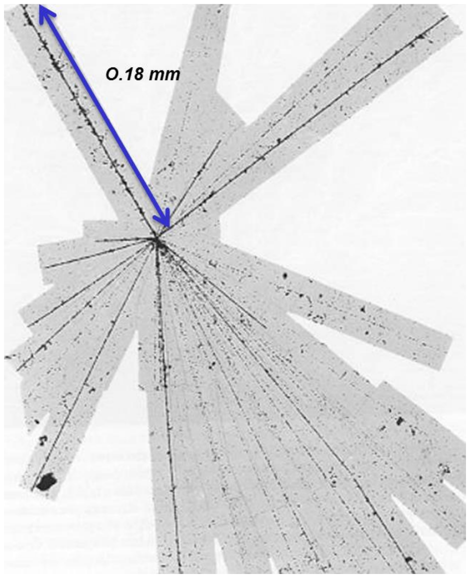
- **Inelastic Nuclear collisions attenuate the primary flux exponentially and generate secondary particle showers via nuclear reactions**
  - **$N(l) = N(0) \exp(-l/\lambda)$**
    - λ = inelastic collision length (grams/cm^2)
    - l = thickness in g/cm^2
  - **http://pdg.lbl.gov/2010/reviews/rpp2010-rev-atomic-nuclear-prop.pdf**
    - **λ** ranges from **42 g/cm^2 to 118 g/cm^2 for protons in various materials**
    - At fixed target mass, number of collisions decreases with increasing atomic weight (i.e. fewer target nuclei per gram)
    - **λ** Scales as **(projectile atomic number)$^{0.77}$**
    - **λ** increases with target atomic number
- **$\langle n_{event} \rangle$ = average number of secondary particles per single collision event**
- **$\langle n_{collision} \rangle$ is proportional to A(projectile) x A(target) x (average nuclear thickness function) and collision energy**
- **$\langle n_{shower} \rangle$ is proportional to primary projectile energy**



Generic GCR secondary particle shower nuclear reaction products

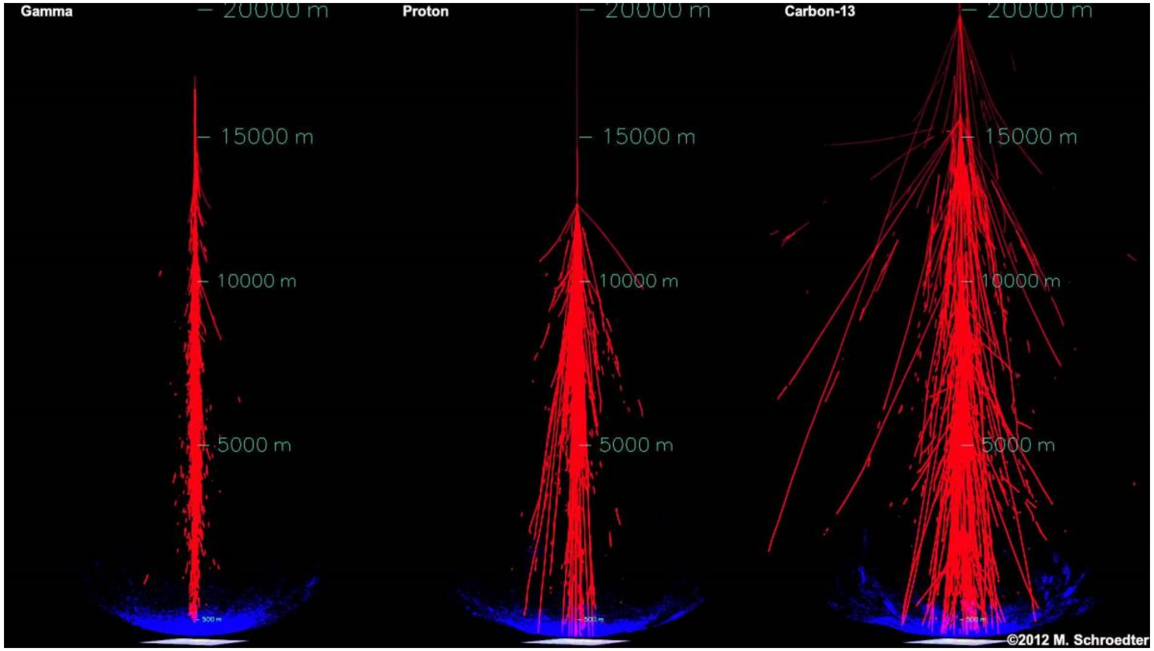


Danysz and Pniewski, Philosophical Magazine 44 348 (1953);



Mg nucleus cosmic ray emulsion "star", i.e. nuclear reaction event- Albert Lim (2000) http://astro.com.sg/articles/Difference_%20btw_Gamma_n_Cosmic_Rays/DiffRays_image001.jpg

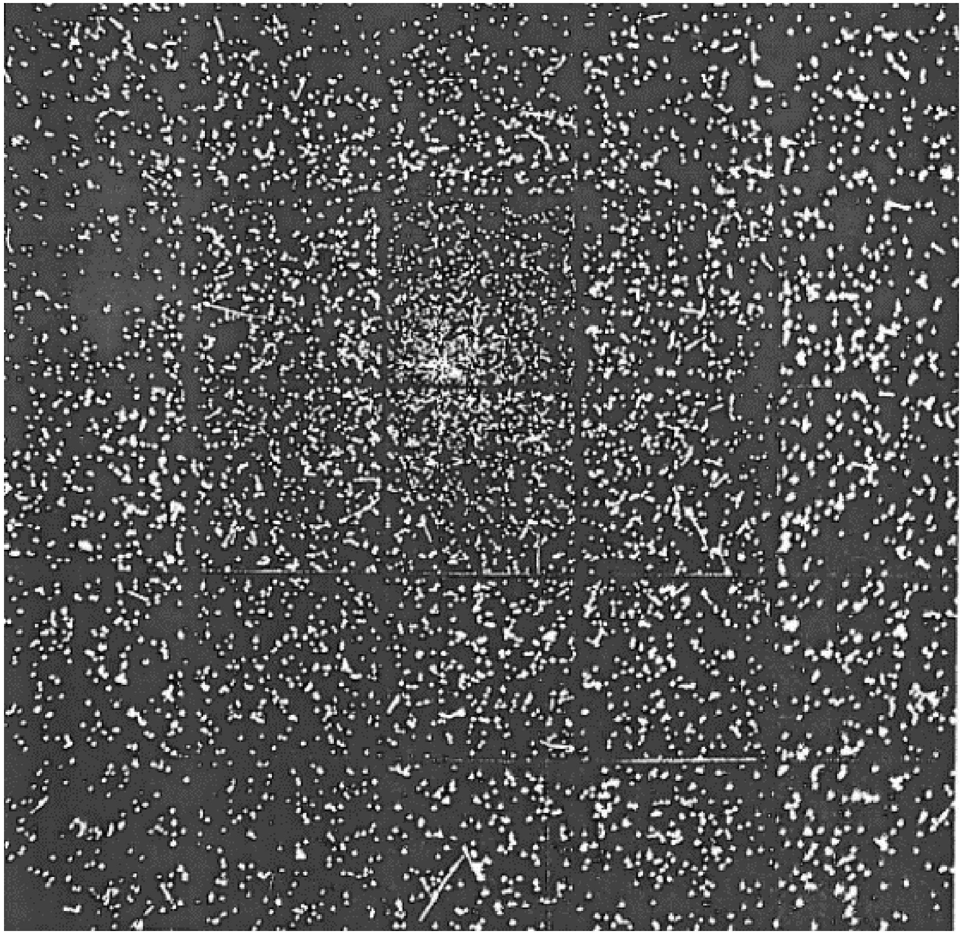
And what does all this look like? (https://www.youtube.com/watch?v=j-BBzWlOai0)



The interactions of 3 types of very-high-energy particles (gamma-ray, proton and Carbon-13 nucleus) were simulated. The fully developed atmospheric particle showers (red) are shown including the Cherenkov light (blue) just before impact on the ground. Even though the 3 particles hve the same initial energy, the most intense Cherenkov light is produced by the gamma ray, less by the proton, and the least by the Carbon nucleus. Each time a very-high-energy particle interacts in the atmosphere, fluctuations cause the shower to develop differently. Shown here are pretty 'average' looking showers. (2012 Martin Schroedter, VERITAS and Harvard Smithsonian Center for Astrophysics

And what does all this look like?

5 meters

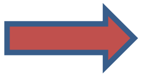


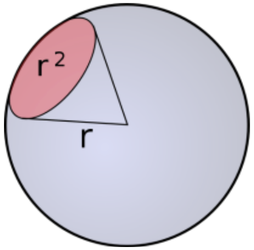
5 meters

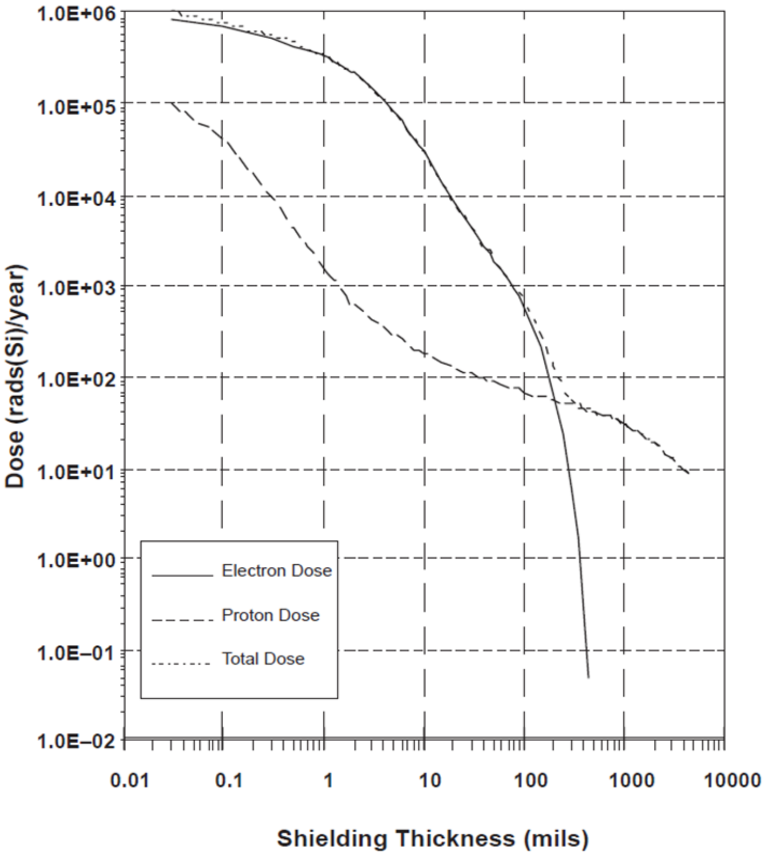
A photograph of the central region of a small, vertically incident air shower as seen by the University of Leeds close packed horizontal array of discharge chambers (5 x 5 meters) Leslie Hodson 1990 (from Gaisser, T. K.; Cosmic Rays and Particle Physics, Cambridge University Press, Cambridge, 1990, Frontpiece)

Some General Features of Space Radiation

- In free space, charged particle flux is approximately isotropic, or nearly so, in all cases , so no shadow shielding (except by planets, asteroids, moons etc.)
  - Fraction of 4π steradians covered by shielding mass is important
    - Any area on a sphere, totaling the square of its radius and observed from its center, subtends precisely one steradian.
- Energetic photons are not isotropic: line-of-sight to source
  - Shadow shielding can work for X-ray flares
- Low energy particles/photons are much more abundant than high energy particles/photons
  - Penetration of active or passive shielding depends on particle kinetic energy:
  - high energy => greater penetration so we have,
  - High spacecraft skin dose – and rapidly decreasing dose as shielding mass increases
    - Greatest % reduction in the first 1 to 10 g/cm^2
    - Much lower % reduction as shielding mass increases beyond 10 g/cm^2
- How and where the dose is distributed in a particular object (Dose/Depth for spacecraft, asteroids, moons, planetary surfaces and atmospheres etc.) depends on the ionizing radiation environment and how that environment interacts with that objects configuration and materials







ISS Design Environment - electron and proton dose to the center of an aluminum sphere of radius = shielding thickness in mils (1 mil = 0.025 mm)

Some Spacecraft Radiation Shielding Basics

- Shielding mass is measured in units of areal density (g/cm^2)
  - Shielded spacecraft weight increases with spacecraft surface area
- Look for the material with the best total ionizing dose (TID) reduction per unit areal density to minimize spacecraft mass for a given dose or particle flux reduction
- Minimize magnitude of secondary particle showers
  - Minimize average atomic number and maximize hydrogen content
  - Chemically and thermodynamic stability are required (problem for LH2)
  - Avoid high Z materials like lead or tungsten (unless you really need to block energetic electrons and/or x/γ rays and the secondary particle shower cost is acceptable - e.g. Juno)
- Engineering Materials Examples:
  - Polyethylene, polypropylene, water methane, ammonium borohydride (unstable) and related low Z hydrides, etc.
- Spacecraft materials that can also serve as shielding:
  - Low Z propellants and consumables (CH_4, hypergolics, H_2O, clothing, food, etc.)

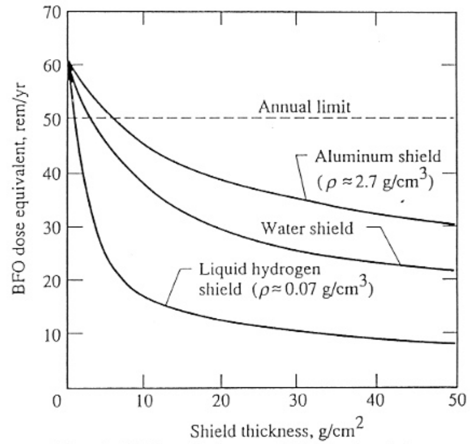
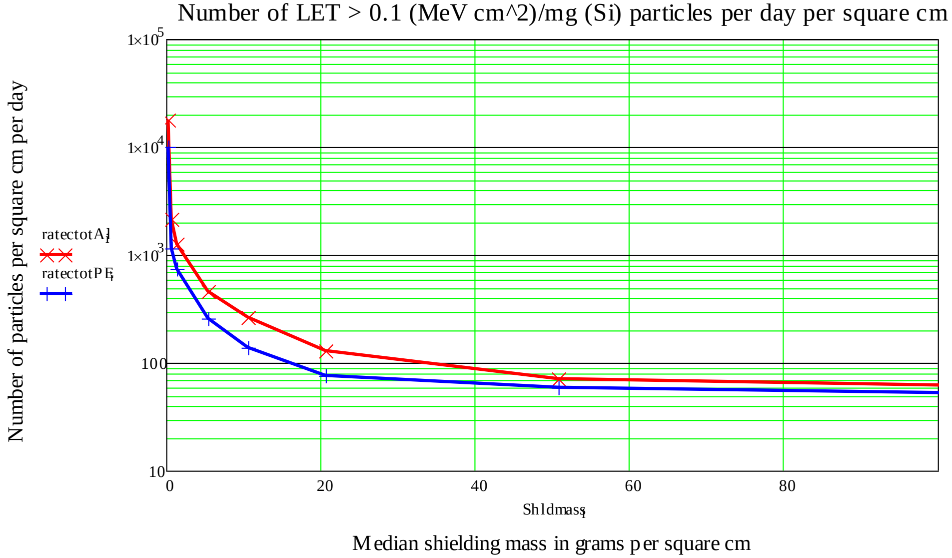


Figure 6. Shielding effectiveness of GCR at solar minimum.

https://srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm

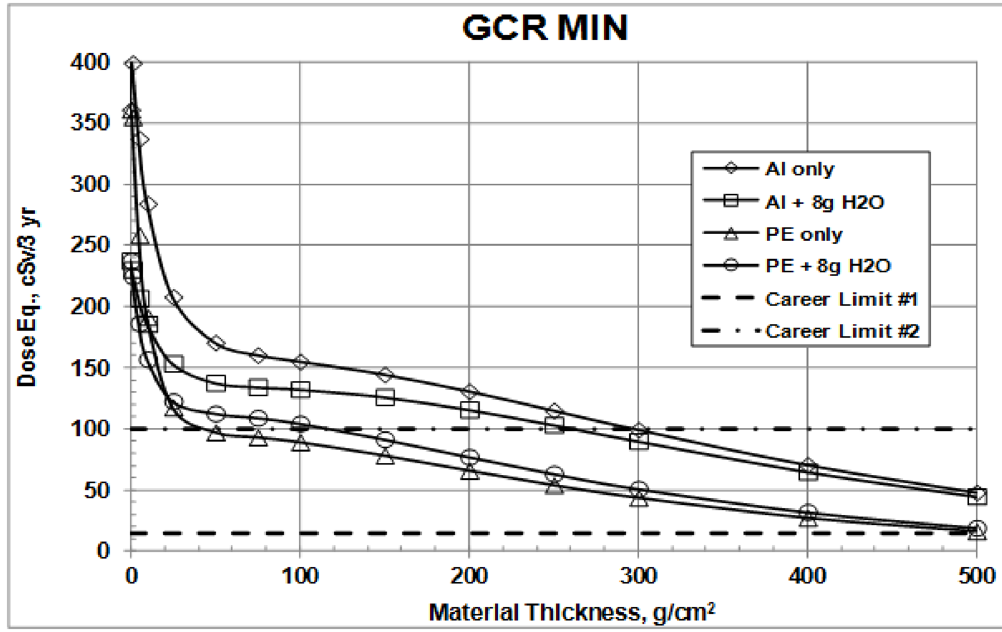
Point Dose (exaggerates material differences) calculations with HZETRN - Interplanetary environment

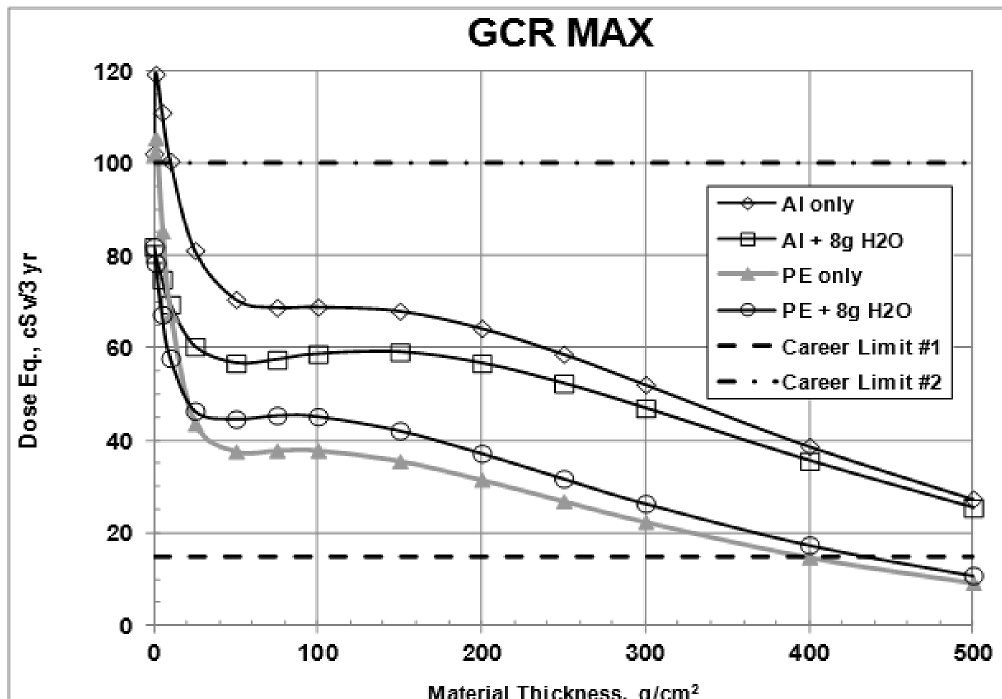


FLUKA calculation of Al vs PE shielding material effect on > 0.1 LET particle flux – interplanetary environment

Shielding materials effects and heliospheric (solar cycle) magnetic shielding compared for human interplanetary flight

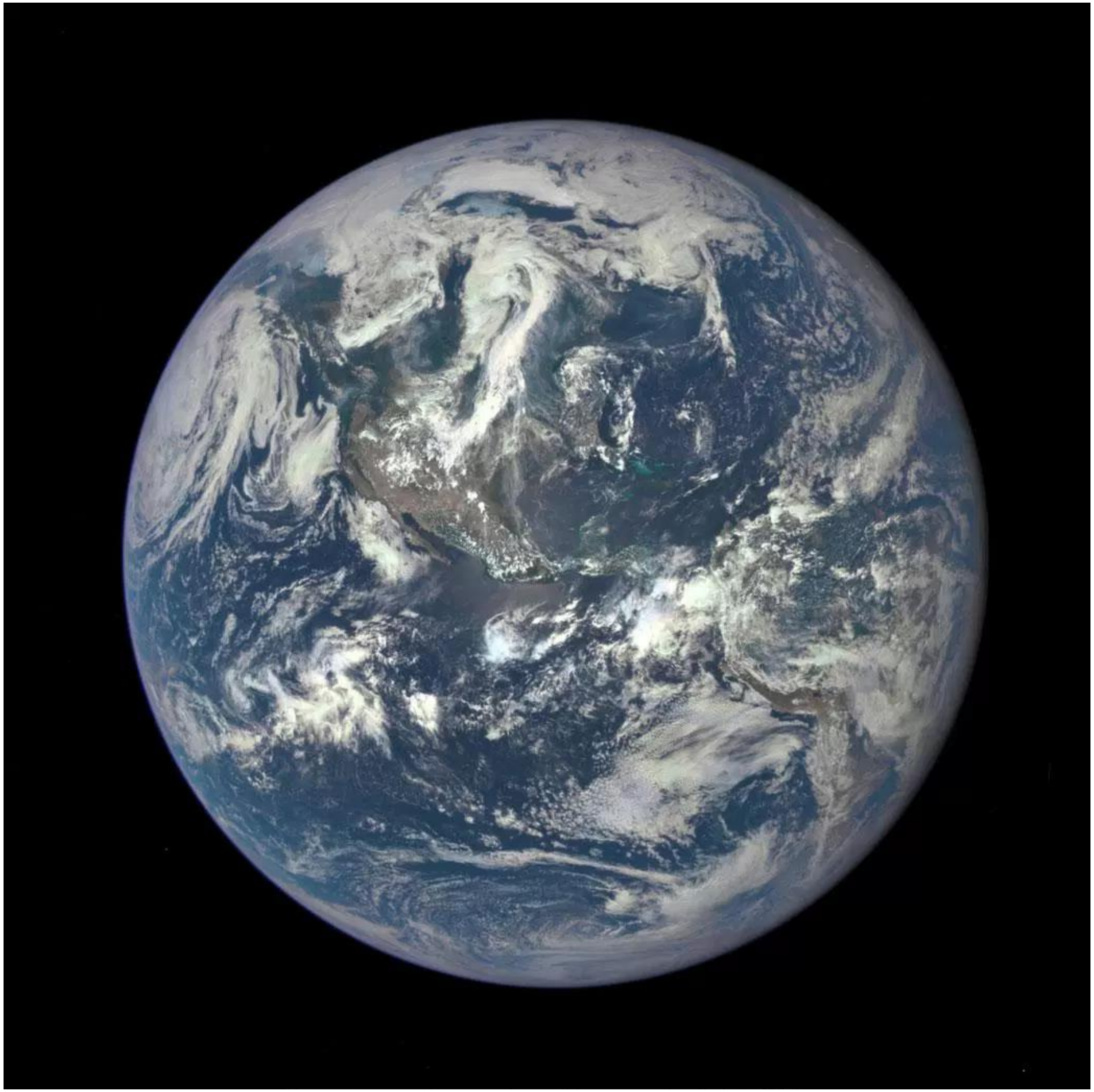
NASA HZETRN 2010 estimates of crew dose vs. shielding mass for a 3 year interplanetary mission assuming solar maximum and solar minimum GCR environments and no SEP event contributions. Putative 10 cSv and 100 cSv flight crew career dose limits are compared.





Koontz S., Rojdev K., Valle G., Zipay J., Atwell W.; "**Estimating the Effects of Astronaut Career Ionizing Radiation Dose Limits on Manned Interplanetary Flight Programs,**" Proceedings of the 43rd International Conference on Environmental Systems, Vail Colorado, July 14-18, 2013

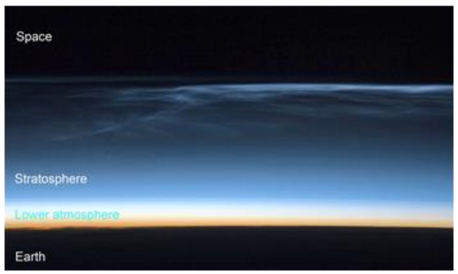
3.0: Space Station Zero (aka Earth)



Space Radiation shielding specifications and performance summary

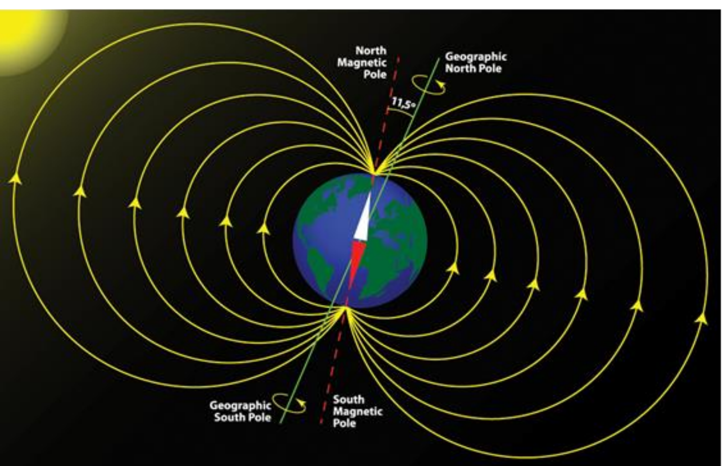
1) Structural shielding mass

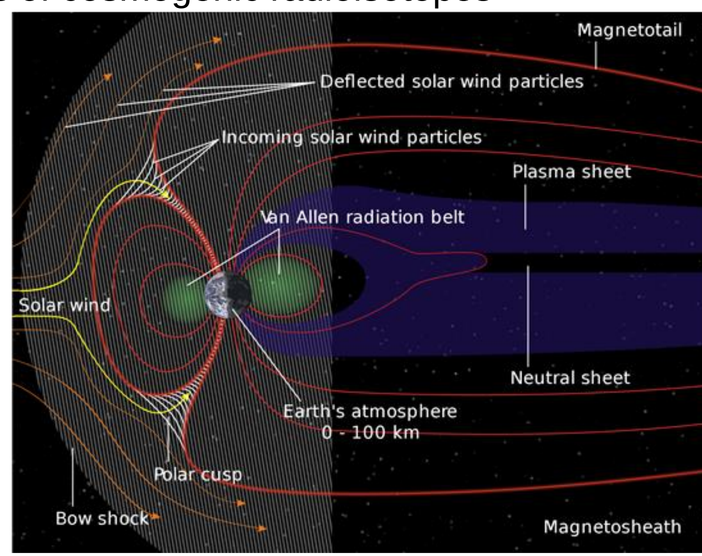
- Diameter = 12,756.3 km
- Mass = 5.9736 x 10^{24} kg
- Composition – silicate rock with iron core (slightly radioactive from naturally occurring radioisotopes)
- At surface, blocks **all** space radiation over ~ 2π steradians (under your feet)



2) Atmospheric shielding mass

- Thickness = ~100 km (1033 g/cm^2) measured along a radius
- Mass = 5.1480×10^{18} kg
- Composition - 77% nitrogen, 21% oxygen, with traces of argon, carbon dioxide and water (note – low Z elements)
- Accounts for most space radiation shielding effect for the remaining 2π Sr (overhead) and synthesis of cosmogenic radioisotopes

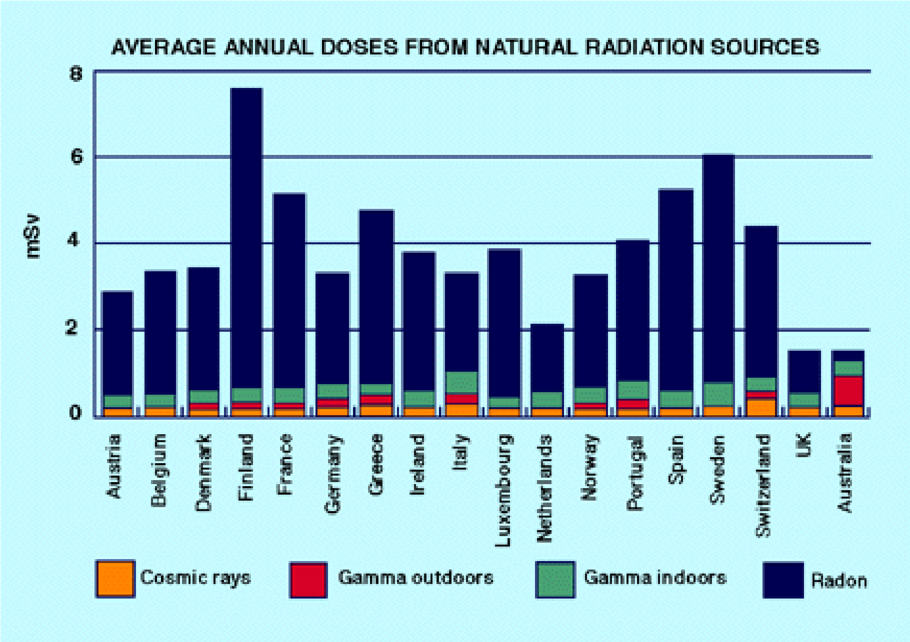


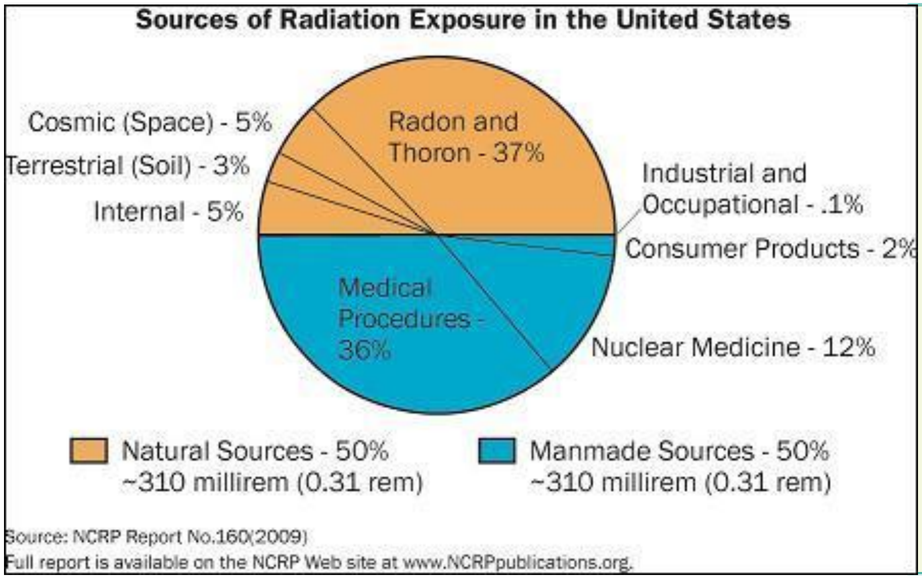


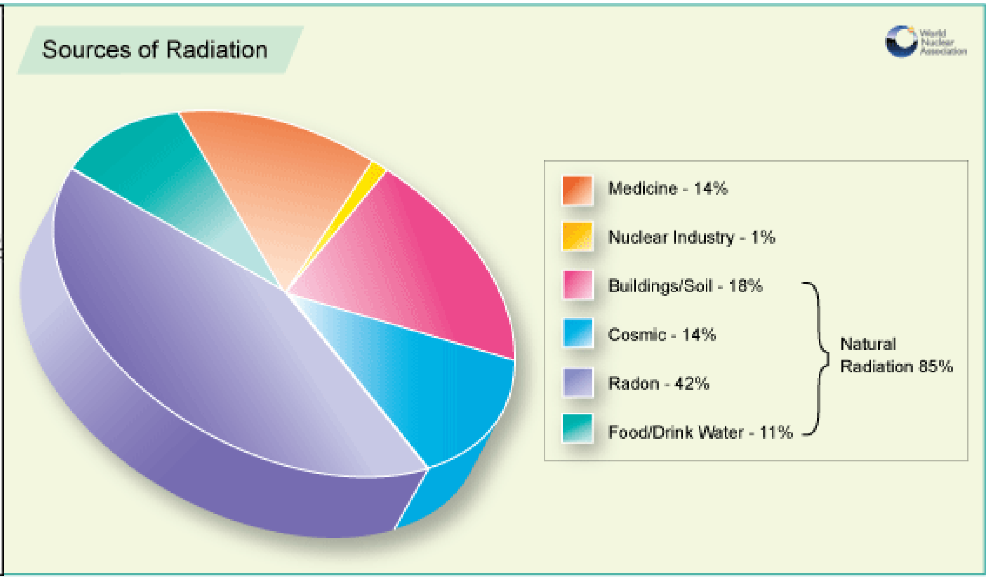
3) Geomagnetic field - At the **Earth's** surface ranges from 25 to 65 microteslas (0.25 to 0.65 gauss). Effectively blocks solar wind. Mitigates GCR and SPE in an altitude and latitude dependent manner.

Shielding Performance - Earth Surface Environments

- Earth surface ionizing radiation dose environments are dominated by natural radioisotope decay and man-made radiation sources
  - **Radon gas is the most important contributor**
- CR contributions are on the order of 10% of the natural environment







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

Performance - Roughly 2 to 8 mSv (~ 0.2 to 0.8 rad) per year at/near the surface

Shielding performance - Earth's atmosphere

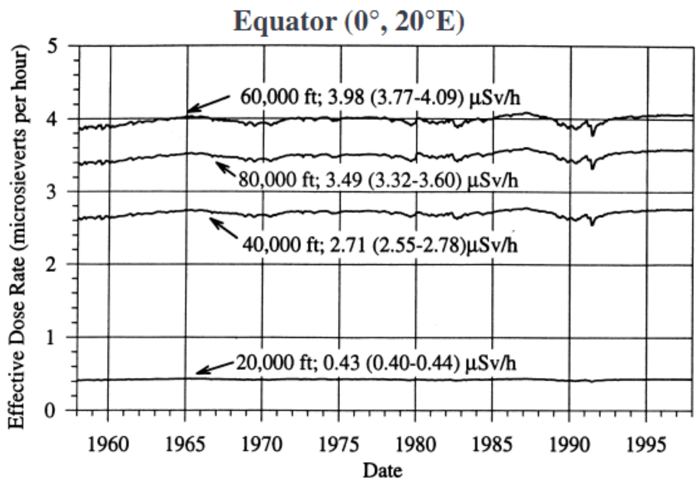
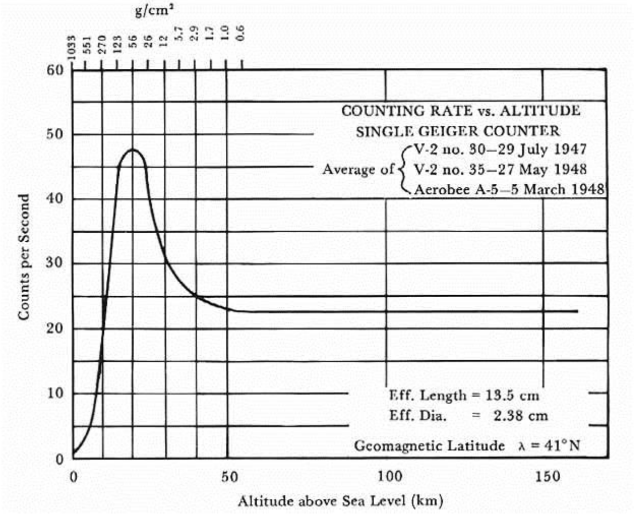
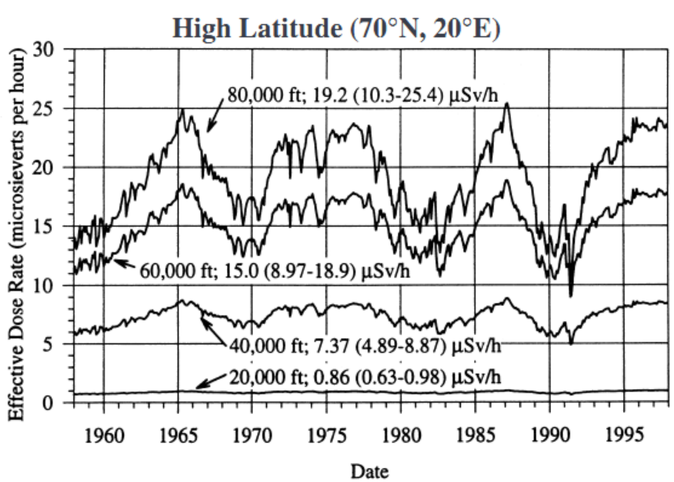


Fig. 1. Galactic radiation levels (monthly means) at various altitudes, at the equator and at a high latitude, January 1958–December 1997. Forty-year mean (minimum-maximum) effective dose rates are also shown. The effect of the 11-year solar cycle on cosmic radiation levels is apparent at high latitude.

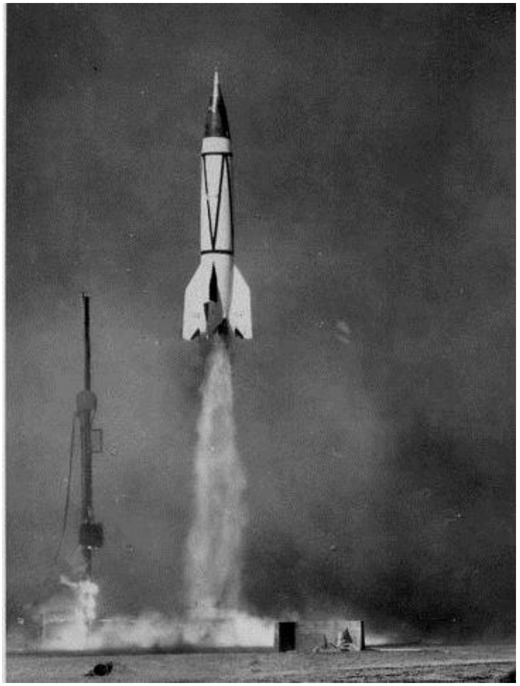
The Pfotzer Maximum: GCR + Earth's Atmosphere





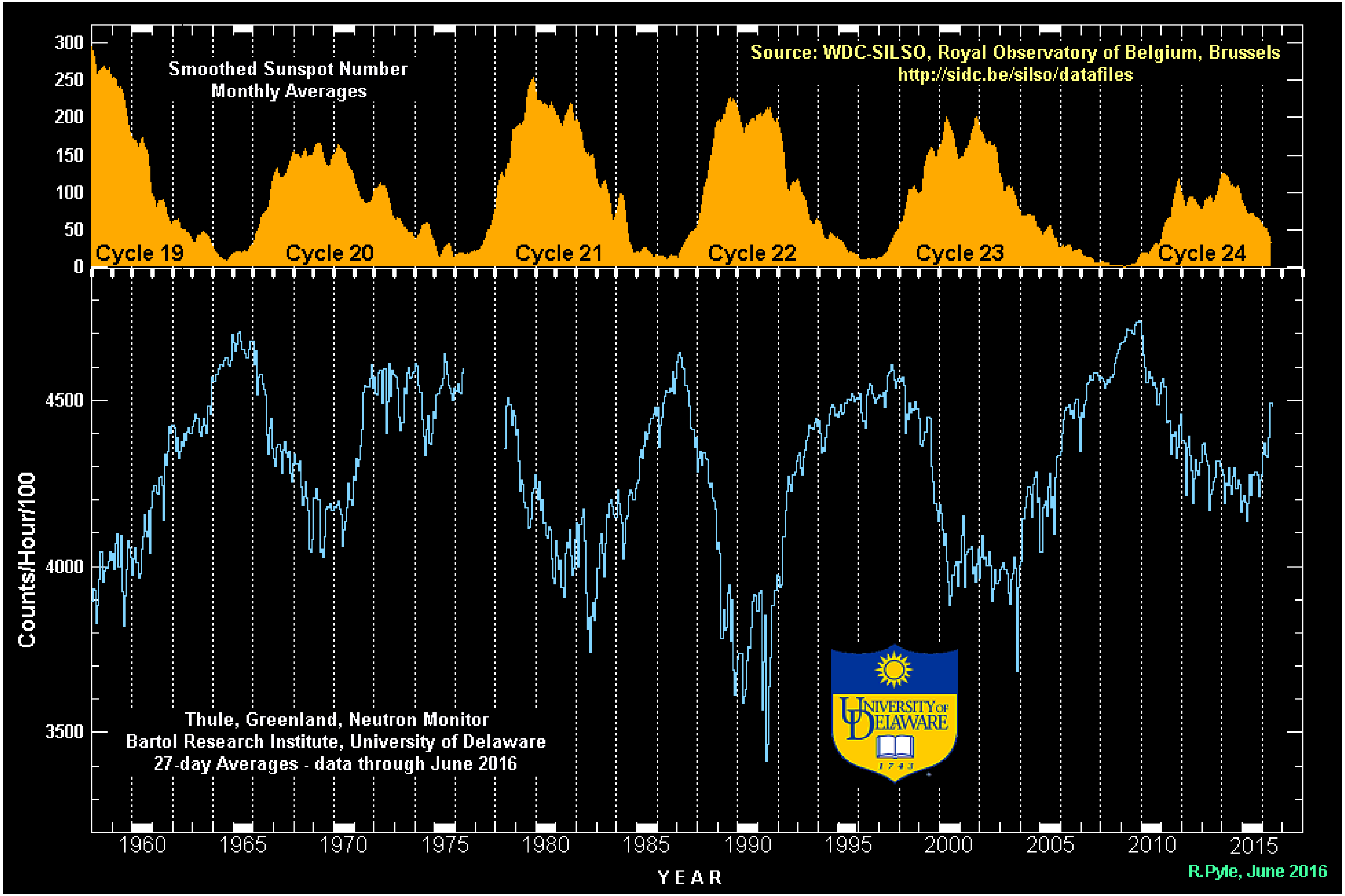
(Source: W. Friedberg, et al. Reproduced from *Cosmic Radiation and Aircrew Exposure*, pp. 323–328, with permission from Nuclear Technology Publishing, P.O. Box 7, Ashford, Kent TN23 1YW, England.)

Average ISS hourly crew dose rates are on the order of 20 µSv/hr – comparable to rates for high altitude aircraft at high latitudes



Want to experience space radiation? – buy a plane ticket for a polar route flight

Solar Cycle Modulation of GCR Flux: Monitoring GCR secondary particle shower neutrons (http://neutronm.bartol.udel.edu/)



Recent example of atmospheric neutron (GCR secondary shower products) effects on supercomputer and commercial aircraft systems (Steve Wender, LANL 2013)

Results of LANSCE/WNR measurements determine problem with ASCI Q-Machine

- The ASCI Q-Machine has 2048 nodes with a total of 8192 processors.
- During commissioning, it was observed that the Q-machine had a larger than expected failure rate. Approximately 20 fails / week (~3 fails / day).
- The question was whether this could be the result of neutron single-event upset.

ASCI Q-Machine at Los Alamos National Laboratory

Fails/day ~ [# of fails/neutron] * [# neutrons/day]

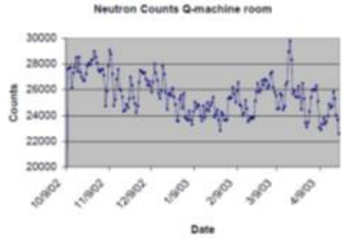
Measured at LANSCE → [# of fails/neutron]

Cosmic-ray neutron flux → [# neutrons/day]

NNSA — Los Alamos

The neutron environment and the system response was measured

- The neutron intensity was measured in the Q-Machine room. The values obtained agreed with the Goldhagen values
- The system response was measured by putting one module of the Q-Machine in the LANSCE/WNR beam.
- Results of measurement accounted for approximately 80% of the failures. (IEEE Trans. Dev. Mat. Reliab. 5 2005)
- The failures were traced to a cache memory that was not error corrected.
- This result may have significant impact on future large computer systems



One neutron can stop a calculation

Santa Fe New Mexican February 2004
"..Q's weakness is the result of….cosmic ray bombardment….a microprocessor that doesn't have a backup system .."

NNSA — Los Alamos

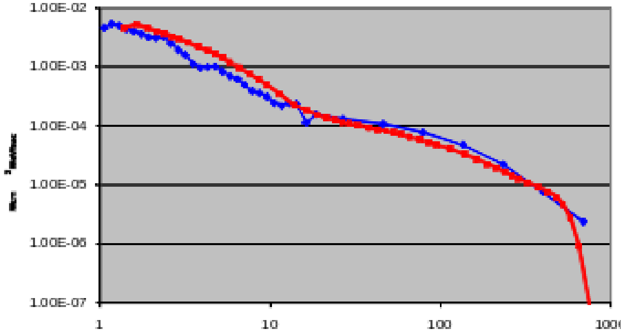
Recent avionics incident highlight Single Event Effects (SEE) problem

- On October 7, 2008 , Quantas 72 was enroute from Singapore to Perth, Australia
- "While ..at 37,000 ft, **one of the aircraft's three air data inertial reference units started outputting intermittent, incorrect values**…Two minutes later … the aircraft flight control primary computers **commanded the aircraft to pitch down. … At least 110 of the 303 passengers and nine of the 12 crew members were injured**: 12 of the occupants were seriously injured and another 39 received hospital medical treatment." (Pg. vii)
- "The other potential **triggering event was a single event effect (SEE)** resulting from a high-energy atmospheric particle striking one of the integrated circuits within the CPU module. There was insufficient evidence available to determine if an SEE was involved, but **the investigation identified SEE as an ongoing risk for airborne equipment**." (pg. xvii)
- "Testing was conducted with neutrons at 14 MeV …the test was not sufficient to examine the …. susceptibility to the full range of neutrons at the higher energy levels that exist in the atmosphere". (pg. 147)

ATSB Transport Safety Report Aviation Occurrence Investigation AO-2008-70

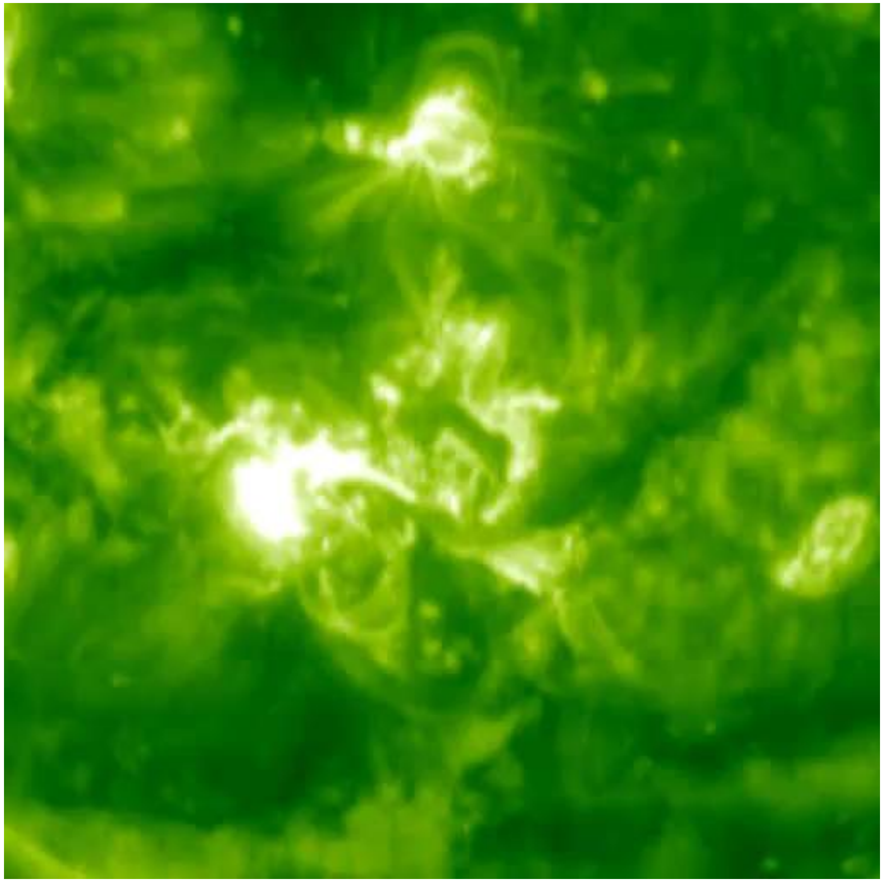
- "The ATSB received expert advice that **the best way of determining if SEE could have produced the data-spike failure mode was to test the affected units at a test facility that could produce a broad spectrum of neutron energies**. However, the ADIRU manufacturer and aircraft manufacturer did not consider that such testing would be worthwhile for several reasons, including that:
- There were significant logistical difficulties in obtaining access to appropriate test facilities"

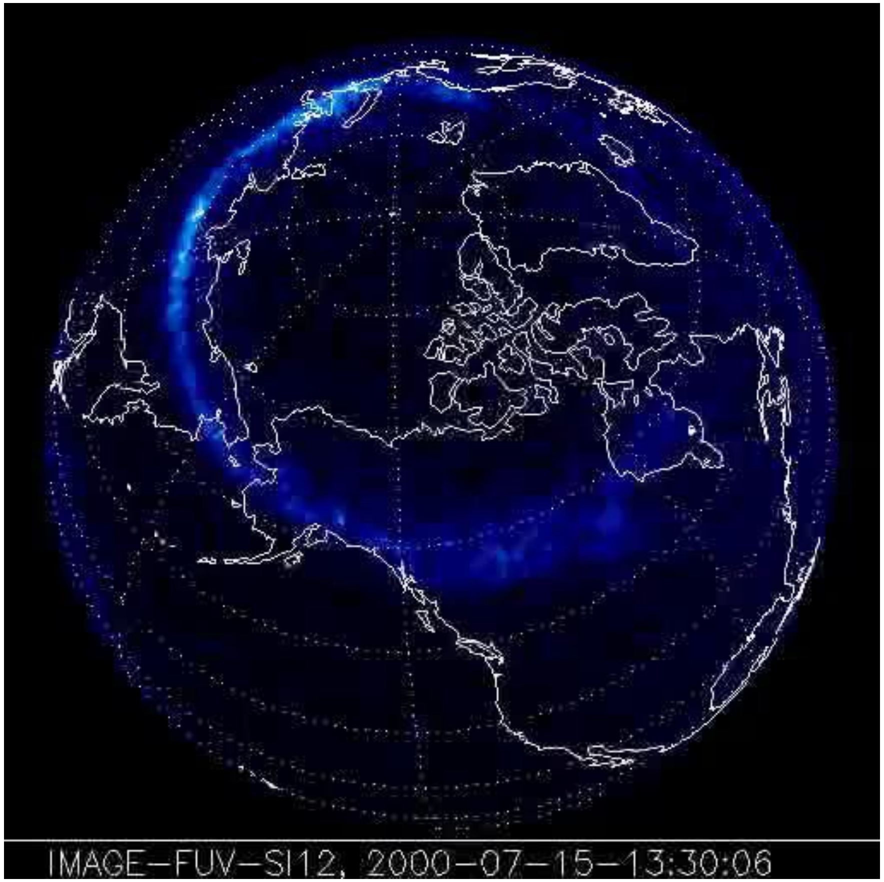
NNSA — Los Alamos



The LANSCE neutron spectrum is very similar to the cosmic-ray-induced neutron spectrum, but it is more than five orders of magnitude more intense. The WNR flux is shown in red, and the Cosmic ray flux is shown in blue.

And what does all this look like (Solar Particle Event)?

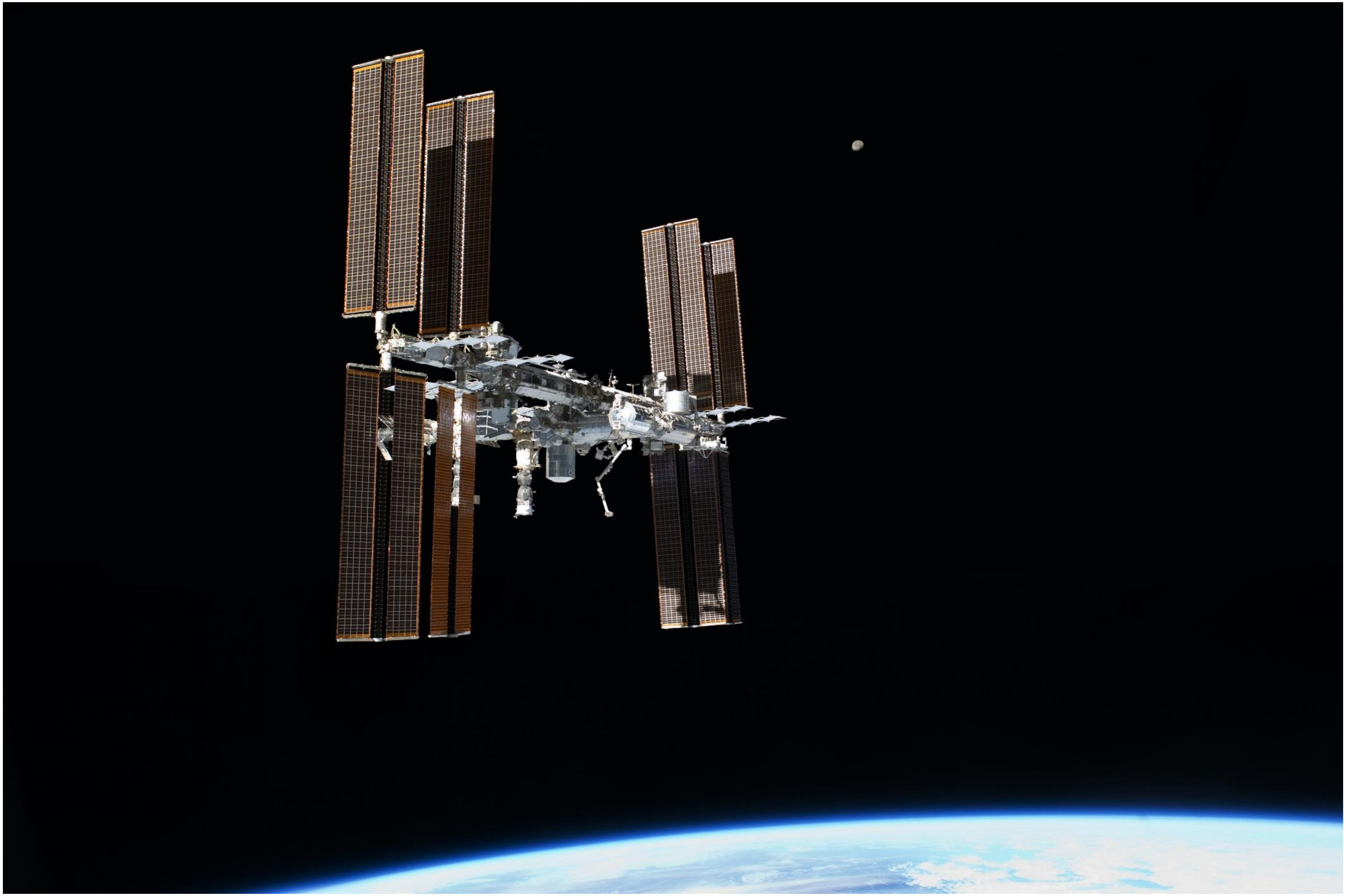




Video clip of 7/14 to 7/15 2000
SEP as viewed by SOHO spacecraft

Video clip of 7/14 to 7/15 2000
SEP protons impacting of Earth as viewed by IMAGE spacecraft (SEP proton induced O fluorescence

4.0: International Space Station



Space radiation shielding specification and performance summary

- ISS Space Radiation Control Design Requirements (SSP-41000) - **None**
  - Primary/secondary structure determined by launch loads and dynamics, pressure vessel safety, and MM/OD protection
  - Materials and avionics to meet performance/safety requirements for the life of the vehicle without special shielding mass considerations
    - Natural Environment Definition for Design – SSP-30512, 500 km/51.6°
      - Worst-Case - we don't fly above 420 km (Soyuz/Progress certification limits)
    - ISS must fail safe and recover from a "worst case" SPE defined in 30512
  - Crew Radiation dose administrative limits enforced by tracking accumulated crew dose and limiting crew exposure time (i.e. limiting stay time on ISS to limit total dose per expedition – "number of safe days in space"
    - Worst-case stay time must be compatible with planned crew change out flight rate
    - Safety requirements (SSP-50021) limits crew dose to less than 40 cSv per year
- So, how did this approach work?
  - No space radiation induced materials or avionics hard failures to date and none expected before end of Program
  - No documented exception to expedition crew dose limits (that I know of – check with the JSC/SRAG on this)

ISS shielding total ionizing dose performance

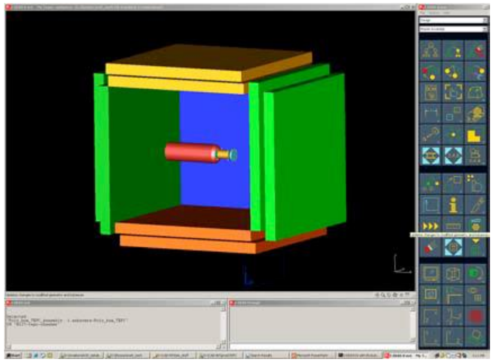
- External (outside the pressurized volume) Materials and Systems
  - Shielding mass distribution functions are highly anisotropic and median ranges from zero to more than 10 g/cm^2
  - Trapped radiation (protons and electrons) dominates (SAA and high latitude regions) – GCR contribution negligible is compression
    - Highly variable environment – altitude, solar activity, and solar cycle effects
  - Boeing Radiation Effect Lab thermo-luminescent dosimeter measurements on MISSE-1, 2, and 3 ISS payloads (Wert, Normand, Perry, Pippin, Bartholet; NSMMS June 2010)
    - Median shielding mass ranges 0.0 to 0.9 g/cm^2
    - 4-year-doses range from **3×10^3 rads** (Si) at 0 g/cm^2 to **10^2 rads** (Si) at 0.9 g/cm^2
      - All well below the annual worst-case Design/Verification Environment (SSP-30512) doses at the corresponding shielding thicknesses (10^6 rads (Si) @ 0.0 g/cm^2, and 3×10^5 rads (Si) @ 0.9g/cm^2)
- Internal (inside the pressurized volume) Materials and Systems
  - Shielding mass distribution functions are more isotropic with ranges from 10 g/cm^2 to more than 100 g/cm^2 (aluminum with cargo, avionics and consumables) with median values of 40 to 50 g/cm^2 (e.g. US Lab module)
  - Pre-flight annual dose estimates (using the SSP-30512 Design/Verification Environment) for the US Lab module range from 8 rads (Si) to 21 rads (Si) with a median value of about 14 rads (Si) depending on location of the dose point
    - Variable environment – altitude, solar activity, and solar cycle effects
  - In-flight TLD measurements during solar max ranged from 4.5 rads (Si) to 8.2 rads (Si) per year. DOSTEL (particle hodoscope) measurements averaged to 7.1 rads Si per year (Reitz et al, AIAA 2001-4903)
  - In-flight solar minimum measurements (Kodiara et. Al, 2013) 11.1 rads (H2O)/year ~ 8.59 rads (Si)/year

ISS Crew Shielding Augmentation Work

- Modeled dosimetry – 4.7 g/cm^2 polyethylene, inside ISS, solar minimum – Annual dose to blood forming organs (BFO) in cGy (rads) - Calculated with HZETRN

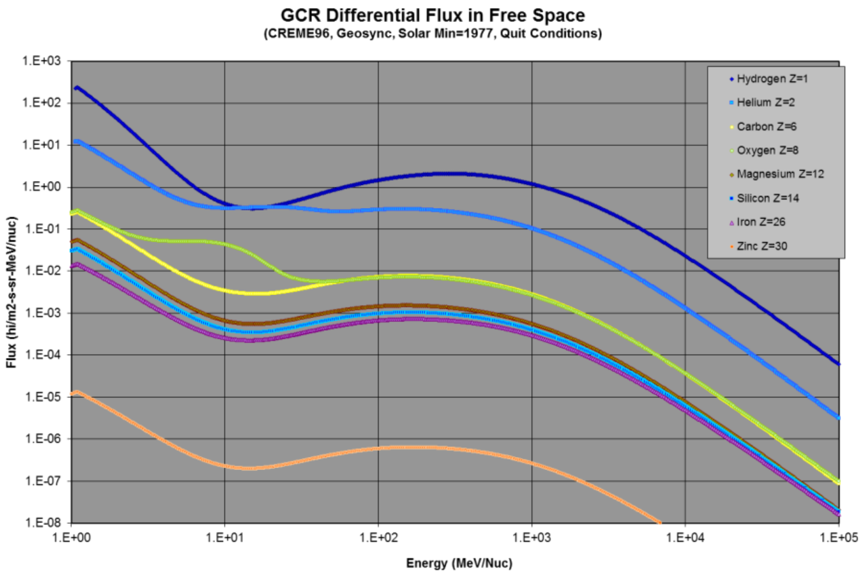
Shavers, Mark; "Radiation Measurements and Shielding Analysis for ISS, Workshop on Radiation Monitoring for the International Space Station, Vienna Austria, Sept 8-10, 2004, http://www.iss-casis.org/files/CASIS_RFP_2013-3_Radiation_Measurements_and_Shielding_Analysis_for_ISS.pdf

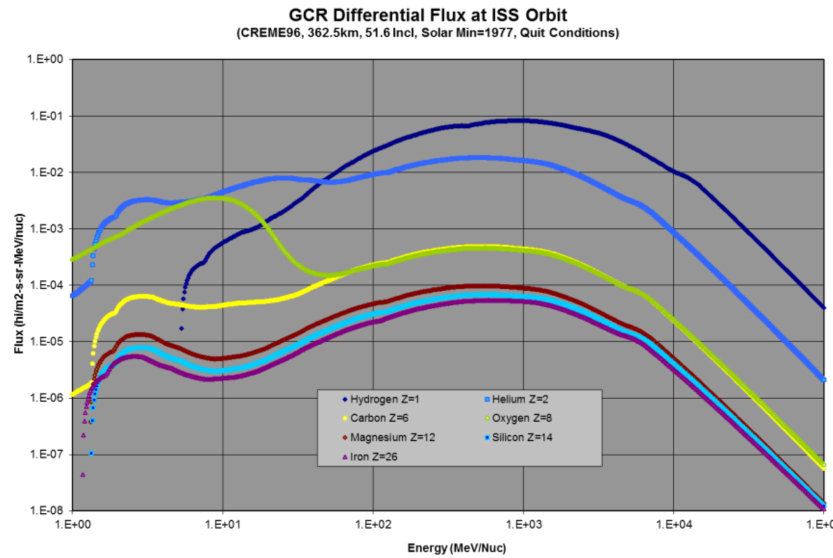
Radiation source	Without poly shield	With poly shield	Percent reduction
Trapped protons	4.234	2.664	37.2%
Galactic Cosmic Radiation	4.782	4.708	1.8%
Combined (GCR + Trapped)	9.016	7.373	18.4%



In-flight measurement results for "TeSS" poly shielded crew quarters:
1) ~ 20 percent reduction Equivalent dose in personal dosimeters
2) ~ 40% reduction in ISS crew chromosome damage via biodosimetry

Cosmic Ray Exposure Environments: Low-Earth Orbit Vs Interplanetary Space at 1 AU
Eight most abundant GCR nuclei (98+% of total flux) - Benefits of Geomagnetic Shielding for ISS



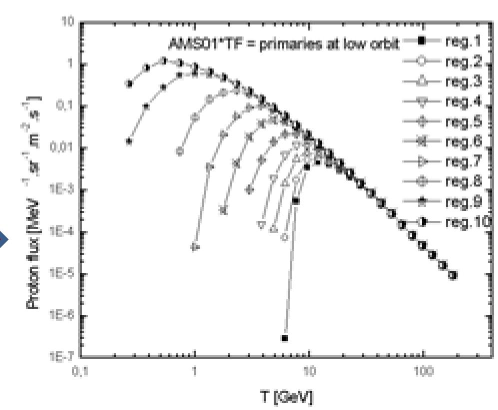


Interplanetary Environment at 1 AU: No geomagnetic shielding; direct solar particle event exposure; solar cycle modulation

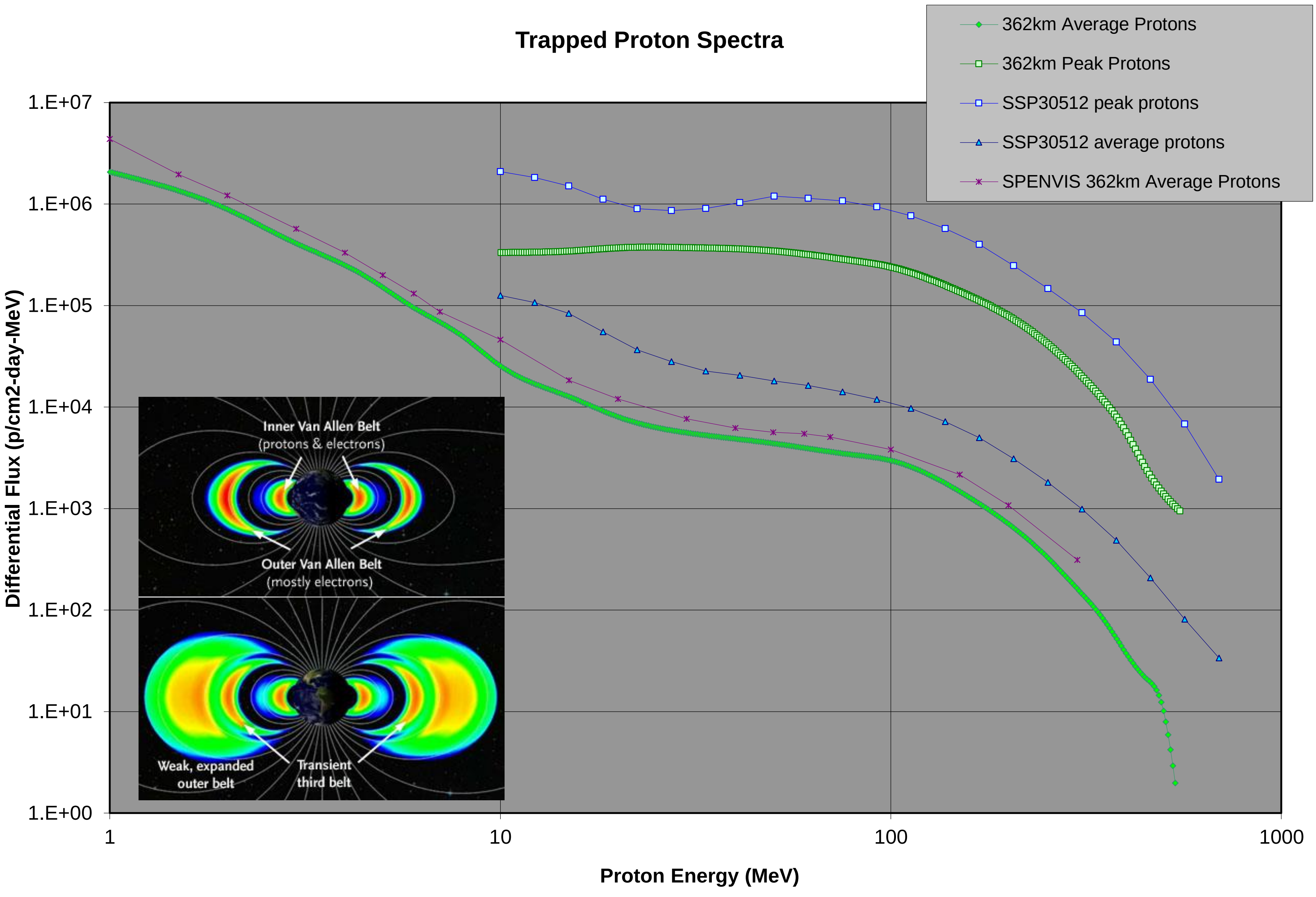
Low-Earth orbit (ISS) environment: Latitude dependent geomagnetic shielding; Latitude dependent solar particle event exposure

Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft Single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011 as well as Refs 1 and 2

Latitude dependence of GCR spectrum for ISS orbit - AMS-1/STS-91. Higher magnetic latitude => Reduced geomagnetic shielding and greater similarity to interplanetary GCR environment



Bobik, P., Boschini, M., Gervasi, M., Grandi, D., Kudela, K., Micelotta, E.;
Journal: In: Solar variability as an input to the Earth's environment. International Solar Cycle Studies (ISCS) Symposium, 23 - 28 June 2003

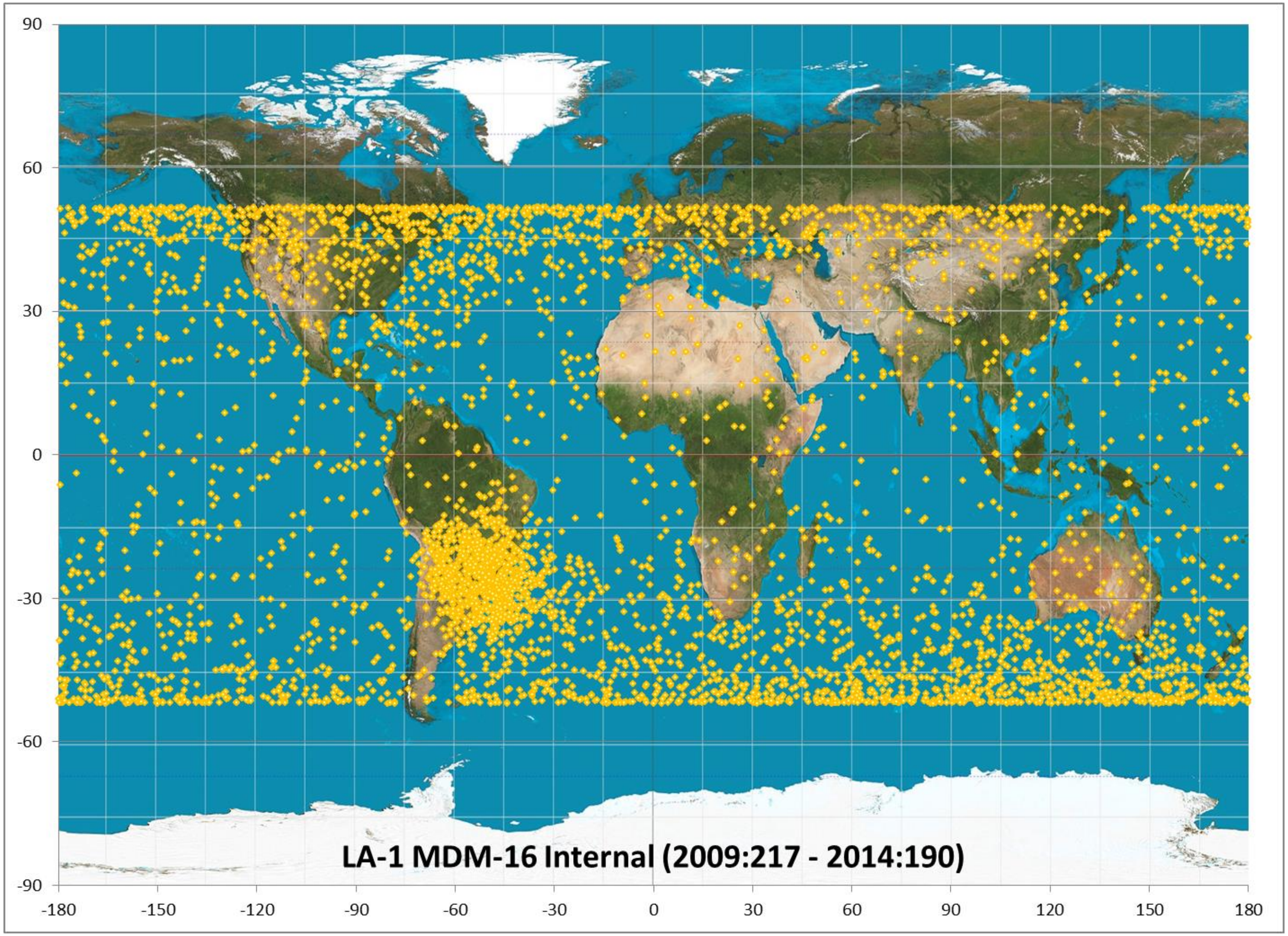

Trapped Proton Spectra
362km Average Protons
362km Peak Protons
SSP30512 peak protons
SSP30512 average protons
SPENVIS 362km Average Protons
Differential Flux (p/cm2-day-MeV)
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
Proton Energy (MeV)
1
10
100
1000
Inner Van Allen Belt
(protons & electrons)
Outer Van Allen Belt
(mostly electrons)
Weak, expanded
outer belt
Transient
third belt

And what does all this look like?

Representative ISS MDM Single event upset (SEU) map

GCR and trapped proton single event upsets detected and corrected by Error Detection And Correction (EDAC) firmware in the ISS computer system (aka MDM) Dynamic Random Access Memory (DRAM). EDAC operation is part of the nominal system design, and does not indicate a failure or anomaly.

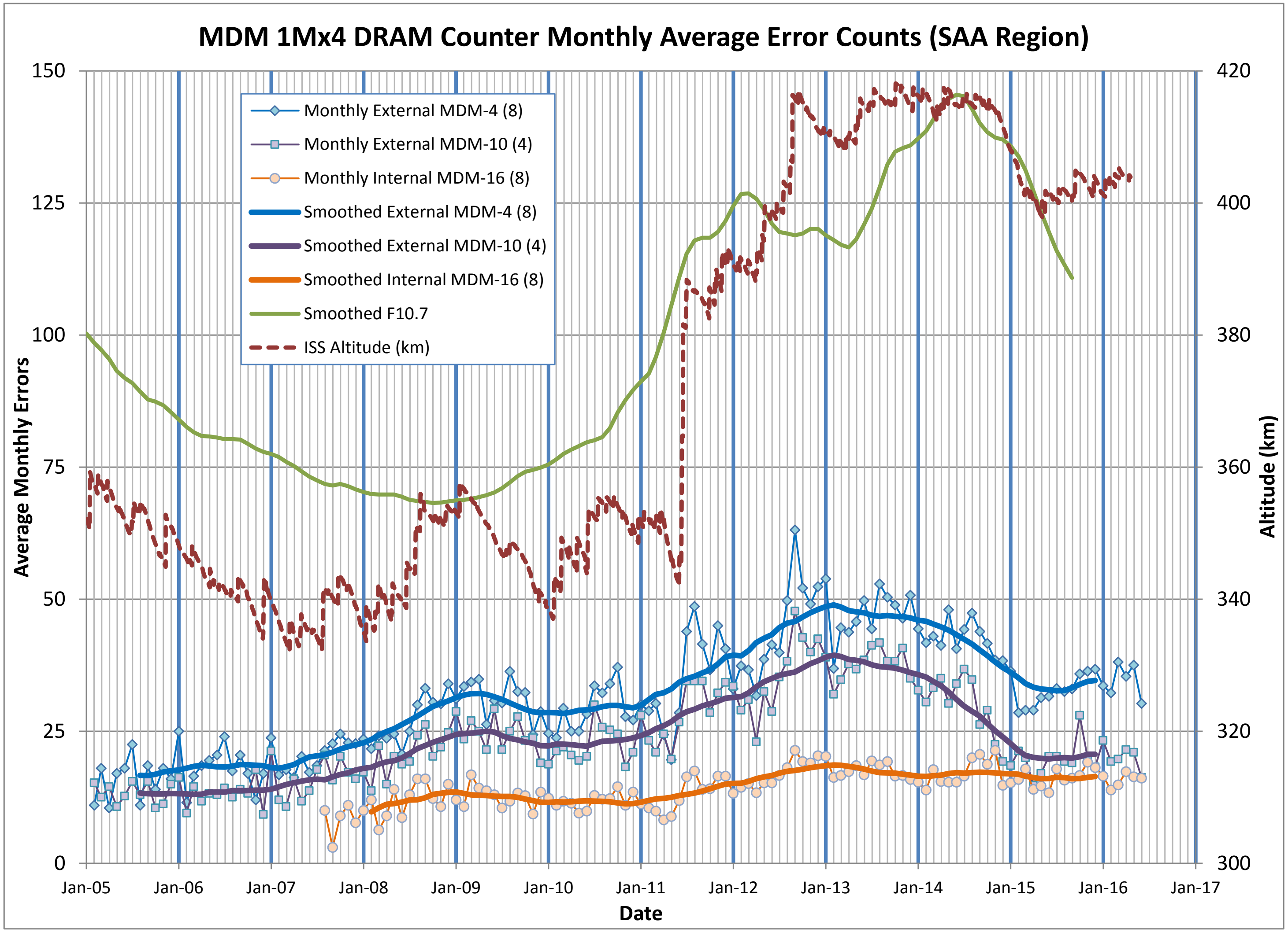
Multiplexer-De-Multiplexer (MDM)



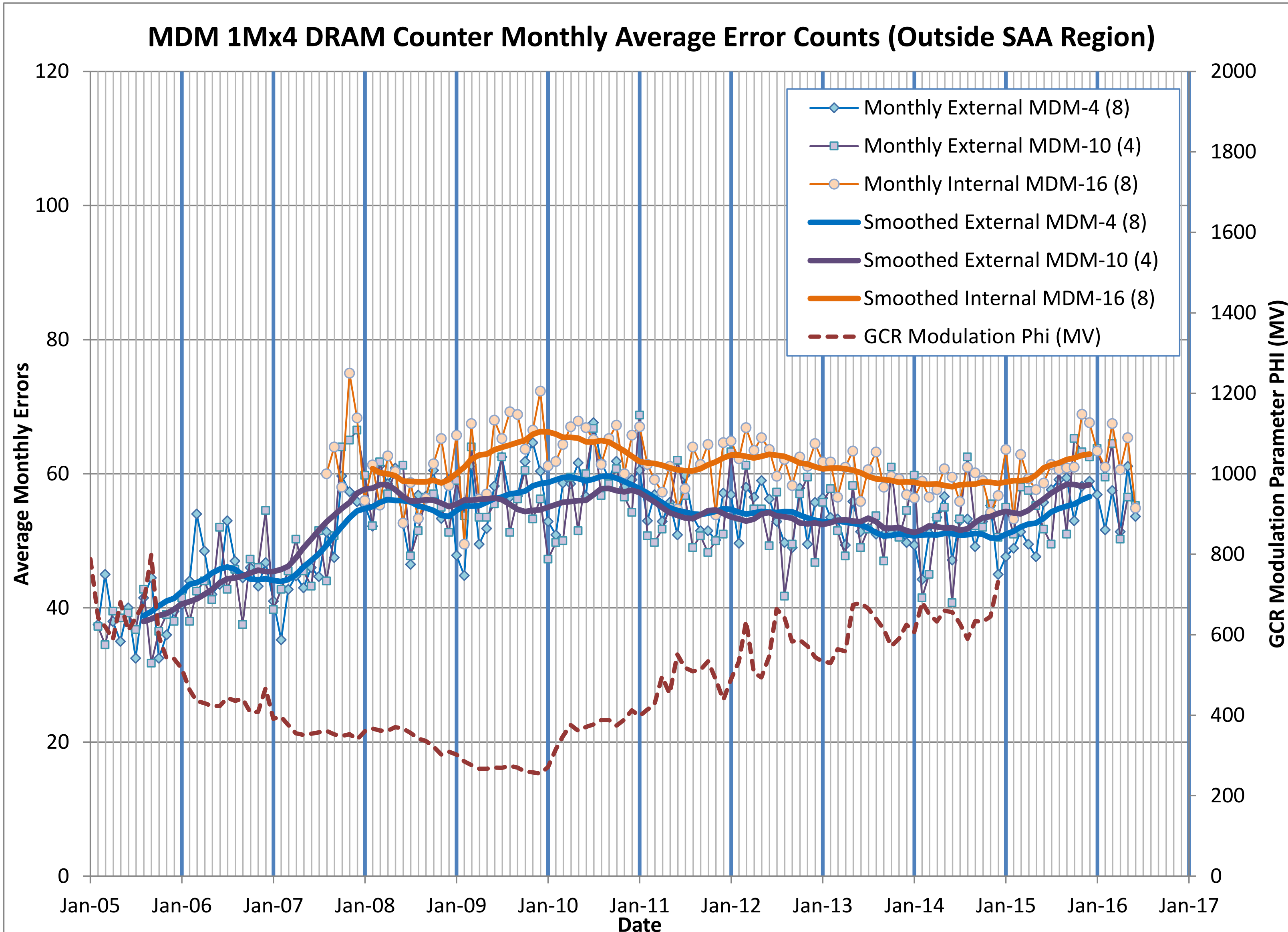
Image/data Credit: NASA

Image Credit: NASA

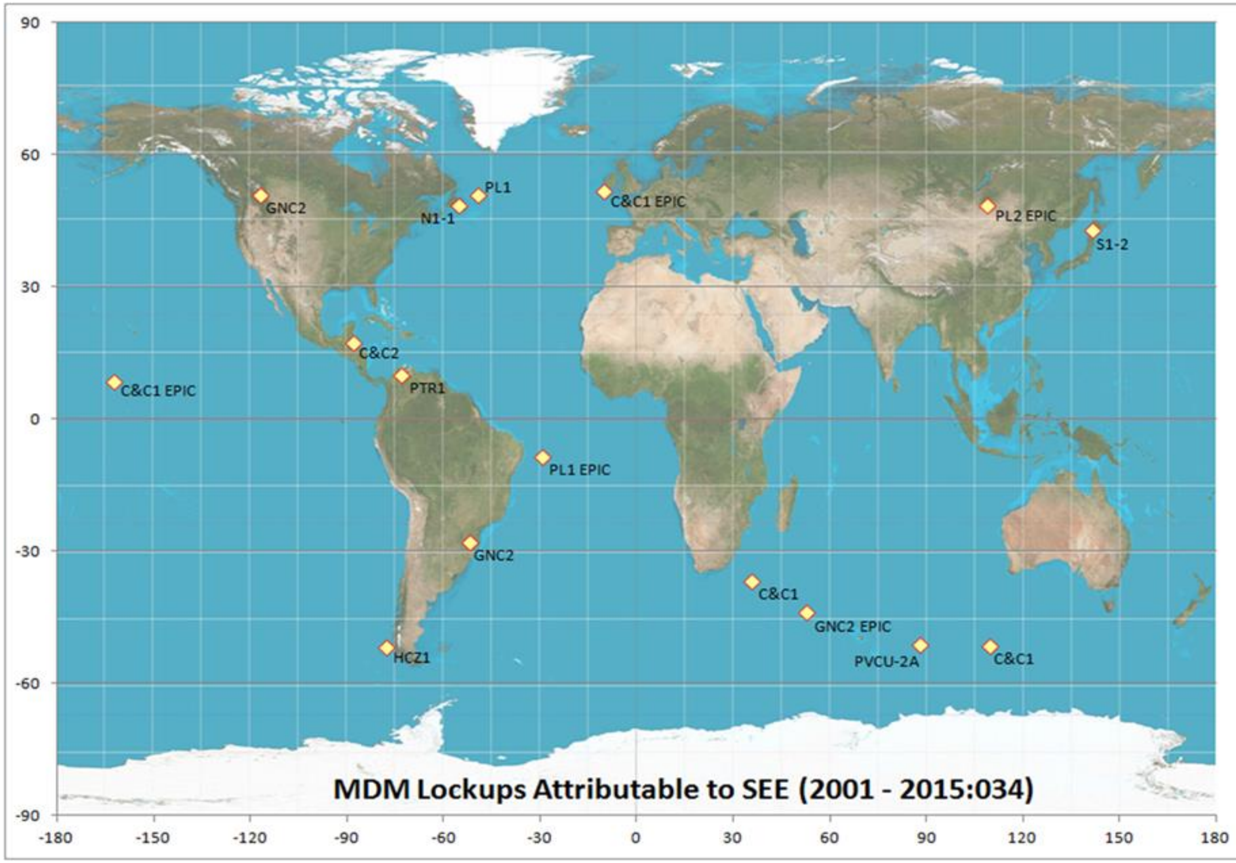
MDM System monthly SEU count: Inside the SAA (trapped protons)
Increasing shielding mass reduces internal MDM SEU count

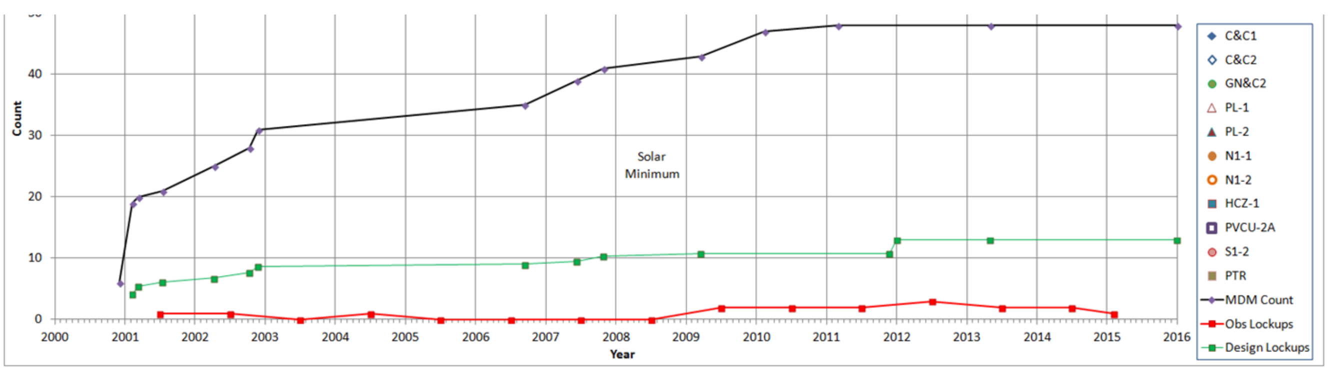


MDM System monthly SEU count: Outside the SAA (GCR)
Increasing shielding mass increases internal MDM SEU count



GCR appears to be the leading cause of ISS SEE attributable MDM functional interrupts or "lock-ups" that require power cycling and rebooting/ resynchronizing to correct, a process requiring 8 to 12 hours to complete.

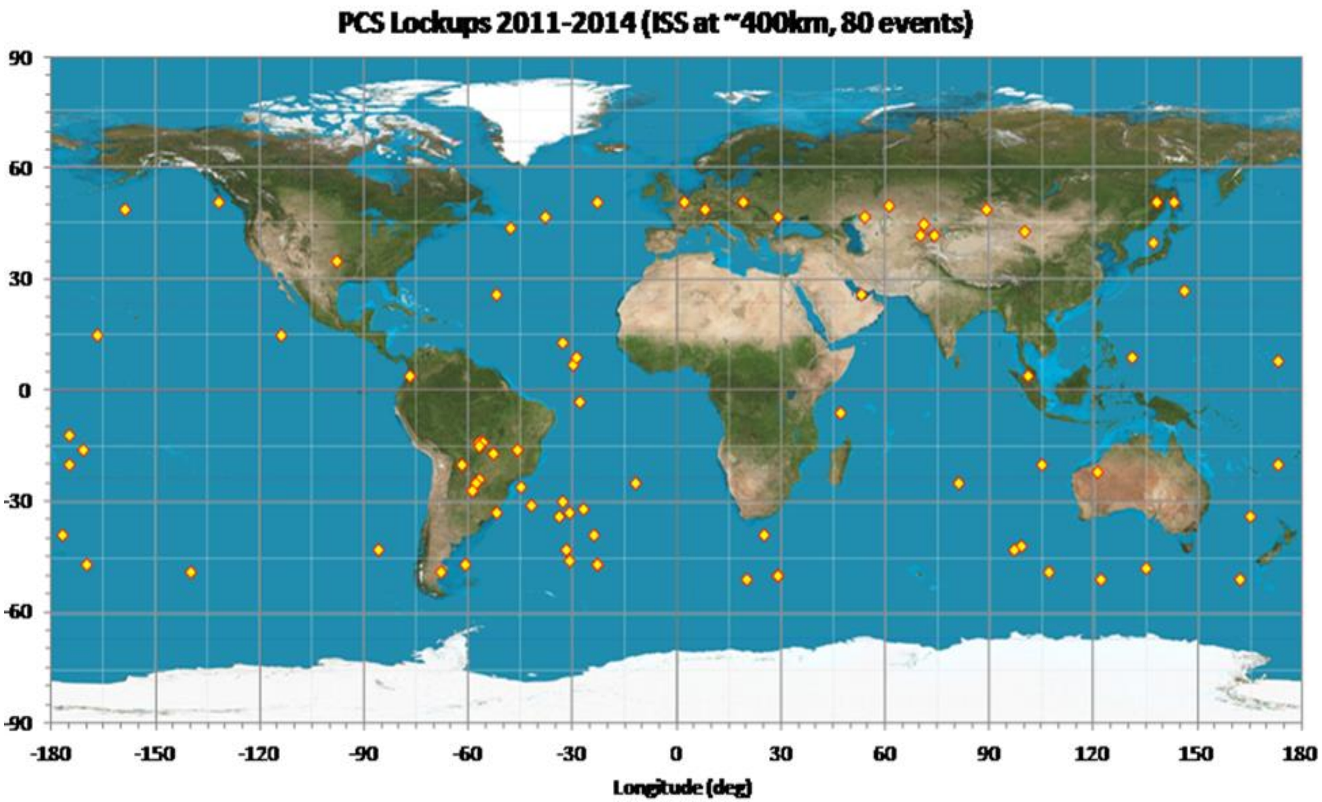




Image/data Credit: NASA

Image/data Credit: NASA

Representative ISS T61P personal computer system (PCS) single event functional interrupt (SEFI) map – Recovered by power cycling and reboot.



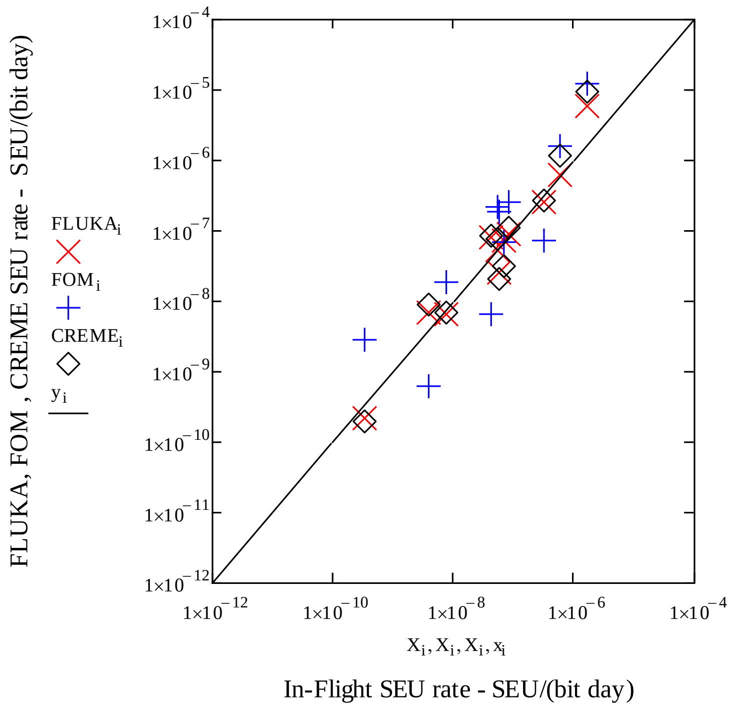
Geographic distribution of 80 observed T61P PCS on-orbit lock-ups and disconnects - 2011 to 2014. Looking at the T61p lockup and disconnect data at ~400 km from July 2011 to July 2014, the shortest time interval between PCS lockups is 4.15 hrs The average interval is ~304 hrs and the maximum is >1800 hrs. About half of the events occur at high latitude and between 10-20% of the events occur in the SAA region.

Population Size = 7 T61Ps, mean MTBF = 82.1 days, standard deviation = 32.2 days

Note that there a re a number of constraints on using the PCS system for safety critical operations given the expected and observed SEFI rate.

In-flight vs. calculated spacecraft device SEU rates

Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft Single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011



Shielding Mass Rate Ratio =(10 g/cm² Rate)/ (40 g/cm² Rate)

Device	Rate Ratio - Flight	Rate Ratio - FLUKA	Rate Ratio - CREME 96	Rate Ratio - FOM
TI (1M x 4) TMS44400	1.2	1.2	3.5	3.7
TI (4M x 4) TI SMJ41640	0.9	1.8	3.4	5.3

Note that only FLUKA correctly quantifies the shielding mass (i.e. secondary particle shower) effects for the ISS TI CMOS DRAM.

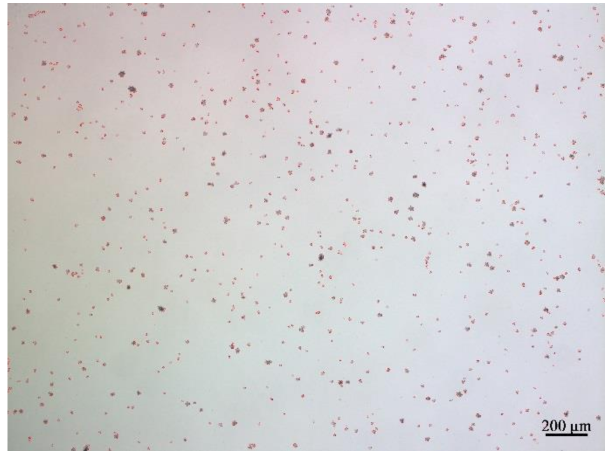
$$\sum_i \left[\frac{\left(X_i - FLUKA_i\right)^2}{\left(X_i\right)^2}\right]^{0.5} = 5.7 \qquad \sum_i \left[\frac{\left(X_i - CREME_i\right)^2}{\left(X_i\right)^2}\right]^{0.5} = 10.6 \qquad \sum_i \left[\frac{\left(X_i - FOM_i\right)^2}{\left(X_i\right)^2}\right]^{0.5} = 26.8$$

Using the same device parameters, the FLUKA based rate calculations show the smallest least squares error and overall acceptable performance compared to CREME-96 and the Peterson FOM, providing some validation for the FLUKA based methods described here.

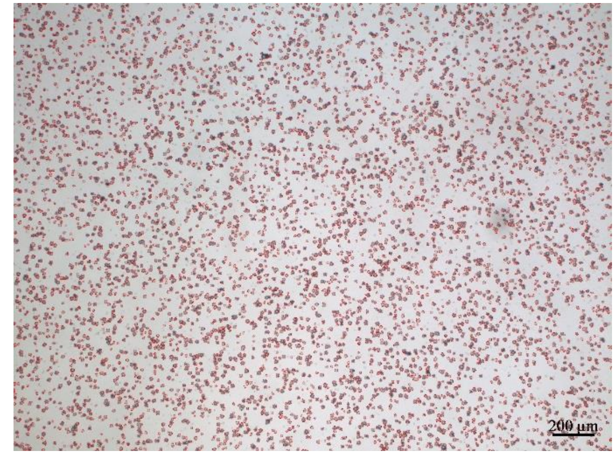
A graphic example of how different it is on ISS:

CR-39 plastic nuclear track detectors (PNTDs) – 925 days inside the ISS US Lab.

Ground Control PNTD

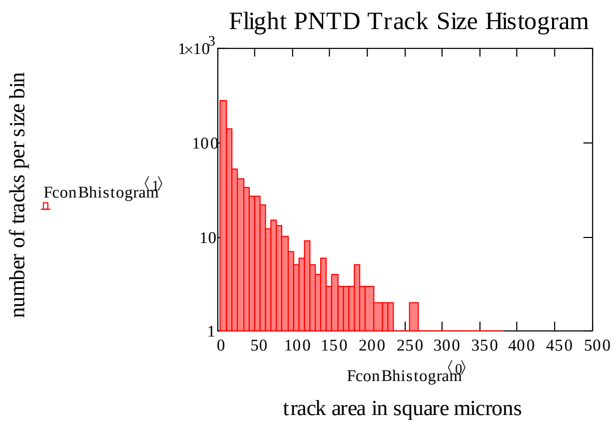


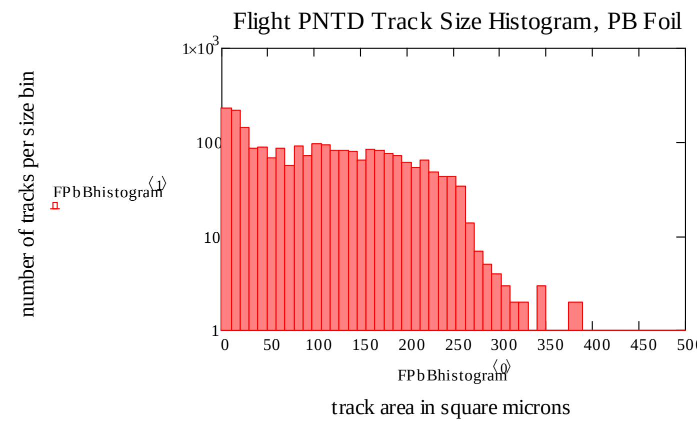
Flight PNTD



Flight PNTD surface in contact with 0.005 cm Pb foil

High Z elements, like Pb, produce more secondary particle shower products than low Z elements





The obvious differences between the flight-PNTD and the Pb-foil-flight PNTD are expected as a result of nuclear reactions, caused by space radiation primary and secondary particles, in the Pb foil with smaller contribution from trace (ppm level) Th and U impurities in the Pb foil itself. Ag, Hf, and W foils produced many fewer nuclear reaction products in their PNTDs. Track area increases with increasing particle LET.

5.0 Summary & Conclusions

- The effects of energetic cosmic ray, solar particle event, and trapped radiation charged particles on contemporary electronic systems as well as human health and safety depends on:
  - The production of ionization/excitation tracks in target materials
  - Nuclear collisions with target material nuclei to initiate secondary particle showers that create even more ionization/excitation
- Secondary particle shower species, especially neutrons, can dominate effects on electronic systems and human health at high shielding mass
  - Earth surface operating environments
  - High altitude aircraft operating environments
  - “Heavily” shielded human spacecraft ,like ISS
  - In massive targets, like the human body, secondary particle showers can contribute on the order of 50% of the total body dose expressed in Sv, and
- SEE effects on electronic systems can be managed by: 1) selection of resistant parts, 2) EDAC and FDIR functions, and 3) robust/highly redundant system architectures
  - State of the art radiation transport codes are accurate enough to support shielding design and avionics system reliability work
- Shielding mass can mitigate electronic system TID and SEE effects from SPE and trapped radiation but is largely ineffective against GCR

6.0) Bibliography, Resources, and Back-up

Bibliography and Resources

- https://srag.jsc.nasa.gov/ JSC Space Radiation Analysis Group (Human Health)
- https://software.nasa.gov/software/LAR-18803-1 HZETRN 2015 home page
- http://www.fluka.org/fluka.php FLUKA home page
- https://creme.isde.vanderbilt.edu/ CREME-96 home page (avionics SEE/TID)
- http://tec-ees.esa.int/ProjectSupport/ISO/CREME96.html ESA CREME-96 page
- https://www.spenvis.oma.be/ ESA space environments modeling and analysis tools home page
- http://dev.sepem.oma.be/ ESA Solar Particle Event modeling and analysis home page
- http://holbert.faculty.asu.edu/eee560/see.html Arizona State university space flight environments effects and analysis hime page
- https://nepp.nasa.gov/ NASA Electronic Parts and Packaging Program home page (SEE/TID effects, testing and analysis
- http://lansce.lanl.gov/ DOE Los Alamos National Laboratory atmospheric Neutron and High Energy Proton Testing Facility home page

Bibliography and Resources

1) S. Koontz, Reddell, B., Boeder, P.; "Calculating Spacecraft Single Event Environments with FLUKA: Investigating the Effects of Spacecraft Material Atomic Number on Secondary Particle Showers, Nuclear Reactions, and Linear Energy Transfer (LET) Spectra, Internal to Spacecraft Avionics Materials, at High Shielding Mass," Radiation Effects Data Workshop (REDW), 2011 IEEE DOI: 10.1109/REDW.2010.6062528, Publication Year: 2011 , Page(s): 188- 195

2) Steven L. Koontz , Kristina Rojdev, Gerard D. Valle, John J. Zipay; "Estimating the Effects of Astronaut Career Ionizing Radiation Dose Limits on Manned Interplanetary Flight Programs," Proceedings of the AIAA 43rd International Conference on Environmental Systems, 14 - 18 July 2013, Vail, Colorado

3) Steve Koontz, Brandon Reddell, Kristina Rojdev, Paul Boeder, and William Atwell; "Spacecraft SPE Shielding: SPE environment models and materials performance in an Enhanced Cygnus Pressurized Cargo Module (PCM)-based Exploration Augmentation Module (EAM)," Proceedings of the AIAA 45th International Conference on Environmental Systems, 12 - 16 July 2015, Bellevue, Washington

4) Durante, M., Cucinotta, F. A., "Physical Basis of Radiation Protection in Space Travel", *Reviews of Modern Physics*, Vol. 83, 2011, pp. 1245-1281.

5) Cucinottaa, F. A., Kim, M-H.Y., Ren, L., "Evaluating Shielding Effectiveness for Reducing Space Radiation Cancer Risks," *Radiation Measurements*, Vol. 41, 2006, pp. 1173 – 1185.

6) G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso`, J. Ranft; "The FLUKA code: Description and benchmarking," Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab, 6-8September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)

7) J. H. Heinbockel, T. C. Slaba, R. K. Tripathi, S. R. Blattnig, J. W. Norbury, F. F. Badavi, L. W. Townsend, T. Handler, T. A. Gabriel, L. S. Pinksy, B. Reddell and A. R. Aumann, "Comparison of the transport codes HZETRN, HETC and FLUKA for galactic cosmic rays," Advances in Space Research, vol. 47, no. 6, pp. 1089-1105, 2011.

8) John W. Wilson, F. A. Cucinotta, Judy L. Shinn, and Lisa C. Simonsen; "Overview of HZETRN and BRNTRN space radiation shielding codes," Proc. SPIE, Vol. 2811, 51 (1996); Online Publication Date: 22 March 2005

9) Hastings, D., Garrett, H., *Spacecraft Environment Interactions*, Cambridge University Press, Cambridge, New York, 1996.

10) Usoskin, I. G., Solanki, S. K., Schussler, M., Mursula, K., Kovaltsov, G. A., "A Physical Reconstruction of Cosmic Ray Intensity since 1610," *Journal of Geophysical Research*, Vol. 107, No. A11, pp. SSH 13-1 – SSH 13-6, 2002.

11) Wiedenbeck, M.E., David, A. J., Leske, R. A., Binns, W. R., Cohen, C. M. S., Cummings, A. C., et. al., "The Level of Solar Modulation of Galactic Cosmic Rays from 1997 to 2005 as Derived from ACE Measurements of Elemental Energy Spectra," *29th International Cosmic Ray Conference*, Vol. 00, Pune, 2005, pp. 101–104.

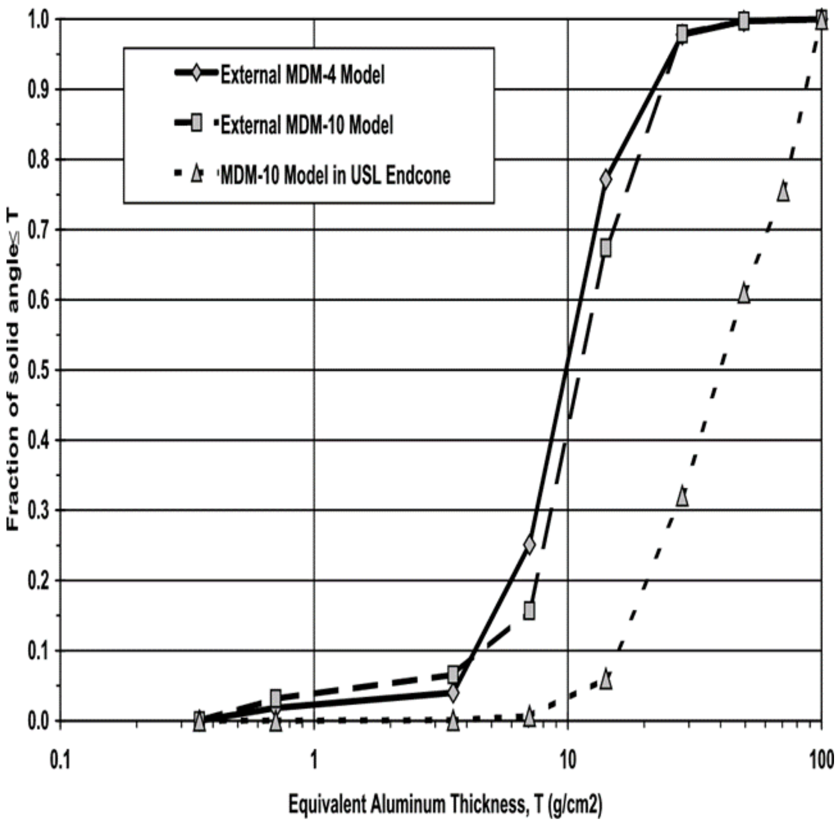
12) Beringer, J., et al. (Particle Data Group), "Cosmic Rays," *Physical Review*, Vol. D86, No.010001, 2012, pp. 1–21.

13) Friedlander, M. W., *A Thin Cosmic Rain: Particles from Outer Space*, Harvard University Press, Cambridge, 2000.

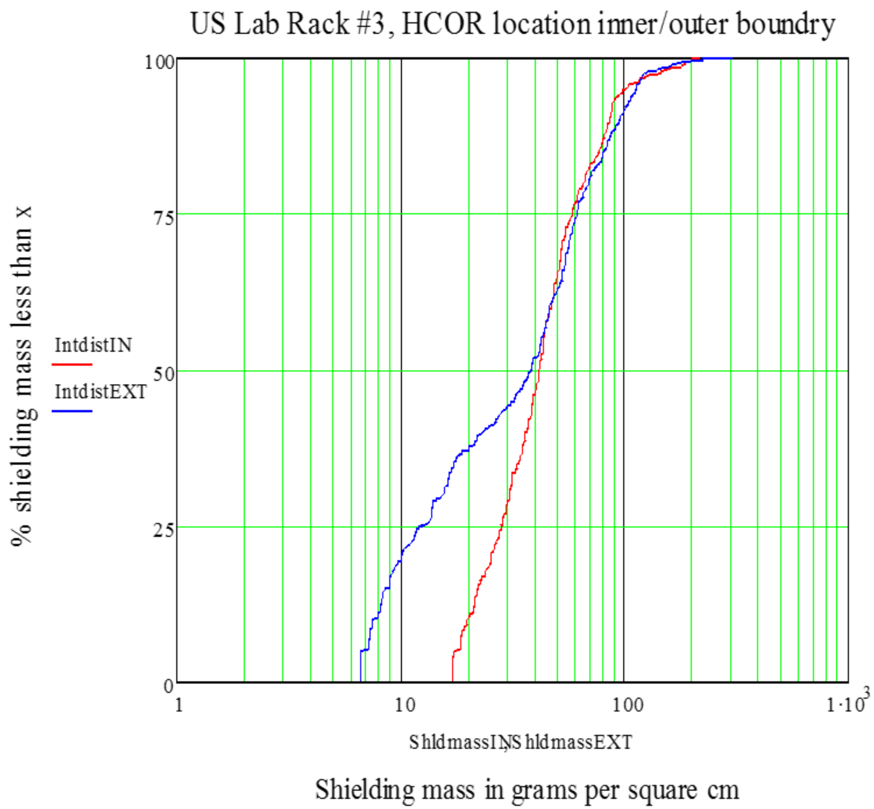
14) Longair, M. S., *High Energy Astrophysics Volume 1: Particles Photons and their Detection*, Cambridge University Press, Cambridge, 1992

15) Gaisser, T., K.; *Cosmic Rays and Particle Physics*, Cambridge University Press, Cambridge, New York, 1990

Typical ISS (Internal) US Lab Shielding Mass Distribution Functions



Typical ISS multiplexer - demultiplexer (MDM) integral shielding mass distribution functions



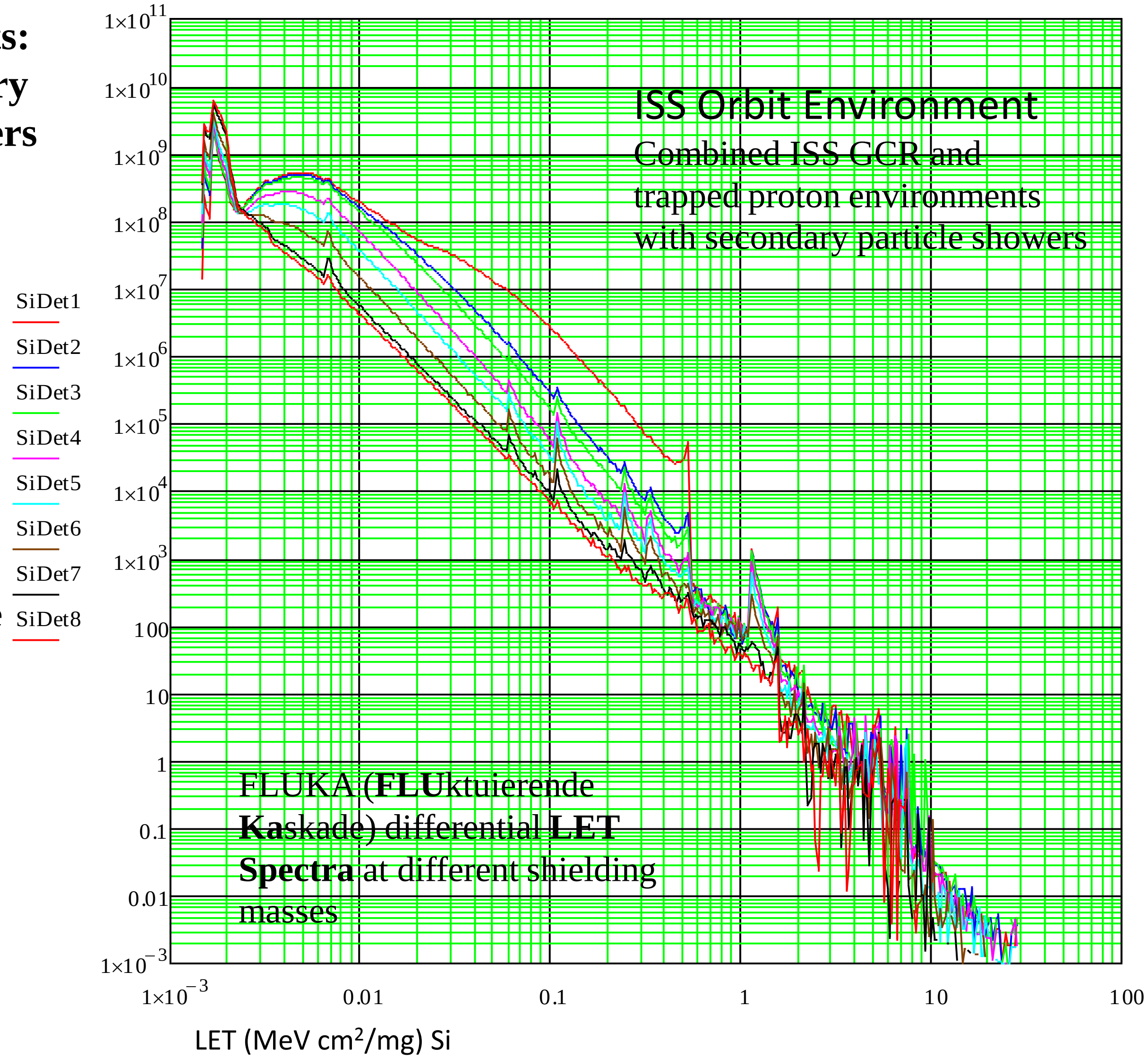
ISS US Lab HCOR SDRAM integral structural shielding mass distribution functions (typical of lab racks)

1.2: GCR Exposure Environments: Low Earth Orbit (LEO) – Primary CR and secondary particle showers

The differential LET spectra [#/(cm^2 week LET)] at various shielding depths in a concentric spherical shell model spacecraft is shown to the right.

LET spectra are calculated, using the FLUKA (1) Monte Carlo radiation transport code, as the number of particles entering each of the Si detector shells placed at various depths in the concentric spherical shell model (see the table below).

All secondary particle shower processes are enabled and full shielding mass distribution function for each Si shell is utilized in a fully three dimensional calculation. Total ionizing dose and nuclear reactions "star" density is also calculated but not reported here.



Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011

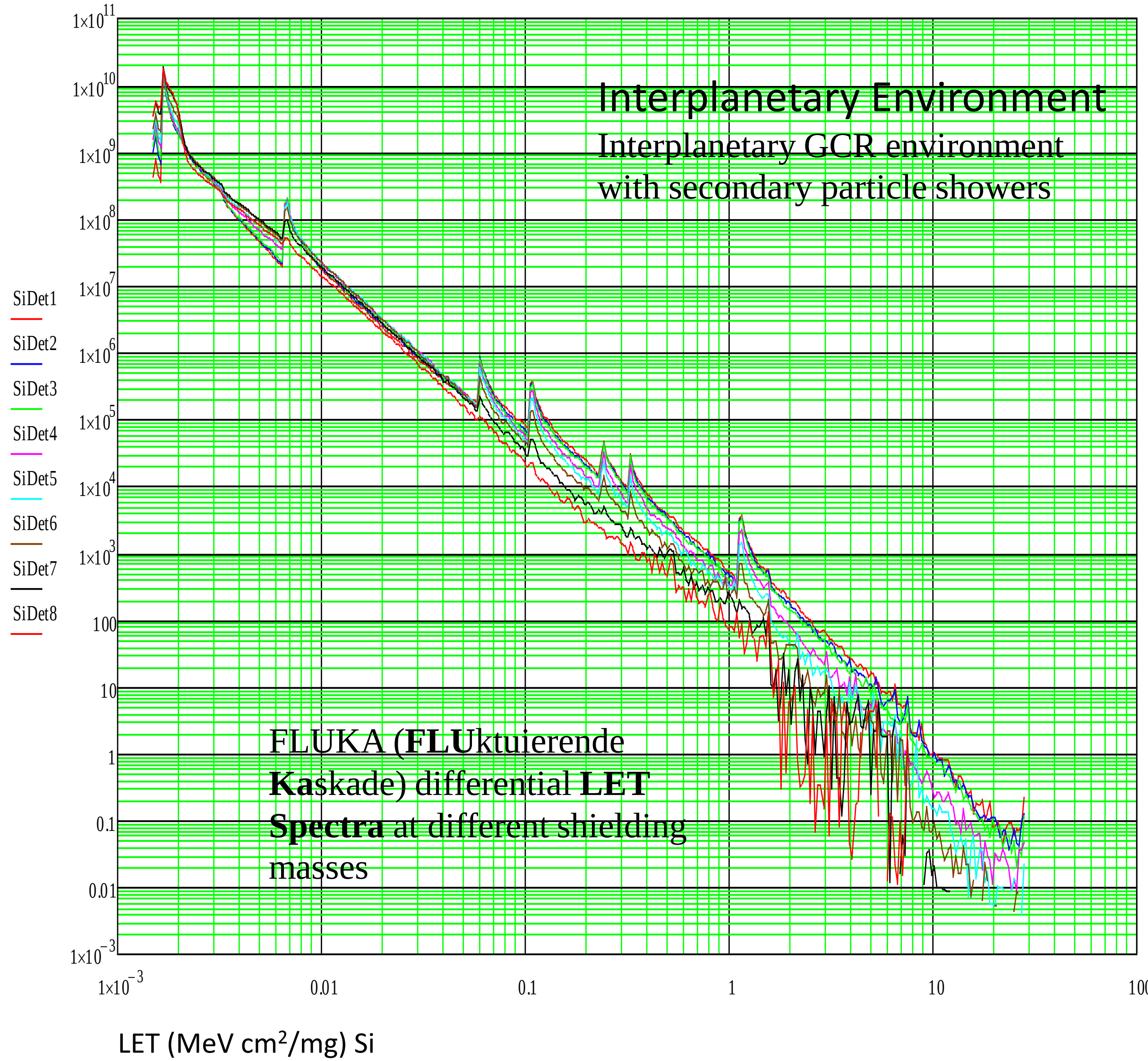
Detector Si Shell	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Detector Shell Radius (cm)	5037.4	5037.3	5037.1	5035.6	5033.7	5030.0	5018.9	5000.0
Si Detector Median Al Shielding Mass in g/cm²	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2

1.3 GCR Exposure Environments: Interplanetary Environment – Primary CR and secondary particle showers

The differential LET spectra [#/(cm^2 week LET)] at various shielding depths in a concentric spherical shell model spacecraft is shown to the right.

LET spectra are calculated, using the FLUKA (1) Monte Carlo radiation transport code, as the number of particles entering each of the Si detector shells placed at various depths in the concentric spherical shell model (see the table below).

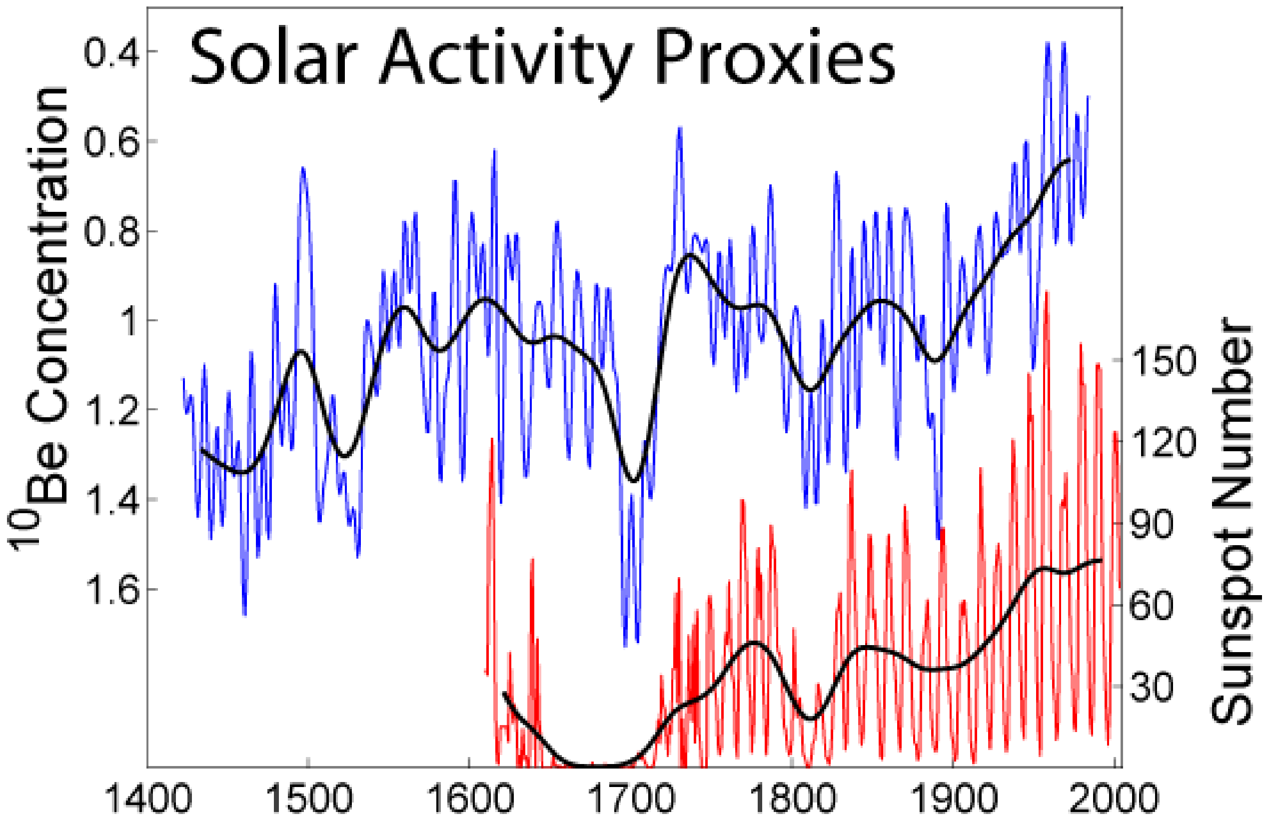
All secondary particle shower processes are enabled and the full shielding mass distribution function for each Si shell is utilized in a fully three dimensional calculation. Total ionizing dose and nuclear reactions "star" density is also calculated but not reported here.



Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011

Detector Si Shell	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Detector Shell Radius (cm)	5037.4	5037.3	5037.1	5035.6	5033.7	5030.0	5018.9	5000.0
Si Detector Median Al Shielding Mass in g/cm^2	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2

Cosmogenic Nuclides example: ^{10}Be in arctic ice and the Maunder Minimum - Solar wind modulation of GCR



Biological Effects of Cosmic Radiation – Manned Space Flight Environments

Spaceflight Radiation Examples - Human Spaceflight Mission Type Radiation Dose:

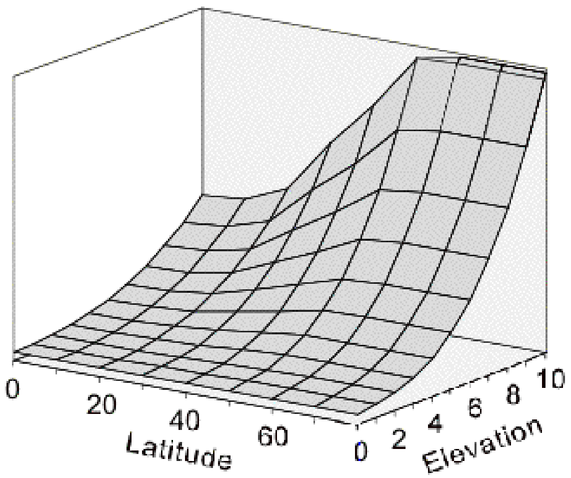
Assuming 20 to 50 g/cm^2 Al shielding and not including secondary particle shower effects internal to the human body which can increase effective dose by about 50%

Space Shuttle Mission 41-C **(8-day mission orbiting the Earth at 460 km)**	**5.59 mSv**
Apollo 14 **(9-day mission to the Moon)**	**11.4 mSv**
Skylab 4 **(87-day mission orbiting the Earth at 473 km)**	**178 mSv**
International Space Station (ISS) Mission **(up to 6 months orbiting Earth at 353 km)**	**80 mSv**
Estimated Mars mission (3 years)	**1200 mSv**

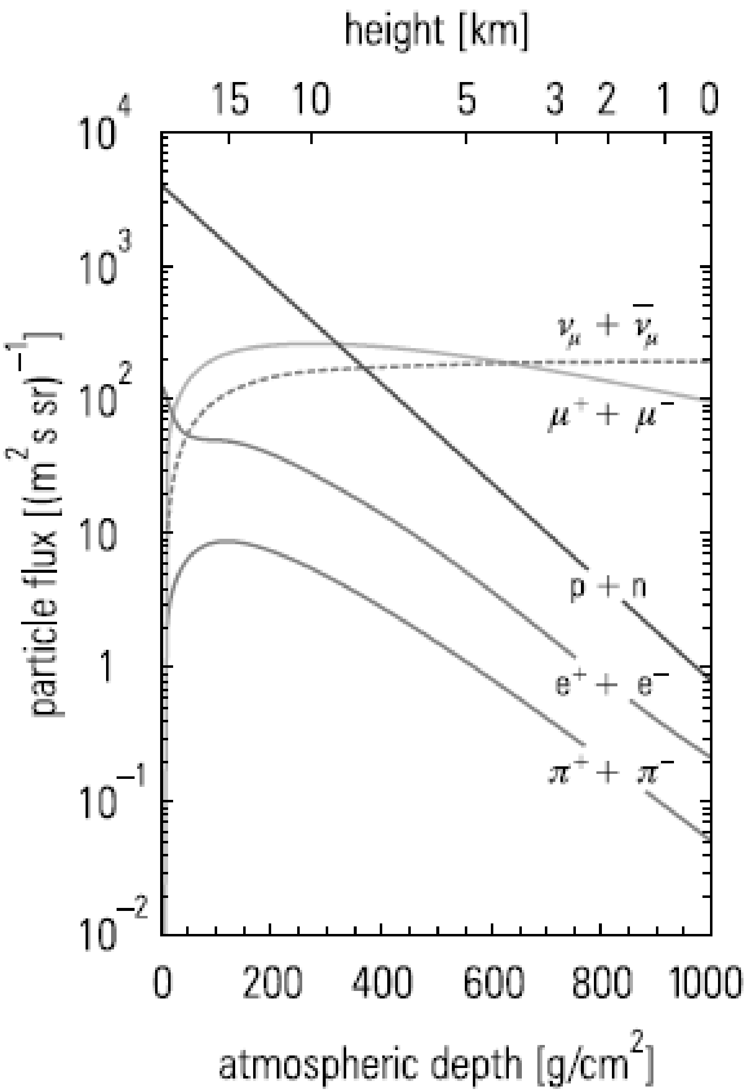
Slow accumulation of whole body dose from GCR (expressed in Effective equivalent Sv) and including secondary particle showers in the human body) presently limits the duration of manned space operations outside earth's magnetosphere to times on the order of 180 days (assuming 20 to 30 g/cm^2 shielding mass). The overall programmatic cost of the available active or passive shielding needed to extend that limit is likely prohibitive at this time (Francis A. Cucinottaa, Myung-HeeY. Kim, Lei Ren; "Evaluating shielding effectiveness for reducing space radiation cancer risks," Radiation Measurements 41 (2006) 1173 – 1185)

GCR Exposure Environments – Earth's Atmosphere

- **Earth surface/atmospheric environments**
  - **1000 grams/cm^2 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)**



Relative variation of cosmic ray flux at the earth's surface as a function of altitude and latitude (Cosmogenic Nuclide Laboratory - University of Glasgow - http://web2.ges.gla.ac.uk/~dfabel/CN_explain.html)



GCR secondary shower particle fluxes in Earth's atmosphere (http://pdg.lbl.gov/2011/reviews/rpp2011-rev-cosmic-rays.pdf)

A comparison of observed in-flight SPE SEU counts with estimates of SPE SEU counts calculated using the FLUKA radiation transport code and the concentric spherical shell spacecraft model

For purposes of spacecraft design and verification, the agreement between the FLUKA based SPE rate estimate sand the observed in-flight SPE upset rates are satisfactory, as shown below.

Spacecraft/System and Device (ref)	**Nov. 1997 SPE** **Upsets/bit**	**July 2000 SPE** **Upsets/bit**	**Nov. 2001 SPE** **Upsets/bit**	**Oct. 2003 SPE** **Upsets/bit**
Cassini/Solid State Recorder DRAM (16) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (no-event) daily upset rate	1) $4.4\text{x}10^{-7}$ 2) $1.4\text{x}10^{-7}$ 3) 0.32 4) $5.8\text{x}10^{-8}$	NA	NA	NA
SOHO /Solid State Recorder DRAM (17) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (n0 event)daily upset rate	1) $4.4\text{x}10^{-6}$ 2) 2.110^{-6} 3) 0.48 4) $5.9\text{x}10^{-7}$	1) $4.7\text{x}10^{-5}$ 2) $2.1\text{x}10^{-5}$ 3) 0.4 4) $5.9\text{x}10^{-7}$	NA	NA
Thuraya/ DSP DRAM (15) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (no event) daily upset rate	NA	NA	1) $2.0\text{x}10^{-6}$ 2) $2.8\text{x}10^{-6}$ 3) 1.4 4) $5.3\text{x}10^{-8}$	1) $1.5\text{x}10^{-6}$ 2) $3.8\text{x}10^{-6}$ 3) 2.5 4) $5.3\text{x}10^{-8}$