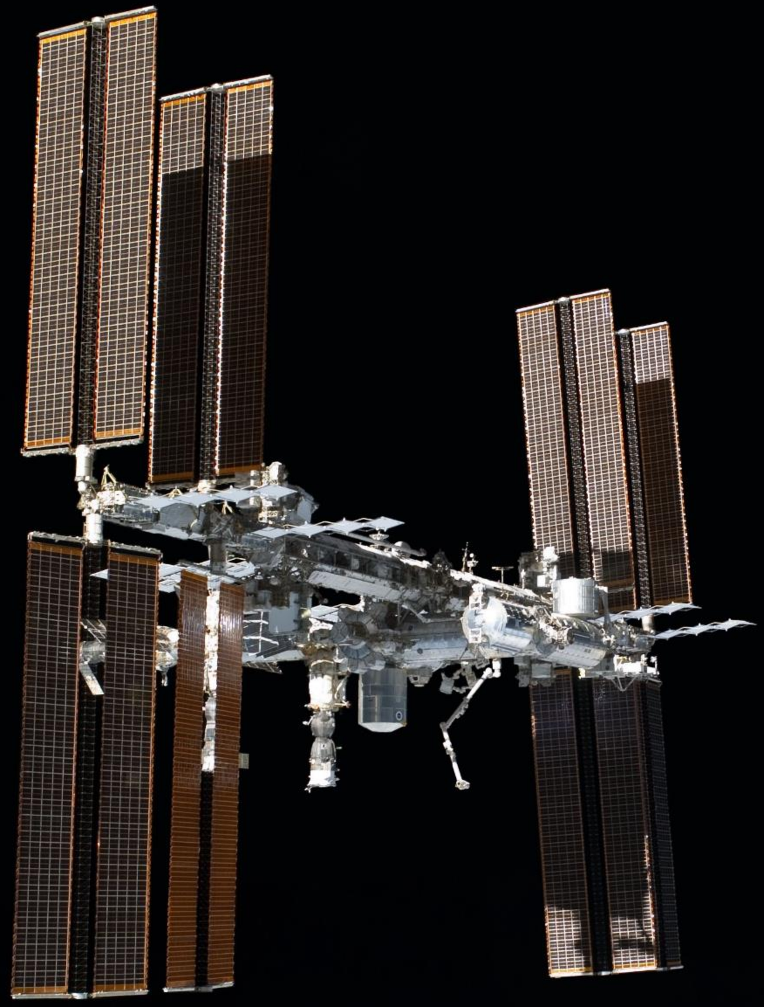

# The International Space Station Space Radiation Environment.

# Avionics systems performance in low-Earth orbit Single Event Effects (SEE) environments.

Steve Koontz , John Alred, Erica Worthy, NASA Johnson Space Center, Houston, Texas, 77058
Robert Suggs , NASA Marshall Space flight Center, Huntsville, Alabama, 35811
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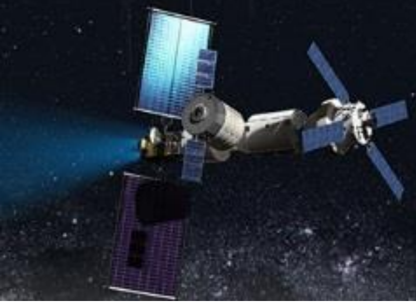
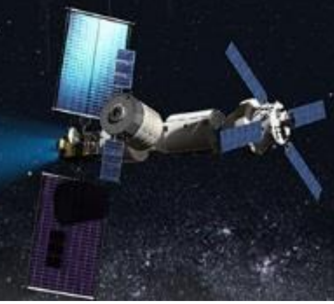
Courtney Steagall, William Hartman, Benjamin Gingras, William Schmidl,*The Boeing Company, Houston, TX 77059 USA*



# Presentation Outline

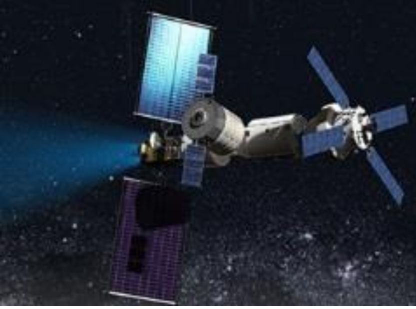
- **What are Single Event Environments/Effects (SEE) and why do we care about them?**
  - SEE environments consist of the energetic charged particle components of space radiation environments
  - SEE effects are observed when a single charged particle passes through a susceptible microelectronic device causing device anomalies/failures that propagate to system level anomalies/failures
  - SEE effects are an important **safety, reliability and mission success** issue for spacecraft avionics systems.
- **International Space Station (ISS) Natural/Induced SEE Environments**
  - 51.6 degrees orbital inclination and ~ 400 km flight altitude determine natural SEE environments
  - Latitude dependent geomagnetic shielding of galactic cosmic rays (GCR) and solar particle events (SPE)
  - Geomagnetic trapping of charged particles create the south Atlantic anomaly (SAA)
  - Avionics systems SEE environment depends on ISS shielding mass processing of the natural SEE environment
- **ISS Command and Data Handling System (C&DH) Multiplexer de-Multiplexer (MDM) in-flight SEE performance**
  - System design and pre-flight test/verification approach
  - Latitude, geographic region, and shielding mass dependence of total single event upset (SEU) counts in ISS MDM dynamic random access memory (DRAM) between 2010 to 2017.
  - Monthly average MDM SEU count timeline from 2005 to 2018
    - Solar cycle, SPE, altitude, and shielding mass effects
  - ISS MDM SEE functional interrupt (SEFI)
    - Geographic dependence
    - Timeline



# Presentation Outline

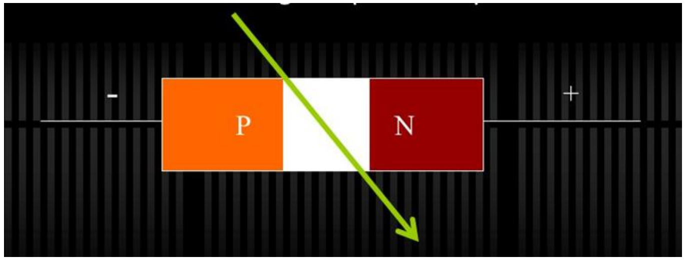
- **ISS Portable Computer System (PCS) in-flight SEE performance**
  - Pre flight testing vs in-flight performance and safety driven constraints on use
    - Assembled article high energy (200 MeV) proton testing
  - ISS T61P Lenovo SEE FI dependence on geographic region
  - SEE vs non-SEE FI rates (commercial off-the-shelf (COTS) hardware general reliability issues)
  - Comparison of 4 month average SEE counts for ISS T61p PCS and 4 internal MDMs
  - T61P SEFIs and solar particle events, 2010 -2012 timeline
- **Can ISS be utilized as a flight demonstration and test platform for cis-lunar and interplanetary flight systems?**
  - ISS High Latitude SEE Environments
    - Summary of prior theoretical/experimental work to date
    - High latitude GCR and SPE environments
      - Geomagnetic shielding effects and planetary shadow shielding using CREME-96 with **McIlwain L-parameter (**L shells) at 400 km fixed altitude and a range of latitudes and longitudes
      - Similarity to NEI GCR environment increases with latitude as expected from observed latitude dependence of GCR SEE effects on ISS avionics systems
      - SPEs are strongly attenuated as expected from the absence of any observable SPE SEE effects on ISS avionics
    - Comparison of Solar Heliosphere Observatory (SOHO) and ISS GCR SEE rates for similar/ comparable DRAM parts
      - Scaling from the ISS SEE environment to the SOHO SEE Environment
        - Peterson Figure of Merit and ISS latitude zone residence time analysis
- **Summary and Conclusions**

# What are Single Event Environment/ Effects (SEE) and why do we care about them?

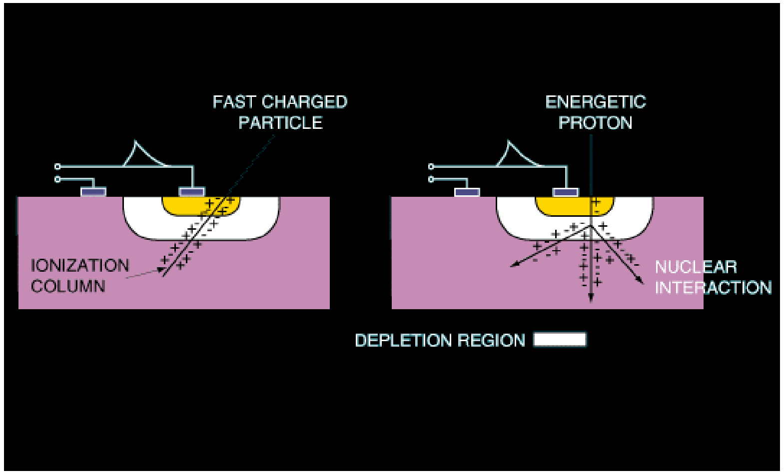


# Single Event Effects (SEE) are those errors, anomalies or failures in microelectronic devices caused by the passage of a single energetic charged particle through the device

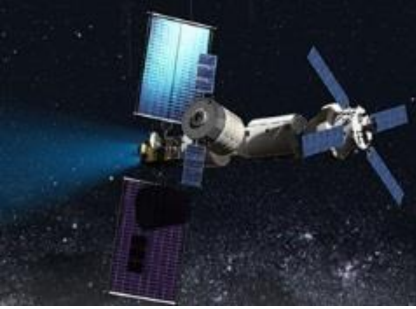
- The charged particle produces ionization/excitation on passage through microelectronic device materials
  - Ionization in the device "sensitive volume" (SV) can cause SEE
  - Every PN junction (and associated depletion region) in solid state microelectronic devices is a potential SV
- Charged particle **Linear Energy Transfer, LET**, is a measure of how much ionization the charged particle can produce by "direct ionization"
  - LET = $dE/dL$ = a function of **charged particle atomic number, z and velocity, v, $[(z/v)^2]$** as well as **target material electron number density** which depends on density, atomic charge number, and atomic mass number
  - LET units used for microelectronics work = (MeV $cm^2$)/mg (Si)
  - High LET => more ionization => greater microelectronics SEE threat
- Charged particles with LET too low to cause SEE by direct ionization can produce high LET nuclear reaction products on collision with device materials nuclei in or near the SV
  - Energetic protons and neutrons cause SEE primarily via in-device nuclear reactions
  - Heavier GCR ions (Z > 1) cause SEE primarily by direct ionization
  - With very few device specific exceptions, natural environment energetic electrons and photons do not cause SEE




A reverse biased PN junction diode. The energetic charged particle produces charge carriers along its track (green arrow) through the depletion region



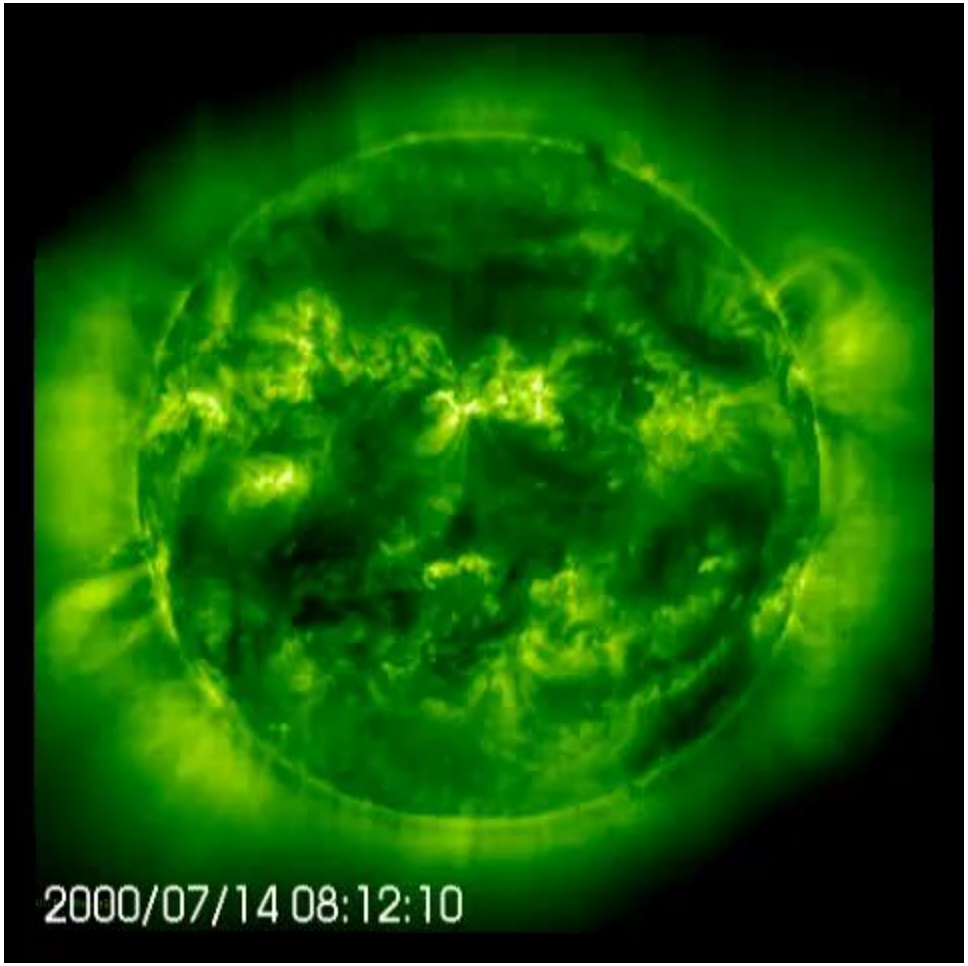

http://holbert.faculty.asu.edu/eee560/see.html

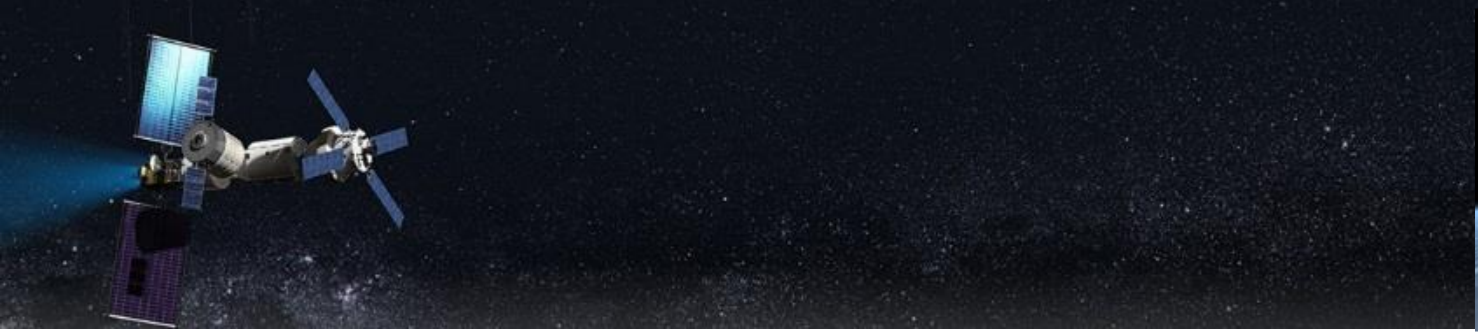


# Single Event Effects: Why do we care about them?

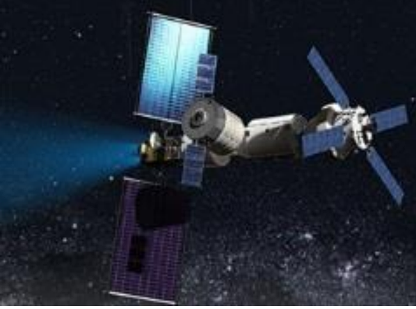
- Meeting Program Reliability and Mission Success Requirements
  - Performance based specification (primary ISS requirement)
    - The probability of losing any mission success or safety critical system or subsystem functionality must meet program requirements**, during the specified time interval, t, and in a specified operational environment.**
    - **Verified by test and analysis at the part, subassembly, sub-system, and system levels prior to flight**
  - Prescriptive specification (secondary ISS requirements – avionics systems assembly and manufacturing)
    - Mandates specific parts, manufacturing and assembly procedures believed to maximize safety and reliability
    - Verified by inspection for compliance with the mandate
- SEE in avionics systems are a potential system failure cause, i.e. a possible cause of not meeting program requirements
  - The most common hazard effects of the SEE space radiation hazard cause are:
    - Avionics system anomalies
      - Single event effects leading to loss of safety related "must-work must-not-work" functions
    - Electrical power system anomalies
      - Destructive failures of MOS power transistors
- ISS uses a performance based SEE specification and one objective of this presentation is to demonstrate how well that worked in more detail than previously reported

# Single Event Effects (visual)





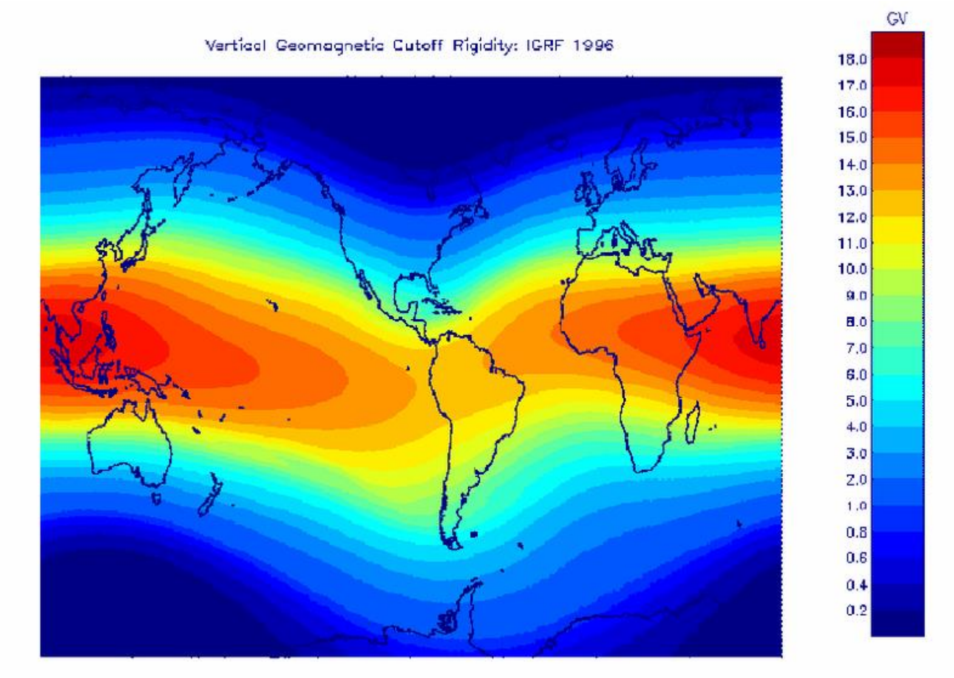

# International Space Station (ISS) Natural/Induced SEE Environments



# ISS SEE Environments

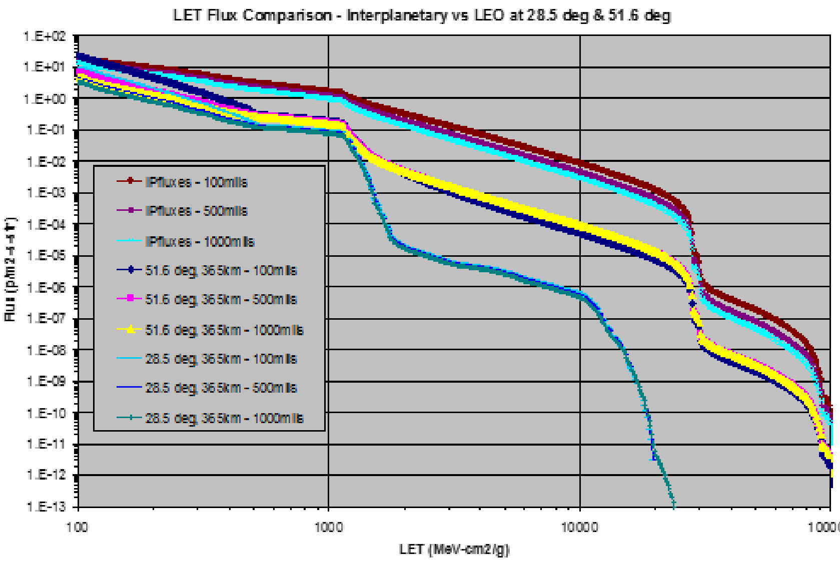
- Galactic Cosmic Rays (GCR)
  - Latitude dependent geomagnetic shielding
    - Little or no effect on higher energy GCR (> 20 GeV/n)
  - Primary cause of ISS avionics systems SEE
- The Van Allen Belts (SAA)
  - Mostly lower kinetic energy protons (than GCR or SEP)
  - Secondary cause of ISS avionics SEE
- Solar Particle Events (SPE)
  - Latitude dependent geomagnetic shielding
  - Predominantly lower kinetic energy protons (than GCR), but higher kinetic energy than SAA protons
  - No observable effects on ISS avionics systems to report to date
- Shielding Mass Effects (Induced Environments)
  - Space radiation charged particles collide with ISS materials and generate secondary particle showers
  - Observable increase in SEE rates with increasing shielding mass in some cases

# Latitude dependent geomagnetic shielding of GCRs

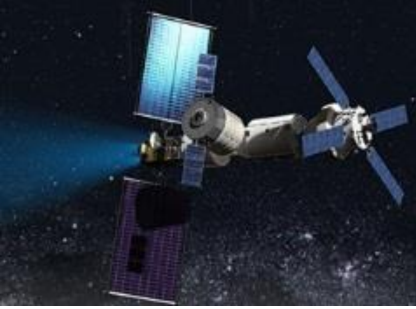



**Global grid of quiescent vertical geomagnetic cutoff rigidities (GV) calculated from charged particle trajectory simulations using the IGRF model for the 1996 epoch (solar cycle 23 minimum). Rigidity increases with particle kinetic energy.**

Christopher J. Mertens, John W. Wilson, Steve R. Blattnig, Brian T. Kress, John W. Norbury, Michael J. Wiltberger, Stanley C. Solomon, W. Kent Tobiska, John J. Murray; 46th AIAA Aerospace Sciences Meeting and Exhibit 7 - 10 January 2008, Reno, Nevada, **AIAA 2008-463**

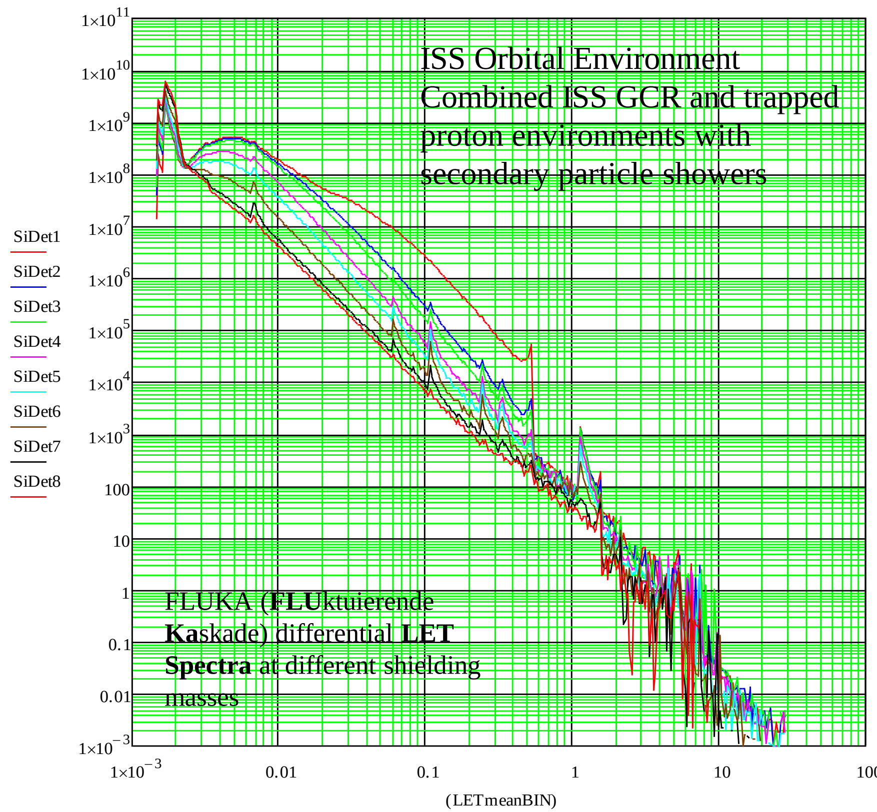


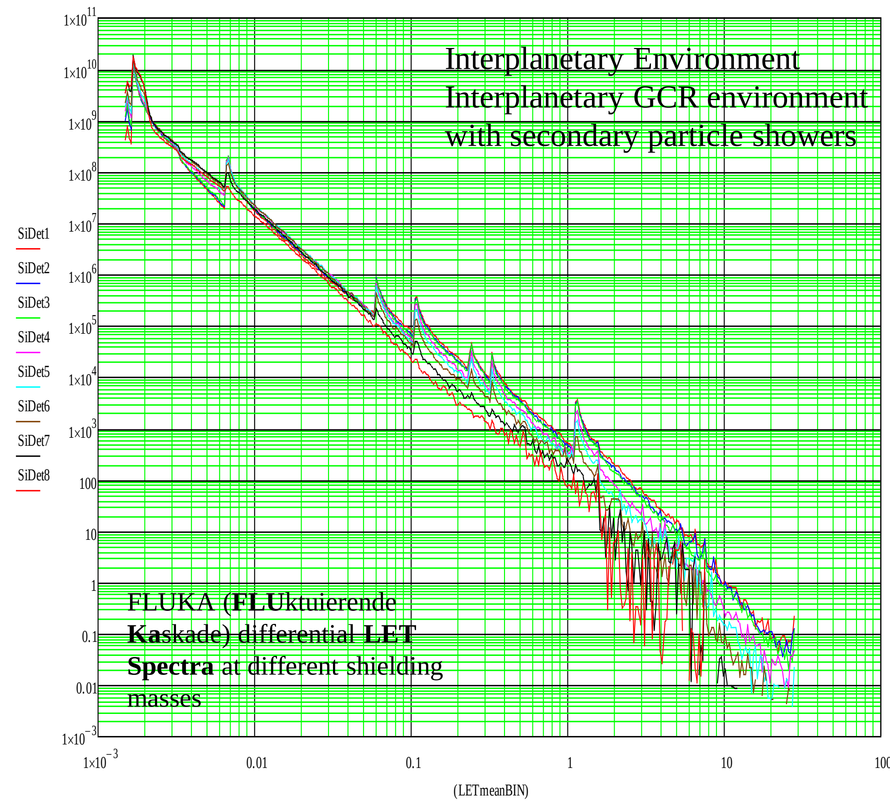

CREME 96 calculations of average daily GCR charged particle flux (#/m$^2$-sec-sr) vs. LET for near-Earth interplanetary (NEI), LEO 365km/51.6°, and LEO 365km/28.5° flight environments. Increasing orbital inclination increases orbit-average similarity to the interplanetary GCR environment.



# Differential LET Spectra: ISS orbit vs. Interplanetary Space

[#/(cm$^2$ week LET)] at various shielding depths in a concentric spherical shell shielding mass model

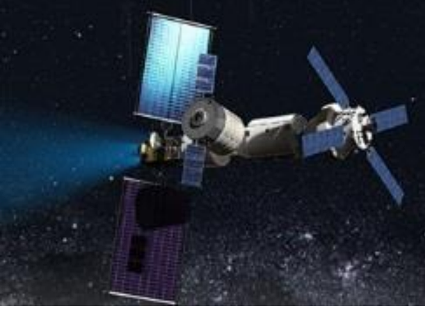



| Detector Si Shell | SiDet1 | SiDet2 | SiDet3 | SiDet4 | SiDet5 | SiDet6 | SiDet7 | SiDet8 |
|---|---|---|---|---|---|---|---|---|
| Detector Shell Radius (cm) | 5037.4 | 5037.3 | 5037.1 | 5035.6 | 5033.7 | 5030.0 | 5018.9 | 5000.0 |
| Si Detector Median Al Shielding Mass in g/cm$^2$ | 0.15 | 0.81 |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

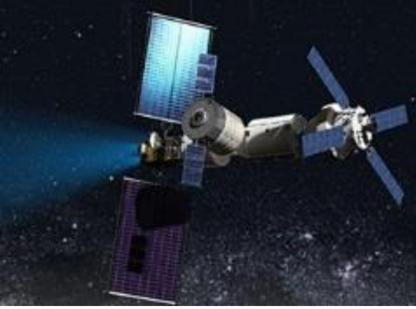
# ISS SEE/TID Environment (Visual)

# ISS Command and Data Handling System (C&DH) Multiplexer de-Multiplexer (MDM) in-flight SEE performance



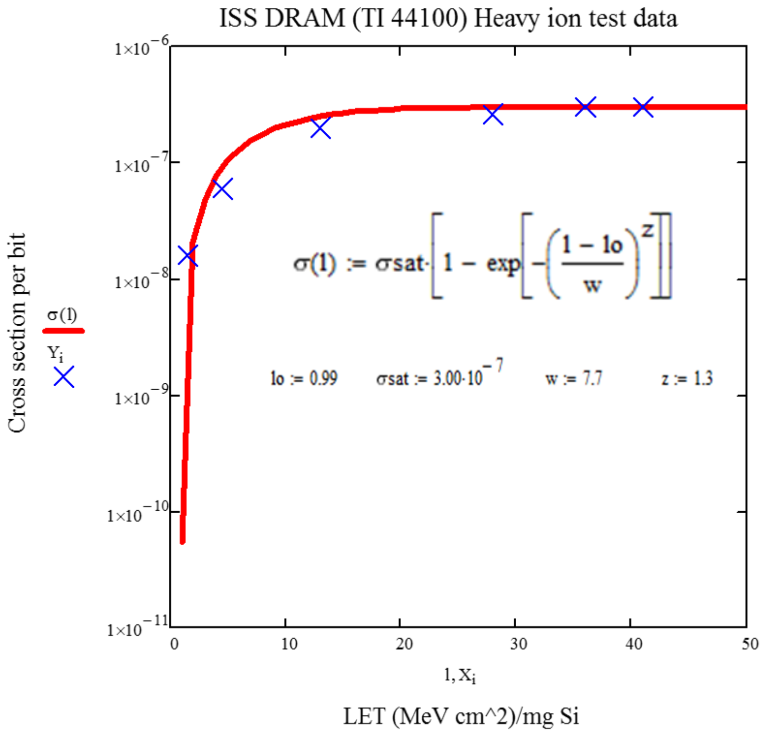
# ISS C&DH System Design and pre-flight test and verification approach

- Nearly 50 standard MDMs on ISS, as of 2016, Configured as a distributed computing network
- The ISS MDM system is configured as a three tiered parallel redundant system
  - Tier 1 MDMs (system wide control functions) are two fault tolerant,
  - Tier 2 MDMs (subsystem control functions) are single fault tolerant
  - Tier 3 MDMs are 0 (really 0.5) fault tolerant (numerous sensors and effectors)
- C&DH Fault Detection Isolation and Recovery (FDIR) functions
  - Bus failures
  - MDM failures
- Each Standard MDM consists of a power supply and an Input/Output Control Unit (IOCU) Card
  - Each IOCU card contains an 80386SX processor, a 1553 Bus Interface adaptor and a total of 33,554,432 bits of DRAM memory configured from 8 Texas Instruments TMS 1Mx4 DRAM memory devices
  - A Hamming code single-error-correction-double-error-detection algorithm is imbedded in the DRAM refresh cycle – SEU bad bit residence time < 10 microseconds
  - DRAM SEU events (along with time of occurrence and ISS location) are reported to the ground via ISS telemetry



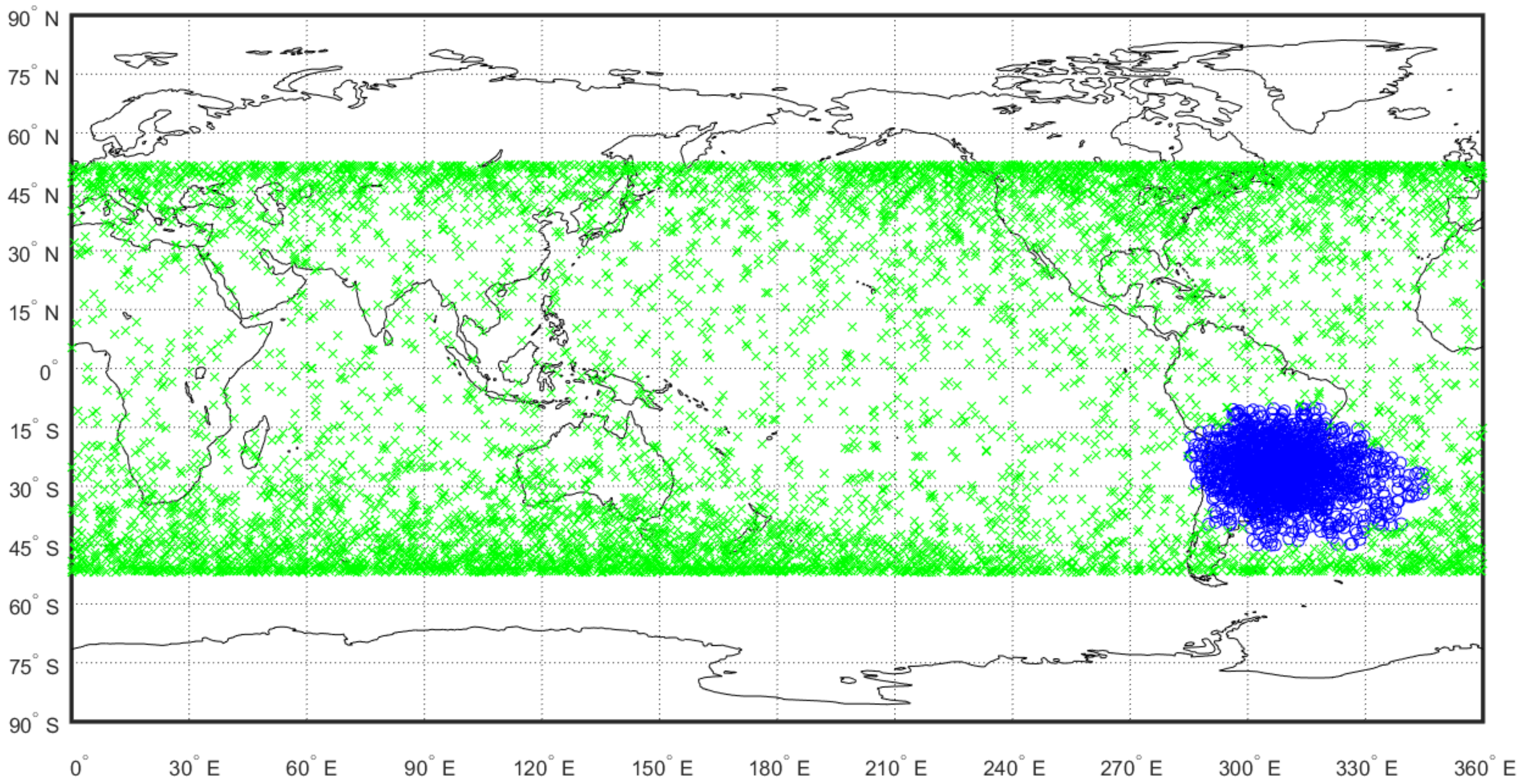
# ISS MDM pre-flight test and verification approach

- MDM parts lists are screened for potentially SEE susceptible devices (SSDs)
- SSDs are subjected to heavy ion testing to determine device SEE cross section (σ) as a function of ion LET
  - Soft errors (SEU)
  - Single Event Functional Interrupt (recoverable)
  - Destructive SEE
- Proton (GCR, trapped, and SPE) σ calculated from heavy ion σ
  - https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4033188
- Expected on-orbit device SEE rates calculated using σ values determined by test combined with CREME-86/96 SEE environment models
- Box and System level SEE rated calculated from device see rates combined with box/system functional block diagrams (and conventional reliability engineering methods) to estimate on-orbit system SEE failure rates




Note: it was assumed that ESA test data for the TI-44100 would be applicable to the TMS-44400 and that turned out to be a good assumption.

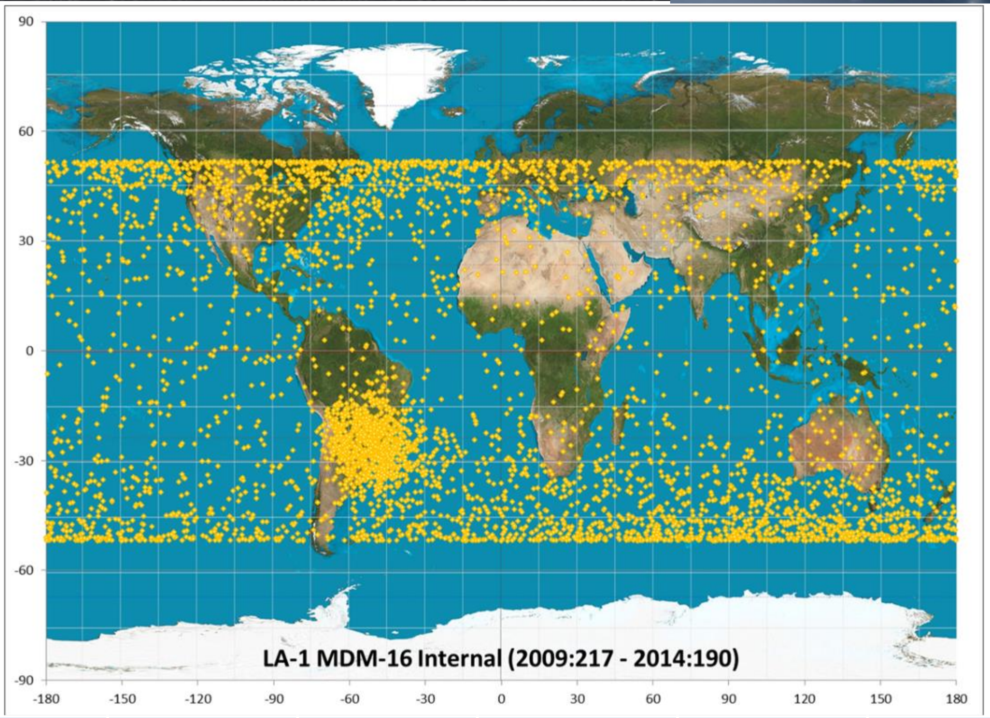
# ISS MDM DRAM SEUs
# What we observe



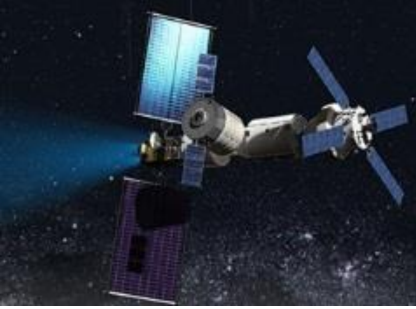

**The geographic distribution of the AL-1 MDM DRAM SEUs for the time period 2005 to 2017.** Blue symbols represent events attributed to Van Allen belt trapped protons in the SAA and green symbols represent events attributed to GCRs.

# ISS MDM DRAM SEUs
# Explaining what we observe

- SEUs in MDM DRAM are identified and corrected by an EDAC algorithm implemented as part of the normal memory refresh cycle
- Each memory location is refreshed every few micro seconds and SEUs are reported in the telemetry stream along with an ISS time mark
  - SEU bad-bit residence time is less than a few microseconds
  - About 20 % of SEUs happen in the South Atlantic Anomaly and about 70% at high latitudes
  - Very few outside the SAA at low latitude




| Device | Median Shielding Mass g/cm$^2$ | In-Flight SEU/bit day | FLUKA Predicted SEU/bit day (FLUKA) | CREME-96 Predicted SEU/bit day (CREME) | FOM Predicted SEU/bit day (FOM) |
|---|---|---|---|---|---|
| TMS44400 | 10 | $8.5 \times 10^{-8}$ | $8.8 \times 10^{-8}$ | $1.1 \times 10^{-7}$ | $2.5 \times 10^{-7}$ |
| TMS44400 | 40 | $7.0 \times 10^{-8}$ | $7.2 \times 10^{-8}$ | $3.1 \times 10^{-8}$ | $6.8 \times 10^{-8}$ |



# MDM DRAM SEU total counts between 2010 and 2018: latitude, geographic region, and shielding mass dependences

| MDM GCR counts versus Geographic Latitude: 02/2010 through 2017 | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Latitude (deg) | % Time | Internal (shielding mass ~ 40g per square cm) | | | | | | | | External (shielding mass ~ 10g per square cm) | | | | | | | | | | | |
| | | AL-1 | LA-1 | LA-2 | LA-3 | N2-1 | N2-2 | N3-1 | N3-2 | P1-1 | P1-2 | P3-1 | P3-2 | PTR1 | S0-1 | S0-2 | S1-1 | S1-2 | S3-1 | S3-2 | STR1 |
| 40 to 52 | 19.5% | 1883 | 1858 | 2032 | 2077 | 1753 | 1725 | 1823 | 1826 | 1766 | 1650 | 1698 | 1624 | 1834 | 1878 | 1672 | 1692 | 1735 | 1641 | 1649 | 1797 |
| 20 to 40 | 16.1% | 697 | 669 | 692 | 738 | 573 | 612 | 656 | 664 | 426 | 446 | 391 | 439 | 432 | 485 | 481 | 483 | 434 | 438 | 438 | 497 |
| -20 to 20 | 28.6% | 719 | 732 | 762 | 768 | 588 | 678 | 720 | 658 | 468 | 467 | 446 | 459 | 447 | 567 | 513 | 497 | 468 | 448 | 486 | 517 |
| -40 to -20 | 16.2% | 790 | 814 | 867 | 849 | 656 | 702 | 799 | 737 | 631 | 584 | 588 | 602 | 635 | 670 | 583 | 597 | 645 | 648 | 607 | 668 |
| -52 to -40 | 19.7% | 2037 | 2067 | 2056 | 2084 | 2024 | 1892 | 2022 | 1946 | 2162 | 2031 | 2129 | 2066 | 2236 | 2025 | 2017 | 1948 | 2155 | 2053 | 2150 | 2171 |

**Total MDM SEU counts for both internal (high shielding mass) and external (low shielding mass) MDMs excluding counts in the SAA region: 02/2010 through 2017.** The counts are reported for 5 different geographic latitude zones with the annual percentage of total flight time in each latitude zone. SEUs in this region are caused predominantly by GCRs.

| MDM SAA counts: 02/2010 through 2017 | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Internal (shielding mass ~ 40g per square cm) | | | | | | | | External (shielding mass ~ 10g per square cm) | | | | | | | | | | | |
| AL-1 | LA-1 | LA-2 | LA-3 | N2-1 | N2-2 | N3-1 | N3-2 | P1-1 | P1-2 | P3-1 | P3-2 | PTR1 | S0-1 | S0-2 | S1-1 | S1-2 | S3-1 | S3-2 | STR1 |
| 1346 | 1619 | 1441 | 1299 | 1755 | 1410 | 1153 | 1275 | 3872 | 3658 | 4172 | 4264 | 3601 | 2373 | 2733 | 3235 | 3628 | 3723 | 3680 | 3182 |

**Total MDM SEU counts for both internal (high shielding mass) and external (low shielding mass) MDMs counts in the SAA region only: 02/2010 through 2017.** SEUs in this region are caused predominantly by Van Allen belt trapped protons.

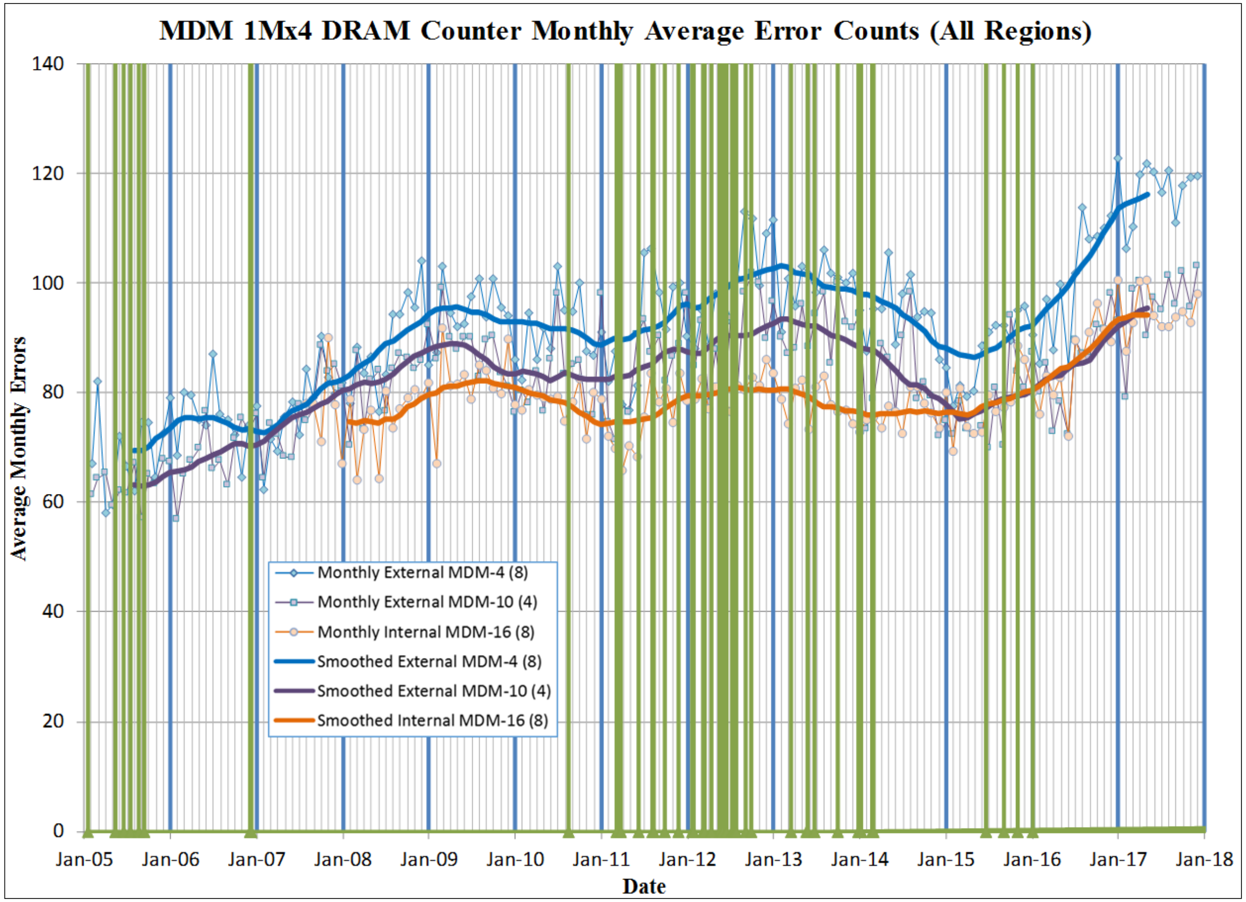
# MDM DRAM SEU total counts between 2010 and 2018: latitude, geographic region, and shielding mass dependences - Statistical Analysis

| Statistical Averages for ISS MDMs | All 20 ISS MDMs | 8 Internal MDMs | 12 External MDMs |
|---|---|---|---|
| **Mean SEU count inside SAA (SAA Region) with standard deviation** | 2671 ± 1112 | 1412 ± 182 | 3510 ± 527 |
| **Mean SEUs count outside SAA (GCR Region) with standard deviation** | 5632 ± 403 | 6030 ± 318 | 5367 ± 168 |
| **% of total counts in SAA Region** | 31.2 % ± 11% | 13% ± 9% | 39% ± 4% |
| **% of total counts in GCR Region** | 68.8% | 87% | 61% |
| **% of GCR region total in highest latitude regions (poleward of 40 degrees latitude)** | 68% ± 4% | 64% ± 1% | 71% ± 2% |

**Statistical Analysis of ISS MDM DRAM SEU count data, 02/2010 through 12/2017**

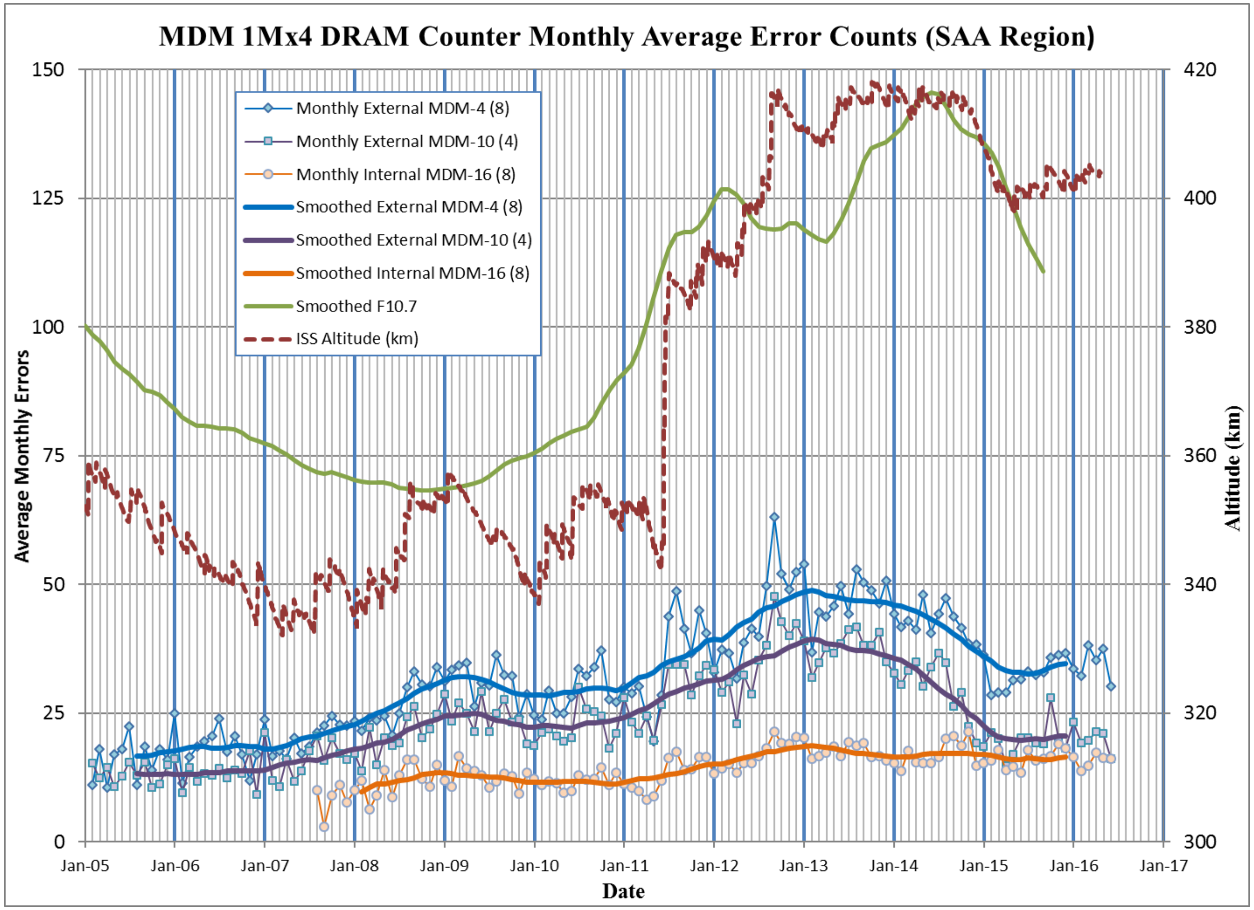
The reported differences between the internal and external MDM group DRAM SEU counts are statistically significant. Applying the "t test" for the significance of the observed differences between the internal and external MDM mean counts results in a t statistic of 6.107, for 18 degrees of freedom, and $p < 0.0001$ for the GCR region and a t statistic of 10.756 for 18 degrees of freedom and $p < 0.0001$ for the SAA region. The p value is the probability that the null hypothesis (i.e. the internal mean count is really the same as the external mean count but only appears different in this case on account of Poisson process random fluctuations) is true.

# Monthly average MDM SEU count timeline from 2005 to 2018: Solar cycle, SPE, altitude, and shielding mass effects



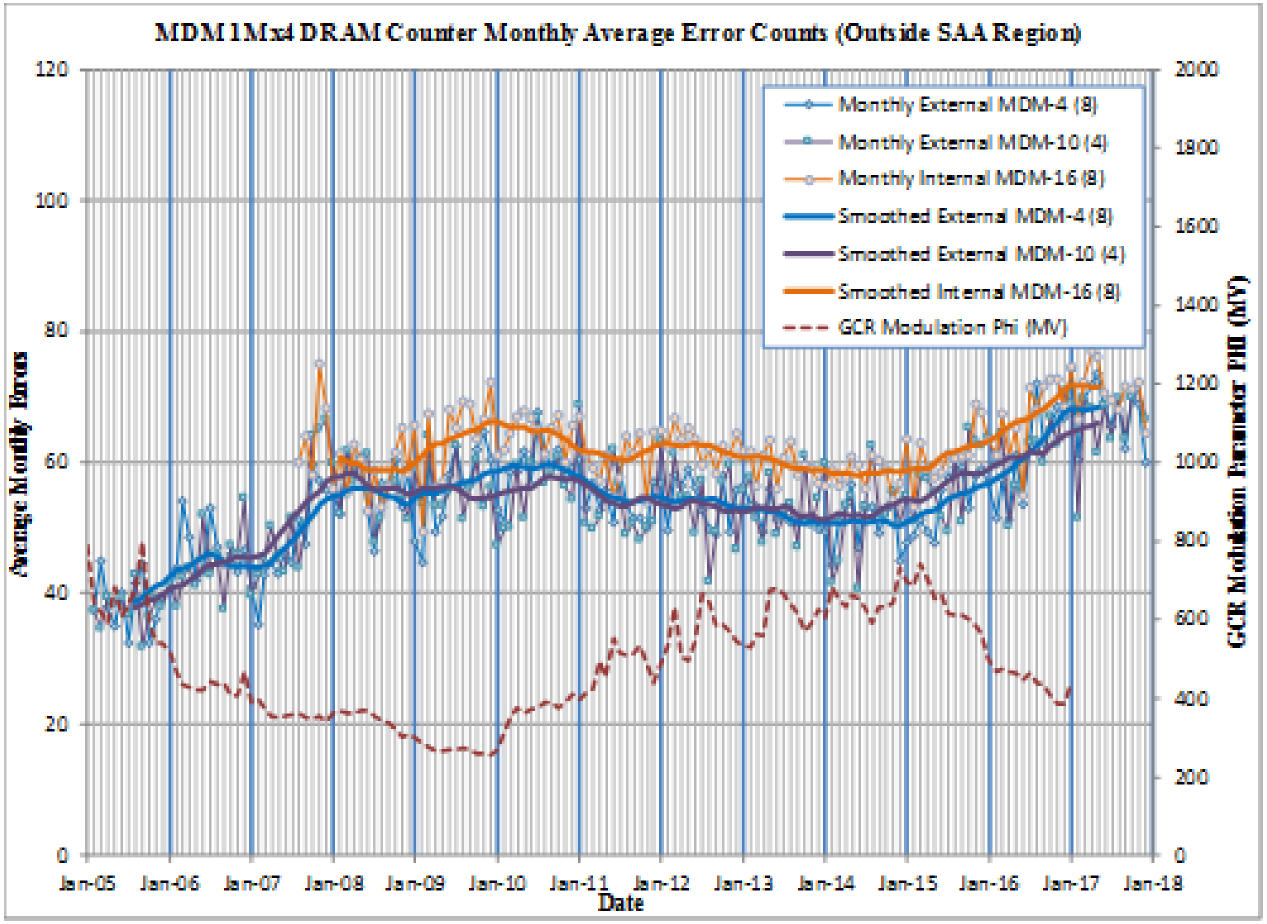

**Monthly average MDM DRAM SEU rates for the 2005 to 2017 time frame, and for all geographic regions.** Monthly average SEU count data for eight external MDM-4s, four external MDM-10s, and eight internal MDM-16s are plotted against calendar year. Green vertical lines mark major solar particle events (NOAA 10/10 criteria, >10 pfu >10 MeV).

# Monthly average MDM SEU count timeline from 2005 to 2018: Solar cycle, SPE, altitude, and shielding mass effects

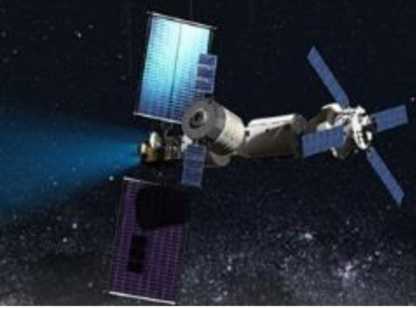



**Monthly average MDM DRAM SEU rates inside the SAA (excluding the GCR region).** Monthly average SEU count data for eight external MDM-4s, four external MDM-10s, and eight internal MDM-16s are plotted against calendar year. DRAM SEU monthly rates compared to solar F-10.7 index and ISS altitude

# Monthly average MDM SEU count timeline from 2005 to 2018: Solar cycle, SPE, altitude, and shielding mass effects




**GCR region MDM DRAM SEU monthly rates compared to the GCR modulation parameter, $\phi$. Note the small variations in external MDM DRAM SEU rate accompanying the small variations in $\phi$ during 2011.**



# Monthly average MDM SEU count timeline from 2005 to 2018: Solar cycle, SPE, altitude, and shielding mass effects

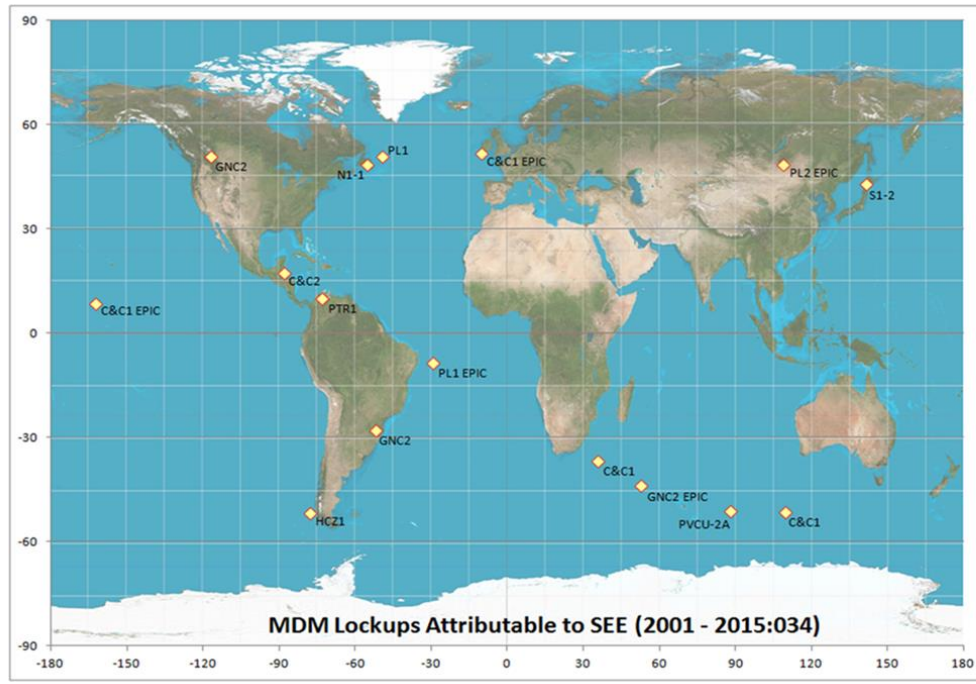
- MDM DRAM SEU rates show very different dependences on shielding mass, altitude, and the 11 year solar cycle inside and outside the SAA.

- Outside the SAA high energy GCRs determine SEU rates which increase with increasing shielding mass (secondary particle shower effects), and show little dependence on altitude, and an expected weak dependence on the solar cycle (GCR modulation factor Phi)

- Inside the SAA, lower energy trapped protons determine SEU rates which increase with decreasing shielding mass and show a strong dependence on altitude and solar cycle (F10.7)

# ISS MDM Functional Interrupts: Pre-flight "lock-up" predictions vs. in-flight observations

- Specific Program Requirement
  - Mean Time To Recover (MTTR) << MTBF
    - Recovery requires ground intervention and takes ~ 24 hours
- On-orbit MTBF calculated from:
  - Heavy ion test data on all SEE susceptible components
  - ISS SEE design environment (SSP-30512)
  - A reliability engineering functional block diagram of the MDM
- For the total compliment of ~50 MDMs:
  - Predicted lock-up rate = 10/year
  - Observed lock-up rate = 1 per year
- The number of observed lock-ups is between about and 10 times smaller than the number of lock-ups predicted
- Flight MDMs are meeting requirements with considerable margin



# ISS Portable Computer System (PCS) in-flight SEE performance

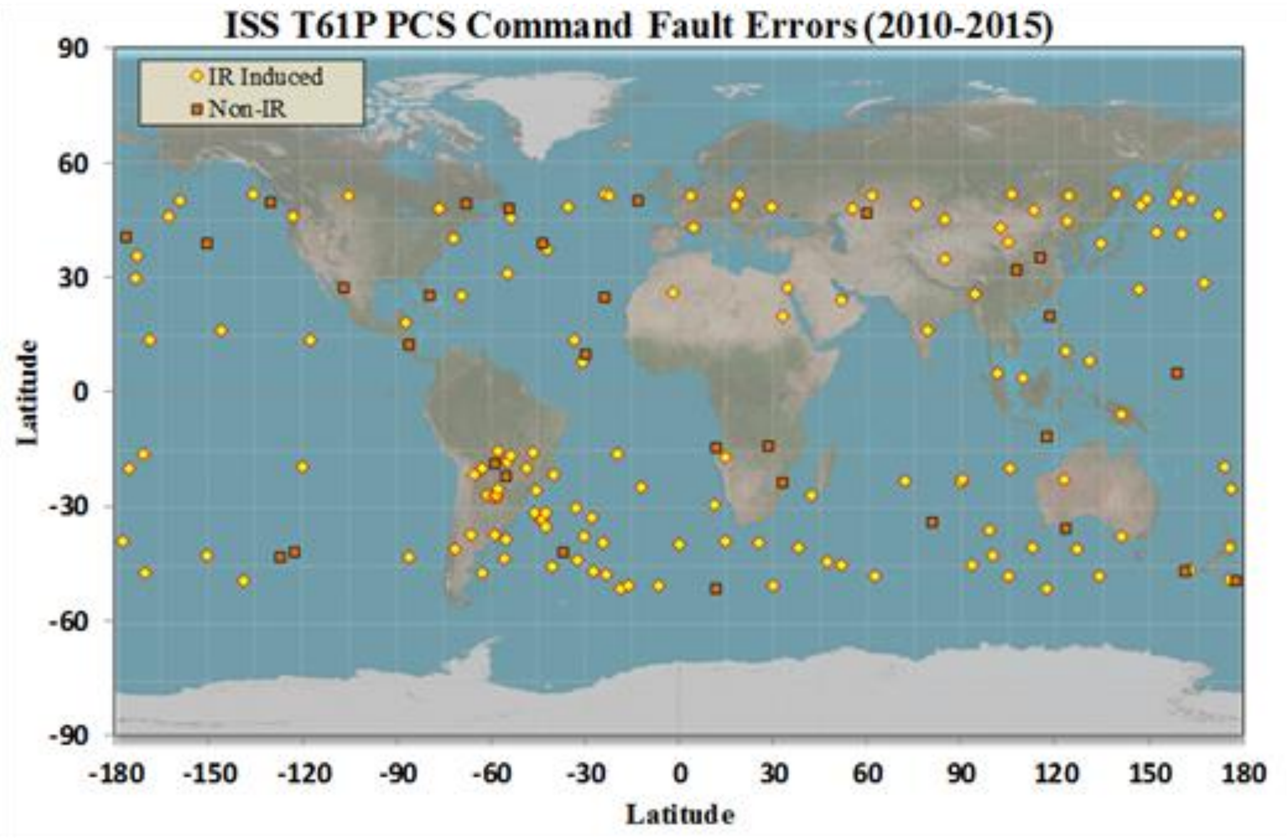
# ISS Portable Computer System (PCS) in-flight SEE performance

**Summary Data: ISS PCS computers pre-flight testing vs in-flight performance.**

| PCS Computer Type | 3 IBM 760 XD Thinkpads Radiation SEFI per day | 7 Lenovo T61Ps Radiation SEFI per day* |
|---|---|---|
| **In-flight observation time frame** | 03/01/2001 to 12/31/2001 | 2011 to 2014 |
| **Expected SEFI rate (high energy proton testing)** | 0.04 | 0.13 |
| **In-flight SEFI rate** | 0.023 $\pm$ 0.012 | 0.013 $\pm$ 0.004 |

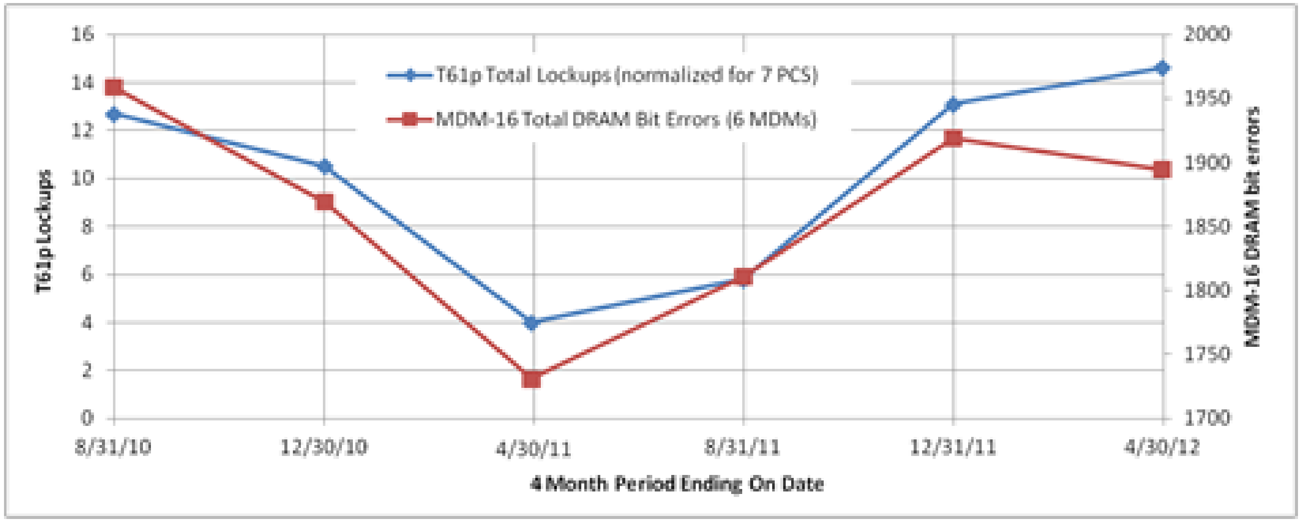
*Observation times for the 7 T61P laptops varied from 877 to 1088 days and two of the 7 T61Ps suffered hard failures that may or may not be radiation induced.

# ISS Portable Computer System (PCS) in-flight SEE performance



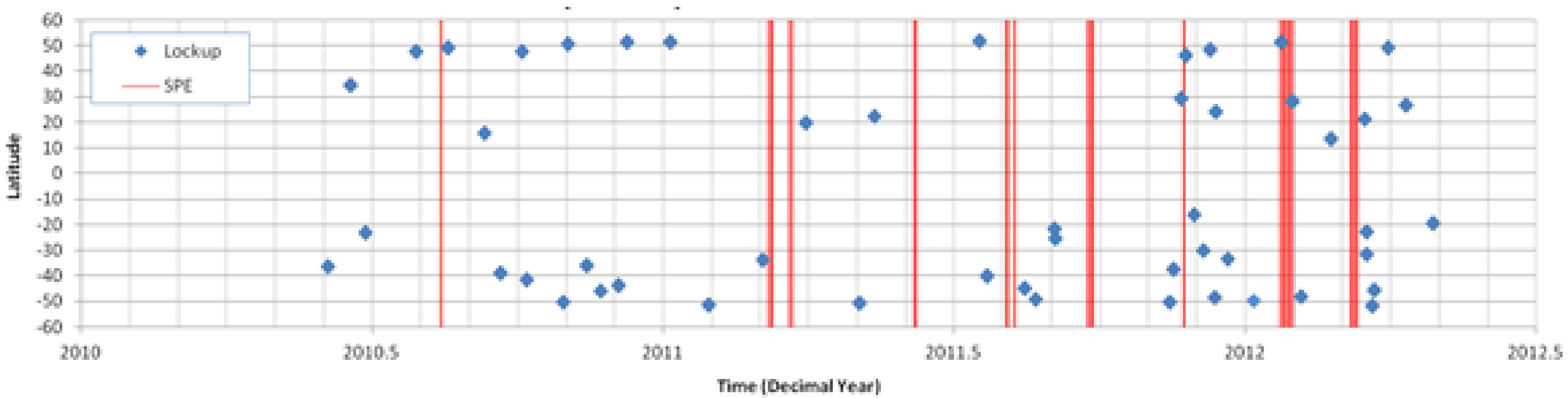

Geographic distribution of T61P command fault error functional interrupts, both radiation induced and not radiation induced from 2010 to 2015.

# ISS Portable Computer System (PCS) in-flight SEE performance

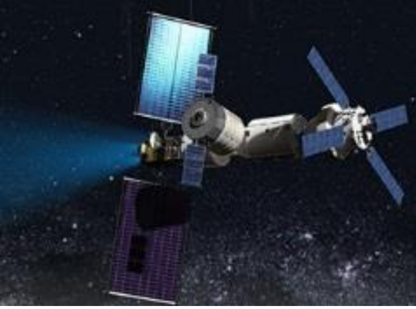



**A comparison of 4 month average SEE effect counts for 7 T61P PCS computers and 6 MDM-16 internal MDMs.** The two different computers appear to be responding to the same SEE environment factors. Compare this plot with the GCR region time line for the year 2011 on slide 22 in this presentation.

# ISS Portable Computer System (PCS) in-flight SEE performance

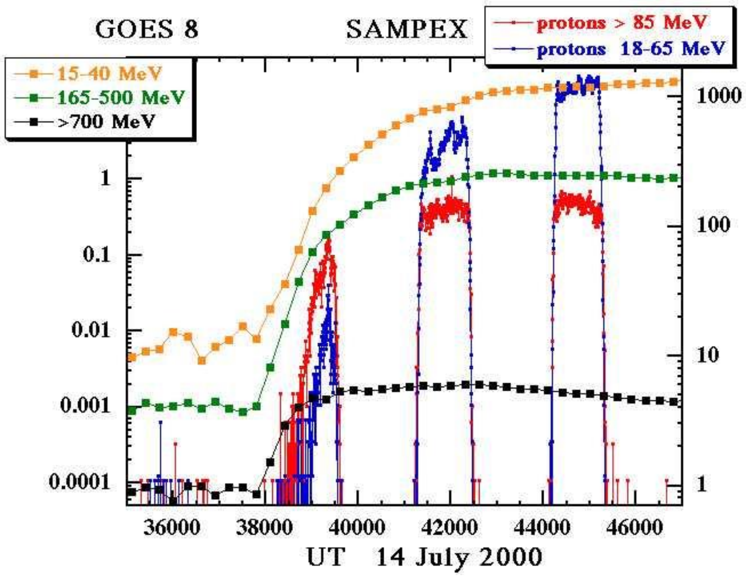


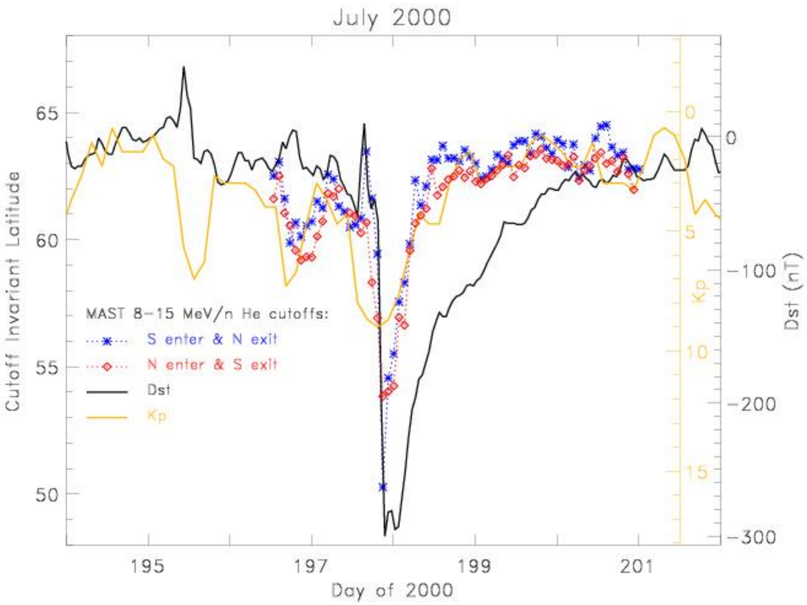

**Date and latitude of T61P SEFIs and dates of SPEs 2010 to 2012.** There is no statistically significant correlation between PCS SEFIs and SPEs, even at high latitude.



# And why don't we see SPE effects in ISS avionics:

## The onset of the July 14 2000 SEP event as seen by GOES 8 and SAMPEX

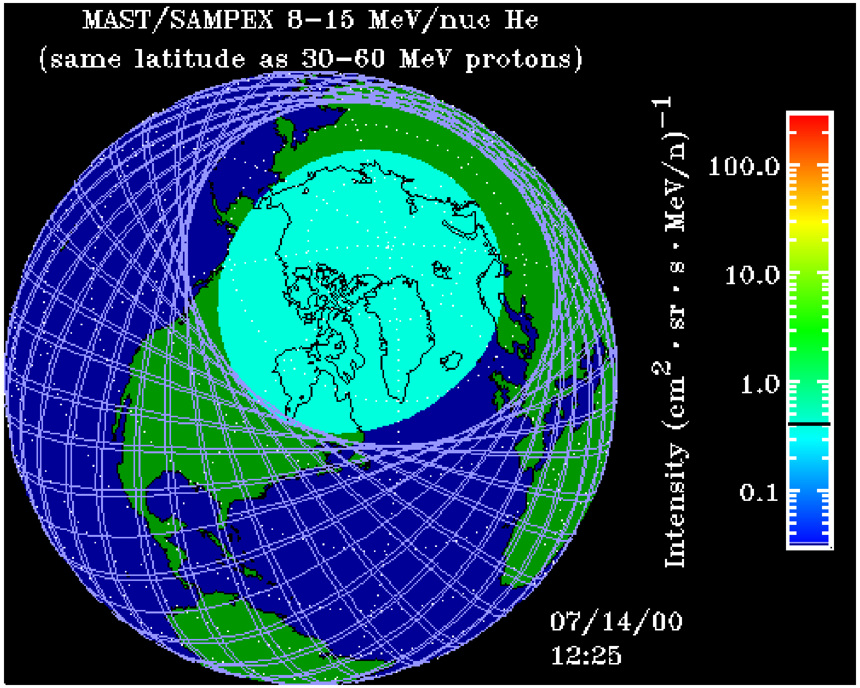


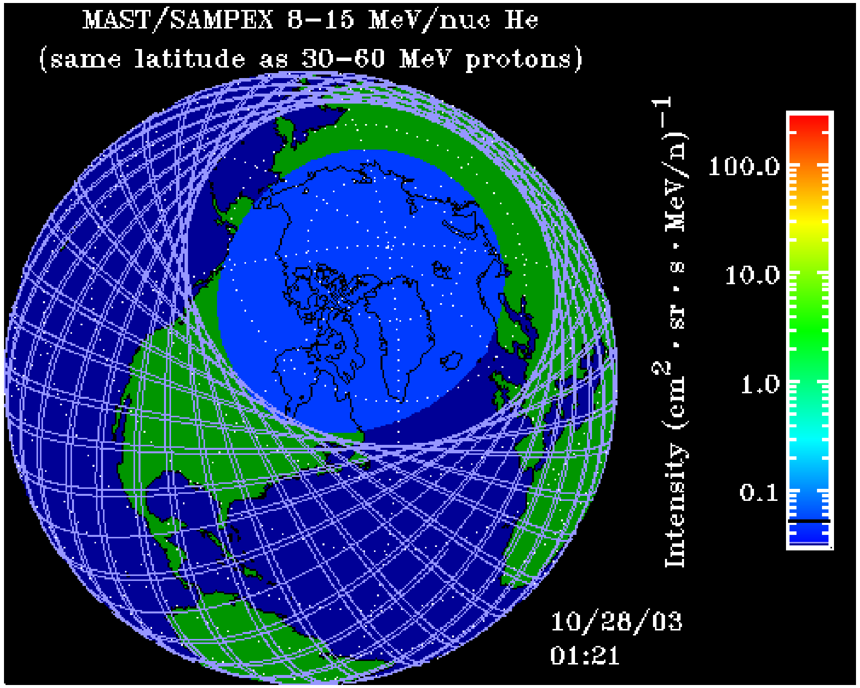




https://www-istp.gsfc.nasa.gov/istp/events/2000july14/SAMPEX_14July00.jpg http://www.srl.caltech.edu/sampex/DataCenter/DATA/CutoffVariations/jpg/jul00.jpg

- Four polar cap traversals by SAMPEX are shown.
- Around 36000 sec UT SAMPEX saw a polar cap population of only the GCR.
- The onset of the SEP occurred just before SAMPEX entered the polar cap the next time at 38200 sec UT.
- SEP event particles were observed only for invariant geomagnetic latitudes > ~ 60 degrees for these polar passes.
- July 14, 2000 corresponds to UTC day 196.

# And why don't we see SPE effects in ISS avionics?




http://www.srl.caltech.edu/sampex/DataCenter/DATA/CutoffVariations/

*Leske, R.A., Mewaldt, R.A., Stone, E.C., and von Rosenvinge, T.T., "Observations of Geomagnetic Cutoff Variations During Solar Energetic Particle Events and Implications for the Radiation Environment at the Space Station", J. Geophys. Res. 106, 30011-30022 (2001).*

# Can ISS be utilized as a flight demonstration and test platform for cis-lunar and interplanetary flight systems?

# Some Relevant Prior Work

- Alpha Magnetic Spectrometer 01 (AMS-01) measurements of GCR spectra in different geomagnetic latitude regions
  - P, He, C, and Fe GCR kinetic energy spectra approach NEI spectra at high latitude
    - Bobik, P.; Boella, G.; Boschini, M. J.; Gervasi, M.; Grandi, D.; Kudela, K.; Pensotti, S.; Rancoita, P. G. “Fluxes and nuclear abundances of cosmic rays inside the magnetosphere using a transmission function approach,” Advances in Space Research, Volume 43, Issue 3, p. 385-393. (AdSpR Homepage), DOI 10.1016/j.asr.2008.11.020
- Using high latitude ISS data to evaluate shielding mass performance expected in the NEI environment
  - Livio Narici, Marco Casolino, Luca Di Fino, Marianna Larosa, Piergiorgio Picozza, Alessandro Rizzo, Veronica Zaconte; “Performances of Kevlar and Polyethylene as radiation shielding on-board the International Space Station in high latitude radiation environment,” Nature Scientific Reports | 7: *1644* | DOI:10.1038/s41598-017-01707-2
  - Livio Narici, Marco Casolino, Luca Di Fino, Marianna Larosa, Piergiorgio Picozza, Veronica Zaconte; “Radiation Survey in the International Space Station,” J. Space Weather and Climate, 5, A237 (2015)
- Note that AMS-02 has been operational on ISS since May 2011
  - https://www.nasa.gov/sites/default/files/files/7_NASA_NAC_April7_TAGGED.pdf

# Modeling latitude dependent geomagnetic GCR and SPE shielding

- Used the CREME-96 SEE TID analysis tool to calculate particle kinetic energy and LET spectra
  - https://creme.isde.vanderbilt.edu/
  - Includes geomagnetic (L shell) and planetary shadow shielding effects as a function of altitude and latitude/longitude
  - Particle spectra as a function of geomagnetic latitude are calculated by fixing the altitude at 400 km over a range of latitude/longitude values
  - NEI and ISS (400km) spectra (as a function of L shell) can be directly compared to assess similarity
    - ISS orbit average
    - Specific geographic regions
- Vehicle shielding mass effects can also be included

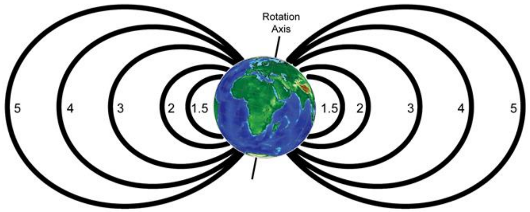
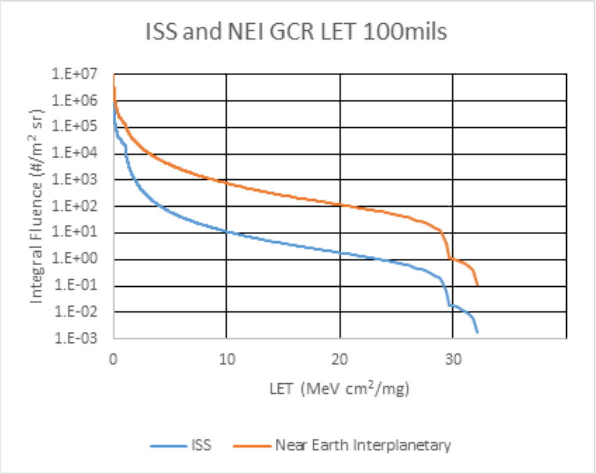
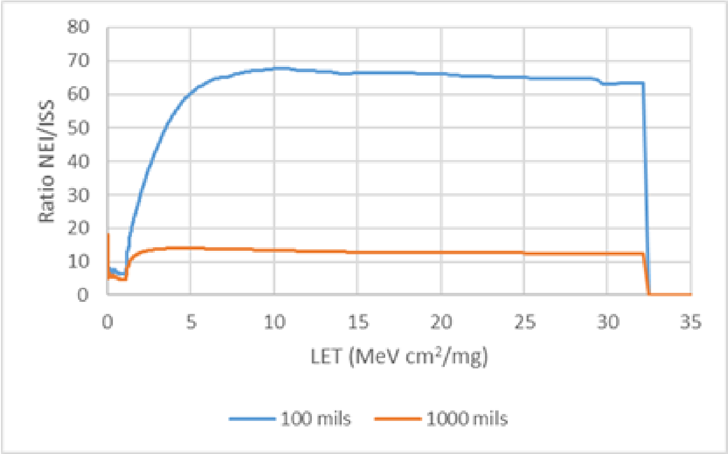



Image Credit - Daniel I Golden - Postdoc in the Stanford University Radiology department. Member of the Stanford Quantitative Imaging Laboratory

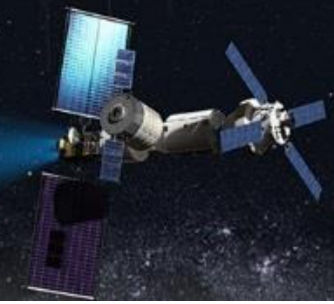
The McIlwain *L*-parameter (Carl E. McIlwain), or L shell, is a parameter describing planetary magnetic field lines. The *L*-value is the number of Earth-radii at which a particular field line crosses the geomagnetic equator.



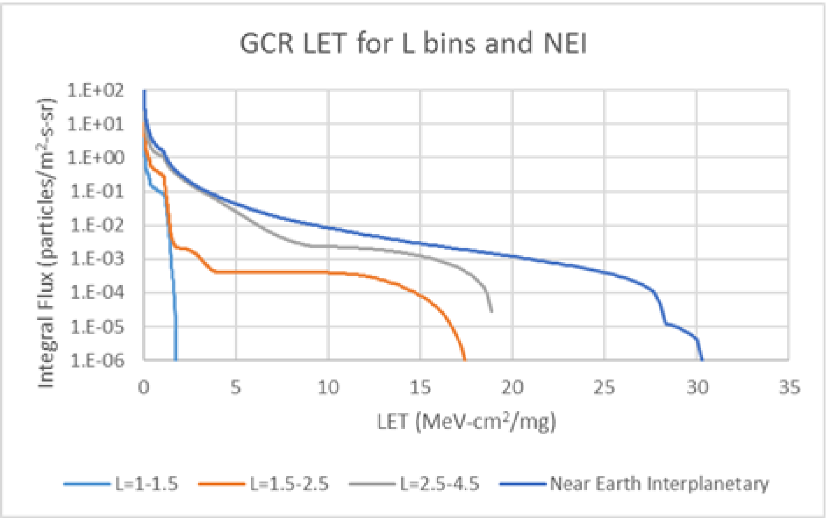

CREME-96 GCR LET fluences compared for 1 day at ISS orbit and NEI (100 mils (0.254 cm) of aluminum shielding)



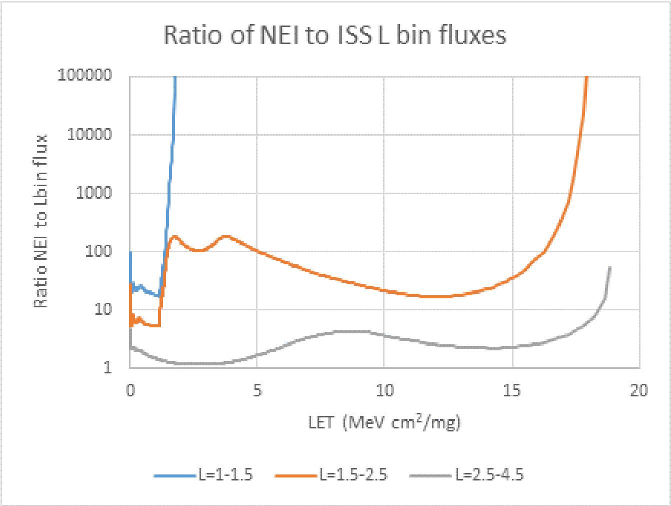

Ratio of integral near-earth interplanetary to ISS orbit GCR fluences for 100 mils (0.254 cm) and 1000 mils (2.54 cm) Al shielding.



# Modeling latitude dependent geomagnetic GCR and SPE shielding



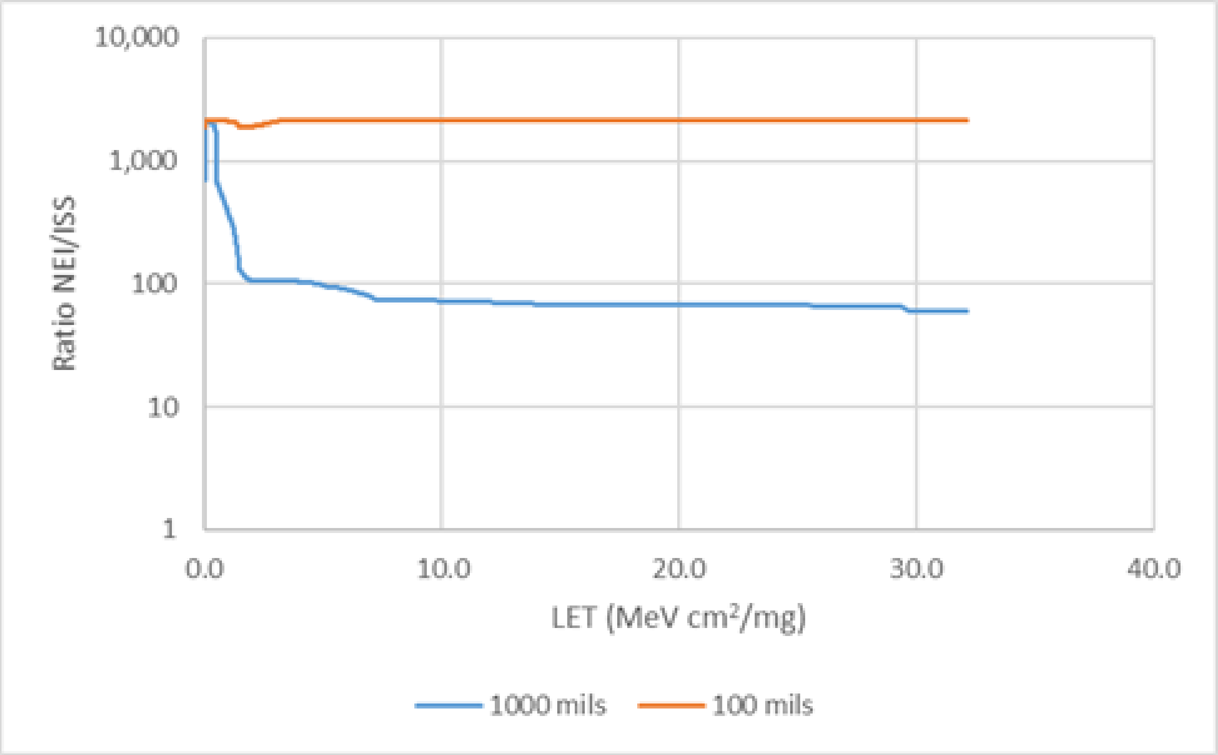

GCR integral flux for NEI and 3 different 400 km altitude L shell bins corresponding to 0 degrees latitude (L=1-1.5), 40 degrees latitude (L=1.5-2.5), and 51.6 degrees latitude (L=2.5-4.5).




Ratio of integral NEI to ISS orbit integral GCR LET fluxes averaged over three different L shell regions with 100 mils (0.254 cm) of aluminum shielding. L=1-1.5 => a geographic latitude 0 degrees. L=1.5-2.5 => a latitude 40 degrees north. L=2.5-4.5 => latitude 51.6 degrees north. A similar range of L values is encountered in the southern hemisphere.

- CREME-96 altitude/L-Shell modeling at 400 km altitude indicates that the ISS GCR environment becomes increasingly similar to the NEI GCR environment at geographic (geomagnetic) latitude increases
- Increasing shielding mass can further increase the similarity between the ISS and NEI environments by screening out low high abundance, low KE GCR particles

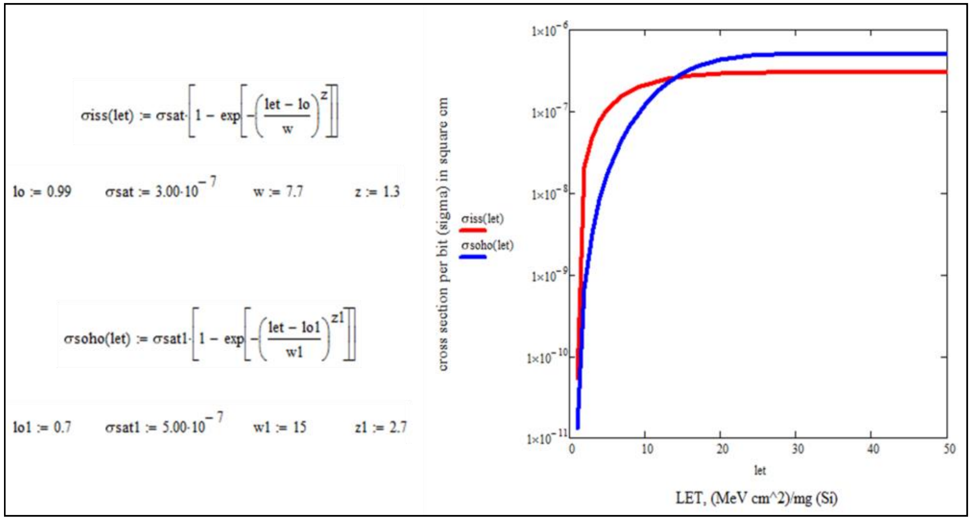
# Modeling latitude dependent geomagnetic GCR and SPE shielding



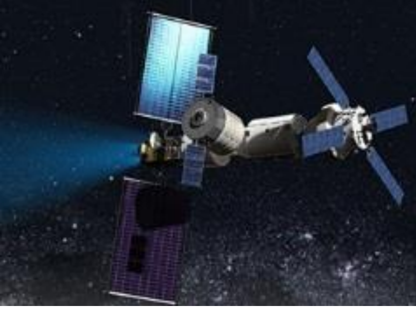

Ratio of NEI to ISS orbit average solar particle event fluence versus LET for two different aluminum shielding thicknesses: 100 mils (0.254 cm) and 1000 mils (2.54 cm). The CREME-96 peak 5 minute (Oct 1989 SPE event) was used in the calculation.

# Can GCR SEE data from ISS be scaled to estimate NEI GCR SEE Effects?

- Approach – compare SEU rates for similar DRAM on ISS and SOHO
  - ISS LEO 400 km, 51.6 degrees, high shielding mass (10g/cm$^2$)
  - SOHO NEI, low shielding mass (1 g/cm$^2$)
- First question, how do the in-flight SEE rates compare without scaling (both at solar minimum)
  - ISS: 8.5 x $10^{-8}$ SEU/bit-day (all geographic regions)
  - SOHO: 5.9 x $10^{-7}$ SEU/bit-day
  - **SOHO/ISS = 7** (not bad, we can make reasonable NEI SEE rate estimates from ISS SEE rate data directly
  - **SOHO FOM/ISS FOM = 6.4**
- Next question – can we do better scaling to account for ISS high latitude residence time, shielding mass and differences in GCR environment?
- FOM = Petersen Figure of Merit SEU rate estimation method



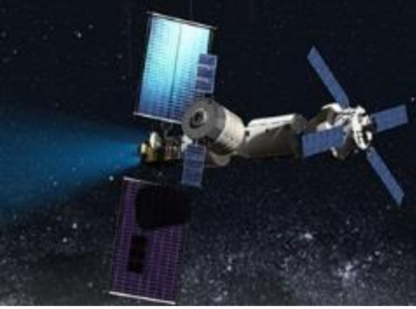

**Cross section vs LET functions for the ISS MDM DRAM and the SOHO DRAM (**ISS MDM DRAM TMS44400 and SOHO DRAM SMJ44100)



# Can GCR SEE data from ISS be scaled to estimate NEI GCR SEE Effects?

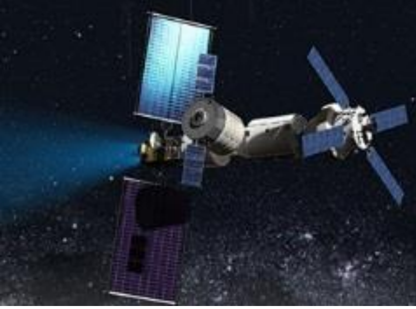
- Scaling approach
  - Start with the observed average ISS MDM DRAM SEU rate (all regions) and the corresponding Petersen Figure of Merit (FOM) ISS MDM DRAM rate
  - Scale both to account for ISS residence time poleward of 40 degrees latitude and the percentage of total counts poleward of 40 degrees latitude
  - Last use FOM equations to correct for differences in GCR environment and spacecraft shielding mass
    - Note that the FOM method is known to overestimate SEE rates, compared to flight data, and in this case the overestimate is about a factor of 3
      - The FOM overestimate is 3.3 $\pm$ 0.3 for all steps in the scaling method for both spacecraft, supporting the validity of the method
- Results
  - ISS DRAM rate scaled to SOHO NEI Environment: 4.4 x $10^{-7}$ SEU/bit-day
  - SOHO DRAM rate: 5.9 x $10^{-7}$ SEU/bit-day
  - **SOHO/scaled ISS = 1.35** (better, we can make more accurate NEI SEE rate estimates from ISS SEE rate data by scaling
  - **SOHO FOM/scaled ISS FOM = 1.07**

# Summary and Conclusions



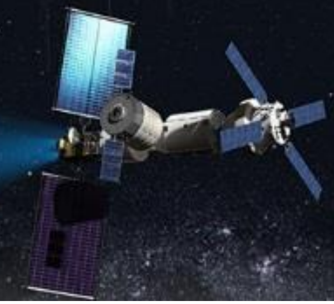
# Summary and Conclusions

- ISS MDM DRAM SEU count rates display a strong dependence on both shielding mass and geographic location
  - Internal (high shielding mass) and external (low shielding mass) MDM DRAM SEU count rates differ in the SAA vs. the GCR regions
    - For the 12 external MDMs, 39% of the total SEU counts were inside the SAA region and 61% in the GCR region
    - For the 8 internal MDMs, 13% of the total SEU counts were inside the SAA region and 87% in the GCR region
    - The observed effects are attributed to:
      - Differences in shielding mass between the two MDM populations,
      - The relatively low kinetic energy of SAA trapped charged particles compared to GCR charged particles and,
      - Secondary particle showers caused by nuclear reactions between ISS shielding mass materials and high energy GCR particles
    - In the GCR region SEU count increases with increasing shielding mass and in the SAA region SEU count decreases with increasing shielding mass
  - In the GCR region, the highest MDM DRAM SEU count rates were observed in the high latitude region, poleward of $40^{o}$, for both MDM shielding mass environments
    - For the 12 external MDMs, 71% of the total GCR region SEU counts were poleward of 40 degrees latitude
    - For the 8 internal MDMs, 64% of total GCR region SEU counts were poleward of 40 degrees latitude
- We have observed no correlations between SPEs and MDM monthly average DRAM SEU rates or MDM SEFI events for either MDM shielding mass environment



# Summary and Conclusions

- Between January 2005 and January 2018, the external MDM SEU rates responded primarily to:
  - The expected increases in trapped proton flux with ISS altitude, offsetting any reduction in trapped proton population through the last solar maximum
- In the SAA region the internal MDM SEU rate shown very little variation between 2005 and 2017
  - As solar cycle 24 winds down, both GCR and trapped proton fluxes are expected to increase and both the internal and external MDM SEU rates observed to be increasing after January 2015
- In the GCR region, the internal MDM DRAM SEU rates are following changes in the heliospheric GCR modulation factor, $\phi$, between 2005 and 2017
  - As solar cycle 24 winds down, $\phi$ is decreasing so that more GCR particles of lower kinetic energy are able to enter the inner solar system and all MDM SEU rates are increasing outside the SAA following January 2015
- The ISS PCS system laptop computers in-flight SEFI rates were lower by a factor of 2 to 10, depending on the make and model of laptop computer, than were predicted before flight on the basis of high energy (200MeV) assembled article proton testing
  - It should be remembered that non-SEE FI rates for both laptops were comparable to SEE rates and that the use of both laptops on ISS is subject to a number of constraints designed to minimize the safety and mission success risks presented by this relatively unreliable consumer COTS hardware



# Summary and Conclusions

- The maximum MDM DRAM SEU counts are observed in the high latitude portion of the ISS orbit poleward of 40 degrees latitude, where geomagnetic shielding of GCRs is minimal and similarity to the NEI GCR environment is maximum

- Decades of GCR transport modeling in the geomagnetic field and direct measurements of GCR flux at high latitude by AMS-01 suggests that the ISS GCR environment at high latitudes bears a high degree of similarity to the NEI GCR environment

- ISS should, therefore, be useful as a flight demonstration and test platform for spacecraft hardware intended for operations in cis-lunar space and beyond

- Modeling the high latitude GCR environment using the CREME-96 SEE/TID analysis tool and comparing the observed SEU rates for comparable DRAM memories on ISS and SOHO lend some support to the credibility of the proposal that ISS can be a useful flight test and demonstration platform for spacecraft components destined for NEI space

- AMS-02 has been operating on ISS for several years now and should be able to produce more complete and detailed high latitude ISS GCR environment date sets, providing a sound basis for scaling ISS high latitude SEE data to the near Earth interplanetary environment

# Back-up

# Predicting on-orbit interplanetary Solar Particle Event (SPE) Rates: FLUKA Calculations of SPE Upset Rate Increases

| **Spacecraft/System and Device** | **Nov. 1997 SPE**<br><br>**Upsets/bit** | **July 2000 SPE**<br><br>**Upsets/bit** | **Nov. 2001 SPE**<br><br>**Upsets/bit** | **Oct. 2003 SPE**<br><br>**Upsets/bit** |
|---|---|---|---|---|
| Cassini/Solid State Recorder DRAM<br>1) Observed event upsets<br>2) Estimated event upsets<br>3) Estimated/Observed<br>4) Quiescent (no event) daily upset rate | 1) $4.4x10^{-7}$<br>2) $1.4x10^{-7}$<br>3) 0.32<br>4) $5.8x10^{-8}$ | NA | NA | NA |
| SOHO /Solid State Recorder DRAM<br>1) Observed event upsets<br>2) Estimated event upsets<br>3) Estimated/Observed<br>4) Quiescent (no event) daily upset rate | 1) $4.4x10^{-6}$<br>2) $2.110^{-6}$<br>3) 0.48<br>4) $5.9x10^{-7}$ | 1) $4.7x10^{-5}$<br>2) $2.1x10^{-5}$<br>3) 0.4<br>4) $5.9x10^{-7}$ | NA | NA |
| Thuraya/ DSP DRAM<br>1) Observed event upsets<br>2) Estimated event upsets<br>3) Estimated/Observed<br>4) Quiescent (no event) daily upset rate | NA | NA | 1) $2.0x10^{-6}$<br>2) $2.8x10^{-6}$<br>3) 1.4<br>4) $5.3x10^{-8}$ | 1) $1.5x10^{-6}$<br>2) $3.8x10^{-6}$<br>3) 2.5<br>4) $5.3x10^{-8}$ |