Using FLUKA to Calculate Spacecraft ge Event Environments: A Practical Approach

Microelectronics Reliability and Qualification Workshop - 2009

Dec. 8-9, 2009

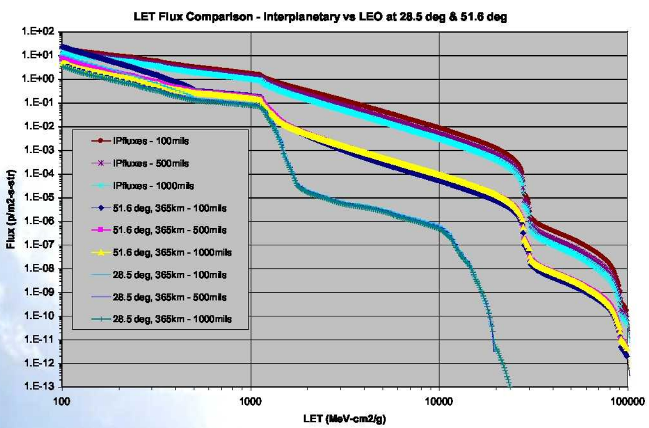
Paul Boeder
Boeing Corporation
13100 Space Center Blvd.,
M/C HB3-20
281-226-6736,
paul.a.boeder@boeing.com

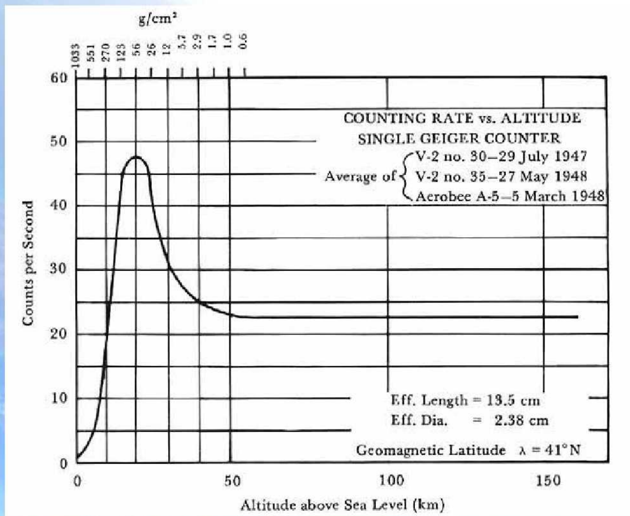
Steve Koontz
NASA Johnson Space Center,
MC ES4
Houston , Texas, 77058
281-483-8860,
steven.l.koontz@nasa.gov

Brandon Reddell
University of Houston
Dept. Of Physics, 617 Science & Research I
University of Houston, Houston, Tx. 77004
brandon.reddell@mail.uh.edu

SPACE ENVIRONMENT EFFECTS
| Spacecraft Contamination | Space Plasmas | Ionizing Radiation | Solar UV | Solar X-rays | Atomic Oxygen | Thermal Vacuum |
Safety • Reliability • Mission Success
Space Environments
ES4

Outline





- **The Spacecraft Microelectronics Reliability and Qualification (MRQ) Process**
  - **Role of the mission and spacecraft specific single event effects (SEE) environment**
  - **Role of nuclear reaction and transport processes in determining the spacecraft SEE environment**
    - Natural vs. induced SEE environments ± nuclear reaction in shielding mass and avionics components
  - **Why FLUKA (FLUktuierende KAskade)?**
- **Comparing in-flight single event upset rates with rates calculated using FLUKA LET spectra**
  - **Low-Earth Orbit (LEO)**
    - Space Shuttle and International Space Station (ISS)
    - Calculated vs. observed single event rates
    - LET spectra as a function of shielding mass
  - **Geosynchronous and Interplanetary orbits**
    - Cassini, SOHO, Mercury Messenger, ETS-V, Thyraya
    - Calculated vs. observed single event rates
    - LET spectra as a function of shielding mass
- **Calculating SEE environments and rates with FLUKA**
  - **Calculating LET Spectra**
  - **Calculating SEE rates**
  - **LET spectrum and SEE rate characteristics**
    - Shielding mass effects
    - Contribution of various CR elements to the expected SEU rates
    - The effects of high Z elements in microelectronic devices
- **Discussion, Summary and Conclusions**

The Spacecraft Microelectronics Reliability and Qualification (MRQ) Process

Step 1- Mission Specific SEE Environment Specification

Step 2 - Microelectronic device SEE Characterization

Step 3 - Calculate (estimate) expected in-flight device SEE rates

Step 4 ± Is the expected SEE rate acceptable in light of system safety and reliability requirements?

How do we know all this works (method validation)?

Why the interest in FLUKA?

The Spacecraft Microelectronics Reliability and Qualification (MRQ) Process

- **Step 1- Mission Specific SEE Environment Specification**
  - **Natural SEE Environment**
    - Galactic Cosmic Ray (GCR) and Trapped Radiation environment definitions from the U.S. Naval Research Laboratory CREME 96 web page, (https://creme96.nrl.navy.mil/) (for solar minimum)
  - **Spacecraft Specific Induced SEE Environment**
    - Results when the natural SEE environment is processed by:
      - 1) spacecraft structural, consumable, and shielding materials
      - 2) avionics device materials
    - Calculated using a nuclear reaction and transport model ± FLUKA in this case
    - The result is a differential, **f[LET],** or integral **F[LET]** probability distribution function providing the particle flux as a function of particle LET - isotropic to first approximation
    - LET units are in (MeV cm^2)/mg (Si)
- **Step 2 - Microelectronic device SEE Characterization**
  - **Device (chip) level heavy ion and/or proton testing**
    - Cross section for single events vs. charged particle Linear Energy Transfer (LET) in the target device at one of several accelerator facilities
    -

The Spacecraft Microelectronics Reliability and Qualification (MRQ) Process

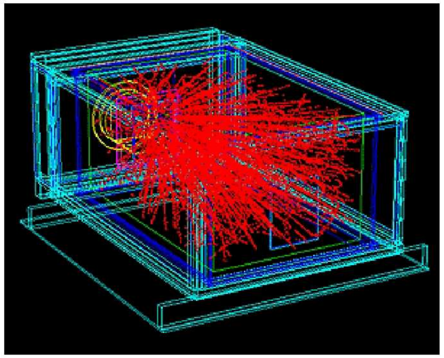
- **Step 3 - Calculate (estimate) expected (in-flight) device single event rates using:**
  - 1) Differential form of the SEE environment definition, **f[LET]**, solar minimum
    - f[LET] is isotropic (ICRU definition)
    - Scale the simulation particle flux/fluence to on-orbit flux/fluence
  - 2) The integral form of the device directional cross section

WHY FLUKA?

- ***Microelectronics are evolving beyond the limits of established single event test and verification methods***
  - The size of microcircuit elements continue to shrink
  - Microcircuit element packing density and VLSI circuit complexity continue to increase
  - High atomic number elements like Ni, Cu, W and Hf are introduced over a range of size scales introducing nuclear reaction issues
  - Many of the assumptions underlying affordable versions of the established test methods (*JEDEC EIA/JESD57 and/or ASTM F1192 -00(2006)) and associated SEE rate models* are increasingly unreliable or not applicable
  - (Johnston, 1998), (Shaneyfelt, Schwank, Dodd, Felix, 2008), (Lacoe, 2008), (Schrimpf, Warren, Ball, Weller, Reed, Fleetwood, Massengill, Mendenhall, Rashkeev, Pantelides, Alles, 2008), (Muntenau, Autran, 2008), (Fulkerson, Nelson, Carlson, 2006), (Reed, Kinnison, Pickel, Buchneer, Marshall, Kniffin, LaBel, 2003)
- ***Increasing community interest in Monte Carlo nuclear reaction and transport codes to understand and evaluate SEE processes in modern microelectronic devices***
  - Spacecraft and planetary/lunar/asteroid shielding mass effects
  - Energy/charge deposition
  - Nuclear reactions in or near microcircuit elements
  - Multi-node charge collection
  - Simulation of heavy ion testing
  - Multiple bit upset analysis
  - Simulation of low energy and high energy proton testing
  - □)RVWHU□□2¶1HLOO□□.RXED□□□□□□□□□□6FKULPSI□□:DUUHQ□□%DOO□□:HOOHU□□5HHG□□)OHHWZRRG□□0DVVHQ Pantelides, Alles, 2008), (Warren, Sierawski, Reed, Weller, Carmichael, Lesea, Mendenhall, Dodd, Schrimpf, Massengill, Hoang, Wan, De Jong, Padovani , Fabula, 2007) (Skutnik, Lajoie, 2006)

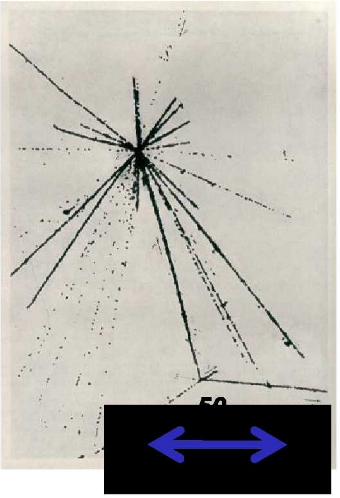
Why FLUKA? - Secondary Particle Production in Spacecraft Shielding, Avionics Components, and the Atmosphere

- Three basic processes
  - **Energy loss (dE/dx) by ionization of material along the particle track**
    - Direct ionization effects ± linear energy transfer (LET)
  - **High energy collision (inelastic) with spacecraft materials nuclei**
    - Nuclear reactions initiate secondary particle showers
    - Proton and neutron SEE effects are often the result of direct nuclear reactions
      - reactions in or near the device sensitive volume
    - Further collisions of secondary particles with spacecraft nuclei leading to expansion and propagation of the secondary particle shower
    - Secondary particles can produce direct ionization and more nuclear reactions
      - Recoil nuclei have short range but high LET
  - **Collisions with material nuclei produce displacement damage**
- Basic physics is similar to cosmic ray air showers except ±
  - Higher atomic number spacecraft target nuclei produce more secondary particles
  - Density of spacecraft materials >> density of air
- Minimum and Median Shielding Mass
  - **Inside ISS - US Lab**
    - **Minimum = 10 g/cm^2 Al**
    - **Median = 40 g/cm^2 Al**
  - **(DUWK¶V□DWPRVSKHUH□DW□□□□NP□DOWLWXGH□□**
    - **Minimum = 56 g/cm^2 air**
    - **Median = 84 g/cm^2 air**



This central Au on Au collision at 4 GeV/nucleon kinetic energy comes from the January 1996 run of E895. Ionization clusters in the EOS Time Projection Chamber are shown in red. The chamber length is about 2 meters.

Analysis of Data from Experiment E895 at the Alternating Gradient Synchrotron; Dieter Best, Gulshan Rai, and Hans-Georg Ritter, Lawrence Berkeley National Laboratory, 1998



WHY FLUKA? - Demonstrated successful applications include:

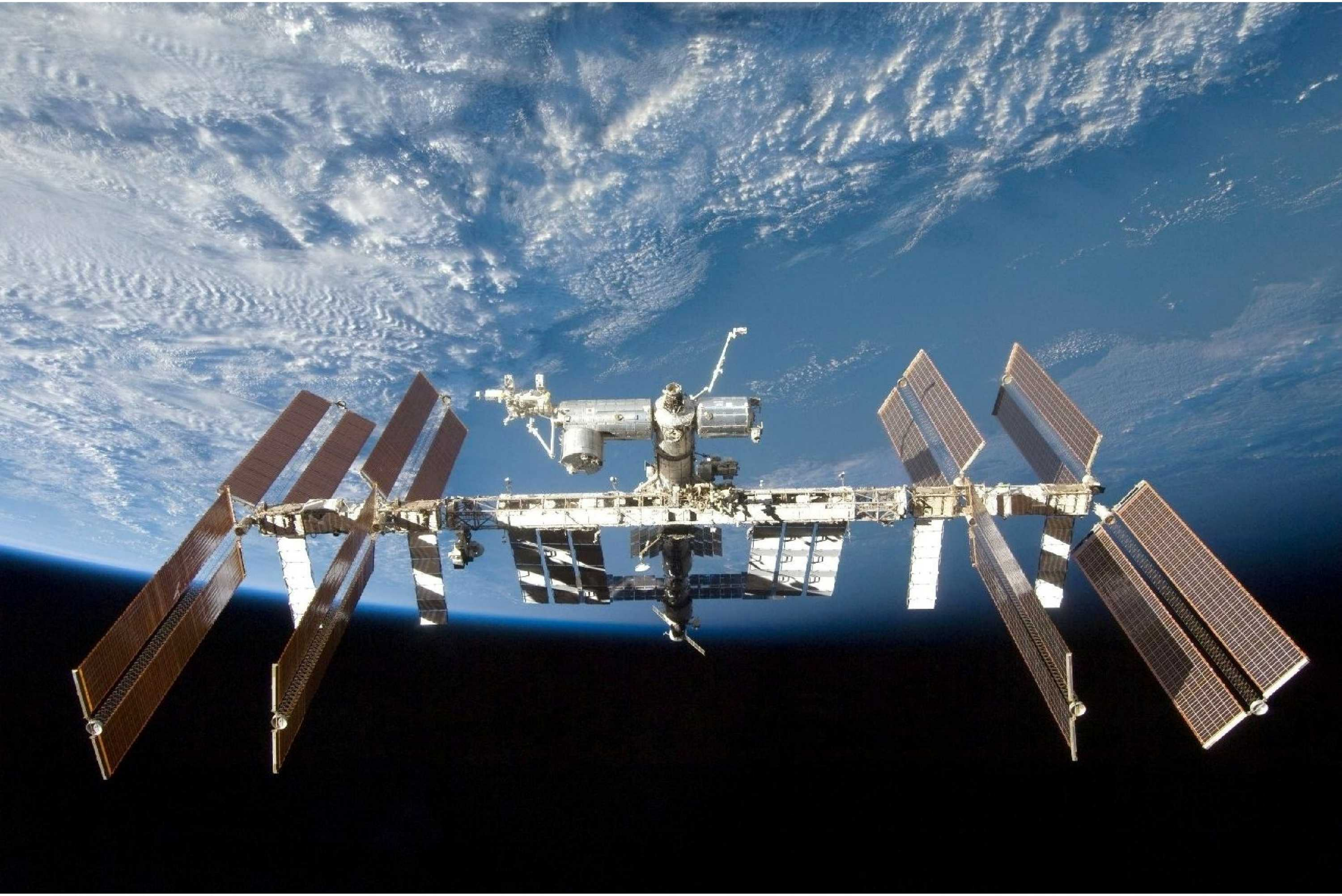
- *Cosmic ray physics*
- *Neutrino physics*
- *$FFHOHUDWRU□GHVLJQ□□*

Spacecraft SEU rate calculations and comparison with in-flight rates

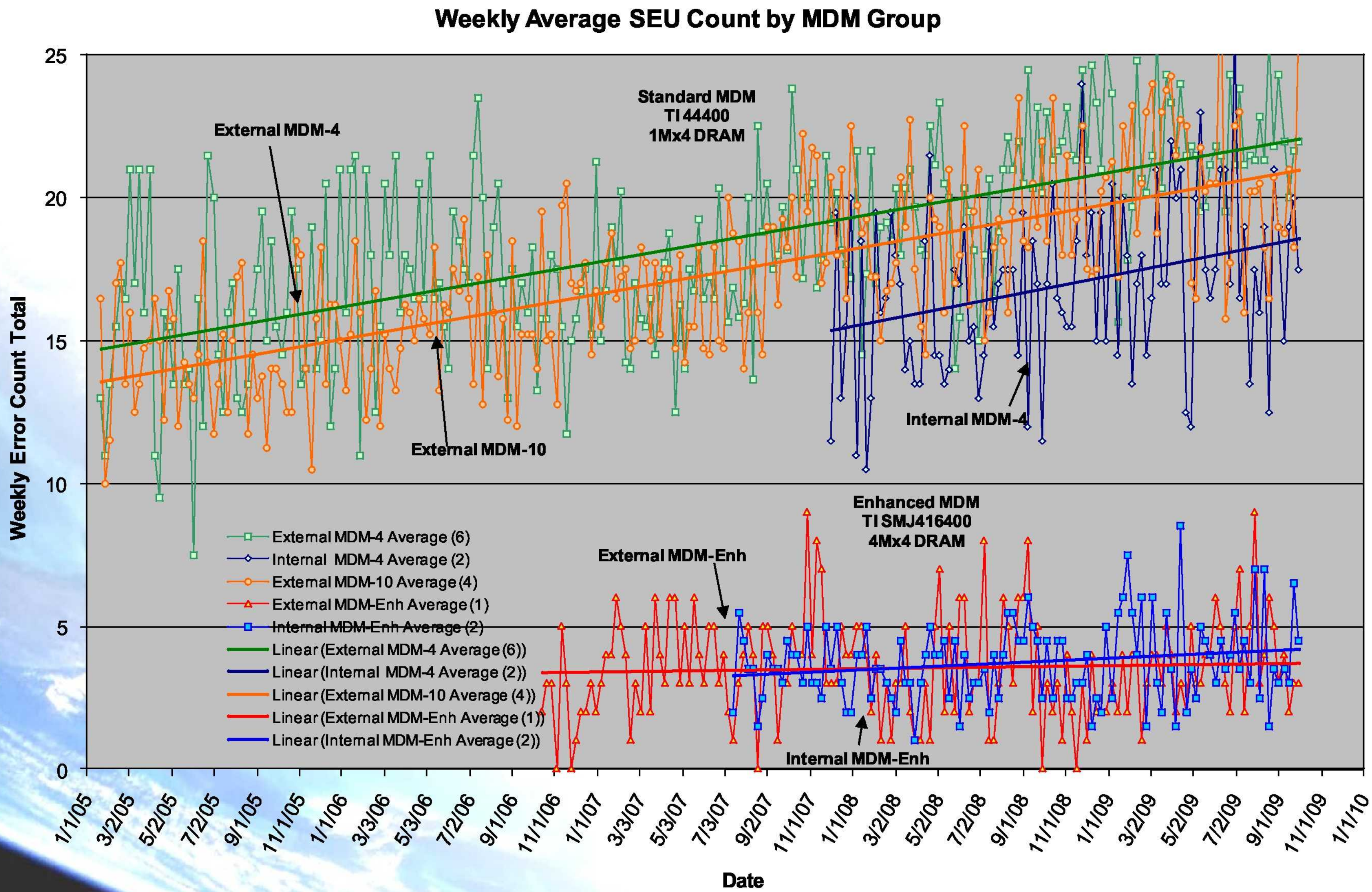
Success Metric Ratio = In-Flight SEU Rate/Predicted SEU Rate

Success Criteria **=** 0.1 < (In-Flight Rate/Predicted Rate) < 10

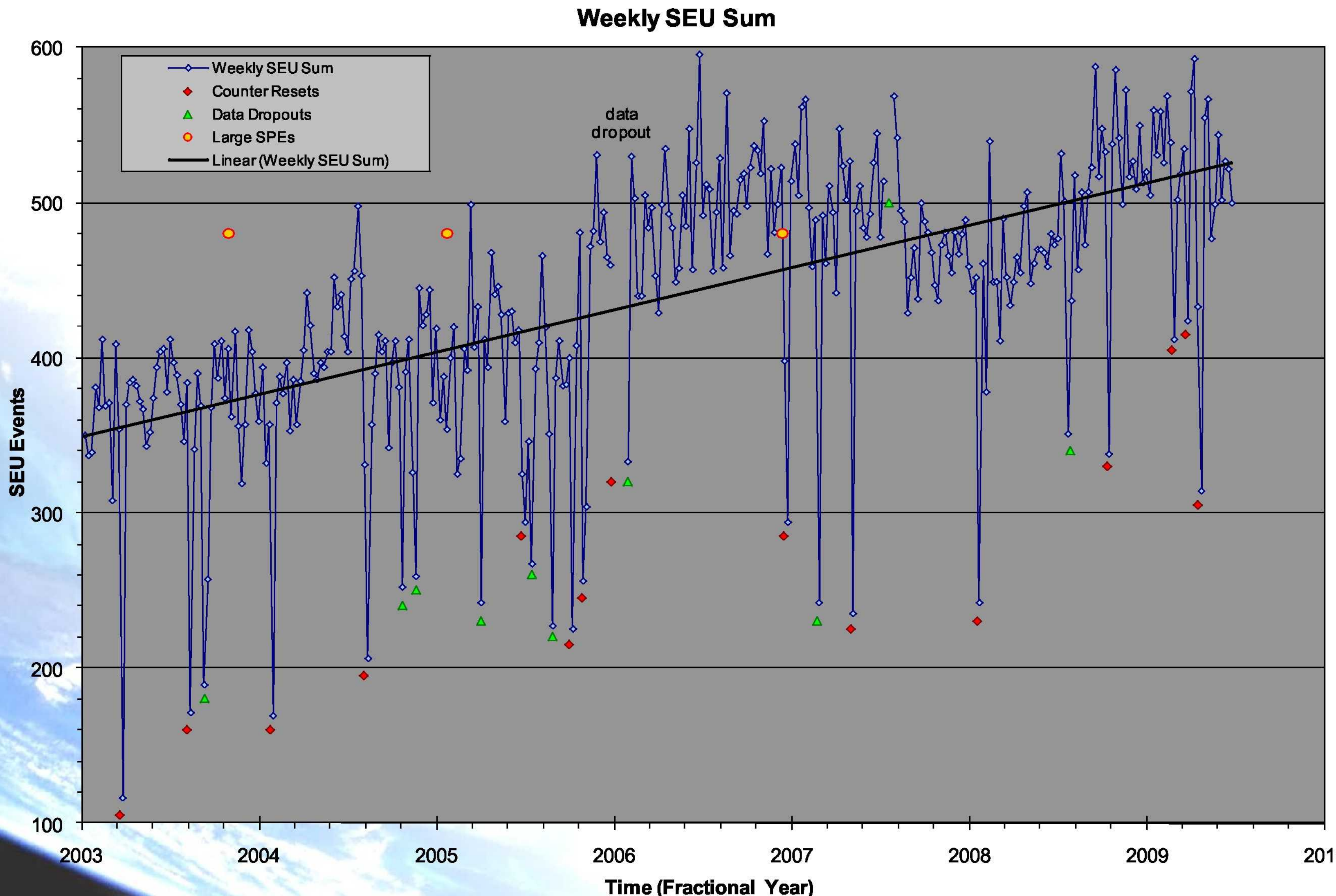
This section presents results only ± details of calculation methods, approximations used, and results will be treated in the section 3



S128E009988

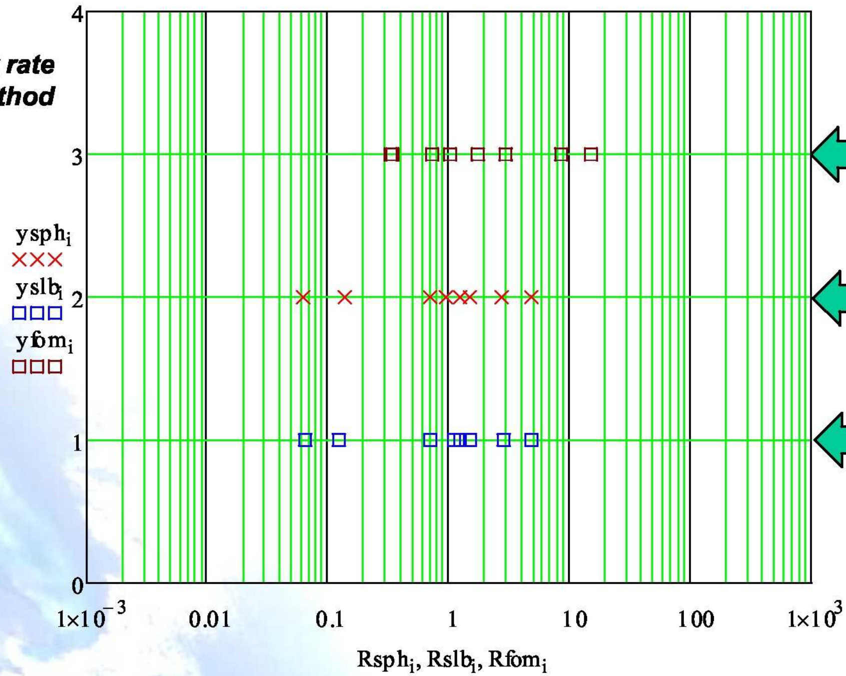


Weekly Average SEU Count by MDM Group
Weekly Error Count Total
Date
Standard MDM
TI 44400
1Mx4 DRAM
Enhanced MDM
TI SMJ416400
4Mx4 DRAM
External MDM-4
External MDM-10
Internal MDM-4
External MDM-Enh
Internal MDM-Enh
External MDM-4 Average (6)
Internal MDM-4 Average (2)
External MDM-10 Average (4)
External MDM-Enh Average (1)
Internal MDM-Enh Average (2)
Linear (External MDM-4 Average (6))
Linear (Internal MDM-4 Average (2))
Linear (External MDM-10 Average (4))
Linear (External MDM-Enh Average (1))
Linear (Internal MDM-Enh Average (2))
0
5
10
15
20
25
1/1/05
3/2/05
5/2/05
7/2/05
9/1/05
11/1/05
1/1/06
3/3/06
5/3/06
7/2/06
9/1/06
11/1/06
1/1/07
3/3/07
5/3/07
7/3/07
9/2/07
11/1/07
1/1/08
3/2/08
5/2/08
7/2/08
9/1/08
11/1/08
1/1/09
3/2/09
5/2/09
7/2/09
9/1/09
11/1/09
1/1/10


Weekly SEU Sum
600
500
400
300
200
100
SEU Events
Weekly SEU Sum
Counter Resets
Data Dropouts
Large SPEs
Linear (Weekly SEU Sum)
data
dropout
2003
2004
2005
2006
2007
2008
2009
2010
Time (Fractional Year)

ISS & Shuttle Success Metric Plot for 2 different spacecraft, 4 different parts, 3 different shielding mass environments

Y axis ± upset rate prediction method



FOM, figure of merit calculation

FLUKA sphere target calculation

FLUKA slab target calculation

X axis ± Success Metric Ratio = In-Flight Rate/Predicted Rate

See Appendix 2: Tables 1-5 for case specific details

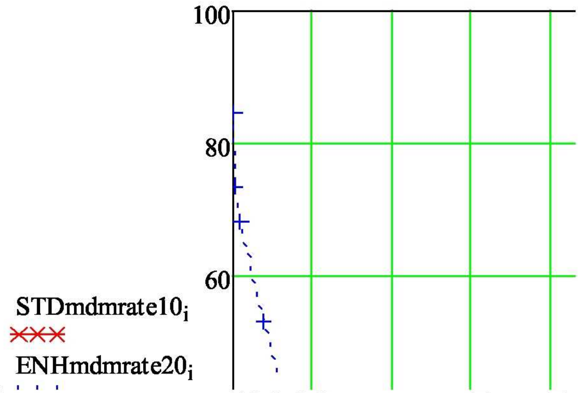
1) **FLUKA and FOM meet the success criteria or are very close in all cases**
2) **FLUKA results for the median shielding mass in the spherical target and the simple shielding mass in the slab target are in agreement**

Shielding mass effects: ISS FLUKA spherical target calculation

Y axis - ISS MDM DRAM, upsets per week per MDM

TI (4M x 4)
TI SMK416400

TI (1M x 4)
TMS44400



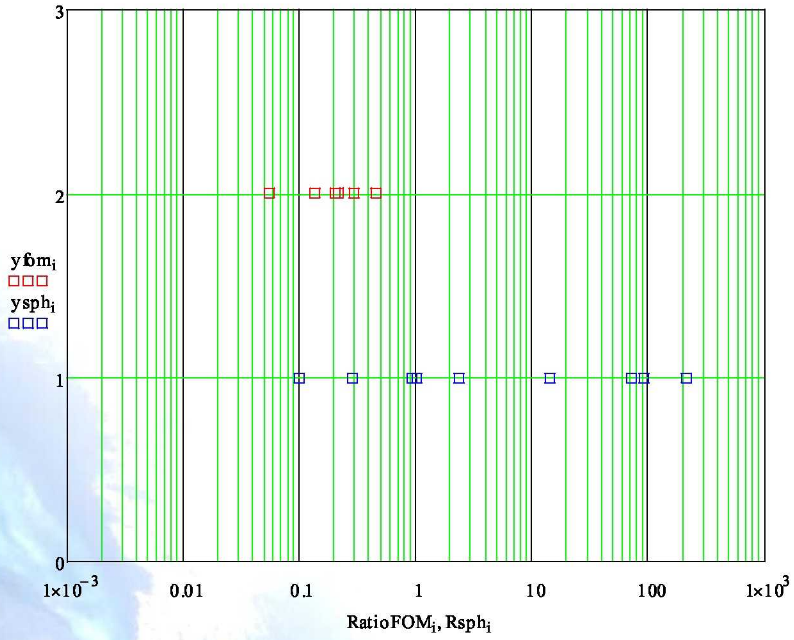
X axis - Median shielding mass in grams/cm²

FLUKA calculation methods predict shielding mass effects on SEU rate accurately for the standard ISS MDM DRAM but not as accurately for the Enhanced MDM DRAM.

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

Device	Rate Ratio - Flight	Rate Ratio ± FLUKA Calculation
TI (1M x 4) TMS44400	1.2	1.2
TI (4M x 4) TI SMK416400	0.9	1.8

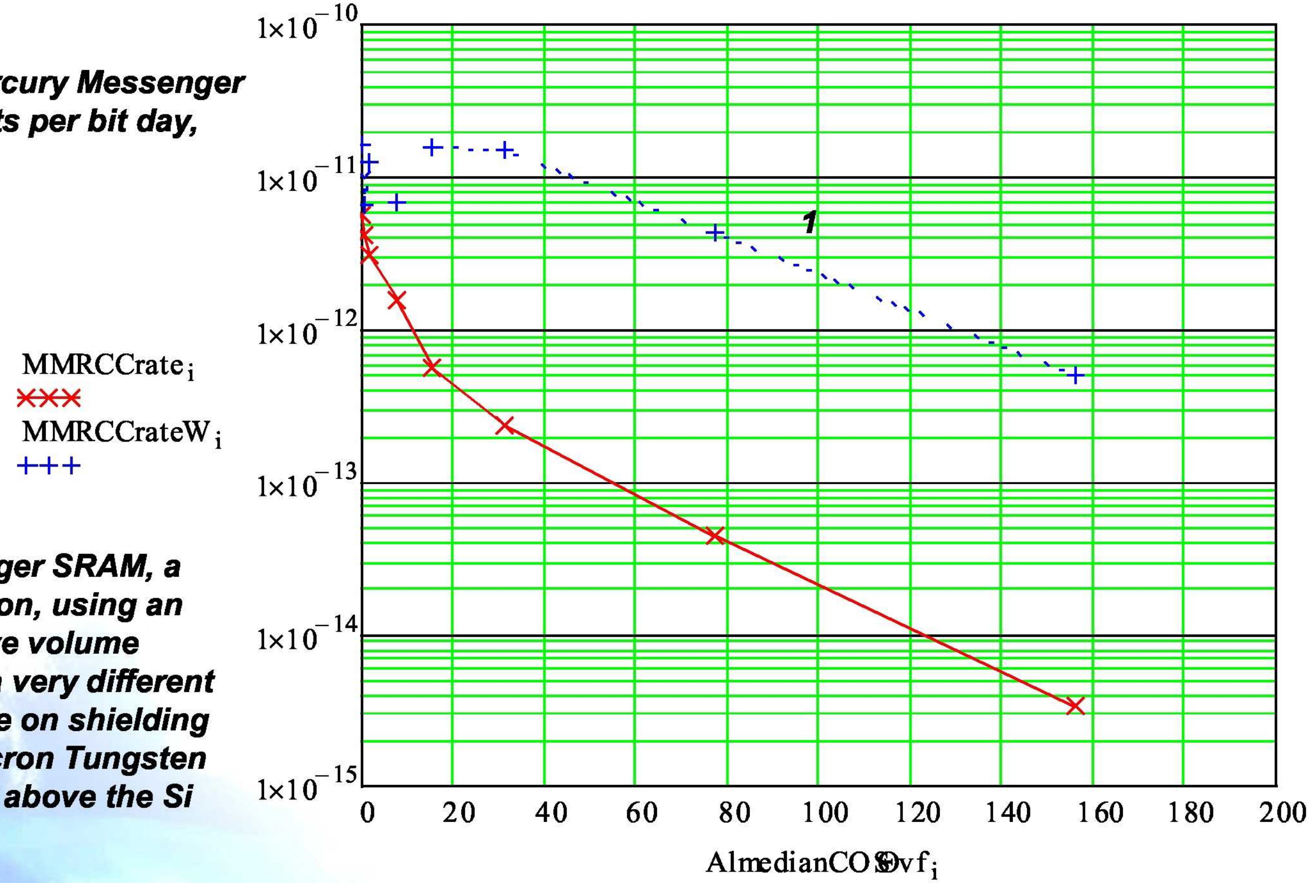
GEO/Interplanetary Success Metric Plot for 5 different spacecraft, 6 different parts and shielding mass environments



Mercury Messenger
Right Circular Cylinder (RCC) Target, T/W=1)
1

Mercury messenger shielding mass and tungsten over layer effects:

Y axis - Mercury Messenger SRAM upsets per bit day, RCC, T/W=1



For Mercury Messenger SRAM, a FLUKA rate calculation, using an approximate sensitive volume geometry, predicts a very different SEU rate dependence on shielding mass when the 1 micron Tungsten over-layer is present above the Si detector shell

X axis ± g/cm² Al median shielding mass (spherical target , cosine and solid angle corrections)

Calculating SEE Environments and rates with FLUKA:

Calculating LET Spectra

Calculating SEE rates

LET spectrum and SEE rate characteristics

FLUKA– Comprehensive basic physics with experimental validation

- *FLUKA is a multipurpose Monte Carlo energetic particle interaction and transport code*
  - *Monte Carlo code (more than 500,000 lines of Fortran Code)*
  - *Theory driven/experimentally benchmarked ± well tested physics based microscopic models (not semi-empirical look-up tables)*
    - Nucleus-nucleus collisions and secondary particle production included explicitly
  - *Benchmarked/verified extensively with high energy accelerator data*
    - not yet benchmarked for spacecraft SEE/TID/DD processes of interest
    - *FLUKA 2006.3b only partly successful (MRQW 2007)*
  - *FLUKA is not a tool kit ± the physical models are fully integrated*
  - *Full development of hadronic (secondary particle) showers*
  - *Complex user generated target geometries and target materials are possible*
- *Basic References*
  - *FLUKA version ± Fluka2008.3b results reported here*
    - *FLUKA results reported at MRQW 2007 generated with an earlier version of FLUKA*
  - *□7KH□)/8.$□FRGH□□'HVFULSWLRQ□DQG□EHQFKPDUNLQJ³□*□□%DWWLVWRQL□□6□□0XUDUR□□ Ferrari, S. Roesler, A. Fasso`, J. Ranft; Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6--8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007)*
  - *"FLUKA: a multi-SDUWLFOH□WUDQVSRUW□FRGH³□$□□)DVVRC□□$□□)HUUDUL□□-□□5DQIW□□DQ CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773*
  - *http://www.fluka.org/fluka.php*

"System Requirements"

- Run Times on the JSC/ES4 blade server
  - For a given CR spectrum and shielding mass or target configuration:
    - We run each cosmic ray element as a single job
    - Using a blade server we can submit all 24 to 27 jobs at once and they will execute in parallel
      - :H□KDYH□□□GXDO□TXDG□FRUH□³EODGHV´□GHGLFDWHG□WR□)/8.$□UXQV
      - (DFK□³FRUH´□LV□HTXLYDOHQW□WR□DQ□LQGHSHQGHQW□SURFHVVRU□IR
      - So, we have 24 processors available and can run up to 24 jobs in parallel
      - All the runs (24 to 27 batch jobs submitted in parallel) generally complete <u>within one week of submission</u> (see chart 18)
    - For a fixed number of primary particles, run time increases dramatically with particle atomic number
- Without the parallel processing capabilities of a blade server, execution times are too long to be of any practical use in most cases
  - Unless only one CR or Trapped particle species is of interest
- JSC/ES4 blade server specification:
  - Blade Hardware - HP ProLiant BL460c G1 x64
    - 2 Quad-Core Intel Xeon 2.6 GHz processors with 32 GB RAM and 146 GB storage
  - OS - RedHat ES5 version 5.2
    - Batch job queue management - MCS Portable Batch System
    - Fortran G77 compiler

Calculating Spacecraft SEE Environments with FLUKA

- **8VH□□JHQHULF□VODE□RU□FRQFHQWULF□VKHOO□³VSDFHFUDIW´□JHRPHWU VLOLFRQ□□RU□RWKHU□□³VFRULQJ´□GHWHFWRUV□EHWZHHQ□OD\HUV□RI□ shielding mass**
  - Simple, well defined shielding mass distribution and median shielding mass for each detector shell in each geometry
  - For the slab target geometry FLUKA simply fires particles into the center of the slab at normal incidence
  - For the concentric shell target, FLUKA fires randomly directed particles, selected from the spacecraft natural SEE environment, into the spherical shell structure from the outside (an ICRU isotropic flux)
- **FLUKA utilities randomly samples natural GCR and Trapped particle spectra to specify particle, particle kinetic energy, and particle direction**
  - **For each particle, FLUKA calculates through the target structure along the particle track:**
    - Energy loss (LET) of primary particles
    - Nuclear reactions and reaction products (secondary particle showers)
    - Energy loss (LET) and further nuclear reactions of secondary particles
- **A FLUKA utility generates the final product, i.e. the LET spectrum entering each Si detector shell which includes all contributions to LET from both primary particles and secondary particles formed in shielding**
  - **FLUKA also calculates nuclear reactions and recoil products interior to the Si layer but efficient methods for scoring those contributions to the detector shell LET spectrum are still in development at this time**
  - **FLUKA reports both forward and backward going particles with respect to the primary beam direction ± only forward going are reproted here.**

Calculating Spacecraft SEE Environments with FLUKA

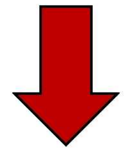
- **As employed here, FLUKA calculates an estimate of the LET spectrum internal to a microelectronic device die material located internal to spacecraft shielding mass**
  - Device or system SEE rates are then calculated using:
    - the FLUKA detector shell LET spectrum
    - device SEE characterization data
    - directional cross section models
  - We do not calculate SEE rates during the FLUKA calculation based on specific sensitive volumes imbedded in the Si detector shells at this time
- **The usual assumption is made**
  - Energy deposition and charge production in the target is proportional to the product of ion LET and ion track length and LET is assumed constant
- **:KDW¶V□QHZ□DQG□GLIIHUHQW□KHUH"□**
  - Detailed treatment of nucleus-nucleus collisions in spacecraft SEE transport calculations with comprehensive treatment of all secondary particles
  - As employed here, FLUKA calculates an estimate of the LET spectrum internal to a microelectronic device die material located internal to a spacecraft
    - Nuclear reactions internal to the detector shell are counted but the contributions of the nuclear reaction products to the detector shell LET spectra are not at this time
- **We compare the FLUKA SEE rate with the in-flight SEE rate for the applicable spacecraft median shielding mass**
  - Success Criteria - As a minimum, the on-orbit SEE rate calculation method should provide SEE rate estimates accurate to within a factor of 10 at one standard deviation when compared to available in-flight data

0.1 < (In-Flight Rate/Predicted Rate) < 10

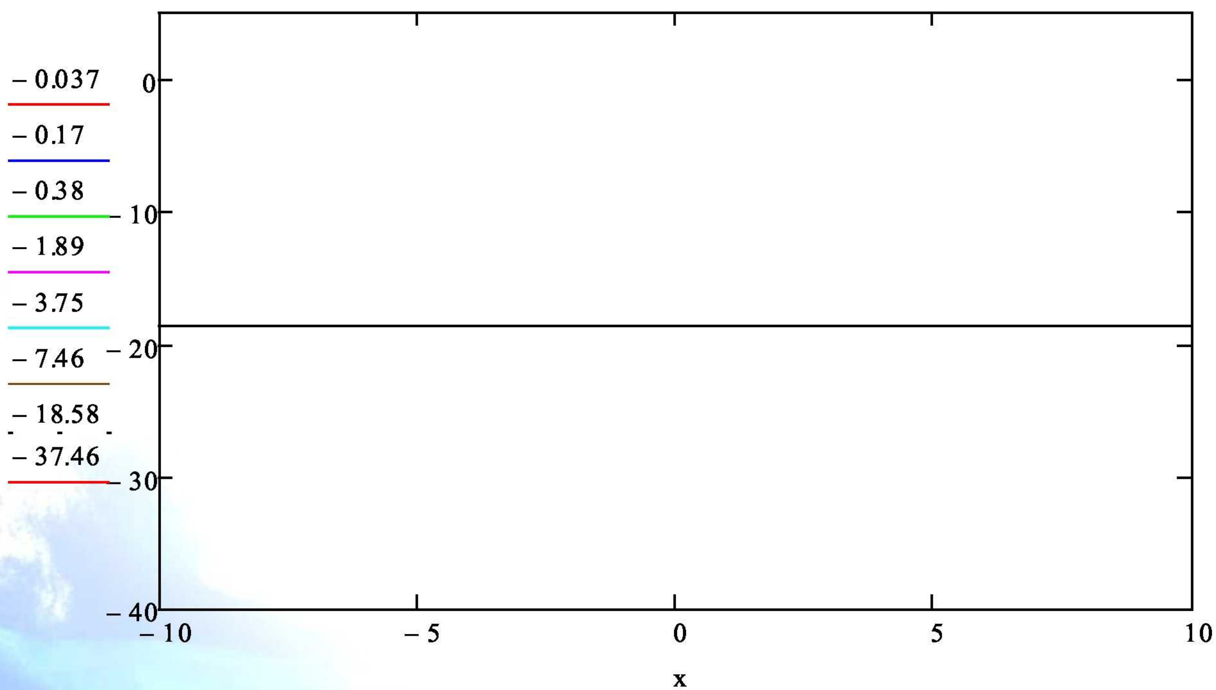
Success Metric Ratio = In-Flight Rate/Predicted Rate

FLUKA Al Slab Target
10 micron silicon detector layers

Particle Beam



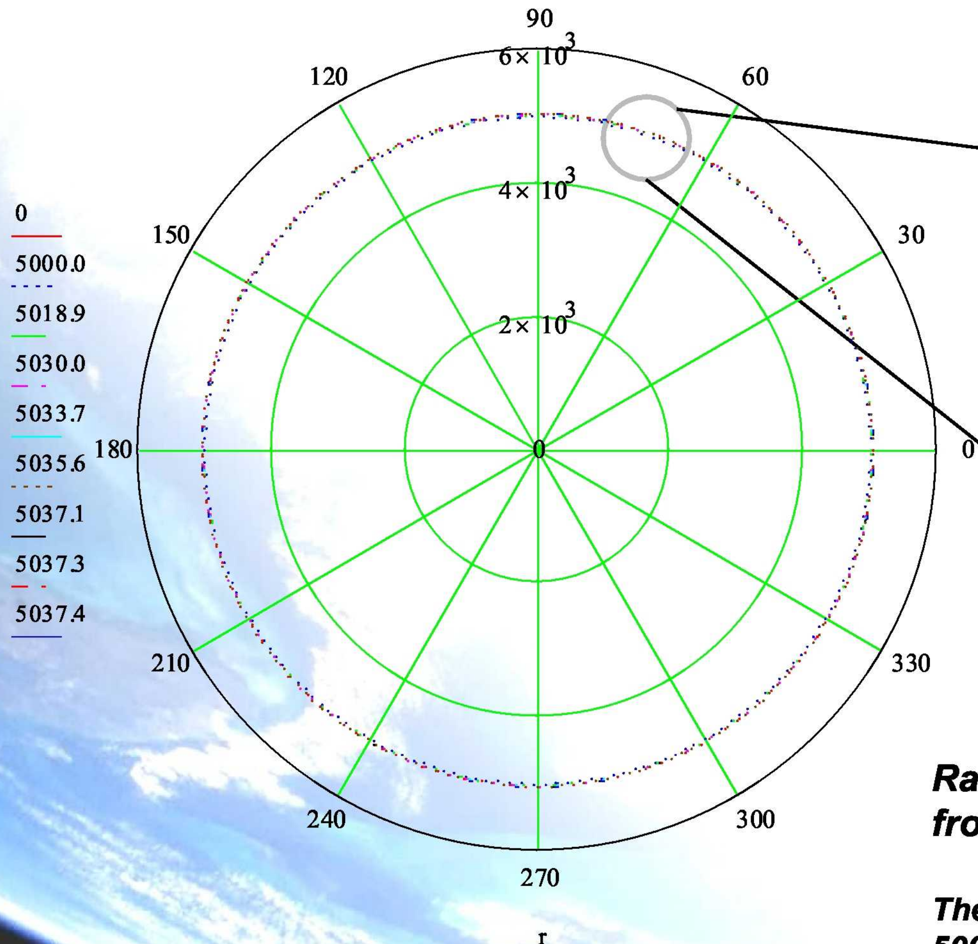
Distance from slab target surface to Si detector layer in cm.

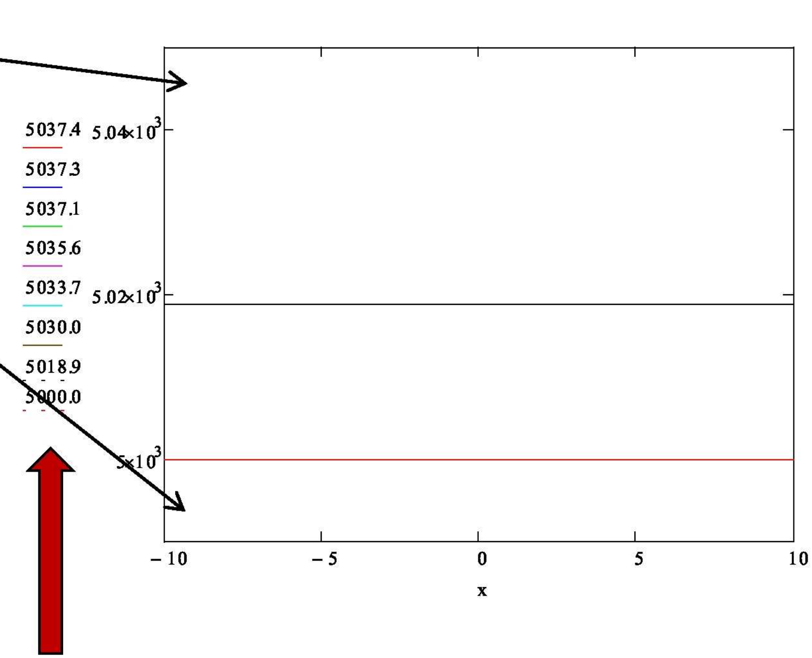


X axis - distance from center of cylindrical AL slab target in cm
(The actual slab target diameter used was 100 cm)
Y axis - distance form top surface of slab to Si detector slab in cm

FLUKA Concentric Al Sphere Target in Cross Section

100 micron Si detector shells, polar coordinates





Radial distance of Si detector shell from the center of the sphere.

The volume of the sphere at radii smaller then 5000 cm is treated as a perfect particle absorber in all FLUKA runs

FLUKA 2008.3b Calculation Details

- Number and identity of GCR primary particles
  - P, He, C, O, Mg, Si, Fe, and Zn only, no higher Z elements
  - Number of primaries particles for FLUKA runs are always greater than the expected CRÈME-96 weekly fluence (#/cm^2 week) to assure adequate and physically realistic statistics

Element	H trapped	H	He	C	O	Mg	Si	Fe	Zn
CREME fluence ISS orbit	2.5×10^7	3.5×10^5	4.7×10^4	1.3×10^3	1.3×10^3	261	193	157	0.14
CREME fluence Interplanetary	0.0	2.82×10^6	2.7×10^5	6.9×10^3	7.1×10^3	1.4×10^3	996	731	0.64
FLUKA primaries ISS orbit	9×10^7	9×10^6	9×10^5	9×10^5	6.8×10^5	4.5×10^5	4.5×10^5	2.3×10^5	9×10^4
FLUKA primaries Interplanetary	0.0	9×10^6	9×10^5	9×10^5	6.8×10^5	4.5×10^5	4.5×10^5	2.3×10^5	9×10^4

- Slab Target - particles flux at normal incidence - slab 10 meters in diameter
- Spherical Shell Target ± FLUKA isotropic (ICRU) flux utility provides an isotropic flux to the exterior surface of the sphere
  - Inner radius of concentric spherical shell structure = 5,000 cm = 50 meters
- LET scoring ± 0.0010 or 0.0100 cm thick Si scoring targets for both slab and concentric spherical shell targets for each shielding mass thickness
  - LET from all particles and interactions to include recoil products from proton and neutron reactions in the Si scoring target

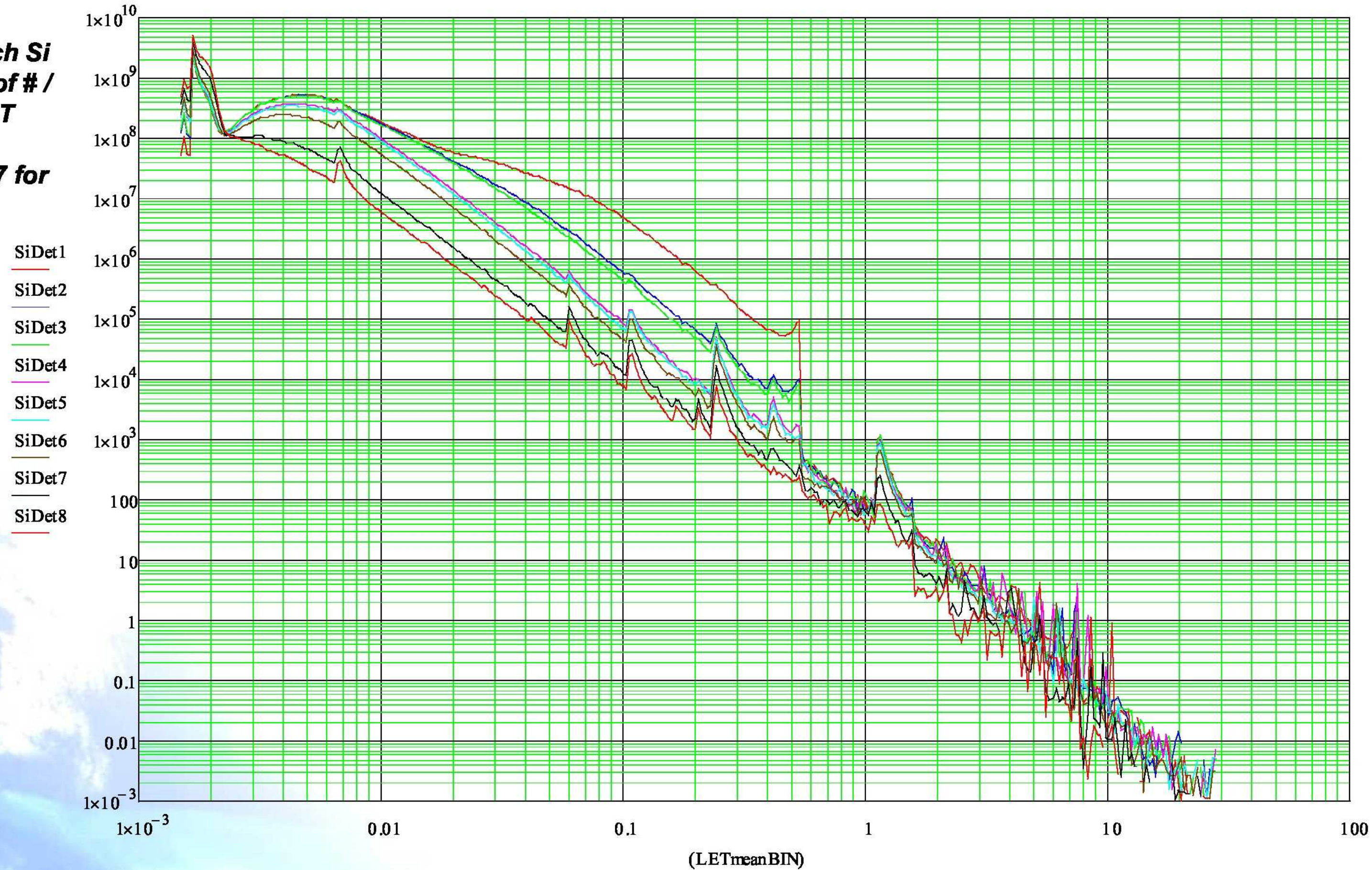
FLUKA 2008.3b Calculation Details

- ***FLUKA Target Shielding mass for each Si detector layer***
  - ***From outside to inside in g/cm² total shielding mass (overlying Al or PE + Si scoring target mass) exterior to each Si scoring detector (SiDet)***
  - ***Spherical shell and slab targets***
  - ***Total areal shielding mass - from outside to inside with respect to the entering particle beam***

FLUKA Target	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Slab	0.1	0.5	1.0	5.0	10.0	20.0	50.0	100
Sphere (minimum)	0.1	0.5	1.0	5.0	10.0	20.0	50.0	100
Sphere - median (cosine correction only)	0.14	0.70	1.40	6.90	13.7	27.3	68.1	137.2
Sphere ± median cosine and solid angle corrections	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2

FLUKA differential LET spectra – ISS Orbit – SLAB Target

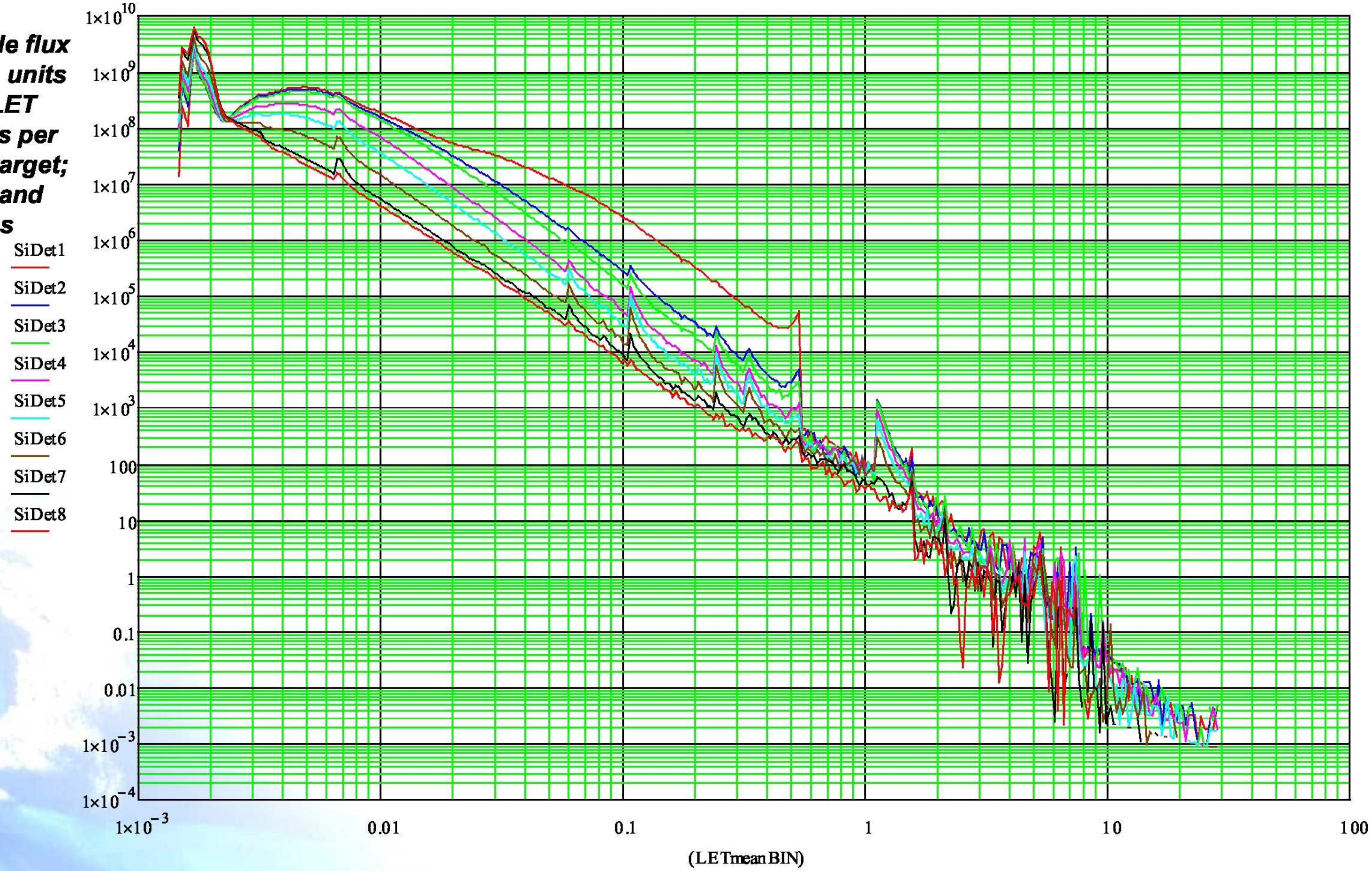
Y axis: on-orbit particle flux to each Si detector in units of # / [cm^2/week] per LET unit ± Shielding values per page 27 for SLAB target



X axis: particle LET in MeV x mg/(cm^2) (Si)

FLUKA differential LET spectra – ISS Orbit – SPHERE Target

Y axis: on-orbit particle flux to each Si detector in units of # / [cm²/week] per LET unit ± Shielding values per page 27 for SPHERE target; median mass, cosine and solid angle corrections



X axis: particle LET in MeV x mg/(cm²)

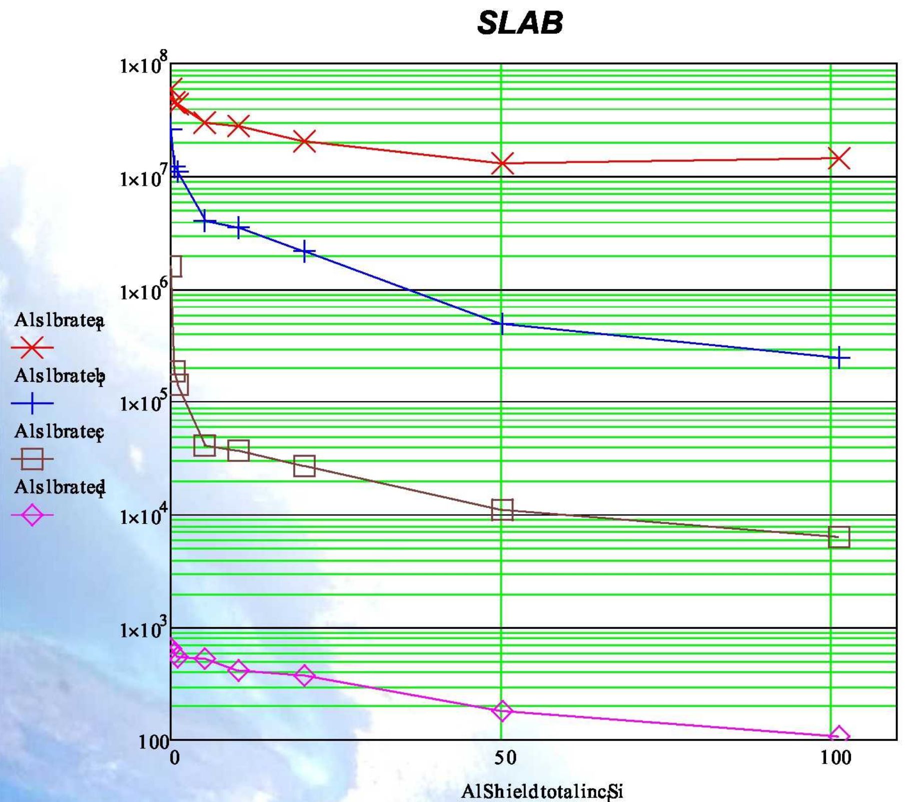
Device Directional Cross Sections

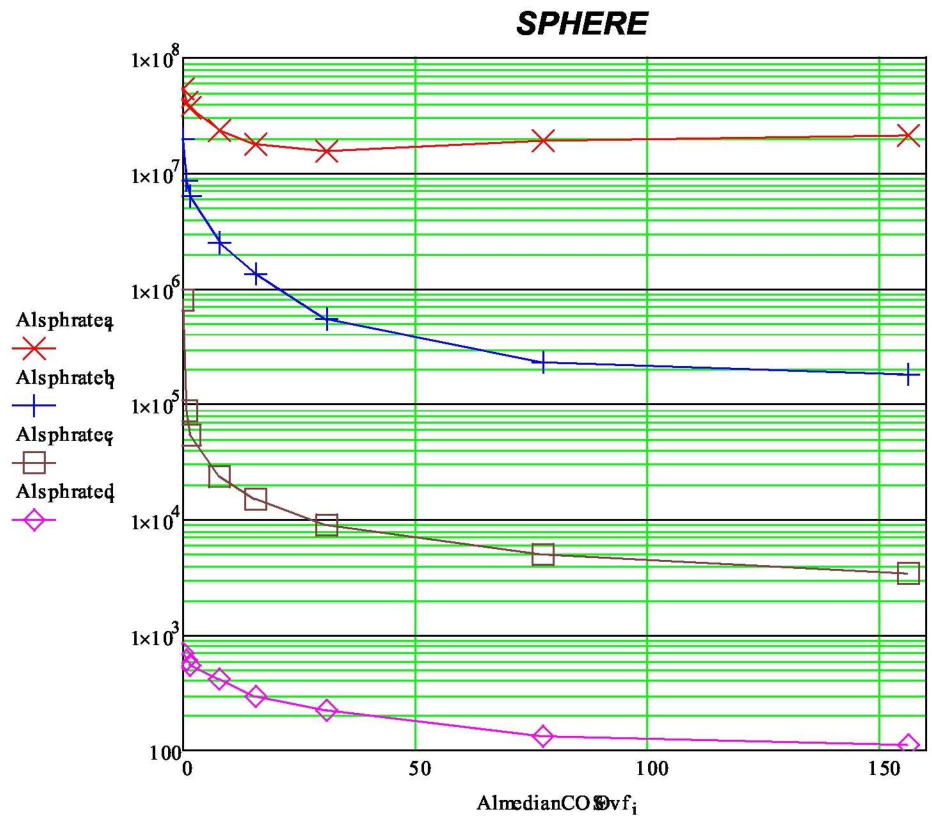
- Problem - isotropic flux on a generally anisotropic target
-

SEE Rate Calculations

- Generalized Rate Equation
  - Polar angle (

ISS orbit SEU rates for a simple Isotropic Step Function σ



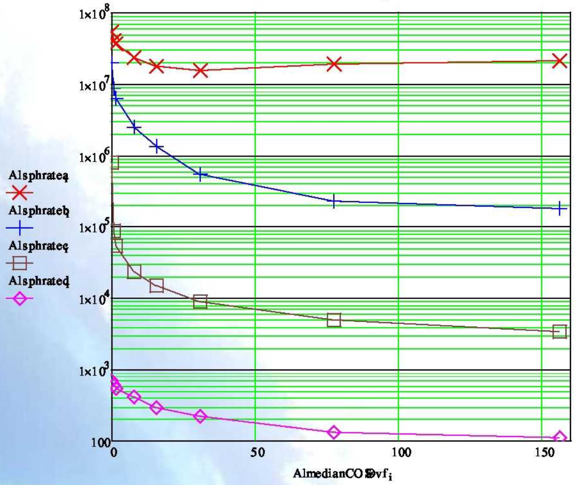


X axis ± g/cm² Al median shielding mass
(For the spherical target , cosine and solid angle corrections per page 27)

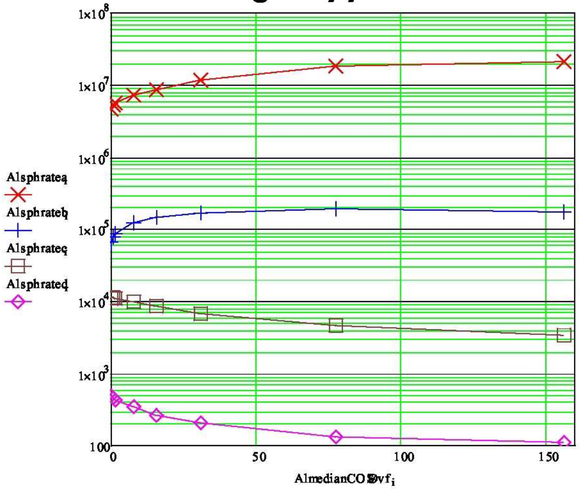
Y axis - number of step function isotropic target hits per week;

Which energetic nuclei contribute most to the step function SEU rates in LEO ?

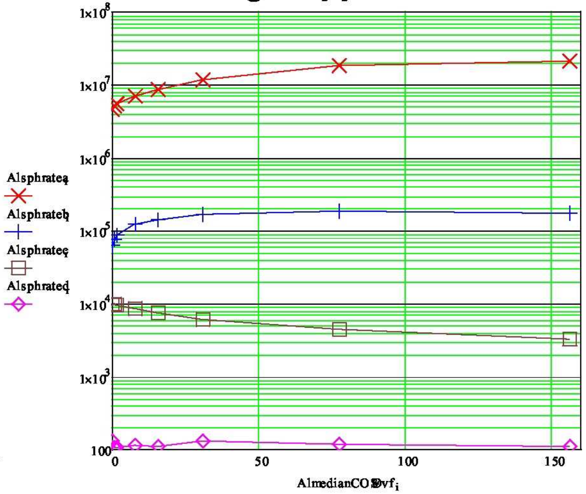
Full FLUKA LEO particle set



Full FLUKA LEO particle set removing Trapped radiation



Full FLUKA LEO particle set removing Trapped radiation and Fe

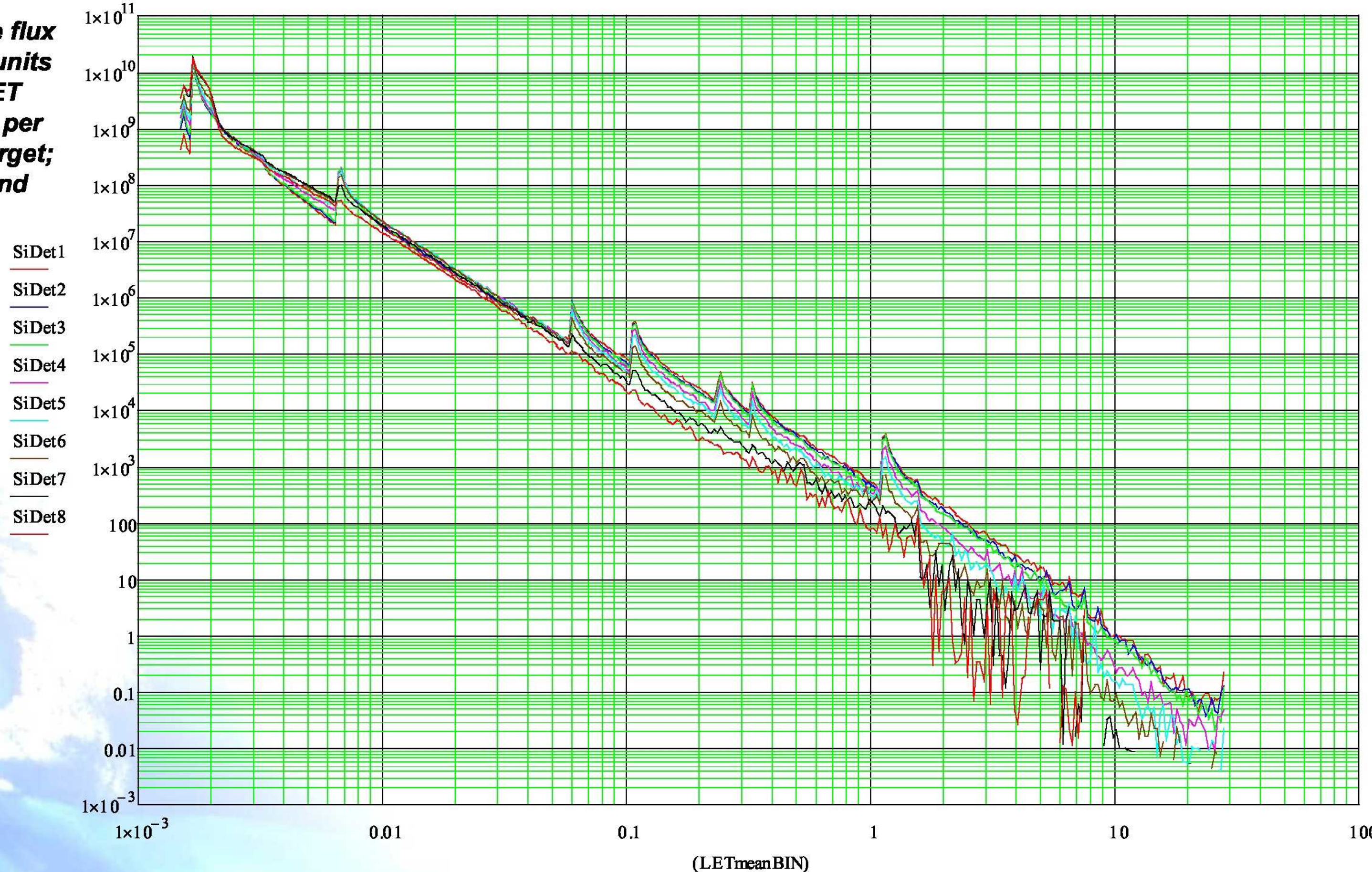


X axis ± g/cm² Al shielding mass, spherical target with cosine and view factor corrections per page 27

Y axis - number of step function isotropic target hits per week;

FLUKA differential LET spectra – GEO/Interplanetary – SPHERE Target – Silicon detector shells only

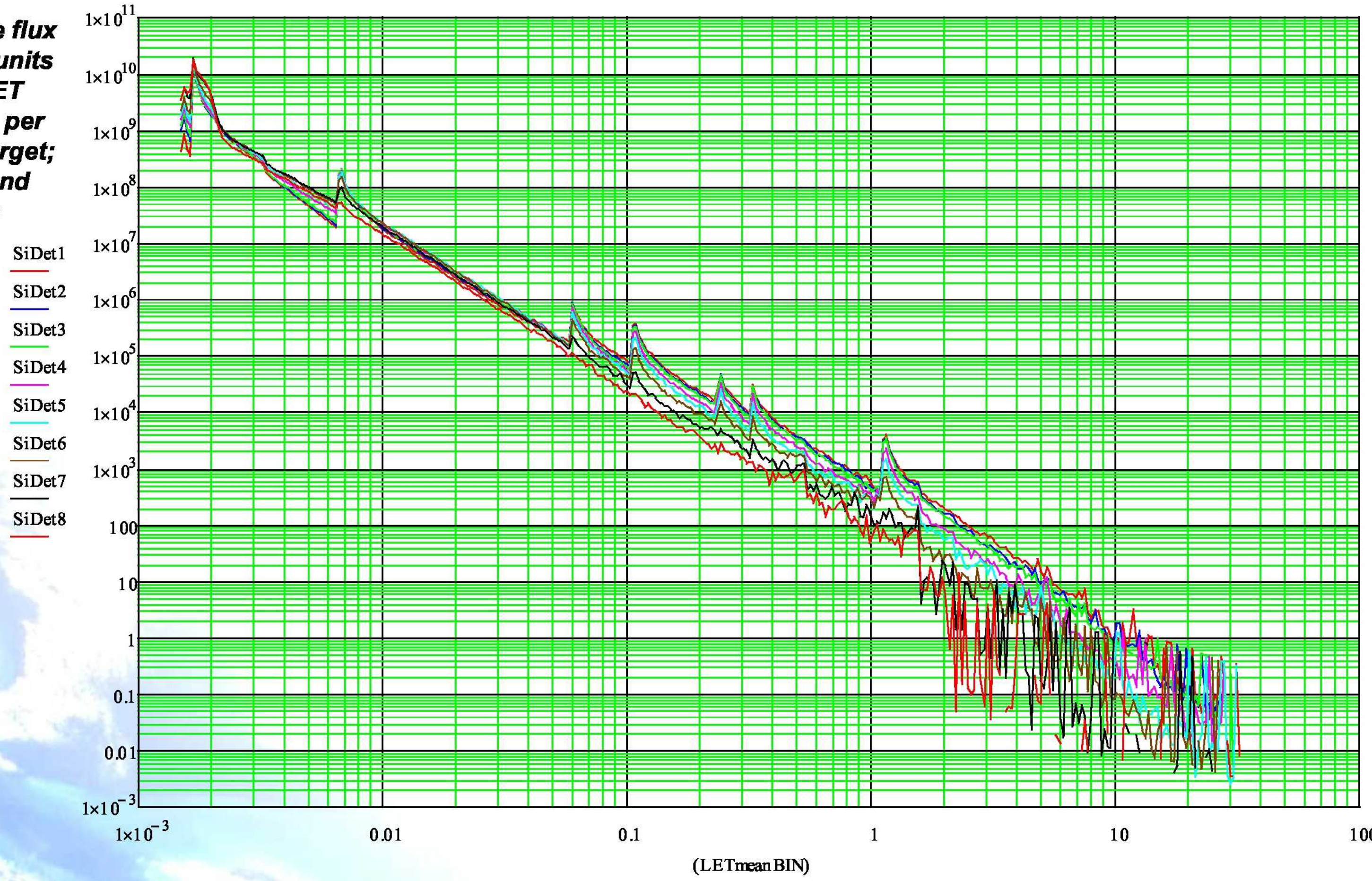
Y axis: on-orbit particle flux to each Si detector in units of # / [cm²/week] per LET unit ± Shielding values per page 27 for SPHERE target; median mass, cosine and solid angle corrections



X axis: particle LET in MeV x mg/(cm²) (Si)

FLUKA differential LET spectra – GEO/Interplanetary – SPHERE Target – Silicon detector shells with 1 micron tungsten over - layer

Y axis: on-orbit particle flux to each Si detector in units of # / [cm²/week] per LET unit ± Shielding values per page 27 for SPHERE target; median mass, cosine and solid angle corrections



X axis: particle LET in MeV x mg/(cm²)

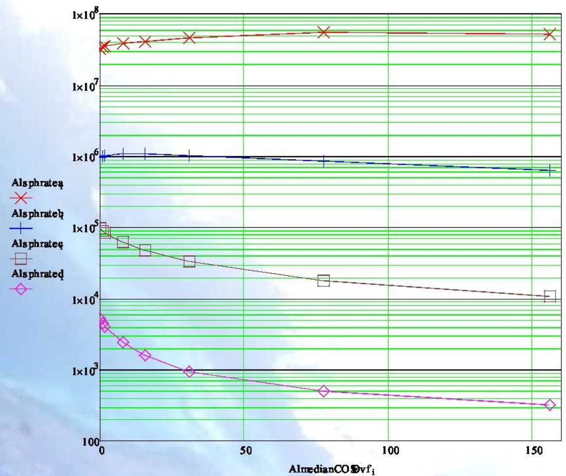
GEO/Interplanetary SEU rates for a simple Isotropic Step Function σ

X axis ± g/cm² median Al shielding mass, spherical target with cosine and solid angle corrections per page 27

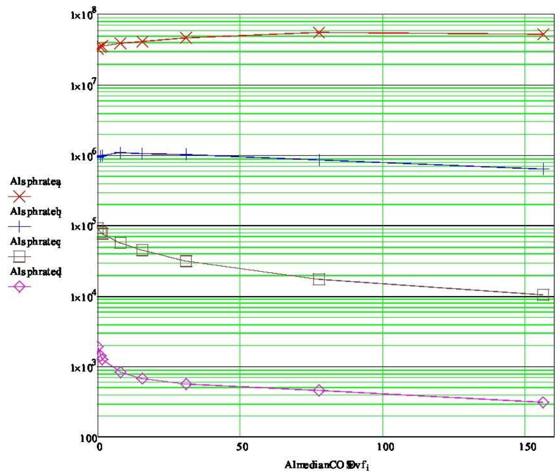
Y axis - number of isotropic target hits per week;

Which Cosmic ray nuclei contribute most to the step function SEU rates ?

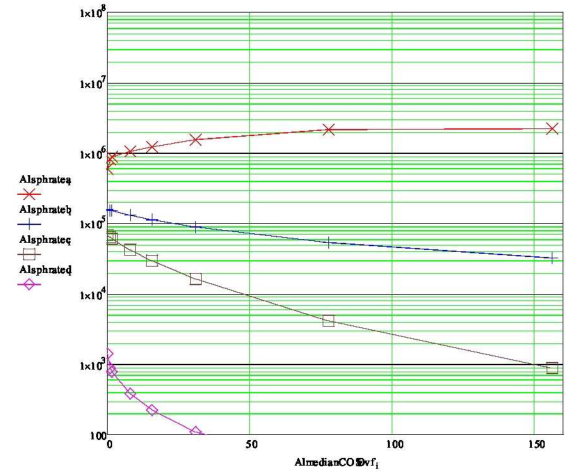
Full FLUKA Free Space GCR set



Removing Free Space GCR Fe



Removing Free Space GCR Fe, He, P



X axis ± g/cm^2 median Al shielding mass, spherical target with cosine and solid angle corrections per page 27

Y axis - number of isotropic target hits per week;

The answer depends on the step function threshold and the shielding mass.

Discussion Summary and Conclusions

- ***The FLUKA LET spectra in combination with heavy ion test data successfully predicts on-orbit SEE rates for several different CMOS SRAM, DRAM, and SDRAM components***
  - ***Success criteria 1 ± The FLUKA predicted rate is within a factor of 10 of the in-flight rate in many cases using approximate treatments of the directional cross section***
    - *Success criteria 2 - Shielding mass effectiveness may still be overestimated in some cases; accurate for the standard ISS MDM CMOS DRAM*
  - ***Compares favorably with the well documented Figure of Merit method for those cases where the Figure of Merit is applicable***
  - ***Predicts an increase in SEU rates produced by inclusion of a high Z element (W) in micro-device structure , all else being equal***
  - ***Predicts important effects of the shielding mass on the SEU rate increase produced by a high Z element (W) in the micro-device architecture***
- ***So what happened between MRQW 2007 and MRQW 2009?***
  - ***FLUKA 2006.3b vs. FLUKA 2008.3b***
  - ***7KH)/8.$ FRQVRUWLXP XSGDWHG WKH ³86(5<,(/' XWLOLW\ WR SURYL more accurate/complete reporting of high LET particles (personal communication, Professor L. S. Pinsky, Physics Department, University of Houston, FLUKA consortium)***

Discussion Summary and Conclusions

- **The FLUKA nuclear transport and reaction code can be developed into a practical tool for calculation of spacecraft and planetary surface asset SEE and TID environments**
  - **Nuclear reactions and secondary particle shower effects can be estimated with acceptable accuracy both in-flight and in test**
    - *More detailed electronic device and/or spacecraft geometries than are reported here are possible using standard FLUKA geometry utilities*
    - *Spacecraft structure and shielding mass*
    - *Effects of high Z elements in microelectronic structure as reported previously* (Schrimpf, Warren, Ball, Weller, Reed, Fleetwood, Massengill, Mendenhall, Rashkeev, Pantelides, Alles, 2008), (Warren, Sierawski, Reed, Weller, Carmichael, Lesea, Mendenhall, Dodd, Schrimpf, Massengill, Hoang, Wan, De Jong, Padovani , Fabula, 2007)
  - **Median shielding mass in a generic slab or concentric sphere target geometry are at least approximately applicable to more complex spacecraft shapes**
    - *Need the spacecraft shielding mass distribution function applicable to the microelectronic system of interest*
  - **SEE environment effects can be calculated for a wide range of spacecraft and microelectronic materials with <u>complete</u> nuclear physics**
    - *Evaluate benefits of low Z shielding mass can be evaluated relative to aluminum*
    - *Evaluate effects of high Z elements as constituents of microelectronic devices*
- **The principal limitation on the accuracy of the FLUKA based method reported here are found in the limited accuracy and incomplete character of affordable heavy ion test data**
  - **To support accurate rate estimates with any calculation method, the aspect ratio of the sensitive volume(s) and the**

Appendices

Appendix 1: FLUKA based in-flight SEE rate calculation details

FLUKA Physics Overview

- **Heavy ion interactions models**
  - **E > 5 GeV/n**
    - Dual Parton Model, DPMJET-III
  - **0.1GeV/n < E < 5GeV/n**
    - Relativistic Quantum Molecular Dynamics, RQMD 2.4
  - **E < 0.1 GeV/n**
    - Boltzmann Master Equation (BME) Theory
    - BME code ± not utilized in this study
- **Hadron - Nucleus Interactions**
  - **Resonance production and decay below a few GeV energy**
  - **Dual Parton model above a few GeV energy**
    - The PEANUT model includes a detailed Generalized Intra-Nuclear Cascade (GINC) and a pre-equilibrium stage
    - Gribov- Glauber multiple collision model included in a less sophisticated GINC
- **Transport of charged particles in matter**
  - **Bethe-Bloch theory**
    - Shell and other low energy corrections,
    - Density effects according to Sternheimer
    - 0ROLHUH¶V□WKHRU\□RI□PXOWLSOH□&RXORPE□VFDWWHULQJ
    - Restricted fluctuations (Landau fluctuations)
    - Delta ray production and transport optional

Typical FLUKA Input (run) Physics Card Choices

With the PRECISION default we request the following nuclear physics model

1) Dual Parton Model Jet (DPMJET)
   with Relativistic Quantum Molecular Dynamics (RQMD)
2) Evaporation, Coalescence, and Electromagnetic Dissociation are enabled
3) The Peanut model is activated at all energies

```
TITLE
CREME 96 GCR Spectrum
DEFAULTS                                                    PRECISIO
BEAM        -100.0                                          HEAVYION
BEAMPOS        0.0      0.0   5037.2
HI-PROPE      26.0     56.0      0.0      0.0      0.0      0.0
EVENTYPE                         2.0                         DPMJET
DPMJET         0.0      0.0      0.0                         my card
PHYSICS        3.0      0.0      0.0      0.0      0.0      0.  EVAPORAT
PHYSICS        1.0                                              COALESCE
PHYSICS        2.0      0.0      0.0      0.0      0.0      0.  EM-DISSO
PHYSICS      1000.    1000.    1000.    1000.    1000.    1000. PEATHRES
```

SEE Rate Calculations

- **Isotropic Target,** (Edmonds, Barnes and Scheick, 2000)

SEE Rate Calculations

Right Circular Cylinder (RCC) Target

- Barak, Akkerman, 2005
- Akkerman, Barak, 2002
- Barak, 2001
- Barak, Reed, LaBell, 1999

Note that we use the average (first moment) cord length for a given

Appendix 2: Spacecraft, Device Data, EDAC Protocols, and Shielding Mass Distribution Functions

ISS DRAM and SDRAM Characteristics

- **ISS standard multiplexer de-multiplexer (std-MDM) input-output control unit (IOCU) board**
  - Texas Instruments (TI) (1M x 4) 4 Mbit CMOS DRAM TMS44400
  - 3.3554 x 10^7 bits in each std-MDM
  - EPIC Process
  - 0.9 micron device scale
  - 5 V
- **ISS enhanced MDM DRAM (enh-MDM) IOCU board**
  - TI (4Mx4) CMOS DRAM TI SMJ416400
  - 1.342 x 10^8 bits in each enh-MDM
  - 5V
- **ISS High Rate Communications Outage Recorder Samsung KM44S32030T-GL CMOS SDRAM 128 Mbit (Rev. A, 34M/4)**
  - ISS High Rate Communications Outage Recorder (HCOR)
  - 2.115 x 10^{11} bits SDRAM in one HCOR (constant since launch± losses made up from reserves)
  - 0.35 micron process/device scale
  - 3.3 V

ISS DRAM and SDRAM Weibull Parameters

STD MDM DRAM cross section vs LET

$lostd := 0.99 \quad \sigma stdsat := 3.00 \cdot 10^{-7} \quad wstd := 7.7 \quad zstd := 1.3$

$$\sigma stdMDM(l) := \sigma stdsat \cdot \left[1 - \exp\left[-\left(\frac{l \cdot 0.1 - lostd}{wstd}\right)^{zstd}\right]\right]$$

ENH (Enhanced) MDM rates - SMJ416400

$loenh := 0.42 \quad \sigma enhsat := 1.10 \cdot 10^{-8} \quad wenh := 0.8 \quad zenh := 1.7$

$$\sigma enhMDM(l) := \sigma enhsat \cdot \left[1 - \exp\left[-\left(\frac{l \cdot 0.1 - loenh}{wenh}\right)^{zenh}\right]\right]$$

STD MDM DRAM (TMS44100DM-80) characterization - Harboe Sorensen, Muller, Daly, Nickson, Schmitt, Rombeck 1991)

ENH MDM DRAM characterization - Brown, R., IBM Manassas Test Report 2/23/93, and Falguere, Duzellier, Ecoffet, Tsourilo, 2000

Heavy ion data for Samsung 128Mbit (Rev. A, 34M/4) SDRAM: average values from Henson, MacDonald, and Stapor, NSREC Workshop 1999 - Samsung KM44S32030T-G Fig. 6, static tests

HCOR SDRAM upper bound cross section vs LET $\quad l := 1..500$

$losdram1 := 13 \quad \sigma satsdram1 := 5.859 \cdot 10^{-8} \quad wsdram1 := 30 \quad zsdram1 := 1$

$$\sigma HCORhigh(l) := \sigma satsdram1 \cdot \left[1 - \exp\left[-\left(\frac{l \cdot 0.1 - losdram1}{wsdram1}\right)^{zsdram1}\right]\right]$$

HCOR SDRAM lower bound cross section vs LET

$losdram2 := 14 \quad \sigma satsdram2 := 1.563 \cdot 10^{-8} \quad wsdram2 := 30 \quad zsdram2 := 1$

$$\sigma HCORlow(l) := \sigma satsdram2 \cdot \left[1 - \exp\left[-\left(\frac{l \cdot 0.1 - losdram2}{wsdram2}\right)^{zsdram2}\right]\right]$$

Heavy ion data for Samsung 128Mbit (Rev. A, 34M/4) SDRAM: values from SEAKER report SDRL number MD005, SDS Number SS-EE-008, transmittal number 00-HCOR-086, PDC Number FM27257,

HCOR rates -HCOR SDRAM cross section vs LET (SEAKR - low ke ions, normal incidence only except for one 40.5 degree angle and one 30.2 degree angle) - Boeing Dr. Tiru Rao-Sahib, and Aerospace Corp. Dr. Rocky Koga; U.C. Berkeley Cyclotron facility August 2, 2000.

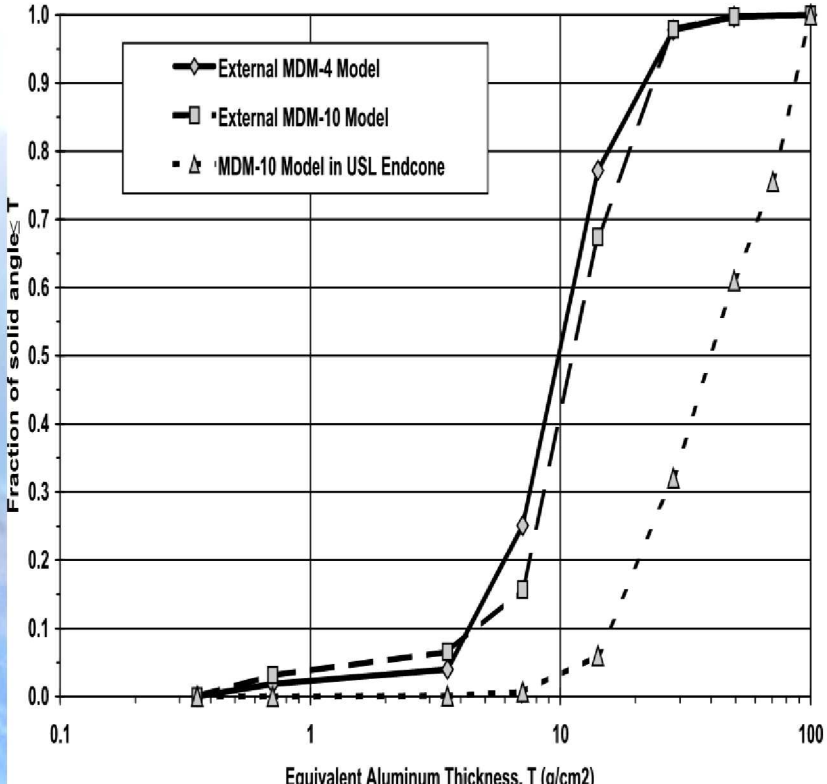
$losdram3 := 1.95 \quad \sigma satsdram3 := 1.863 \cdot 10^{-9} \quad wsdram3 := 30 \quad zsdram3 := 1.9$

$$\sigma HCOR3(l) := \sigma satsdram3 \cdot \left[1 - \exp\left[-\left(\frac{l \cdot 0.1 - losdram3}{wsdram3}\right)^{zsdram3}\right]\right]$$

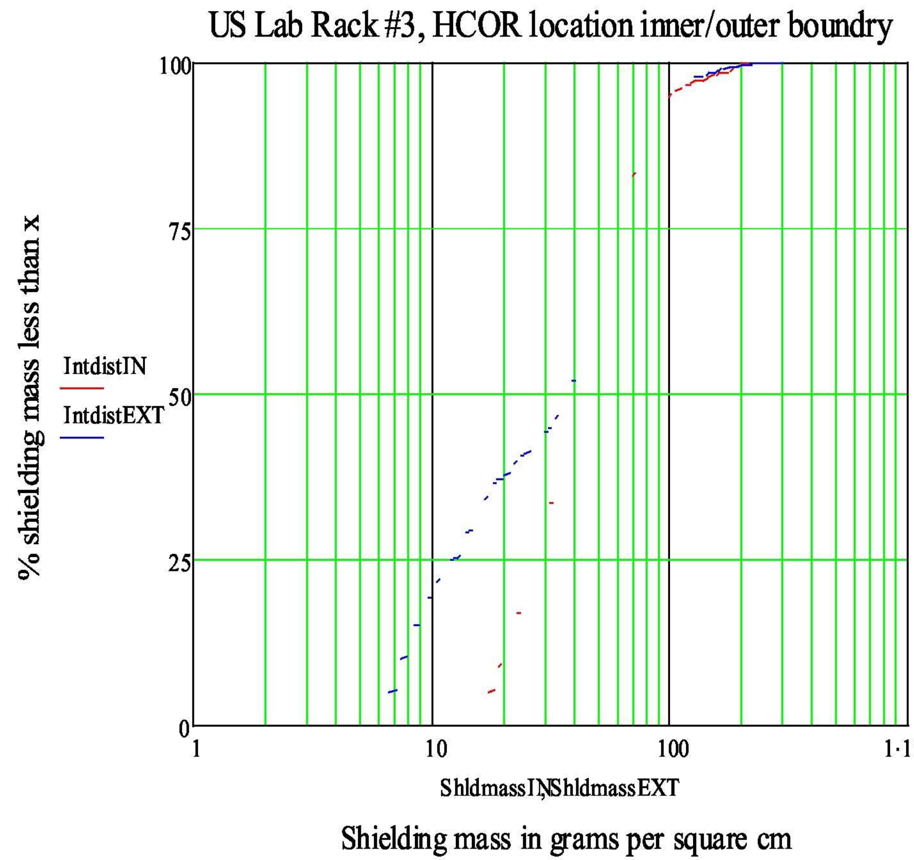
ISS: Memory device information and Error Detection and Correction (EDAC) Protocols

- Standard MDM Memory Information (MDM-4, MDM-10, MDM-16)
  - Part Number = TMS44400; Part Type = 1Mx4 DRAM
  - Manufacturer = Texas Instrument (TI)
  - Device count (per MDM) = 8
  - Total Bits (per MDM) = 33,554,432
  - Memory Scrub Rate = memory initiated every 8 usec, 8.2 seconds total to scrub entire DRAM memory
- Enhanced MDM Memory Information
  - Part Number = SMJ416400 ;Part Type = 4Mx4 DRAM
  - Manufacturer = Texas Instrument (TI)
  - Device count (per MDM) = 8
  - Total Bits (per MDM) = 134,217,728
  - Memory Scrub Rate = initiated every tbd usec, 28.6 seconds total to scrub entire DRAM memory
- HCOR Memory Device Information
  - Part Number = KM44S32030AT
  - Part Type = 128MB SDRAM
  - Manufacturer = Samsung Memory
  - Array = 140 128Mbit devices (70 stacks of 2 high)
  - Memory Utilization = 211,452 Mbits (this is the amount of scrubbed memory available for users, accounting for spare boards, image RAM, etc.)
  - Scrub Rate = 3.25 usec/row, 7.3 min/board, 96 minutes total to scrub entire memory (assumes minimal errors encountered. One scrub in progress at any given time). It is not possible to generate position data with the HCOR SDRAM error counter data because of the delay (up to 95 minutes) between an SEU event occurring and the EDAC scrub correcting and counting the error. Refresh rate for error counter telemetry is 1hz prior to January 12, 2005 and 0.1hz from January 12, 2005 to the present.

ISS Shielding Mass Distribution Functions: 1) Multiplexer/De-multiplexer (MDM) intrenal vs external 2) High Rate Communication Outage Recorder (HCOR)



MDM DRAM Structural Shielding Distributions.



HCOR SDRAM Structural Shielding Distributions.

Pendleton, G. N.; ³5DGLDWLRQ Dose Sector Shielding Track Analysis Tool Results for the International Space 6WDWLRQ Colsa Corporation Report Colsa-RTD-ISS-DR-03-008-DOC-B, Colsa Corporation, Huntsville Alabama, USA, March 2003 (Marshal Space Flight Center cooperative agreement NCC8-200, J. W. Watts Jr. Project Technical Representative)

Table 1: Std-MDM DRAM and enh-MDM DRAM upset rates are in reasonable agreement with FOM predictions and FLUKA predictions

Device	Number of bits Per MDM	Median Shielding Mass	Device FOM	FOM calculated upsets per week per MDM	FLUKA Sphere Target RCC calculated upsets per week per MDM (SV aspect ratio)*	Range of Observed In-Flight Upsets per week
TI (1M x 4) TMS44400	*$33.55x10^6$*	*40 g/cm^2*	*$1.93x10^{-8}$*	*16*	*17 (1)*	*15 to 18 Regression line*
TI (1M x 4) TMS44400	*$33.55x10^6$*	*10 g/cm^2*	*$1.93x10^{-8}$*	*59*	*21 (1)*	*18 to 22 Regression line*
TI (4M x 4) TI SMK416400	*1.342 x 10^8*	*40 g/cm^2*	*$8.98x10^{-9}$*	*2*	*26 (2)* (Falguere, Duzellier, Ecoffet, Tsourilo, 2000),	*3 to 4 Regression line*
TI (4M x 4) TI SMK416400	*1.342 x 10^8*	*10 g/cm^2*	*$8.98x10^{-9}$*	*9*	*48 (2)* (Falguere, Duzellier, Ecoffet, Tsourilo, 2000),	*3 Regression line*

Range of observed weekly rates from 2007 to 2009 for: 1) two std-MDMs at 40 g/cm^2, 2) six std-MDMs at 10 g/cm^2, 3) two enhanced MDMs at 40 g/cm^2, 4) one enhance MDM at 10g/cm^2

**** SV aspect ratio = Sensitive volume aspect ratio = T/W***

Table 2: HCOR CMOS SDRAM upset rates are in reasonable agreement with FOM predictions

Device Test Data	Number of bits per HCOR	Median Shielding Mass	Device FOM	FOM Calculated Upsets per week	FLUKA Sphere Target RCC calculated upsets per week per MDM (SV aspect ratio)*	Range of Observed In-Flight Upsets per week
Samsung KM44S32030T-GL (high						

Shuttle Flights	*Device*	*Median shielding Mass*	*Observation Time*	*Device FOM*	*Weibull*			

ISS016E028521

Table 6

Vehicle	System	Device	Observation Period	Median Shielding Mass
Cassini (interplanetary near 1 AU)	Solid state recorder	*OKI (4Mx1) DRAM 640/SSR*	*March 2000*	*3.4 g/cm^2* (NASA/JPL estimate)
SOHO (Interplanetary near 1 AU)	*Solid state recorder*	*TI (4Mx1) DRAM SMJ44100*	*1996 ± 2001*	*1.0 g/cm^2* (ESA estimate)
SOHO (Interplanetary near 1 AU)	*GOLF instrument*	*ATMEL CP65656EV-45 32kx8 SRAM*	*1996 - 2001*	*1.0 g/cm^2* (ESA estimate)
Mercury Messenger (Interplanetary near 1 AU)	*Solid state recorder*	*CMOS SRAM (4M x 1) (ASIC SEE/RAD KDUG³65$0□□´□*	*2004 to 2006*	*1.0 g/cm^2* (NASA estimate)
ETS-V (GEO)	Technical Data Acquisition Instrument (TEDA)	*NEC (64k x 1) CMOS SRAM µ PD4464D-20*	*1987-1997 2345 days sol max 1230 days sol min*	*5.8 g/cm^2* (JAXA estimate)
Thuraya (GEO)	Digital Signal Processor (DSP)	*0.25 □ SRAM, ASIC, IBM SA-12 Library*	*2001 - 2007*	*0.68 g/cm^2* (Boeing Satellite Development Center estimate)

Vehicle	*Device*	Median Shielding Mass	*FOM Calculated Upsets per bit day*	*FLUKA (RCC or Isotropic (ISO)) Calculated Upsets per bit day (SV aspect ratio)*	*In-Flight Upsets per bit day*	*References*
Thuraya (GEO)	*ASIC DSP 0.25*					

GEO/Interplanetary spacecraft device weibull parameters *

Thuraya DSP 0.25 micron CMOS megagate ASIC cross section vs LET, aspect ratio, T/W = 0.71, Hansen et al 2007

$lodsp := 2.7 \quad \sigma dspsat := 6.3 \cdot 10^{-8} \quad wdsp := 20.6 \quad zdsp := 1.2$

$$\sigma dsp(l) := \sigma dspsat \cdot \left[1 - \exp\left[-\left(\frac{l \cdot 0.1 - lodsp}{wdsp}\right)^{zdsp}\right]\right]$$

ETS-V. 64K SRAMNEC μ PD4464D-20; 8 devices in ETS-V SEL masked SEU in ground tests - SV depth 1 micron aspect ratio = T/W = 0.05, Goka, 1998

$`S := 0.5 \quad \sigma satETS := \frac{0.24}{64000} \quad wETS := 15 \quad zETS := 2.9$

$$\sigma ETS(l) := \sigma satETS \cdot \left[1 - \exp\left[-\left(\frac{l - loETS}{wETS}\right)^{zETS}\right]\right]$$

** Note ± Weibull parameters are either taken directly from references or were produced by nonlinear least squares fitting to heavy ion test data published in the references. The Pearson R correlation coefficients are greater than 0.9 in all cases.*

Mercury Messenger, aspect ratio approximately 1 , Reed et. al. 2007

$lomm := 0.3 \quad \sigma satmm := 4 \cdot 10^{-8} \quad wmm := 60 \quad zmm := 6$

$$\sigma mm_i := \sigma satmm \cdot \left[1 - \exp\left[-\left(\frac{LETmm_i - lomm}{wmm}\right)^{zmm}\right]\right]$$

Cassini Solid State Recorder, isotropic target - Swift 200

$locs := 0.5 \quad \sigma satcs := 4 \cdot 10^{-7} \quad wcs := 32 \quad zcs := 3$

$$\sigma cs_i := \sigma satcs \cdot \left[1 - \exp\left[-\left(\frac{LETcs_i - locs}{wcs}\right)^{zcs}\right]\right]$$

SOHO TISMX44100-80 4 M x 1, thinckess = 2 microns; Harboe-Sorensen, 2002

$loti := 0.7 \quad \sigma satti := 5 \cdot 10^{-7} \quad wti := 15 \quad zti := 2.7$

$$\sigma ti_i := \sigma satti \cdot \left[1 - \exp\left[-\left(\frac{LETti_i - loti}{wti}\right)^{zti}\right]\right]$$

SOHO MHS CP65656EV 32K x 8 SRAM; thickness = 2 microns - Harboe-Sorensen, 2

$locp := 1.9 \quad \sigma satcp := 6 \cdot 10^{-7} \quad wcp := 17 \quad zcp := 1.2$

$$\sigma cp_i := \sigma satcp \cdot \left[1 - \exp\left[-\left(\frac{LETcp_i - locp}{wcp}\right)^{zcp}\right]\right]$$

References

$NNHUPDQ□□$□□□%DUDN□-□□□7DFN□6WUXFWXUH□DQG□LW¶V□(IIHFWV□LQ□6PDOO□9ROXPHV□RI□6LOLFRQ□´□,(((□7UDQVDFWLRQV□ IEEE 49(6), December 2002, pp 3022-3031

%DUDN□□-□□□$NNHUPDQ□□$□□□³6WUDJJOLQJ□DQG□H[WUHPH□FDVHV□LQ□WKH□HQHUJ\□GHSRVLWLRQ□GLVWULEXWLRQ□LQ□VXEPLF Transactions on Nuclear Science, 52(6), December 2005, pp 2175-2181

%DUDN□□-□□□³(PSLULFDO□PRGHOLQJ□RI□SURWRQ□LQGXFHG□6(8□UDWHV□´□,(((□7UDQVDFWLRQV□RQ□1XFOHDU□6FLHQFH□□ 55(

%DUDN□□-□□□5HHG□□5□□$□□□/D%HO□□.□□$□□□³2Q□WKH□)LJXUH□RI□0HULW□0RGHO□IRU□6(8□5DWH□&DOFXODWLRQV□´□,(((Science 46(6), December 1999 , pp 1504-1510

Edmonds, L. D., Barnes, C. E., Scheick, L. Z., An Introduction to Space Radiation Effects on Microelectronics, NASA, Jet Propulsion Laboratory, California Institute of Technology , Pasadena, California, JPL Publication 00-06, May 2000

)DOJXHUH□□'□□□'X]HOOLHU□□6□□□(FRIIHW□□5□□□-IEEE Radiation Effects Data Workshop Proceedings, pp89-95, 2000.

)RVWHU□□&□&□□□2□1HLOO□□3□0□□□.RXED□□&□.□□□³5LVN□$VVHVVPHQW□%DVHG□RQ□8SVHW□5DWHV□)URP□+LJK□(QHUJ\□3 6LPXODWLRQV□´□,(((□7UDQVDFWLRQV□RQ□1XFOHDU□6FLHQFH□□□□□□□-296HSWHPEHU□□□□□□□□□SS□□□□□

)XONHUVRQ□□'□□(□□□1HOVRQ□□'□□.□□□&DUOVRQ□□5□□0□□□³%R[HV□□$Q□(QJLQHHULQJ□0HWKRGRORJ\□IRU□&DOFXODWLQ IEEE Transactions on Nuclear Science, 53(6), December 2006, pp 3329-3335

*DWHV□□0□□0□□□/HZLV□□0□□-□□□³6HPLHPSLULFDO□0HWKRG□IRU□3UHGLFWLQJ□6LQJOH□(YHQW□(IIHFW of Spacecraft and Rockets, 35(4), July - August 1998, pp 559- 564

*RND□□7□□□0DWVXPRWR□□+□□□6(8□GDWD□IURP□-DSDQHVH□VDWHOOLWHV´□ IEEE Transactions on Nuclear Science 45(6) December 1998 , pp 2771-2778

+DQVHQ□□'□/□□□-REH□□.□□□:KLWWLQJWRQ□□-□□□6KRJD□□0□□□6XQGHUODQG□□'□□□-Orbit Performance for a Commercial 0.25-□P□&026□65$0□´IEEE Transactions on Nuclear Science, 54(6), December 2007, pp 2525-2533

Harboe-Sorensen, R.; Daly, E.; Teston, F.; Schweitzer, H.; Nartallo, R.; Perol, P.; Vandenbussche, F.; Dzitko, H.; Cretolle, J., ³2EVHUYDWLRQ□DQG analysis of single event effects on-ERDUG□WKH□62+2□VDWHOOLWH´□ IEEE Transactions on Nuclear Science, 49(3), June 2002, pp 1345- 1350

Harboe-6RUHQVHQ□□5□□□0XOOHU□□5□□□'DO\□□(□□□1LFNVRQ□□%□□□6FKPLWW□□-□□□5RPEHFN□□)□□□-□□random access PHPRULHV□IRU□VSDFH□DSSOLFDWLRQ□´□5$'(&6, Sept 9-12, 1991

-RKQVWRQ□□$□+□□□³5DGLDWLRQ□HIIHFWV□LQ□DGYDQFHG□PLFURHOHFWURQLFV□WHFKQRORJLHV□□´□,(((□7UDQVDFWLRQV□R ne 1998, pp 1339-1354

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

/DFRH□□5□&□□□³,PSURYLQJ□,QWHJUDWHG□&LUFXLW□3HUIRUPDQFH□7KURXJK□WKH□$SSOLFDWLRQ□RI□+DUGQHVV□ ,(((□7UDQVDFW Nuclear Science, 55(4), August 2008, pp 1903-1925

Munteanu, D.; Autran, J.-L., ³□0RGHOLQJ□DQG□6LPXODWLRQ□RI□6LQJOH□(YHQW□(IIHFWV□LQ□'LJLWDO□'HYLFHV□DQG□,&V□´□,(((□7UDQVDFWLRQV Science, 55(4), August 2008, pp 1854-1878

2¶1HLOO□□3□□□%DGKZDU□□*□□□³6LQJOH□(YHQW□8SVHWV□IRU□□6SDFH□6KXWWOH□)OLJKWV□RI□1HZ□*HQHUDO□3XUSRVH□&R Transactions on Nuclear Science, 41(5), October 1994, pp 1755-1764

3HWHUVHQ□□(□□/□□□3LFNHO□□-□□&□□□$GDPV□□-□□+□□□³5DWH□3UHGLFWLRQV□IRU□6LQJOH□(YHQW□(IIHFWV´□,(((□7UDQVDFWLRQV□RQ□1XF Science, 39(6), December 1992, pp 1577-1598

3HWHUVHQ□□(□□□/□□□³3UHGLFWLRQV□DQG□2EVHUYDWLRQV□RI□6(8□5DWHV□LQ□6SDFH□´□,(((□7UDQVDFWLRQV□RQ□1XFOH 1997, pp 2174-2287

3HWHUVHQ□□(□□/□□□³7KH□6(8□)LJXUH□RI□0HULW□DQG□3URWRQ□8SVHW□5DWH□&DOFXODWLRQV□´□,(((□7UDQVDFWLRQV□R December 1998, pp 2550-2562 (Section VII, p. 2557)

3HWHUVHQ□□(□□□/□□□³3DUDPHWULF□DQG□7KUHVKROG□6WXGLHV□RI□6LQJOH□(YHQW□6HQVLWLYLW\□´□,(((□7UDQVDFWLR August 2007, pp 1392- 1405

5HHG□□5□$□□□.LQQLVRQ□□-□□□3LFNHO□□-□&□□□%XFKQHU□□6□□□0DUVKDOO□□-event effects ground testing and %HOO□□.□$□□□³6L on-RUELW□UDWH□SUHGLFWLRQ□PHWKRGV□□WKH□SDVW□□SUHVHQW□□DQG□IXWXUH□´□,(((□7UDQVDFWLRQV□RQ□1XF 622 ± 634

Reed, R.A.; Weller, R.A.; Mendenhall, M.H.; Lauenstein, J.-M.; Warren, K.M.; Pellish, J.A.; Schrimpf, R.D.; Sierawski, B.D.; Massengill, L.W.; Dodd, P.E.; Shaneyfelt, M.R.; Felix, J.A.; Schwank, J.R.; Haddad, N.F.; Lawrence, R.K.; Bowman, J.H.; &RQGH□□5□□□³,PSDFW□RI□,RQ□(QHUJ\□DQG□6SHFLHV□RQ□6LQJOH□(YHQW□(IIHFWV□$QDO\VLV□´□,(((□7UDQVDFWLRQV December 2007, pp 2312-2321

Schrimpf, R.D.; Warren, K.M.; Ball, D.R.; Weller, R.A.; Reed, R.A.; Fleetwood, D.M.; Massengill, L.W.; Mendenhall, M.H.; Rashkeev, 6□1□□□3DQWHOLGHV□□6□7□□□$OH[DQGHU□□-Scale Simulation of Radiation□(IIHFWV□LQ□(OHFWURQLF□'HYLFHV□´□,(((□7UD Nuclear Science, 55(4), August 2008, pp 1891-1902

6NXWQLN□□6□□□/DMRLH□□-Based Model for Single Event Upsets in SRAM FPGAs for Use in On-'HWHFWRU□(OHFWURQLFV□´□,(((□ Transactions on Nuclear Science, 53(4), August 2006, pp 2353-2360

6KDQH\IHOW□□0□5□□□6FKZDQN□□-□5□□□'RGG□□3□(□□□)HOL[□□-□$□□□³7RWDO□,RQL]LQJ□'RVH□DQG□6LQJOH□(YHQW□(IIHF 4XDOLILFDWLRQ□,VVXHV□IRU□0LFURHOHFWURQLFV□´□,(((□7UDQVDFWLRQV□RQ□1XFOHDU□6FLHQFH 1996 □□□□□□□□$XJXVW

6ZLIW□□□0□□□*XHUWLQ□□6□0□□□³In-flight observations of multiple-ELW□XSVHW□LQ□'5$0V´ IEEE Transactions on Nuclear Science 47 (6)* December 2000, pp *2386-2391*

Warren, K.M.; Sierawski, B.D.; Reed, R.A.; Weller, R.A.; Carmichael, C.; Lesea, A.; Mendenhall, M.H.; Dodd, P.E.; Schrimpf, R.D.; 0DVVHQJLOO□□/□:□□□7DQ□+RDQJ□□+VLQJ□:DQ□□'H□-RQJ□□-□/□□□3DGRYDQL□□5□□³Monte-Carlo Based On-Orbit Single Event 8SVHW□5DWH□3UHGLFWLRQ□IRU□D□5DGLDWLRQ□+DUGHQHG□E\□'HVLJQ□/DWFK□´□,(((□7UDQVDFWLRQV□RQ□1XFOHDU 2007, pp 2419-2425