HARDENED
ELECTRONICS
AND
RADIATION
TECHNOLOGY

Radiation Requirements and Requirements Flowdown:
Single Event Effects (SEEs) and Requirements

JAYCOR

MRC

ITI

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Abstract

- In this short course session, we will provide
  - An overview of the single particle-induced hazard for space systems as they apply in the natural space environment.
    - This shall focus on the implementation of a single event effects hardness assurance (SEEHA) program for systems including system engineering approach and mitigation of effects.
  - The final portion of this session shall provide relevant real-life examples of in-flight performance of systems.

Outline (1 of 2)

- Introduction
  - SEE: Impacting Space Operation
  - The SEE Hazard
  - SEE Effects
- Implementing SEEHA for a Space System
  - Hazard definition
  - SEE Requirements – a criticality-based method
  - Parts list review
  - Testing
  - Mitigative approaches
  - Monitoring performance during flight

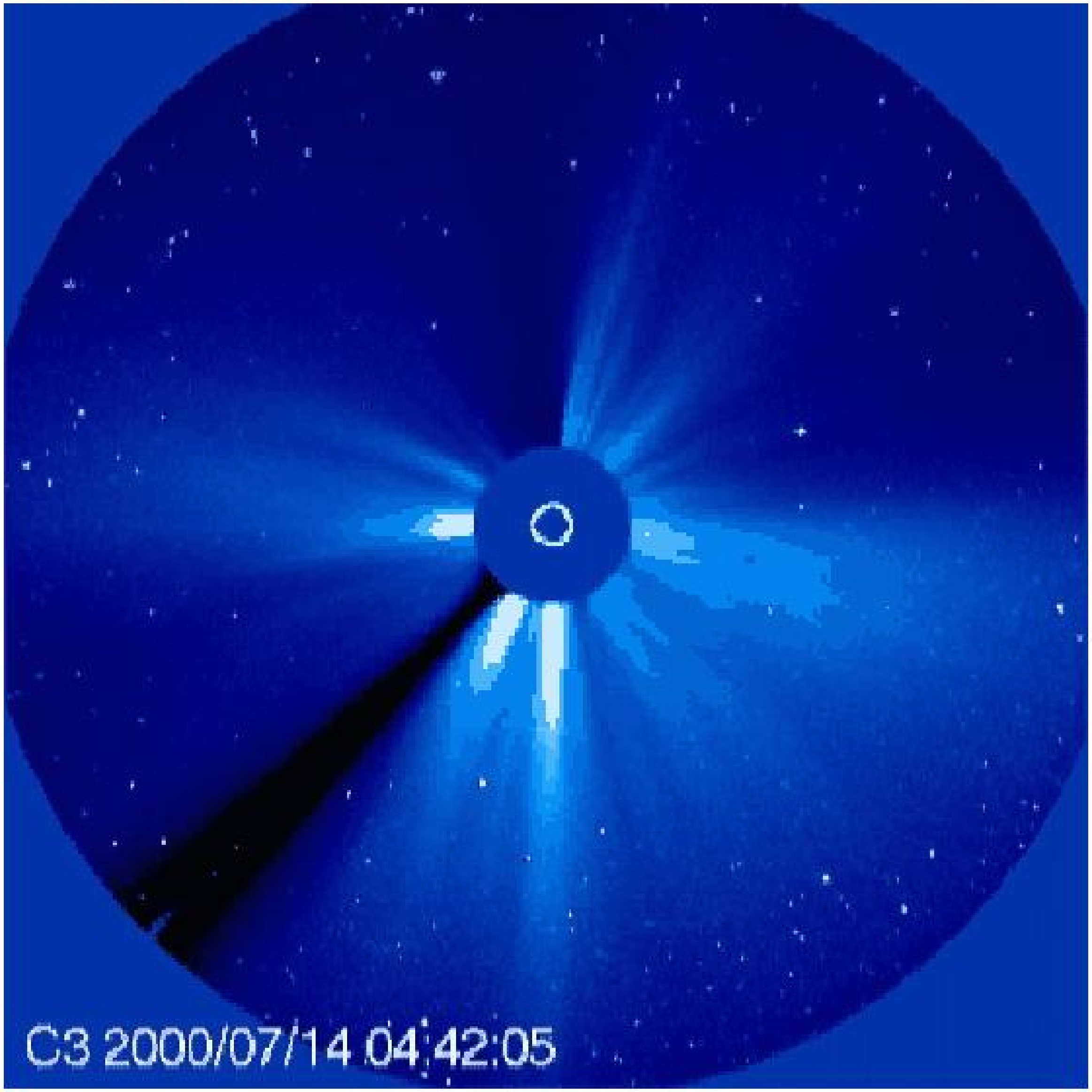
Outline (2 of 2)

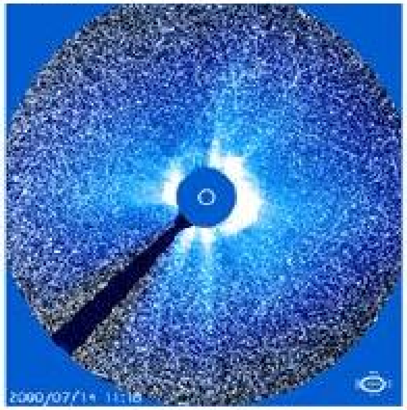
- In-flight performance of systems
  - Systems with appropriate mitigation – success stories
  - Anomalies in flight
    - Examples of impacts in-flight
- Summary
- Acknowledgements

Introduction

SOHO/LASCO C3 Coronograph

July 14, 2000

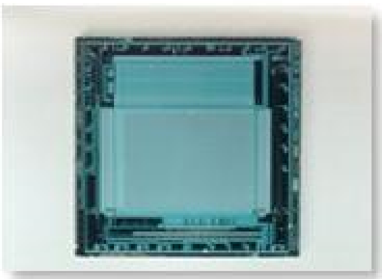




Solar storm induces single particle-induced transients in a Charge-Coupled Device (CCD)

SEE: Definition

- An SEE is caused by a *single charged particle* as it passes through a semiconductor material
  - Important attribute for impact on electronics is how much energy is deposited by this particle as it passes through a semiconductor material. This is known as Linear Energy Transfer or LET (dE/dX).
  - Particles of concern are
    - Heavy ions (direct ionization – the energy deposited directly by the particle)
      - A heavy ion is a charged particle (H, He, Fe, etc)
    - Protons (indirect ionization – the energy deposited by the nuclear reaction particles from collisions with the protons)
      - Very sensitive electronics or optical devices may also have direct ionization impacts from protons
      - Neutrons have similar mechanisms (avionics issues)

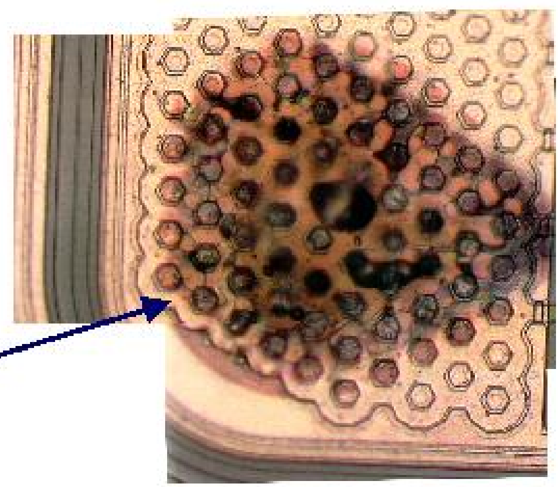


A 1,300,000 pixel CMOS Image Sensor for high-Resolution Digital Cameras

SEE: The Effects

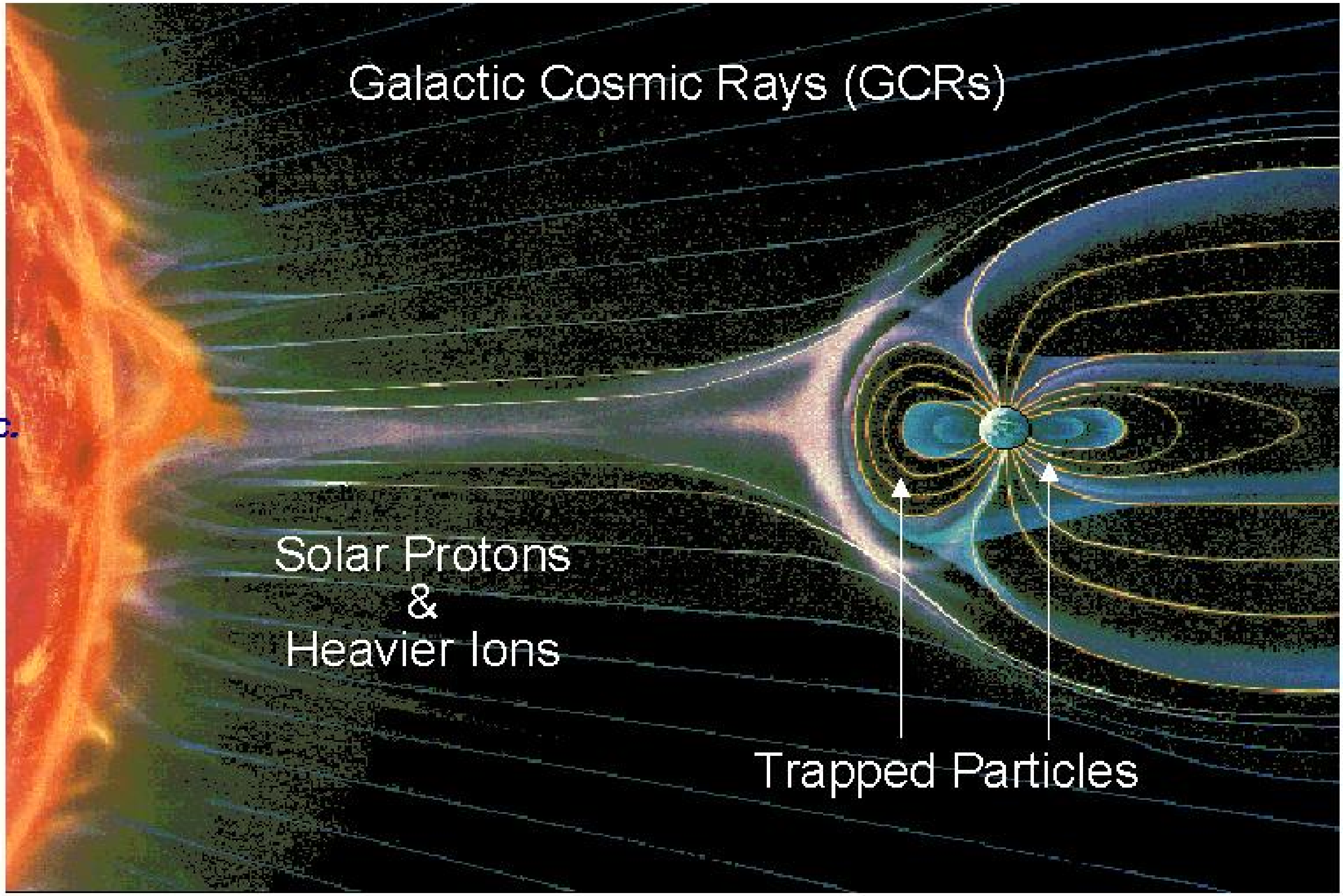
- **Effects on electronics**
  - If the LET of the particle (or reaction) is greater than the <the> minimum required amount of deposited energy or critical charge, an effect may be seen
  - Effects include
    - Soft errors such as upsets (SEUs) or transients (SETs), or
    - Hard errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)
- **Severity of effect is dependent on**
  - type of effect
  - system criticality

Destructive event in a COTS 120V DC-DC Converter
after O'Bryan, 2002



Space Radiation Environment

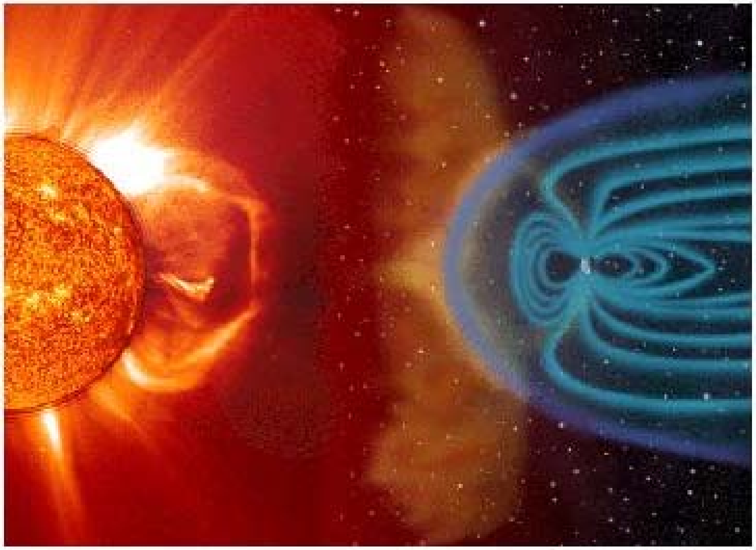
Nikkei Science, Inc.
of Japan,
by K. Endo



Deep-space missions may also see: neutrons from background or radioisotope thermal generators (RTGs)

SEE and the Space Environment

- Three portions of the natural space environment contribute to the SEE hazard
  - Solar particles
    - Protons and heavier ions
  - Free-space particles
    - GCR
      - For earth-orbiting craft, the earth's magnetic field provide some protection for GCR
  - Trapped particles (in the belts)
    - Protons including in the South Atlantic Anomaly (SAA)
- Hazard observed is a function of orbit and timeframe

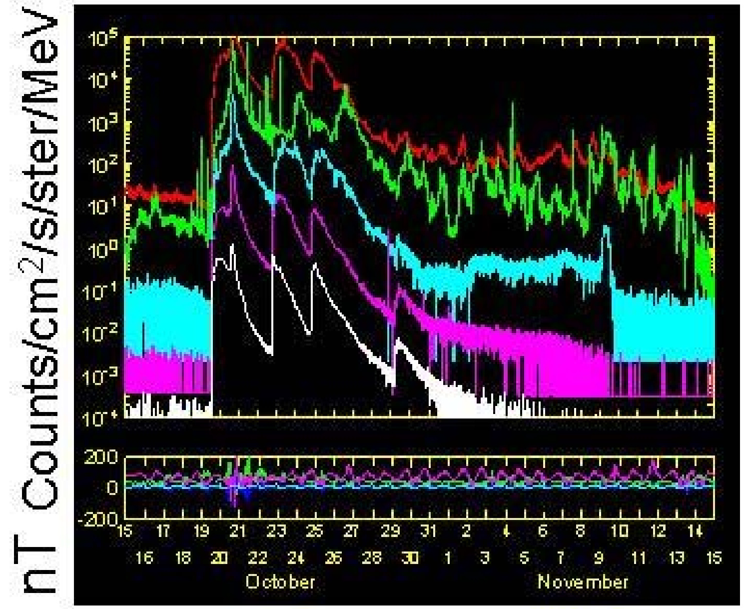


The sun acts as a modulator and source in the space environment

Solar Particle Events

- Cyclical (Solar Max, Solar Min)
  - 11-year AVERAGE (9 to 13)
  - Solar Max is more active time period
- Two types of events
  - Gradual (Coronal Mass Ejections – CMEs)
    - Proton rich
  - Impulsive (Solar Flares)
    - Heavy ion rich
- Abundances Dependent on Radial Distance from Sun
- Particles are Partially Ionized
  - Greater Ability to Penetrate Magnetosphere than GCRs

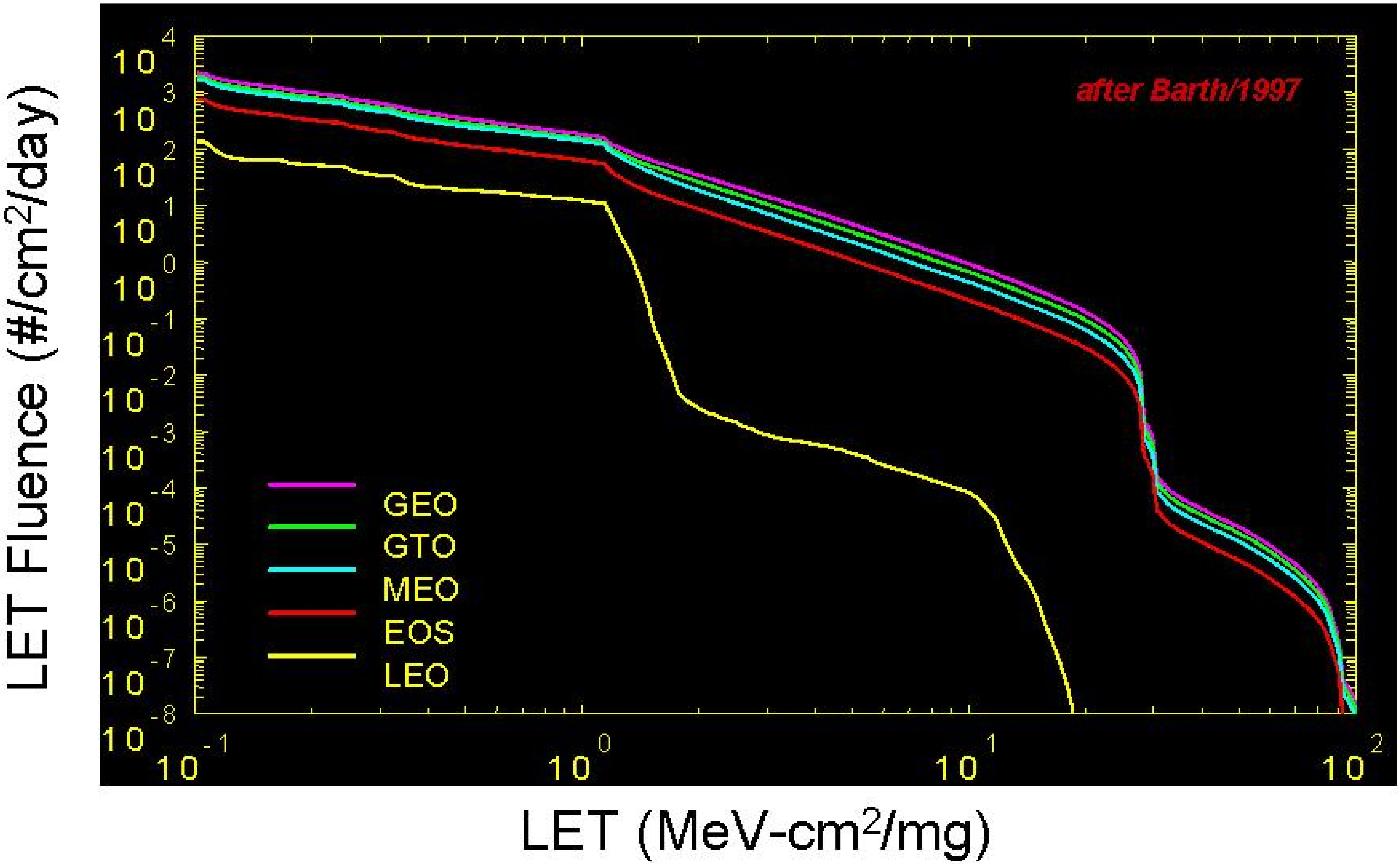
Proton Fluxes - 99% Worst Case Event



GOES Space Environment Monitor

GCR Abundance: Integral LET Spectra

CREME 96, Solar Minimum, 100 mils (2.54 mm) Al



Implementing SEE Hardness Assurance (SEEHA) for a Space System

Presented by Ken LaBel, HEART Short Course Albuquerque, NM, March 12, 2003

Sensible SEEHA Programmatics
A Two-Pronged Approach

- Lead radiation PROJECT engineer
  - Integrate radiation like other engineering disciplines
    - Parts, thermal,...
  - Single point of contact for all radiation issues
    - Environment, parts evaluation, testing,…

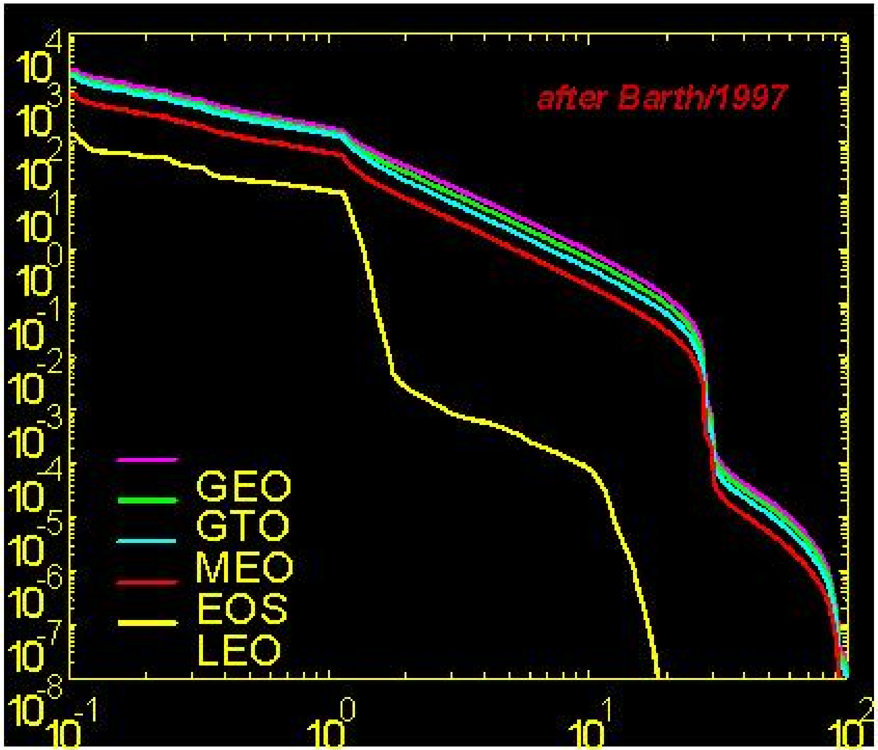
- Follow a systematic approach to SEEHA
  - SEEHA active early in program reduces cost in the long run
    - Issues discovered late in programs can be expensive and stressful
- Mission requirements and philosophies vary to ensure mission performance
  - What works for a shuttle mission may not apply to a deep-space mission

Rational SEEHA for Space Systems

- Define the Environment
  - External to the spacecraft
  - Internal to the spacecraft
- Develop SEE Specification based on Criticality Factors
- Evaluate Design/Components
  - Existing data/Testing/Performance characteristics
- Work with spacecraft designers
  - Mitigative Approaches
- Iterate Process
  - Ex., Review parts list and usage on six month intervals based on updated knowledgebase
- Monitor Performance During Flight

Define the Hazard for SEE: External Environment

- Environment external to the spacecraft
  - Trapped particles
    - Protons
    - Electrons
  - GCRs (heavy ions)
  - Solar particles (protons and heavy ions)
- Based on
  - Time of launch, mission duration
  - Orbital parameters, …
- Provide
  - Nominal and worst-case trapped particle fluxes
  - Peak "operate-through" fluxes (solar or trapped)

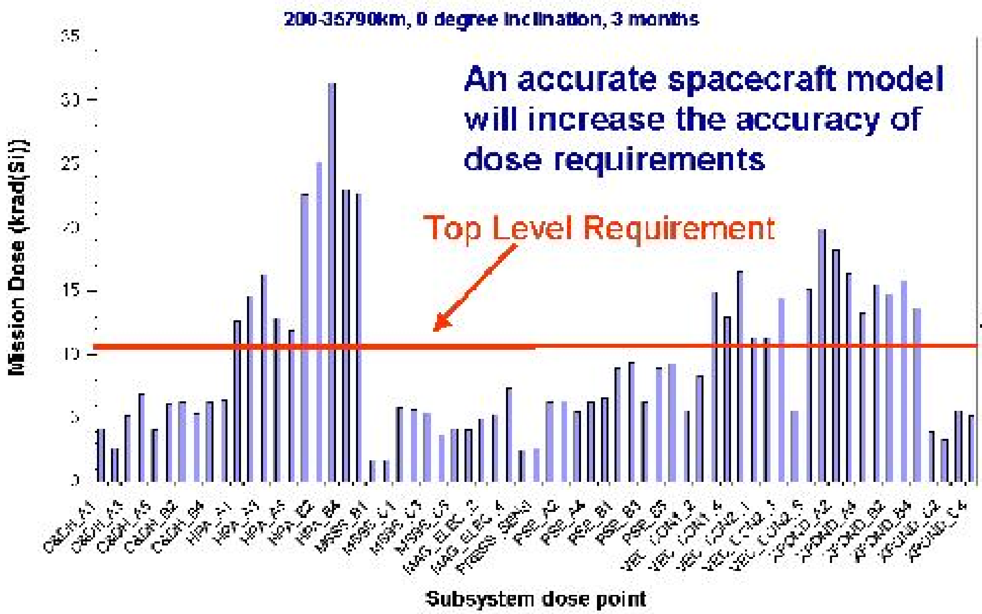


GCR spectra for various orbit types

Caveat: We are currently using static models for a dynamic environment

Define the Hazard for SEE: Internal Environment

- Determine particle fluxes after transport through spacecraft to electronic systems
  - Top level specification may utilize a nominal shielding level such as 100 mils Al
  - For more accurate predictions, utilize mission-specific geometry to determine particle fluxes at locations inside the spacecraft
- 3-D ray trace (geometric sectoring)
  - Basic geometry (empty boxes,…) or single electronics box
  - Detailed geometry
- Often an iterative process as spacecraft design is developed



Dose, an indicator of cumulative particle fluences, can vary greatly throughout the spacecraft.

after Poivey, 2002

SEE Requirements based on Criticality Factors

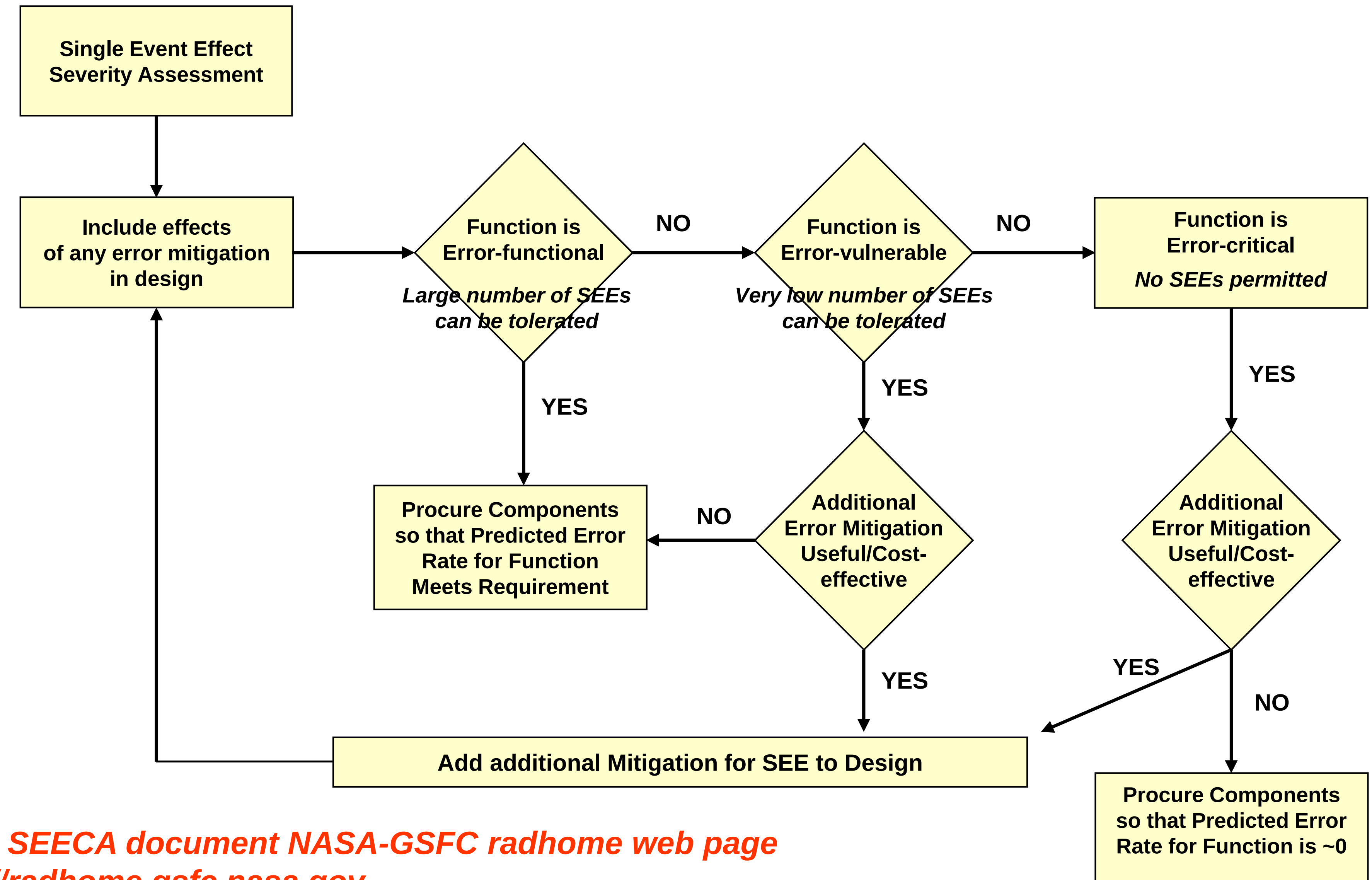
- SEE is very application specific
  - Utilize a criticality analysis (SEECA) based on function
    - Often allows use of non-SEE immune devices in a rational manner
- Note: SEE are probabilistic events (MTBF), not long-term degradation (MTTF)
  - Relatively equal probabilities for 1st day of mission or last day of mission (maybe by definition!)
  - Remember to consider worst-case environments
- Requirements may alternately be defined by system-level parameters such as data coverage rather than by piecepart requirements

SEE - System Requirements (1 of 2)

- **Perform SEECA based on predicted environment and criticality of function performed***
  - **Define 3 categories of criticality:**
    - **Error-critical: SEEs are unacceptable**
    - **Error-vulnerable: A low risk of SEE is acceptable**
    - **Error-functional: SEEs are acceptable. Mitigation means may be added to make these SEEs acceptable.**
  - **Examples:**
    - **Motion controller with a fatal error would be *error-critical***
    - **A processor with a predicted upset rate of 1 per 10 years for a 1 year mission may be deemed *error-vulnerable* by the project management**
    - **A solid state recorder (SSR) that has many errors coupled with a robust error detection and correction (EDAC) scheme would be *error-functional*.**

* ***For further information see: Single Event Effects Criticality Analysis (SEECA) at http://radhome.gsfc.nasa.gov/radhome/papers/seecai.htm***

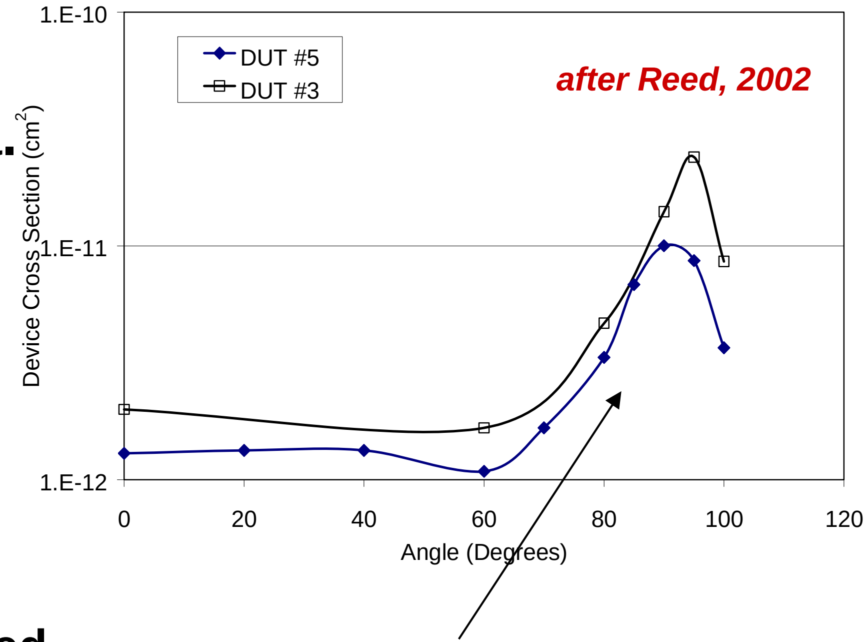
SEE – Criticality Decision Tree



From SEECA document NASA-GSFC radhome web page
http://radhome.gsfc.nasa.gov

SEE - System Requirements (2 of 2)

- No SEE may cause permanent damage to a system or subsystem
- Evaluation based on Linear Energy Transfer (LET) threshold (LET_{th}) criteria. LETth is the maximum LET value at which no SEE is observed.
  - LET_{th} > 100 MeV*cm^2/mg. No analysis required.
  - LET_{th} between 15$^+$-100 MeV*cm^2/mg. Analysis performed for heavy ion component.
  - LET_{th} < 15 MeV*cm^2/mg. Analysis performed for heavy ion and proton components.
  - *Analysis (SEE rate prediction) must be performed not only for nominal conditions, but worst-case operate-through conditions*.



Proton-induced angular effects in SOI device with high aspect ratio

$^+$ **These numbers are technology and mission specific. The numbers here are simply examples.**

Sample Single Event Effects Specification (1 of 3)

1. Definitions and Terms

Single Event Effect (SEE) **- any measurable effect to a circuit due to an ion strike. This includes (but is not limited to) SEUs, SHEs, SELs, SEBs, SEGRs, and Single Event Dielectric Rupture (SEDR).**

Single Event Upset (SEU) **- a change of state or transient induced by an energetic particle such as a cosmic ray or proton in a device. This may occur in digital, analog, and optical components or may have effects in surrounding interface circuitry (a subset known as Single Event Transients (SETs)). These are “soft” errors in that a reset or rewriting of the device causes normal device behavior thereafter.**

Single Hard Error (SHE) **- an SEU which causes a permanent change to the operation of a device. An example is a stuck bit in a memory device.**

Single Event Latchup (SEL) **- a condition which causes loss of device functionality due to a single event induced high current state. An SEL may or may not cause permanent device damage, but requires power strobing of the device to resume normal device operations.**

Single Event Burnout (SEB) **- a condition which can cause device destruction due to a high current state in a power transistor.**

Single Event Gate Rupture (SEGR) **- a single ion induced condition in power MOSFETs which may result in the formation of a conducting path in the gate oxide.**

Multiple Bit Upset (MBU) **- an event induced by a single energetic particle such as a cosmic ray or proton that causes multiple upsets or transients during its path through a device or system.**

Linear Energy Transfer (LET) **- a measure of the energy deposited per unit length as a energetic particle travels through a material. The common LET unit is MeV*cm^2/mg of material (Si for MOS devices, etc.).**

Onset Threshold LET (LET$_{th0}$) **- the minimum LET to cause an effect at a particle fluence of 1E7 ions/cm^2(per JEDEC). Typically, a particle fluence of 1E5 ions/cm^2 is used for SEB and SEGR testing.**

Single Event Effects Specification (2 of 3)

2. Component SEU Specification

2.1 No SEE may cause permanent damage to a system or subsystem.

2.2 Electronic components shall be designed to be immune to SEE induced performance anomalies, or outages which require ground intervention to correct. Electronic component reliability shall be met in the SEU environment.

2.3 If a device is not immune to SEUs, analysis for SEU rates and effects must take place based on LET_{th} of the candidate devices as follows:

Device Threshold	Environment to be Assessed
LET_{th} < 15* MeV*cm²/mg	Cosmic Ray, Trapped Protons, Solar Proton Events
LET_{th} = 15*-100 MeV*cm²/mg	Galactic Cosmic Ray Heavy Ions, Solar Heavy Ions
LET_{th} > 100 MeV*cm²/mg	No analysis required

2.4 The cosmic ray induced LET spectrum which shall be used for analysis is given in Figure TBD.

2.5 The trapped proton environment to be used for analysis is given in Figures TBD. Both nominal and peak particle flux rates must be analyzed.

2.6 The solar event environment to be used for analysis is given in Figure TBD.

2.7 For any device that is not immune to SEL or other potentially destructive conditions, protective circuitry must be added to eliminate the possibility of damage and verified by analysis or test.

**This number is somewhat arbitrary and is applicable to "standard" devices. Some newer devices may require this number to be higher.*

Single Event Effects Specification (3 of 3)

2. Component SEU Specification (Cont.)

2.8 For SEU, the *criticality* of a device in it's specific application must be defined into one of three categories: error-critical, error-functional, or error-vulnerable. Please refer to the /radhome/papers/seecai.htm Single Event Effect Criticality Analysis (SEECA) document for details. A SEECA analysis should be performed at the system level.

2.9 The improper operation caused by an SEU shall be reduced to acceptable levels. Systems engineering analysis of circuit design, operating modes, duty cycle, device criticality etc. shall be used to determine acceptable levels for that device. Means of gaining acceptable levels include part selection, error detection and correction schemes, redundancy and voting methods, error tolerant coding, or acceptance of errors in non-critical areas.

2.10 A design's resistance to SEE for the specified radiation environment must be demonstrated.

3. SEU Guidelines

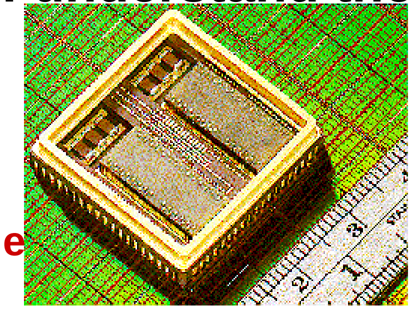
Wherever practical, procure SEE immune devices. SEE immune is defined as a device having an $LET_{th} > 100$ MeV*cm^2/mg.

If device test data does not exist, ground testing is required. For commercial components, testing is recommended on the flight procurement lot.

Evaluate Design/Component Usage

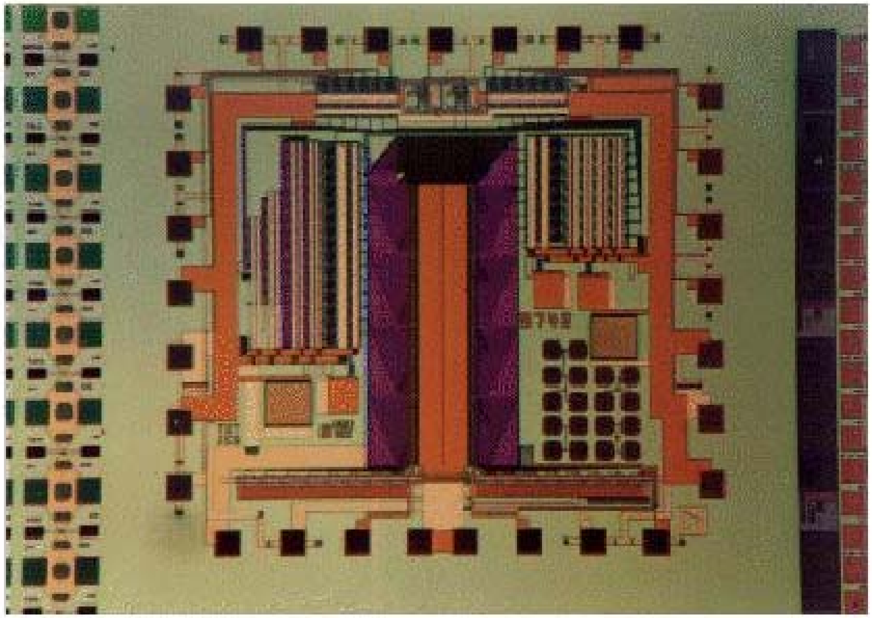
- Screen/review parts list
  - Use existing databases
    - DTRA's ERRIC, RADATA, REDEX, Radhome, ESA Database,IEEE TNS, IEEE Data Workshop Records, Proceedings of RADECS, etc.
    - Evaluate completeness and relevance of test data
  - Look for processes or products with known radiation tolerance (beware of SEE and displacement damage!)
    - BAE Systems, Honeywell Solid State Electronics, UTMC, Intersil, etc.
- Radiation test unknowns or non-RH guaranteed devices
  - Lot qualification recommended
  - Qualification by similarity is a risk trade
- Provide performance characteristics
  - Usually requires application specific information: understand the designer's sensitive parameters
    - SEE rates and impacts to system

Stacked devices and hybrids can present a unique challenge for review and test



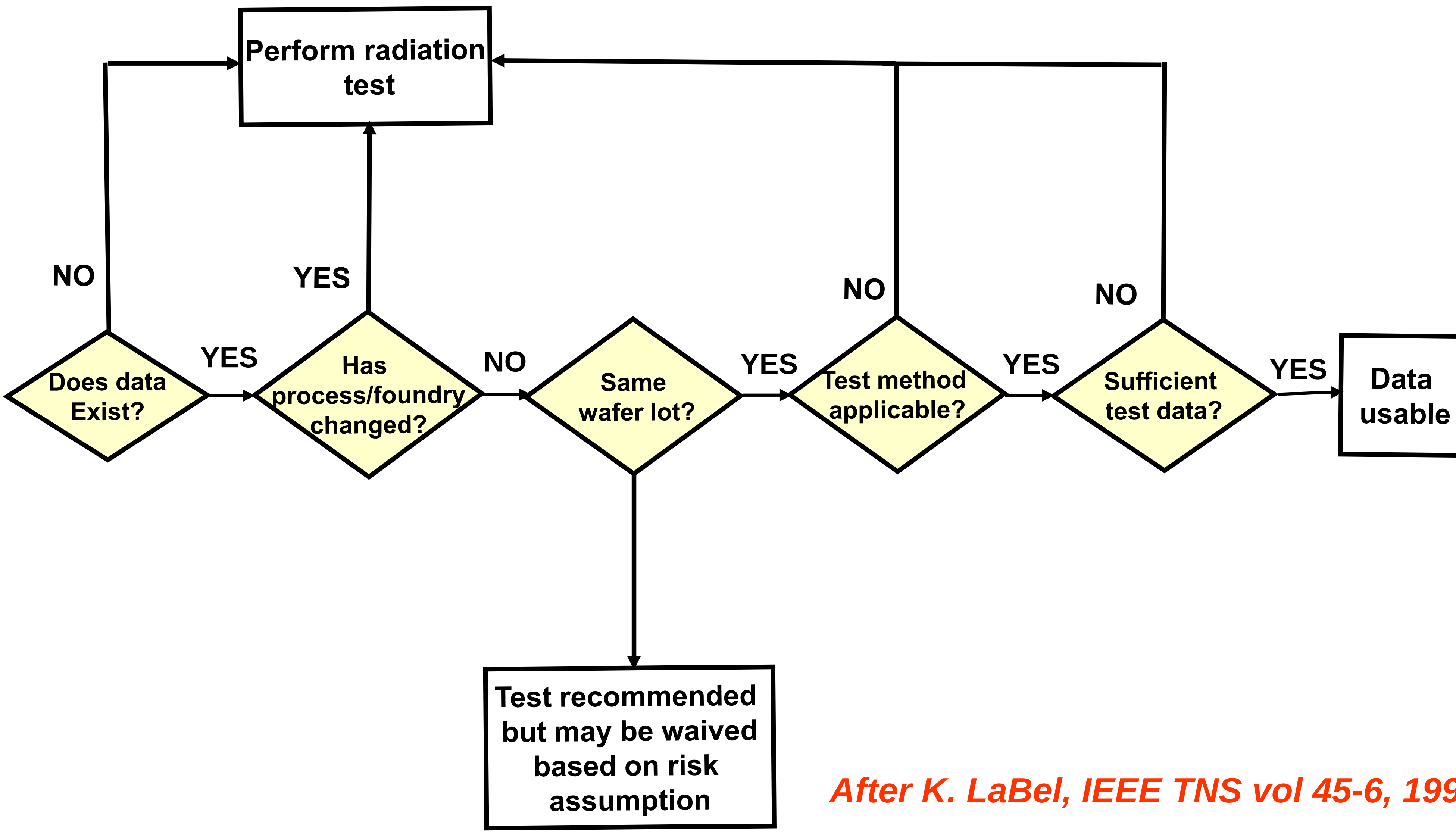
Scrubbing of parts lists

- Information required on a parts list (Ken's recommended minimum)
  - Part number (generic and military)
    - Procurement numbers are difficult to use to search for radiation data
  - Manufacturer
  - Lot date code
  - Function
  - Process Information
  - Application information, if available
  - *Any manufacturer guarantee on radiation tolerance*



Make sure single event transients (SETs) are reviewed especially in higher speed operation such as this SiGe device

Data Search and Definition of Data Usability Flow

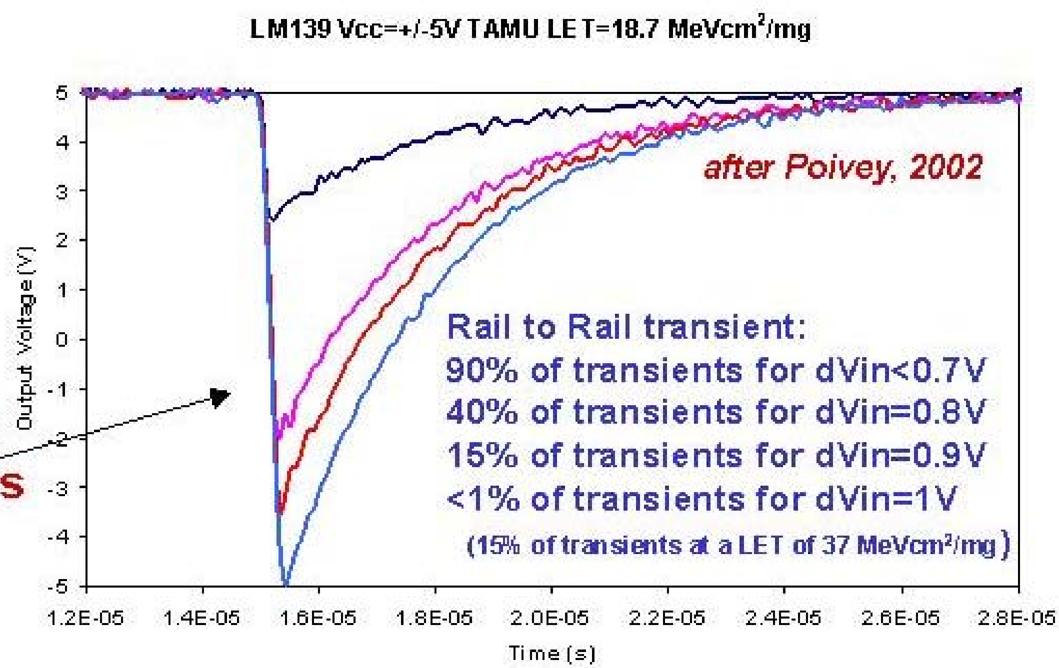


After K. LaBel, IEEE TNS vol 45-6, 1998

Data Applicability – Example 1

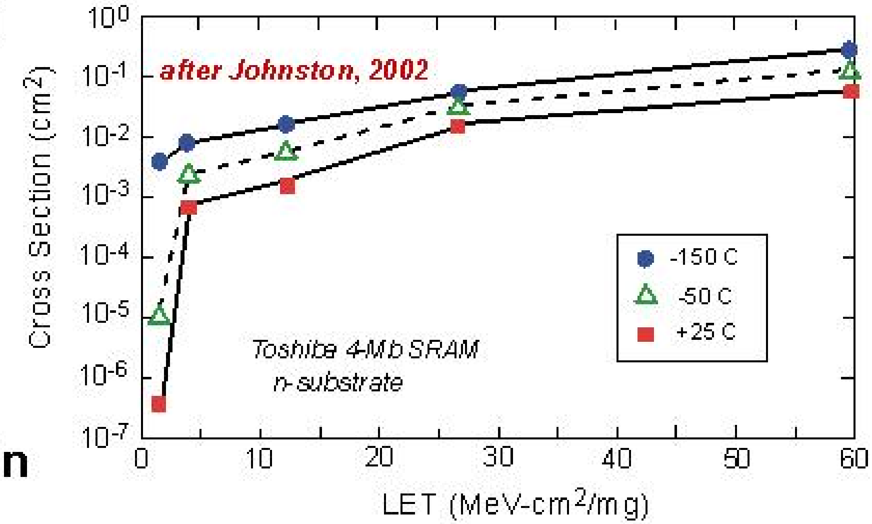
- Most SEE data available is application-specific
  - Power supply voltages
  - Operating frequency
    - Fidelity of response measured
      - Ex., Was the scope fast enough to capture "small" transients that might perturb sensitive data?
  - Circuit load
  - Test patterns
  - Temperature
  - Bias configuration

Transients in a linear device can vary with input parameters



Data Applicability - Example 2

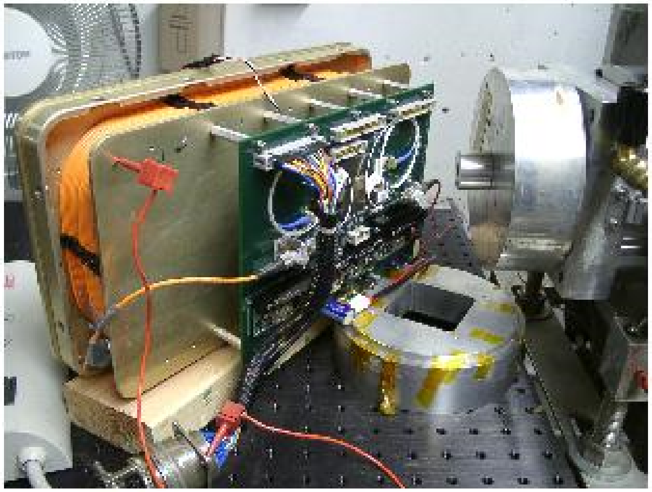
- SRAM used in a solid state recorder (SSR)
  - SEE ground test data may have been in dynamic mode with a 1 MHz operating frequency
  - Application may be quasi-static
    - Write once an orbit (collect data)
    - Read once an orbit (downlink data)
  - There is often a duty cycle effect for SEE sensitivity
    - Device may be more or less sensitive in a quasi-static mode of operation
  - Device may also have a prevalence of 0-1 vs. 1-0 upset
    - Implies SEU sensitivity is a function of data patterns
      - If test pattern is all 1's or all 0s, data may not be applicable
        - » Hitachi 1 Mbit SRAM was 49X more sensitive in one direction than the other!



Sample effect of temperature on SEE sensitivity

SEE Radiation Test Requirements

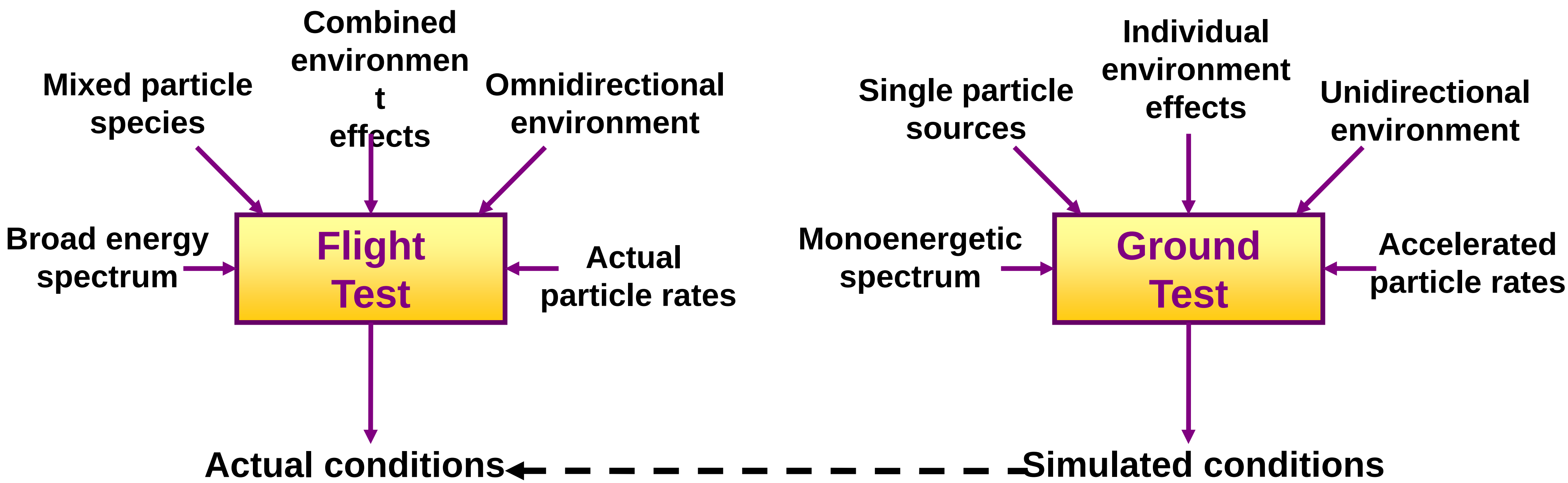
- Determine if heavy ion, proton, or both types of test are needed
  - Mission-specific issues
- Define appropriate test levels
  - Sample size, particle, and fluence
- SEE testing should mimic or bound the flight usage, if possible
  - *Worst-case issues should be included*
- It may be acceptable to avoid testing if the design is robust to SEUs/SETs
  - Ex., A transient filter is added to the output of linear device



A fiber optic link awaiting protons for SEE tests at UCDavis

Beware of stray neutrons during proton testing on your test equipment.
Here, Borax is shown on top of a power supply.
We have seen failures in test equipment from stray neutrons.

Radiation Test Issues - Fidelity



How accurate is the ground test in predicting Space Performance?

Example, how does dose degradation and aging effects affect SEE performance?

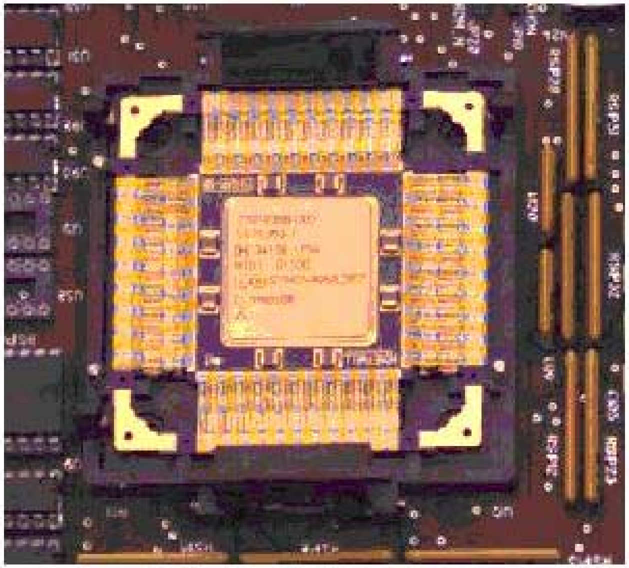
After Stassinopoulos

Work with Space System Designers

- Determine and validate "acceptable" performance characteristics
  - E.g., SEU rates using accepted methods
    - By test
    - By simulation or circuit analysis
    - By determining SEU rate (CREME96, SPACERAD, etc) and managing risk
      - I.e., is the probability/risk of observing an SEU sufficiently low?
        - » e.g., a SEU rate of 1 per 10 years for a 1 month mission
- Recommend mitigation schemes
  - Recommend alternate parts that meet performance requirements
  - Recommend error detection and correction (EDAC) schemes, redundancy, voting,...
  - The following few charts are overviews of device and circuit hardening concepts

IC Hardening (1 of 2)

- Implies building an IC that meets system radiation requirements
- Features may include process characteristics or internal circuit approaches:
  - SEL immune process
  - Hardened transistors
  - Internal redundancy/voting
  - Internal error correction, etc.
- Examples
  - Temporal and spatial latches



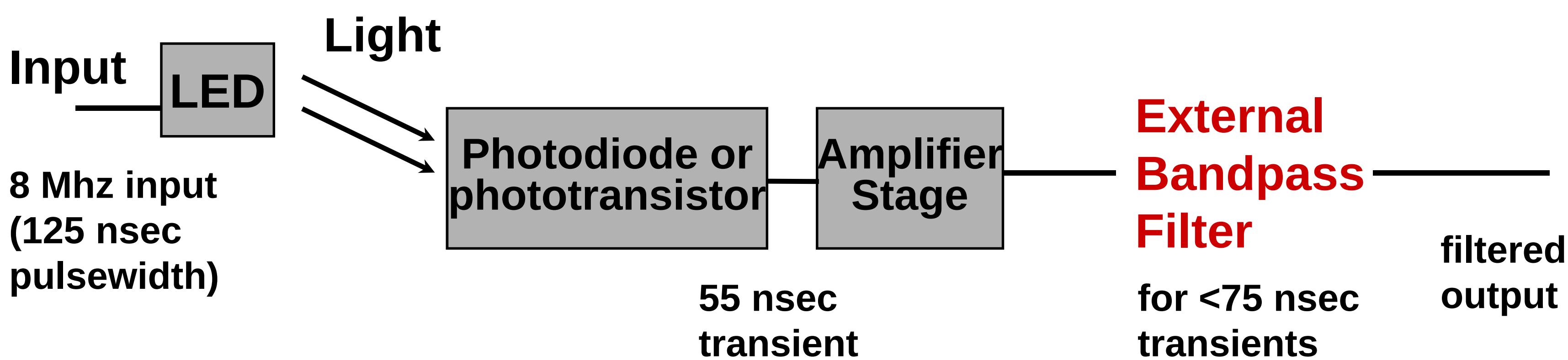
Mongoose V

IC Hardening (2 of 2)

- Advantages
  - Simplifies system design to meet radiation requirements
- Challenges
  - Performance, Cost, Schedule
- Examples
  - Hardened process
  - Compiled or hardened library design (hardness by design (HBD) techniques)

Circuit Hardening (1 of 2)

- **Implies adding an external feature to an IC to reduce radiation sensitivity**
  - Shielding
  - RC filter
  - Voting logic
  - Error detection and correction (EDAC) codes
  - Watchdog timers, etc.
- **Maybe be implemented or controlled by either hardware, software, or firmware**

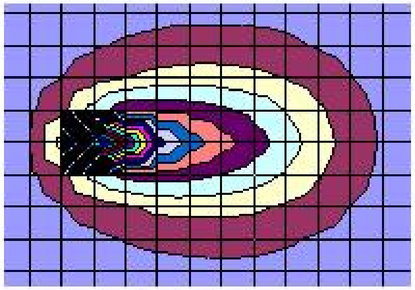


Circuit Hardening (2 of 2)

- Advantages
  - Allows use of higher (non-radiation) performance ICs
    - Faster processors
    - Denser memories, etc…
- Challenges
  - Adds complexity (cost and schedule?) to design
  - Often difficult to retrofit if problem is discovered late
    - Modification to flight hardware

Circuit Mitigation of SEUs

- Three types of SEUs
  - Data (Ex., bit-flip to a memory cell or error on a communication link)
  - Control (Ex., bit-flip to a control register)
    - May sometimes be called single event functional interrupts (SEFIs)
  - Transient (noise spike that may or may not propagate)
- Some overlap may exist
  - Ex., RAM with program memory stored inside



after Marshall, 2002

75°

Energetic particle diffusing in a silicon active pixel sensor device

Data SEUs - Sample EDAC Methods

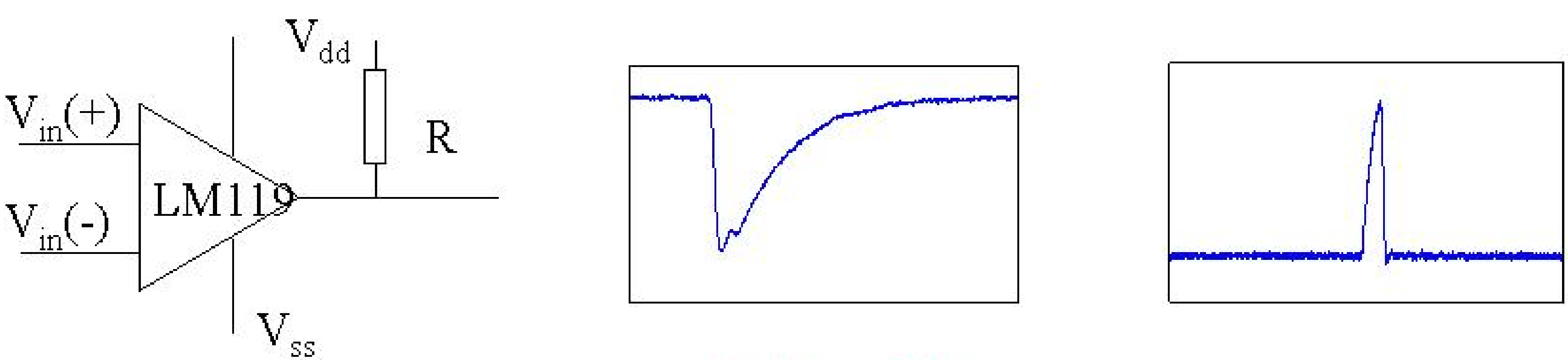
EDAC Method	EDAC Capability
Parity	Single bit error detect
Cyclic Redundancy Check (CRC)	Detects if any errors have occurred in a given structure
Hamming Code	Single bit correct, double bit detect
Reed-Solomon Code	Corrects multiple and consecutive bytes in error
Convolutional Code	Corrects isolated burst noise in a communication stream
Overlying Protocol	Specific to each system. Example: retransmission protocol

Control SEUs - Sample EDAC Schemes

- Software-based health and safety (H&S) tasks
- Watchdog timers
- Redundancy
- Lockstep
- Voting
- "Good engineering practices"
  - Ex., send two commands with different values to initiate a sequence
- Improved Designs (i.e., noise margins, method of sampling, etc.)

Transients from SEUs (SETs)

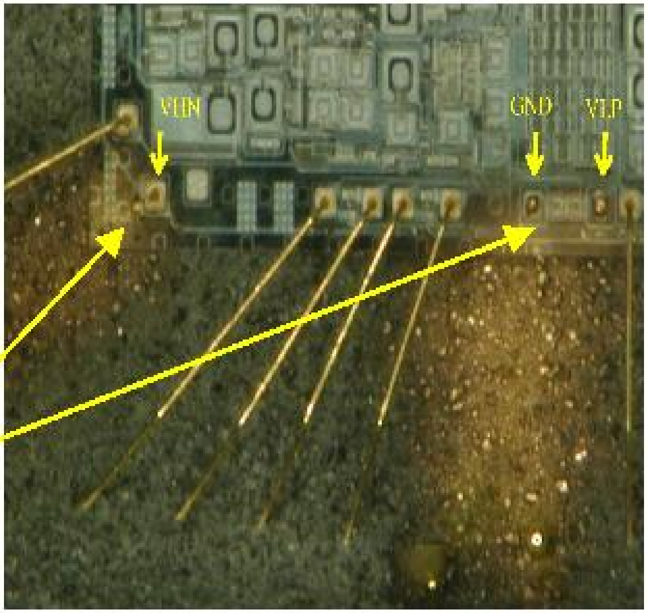
- Examples of issue
  - ADCs, Analog, and Optical Links are among the device types affected
  - Optocoupler transients in HST and Terra (and IRIDIUM!)
  - Linear devices such as LM139 analog comparator (MAP, MPTB)
- Most commonly mitigated by
  - Filtering techniques
  - Over-sampling
  - High-speed device with a slow response following circuit



after Poivey, 2002

Destructive SEE - Mitigation

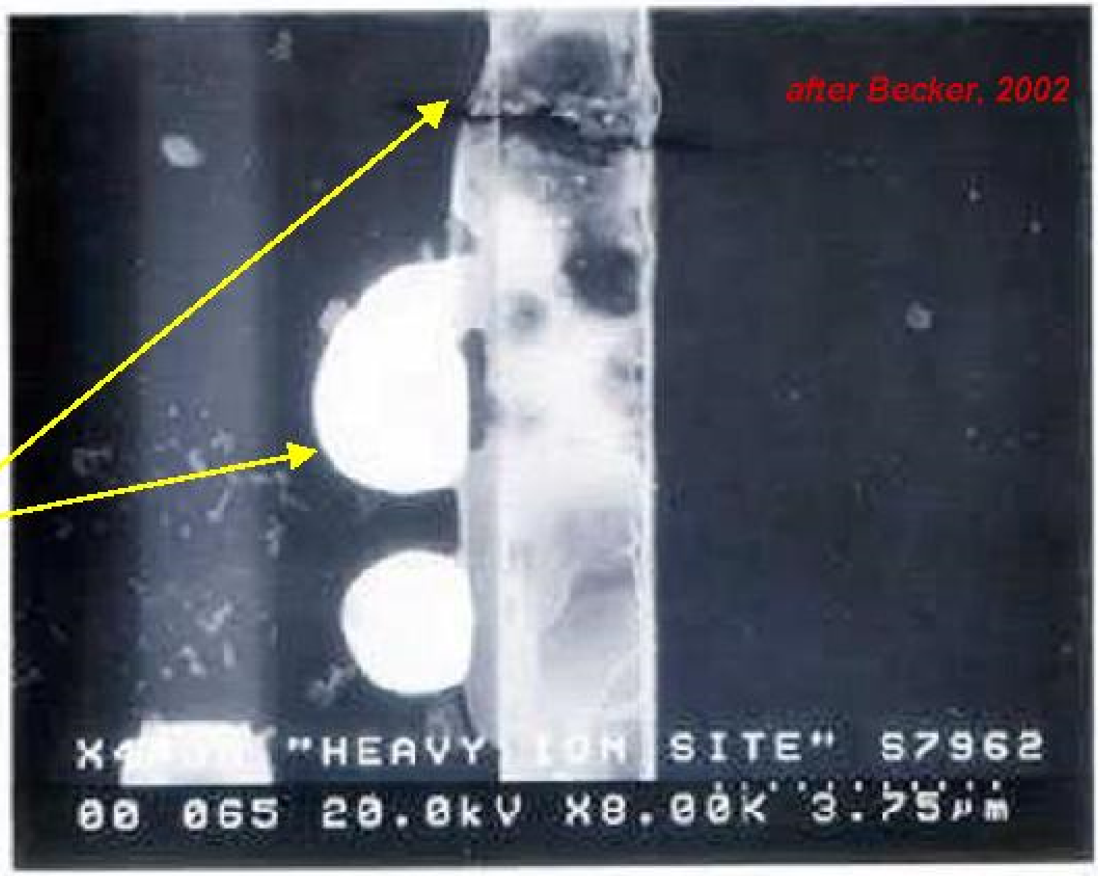
- Recommendation 1: Do not use devices that exhibit destructive conditions in your environment and application
- Difficulties:
  - May require redundant components/systems
  - Conditions such as low current latchup (SEL) may be difficult to detect
- MANY DESTRUCTIVE CONDITIONS MAY NOT BE MITIGATED
- Mitigation methods
  - Current limiting
  - Current limiting w/autonomous reset
  - Periodic power cycles
  - Device functionality check
- Latent damage is also a grave issue
  - *"Non-destructive" events may be false!*



Vaporized wirebonds in a Agere LSP2916 MEMS Driver from an SEL, *after O'Bryan, 2002*

Latent Damage

- SEL events
  - Device may not fail immediately from SEL, but "recover" after a power cycling
- However, in some cases
  - Damage has occurred such as shown here
  - Metal is ejected or cracking has occurred (heat, melt, harden) that may fail catastrophically at some time after event occurrence
    - Reduced reliability/lifetime



SEL test qualification methods need to take latent damage into consideration;

Post-SEL screening techniques required;

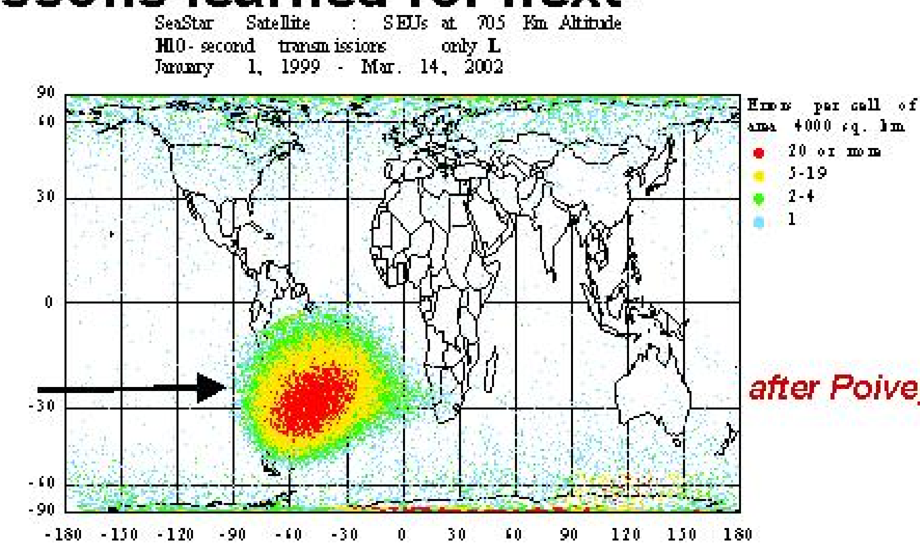
Mitigative approaches may not be effective

Iterate Process as Necessary

- Design or requirement changes often occur during design and build of space systems
  – New parts (or new usage of existing parts) need review or test
  – Internal hazard may require re-evaluation (I.e., new 3-D ray trace)
- Re-review of parts list and applications
  – If the design/development is more than a few months, new knowledge (research) is sometimes obtained making "old parts, new issues"
    - Presentations at conferences highlight new sensitivities in devices/technologies
      – New SEE modes are sometimes uncovered
      – Ex., optocoupler SETs

Monitor System Performance In-Flight

- It is recommended that adequate measures be taken to gather appropriate in-flight performance information
  - Ex.
    - Number and type of errors observed in SSRs
  - This includes correlative information
    - When and where events are occurring
    - Environment monitoring (proton fluxes, etc…)
- Helps determine effectiveness of system hardening approaches and provides lessons learned for next-generation designs



Memory upsets in a polar orbiting mission occurring in the SAA

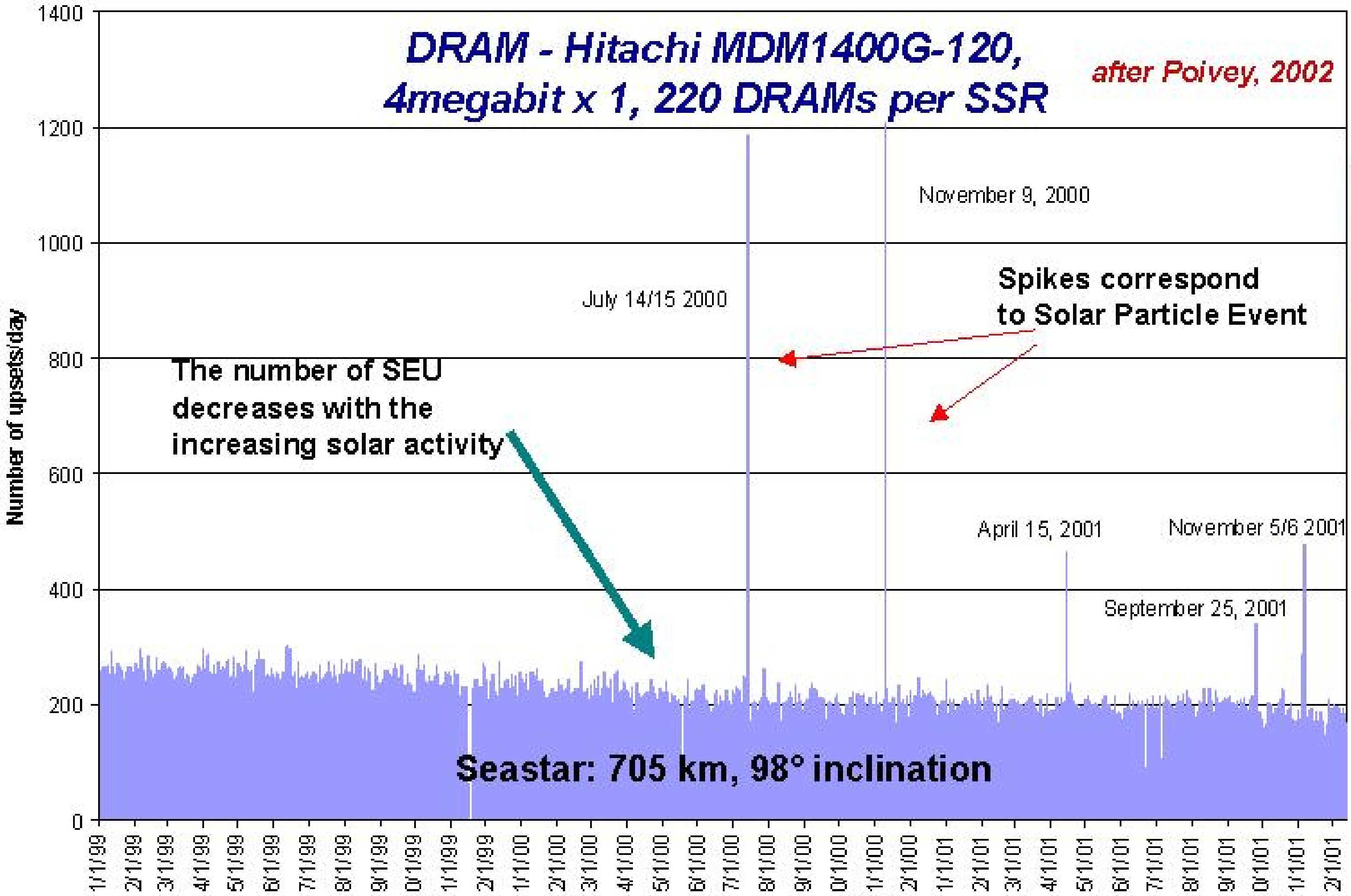
after Poivey, 2002

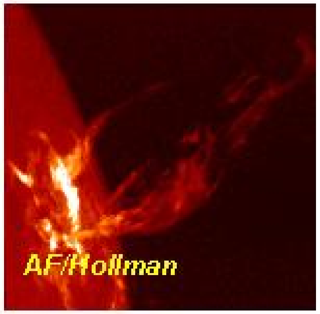
In-Flight Performance of Actual NASA Systems

Success Stories

- A brief overview will be provided of several NASA missions which performed as expected in space due to SEEHA
  - Each can be traced back to particular lessons they provided
- Three examples
  - Solid State Recorders (SSRs)
    - SeaStar
    - Hubble Space Telescope (HST)
  - COTS Processors
    - HST Co-processor

SeaStar SSR





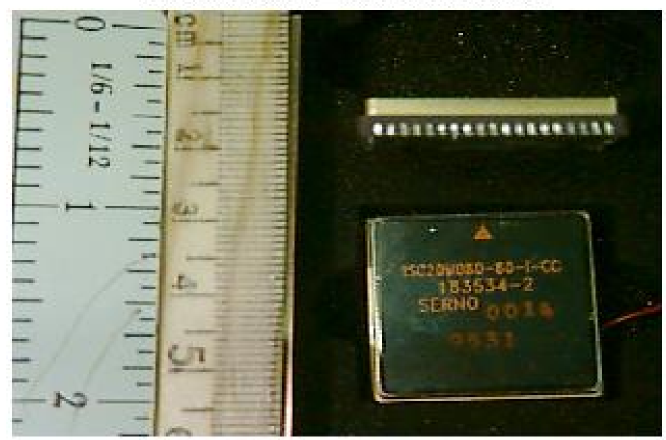
Single bit EDAC can be used effectively with x1 devices in most system implementations

Caveat: beware of more modern devices that have complex SEUs

Hubble Space Telescope (HST) SSR

- Feb 1996 Hubble Space Telescope
  - Upgraded SSR installed on HST with 1440 16Mbit IBM Luna ES Rev C DRAMs (12 Gbits)
- Ground testing performed on small sample sizes
  - Row and column errors observed with heavy ions, but not protons: concept of limiting cross-section
- HST is a low-inclination, low altitude mission
  - Very few heavy ions expected
- However
  - Row and column errors observed in flight!
  - Larger sample size proton tested
    - Events similar to flight anomalies noted at a rate consistent with flight observations
- RS Encoding scrubbed all errors = no data lost

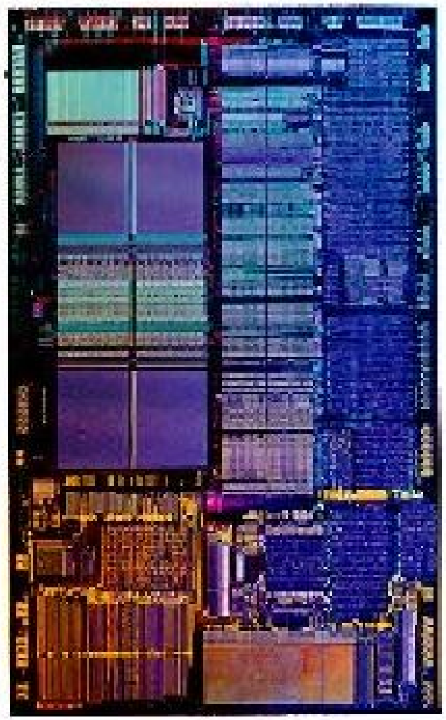
Stacked IBM DRAMs



Use of a robust EDAC scheme and testing significant sample size

HST Co-Processor:
Acceptable Mission Risk

- HST wanted to increase in-flight processing capabilities
  - GSFC Radiation Group was hired to evaluate the Intel 80486DX33 (CHMOS III) processors radiation characteristics
    - A sample of a Intel 80486DX2-66 (CHMOS IV) was also available for tests
  - High currents noted on DX33 device, but not on DX2-66
- Decision made to go forward with design using DX2-66
  - 3 additional lots tested (first 2 had procurement issues)
  - 3rd lot ("same process") showed high current events NOT observed in previous lots
    - This is the lot that was procured for flight
- Despite high current events, probability of occurrence in-flight for HST orbit was low
  - < 1 per 100,000 years
- Deemed acceptable risk
  - No incidents noted in over 6 years in flight

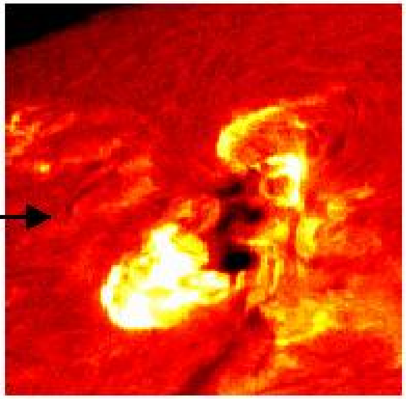


INTEL 80486DX

Anomalies In-Flight

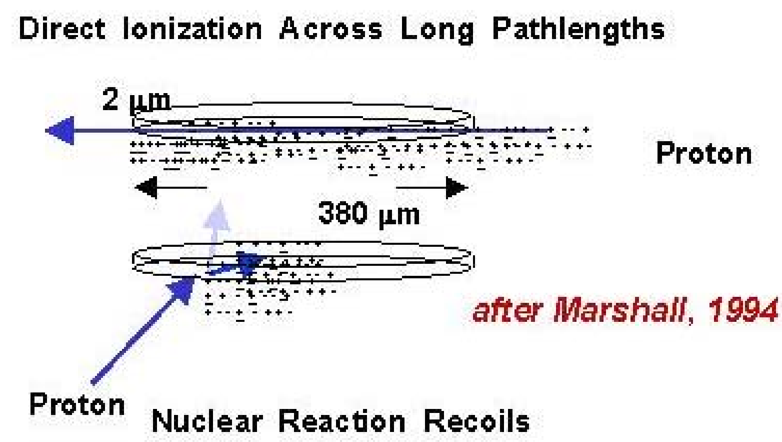
- Anomalies can have a wide variety of impacts on space systems from minimal to mission failure
- Examples include
  - Data loss
  - Misoperation
  - Safing of spacecraft
- Two samples of anomalies are presented
  - An impact to science data operations, and
  - Periodic system outages

Heavy ion or proton-rich solar events can cause anomalies



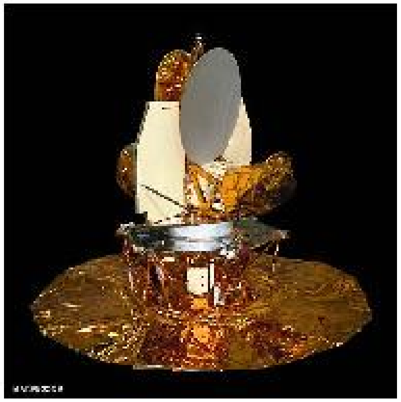
HST Optocouplers

- In February of 1997, several anomalies occurred in a HST instrument while transiting through the SAA
  - High-speed optocoupler identified as the potential source
    - This was verified by ground testing in March 1997 for SETs
  - Device was not reviewed for radiation issues other than total dose
    - Common thought before this timeframe on slower optocouplers
- Science instrument operations modified such that no operations were active during SAA transits
  - Loss of some (luckily non-critical) science data
    - Mission still successful

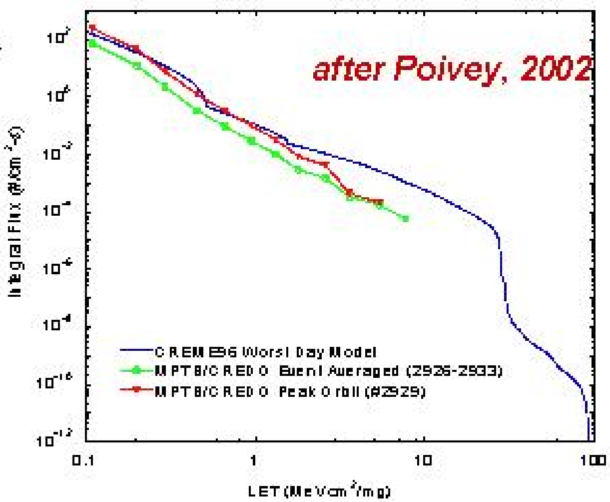


Microwave Anisotropy Probe (MAP): SETs in a Linear Device

- MAP was launched in June 2001 to a L2 orbit
  - Anomaly occurred in Nov 2001 causing the command and data handling processor to reset
    - System worked as designed for recovery of anomalies (safehold, await command to restart)
- Event occurred during a solar particle event
  - Heavy ion (not proton) contribution was likely the cause
- Linear comparator used with a small differential input
  - Much more sensitive than with larger differential input
- Design requirements changed during mission design and what was originally a tolerant application (large differential) became "soft" to SETs



MAP Spacecraft



Robust system design recovered from unexpected event

Summary

- In this brief time, we have presented an system-level approach to dealing with space system design and SEE
- It is important to start ANY radiation assurance planning early in mission design and to continue throughout
- It is the challenge of every design engineer to make sure his or her design is robust with the aid of the radiation specialist

Acknowledgements

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