Assurance Against Radiation Effects on Electronics

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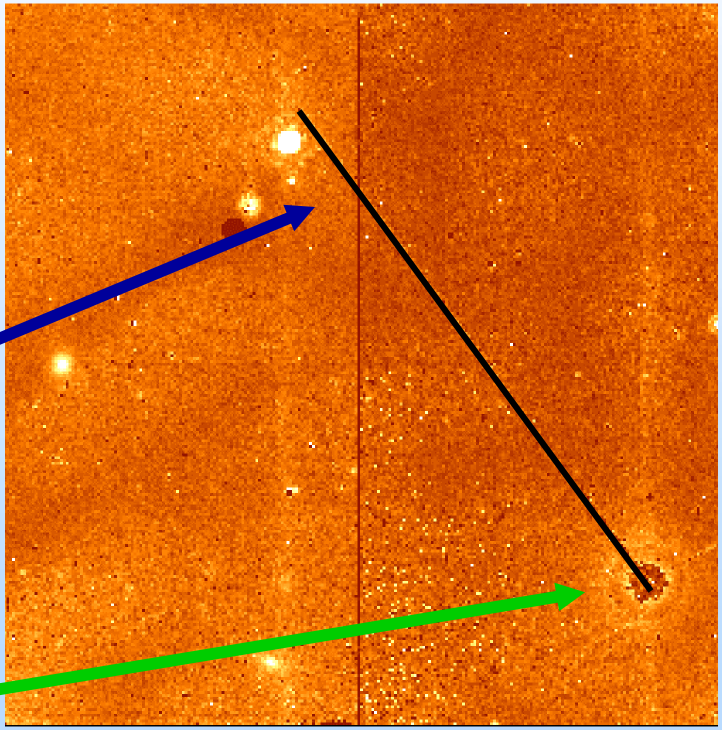
Outline

- The Space Radiation Environment
- The Effects on Electronics
- The Environment in Action
- NASA Approaches to Commercial Electronics
  - The Mission Mix
  - Flight Projects
  - Proactive Research
- Final Thoughts

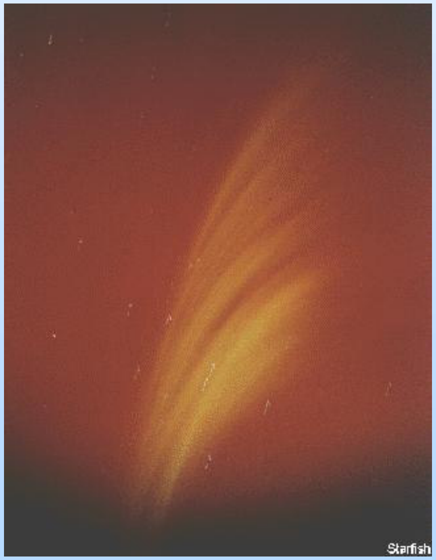
Atomic Interactions
- Direct Ionization

Interaction with Nucleus
- Indirect Ionization
- Nucleus is Displaced



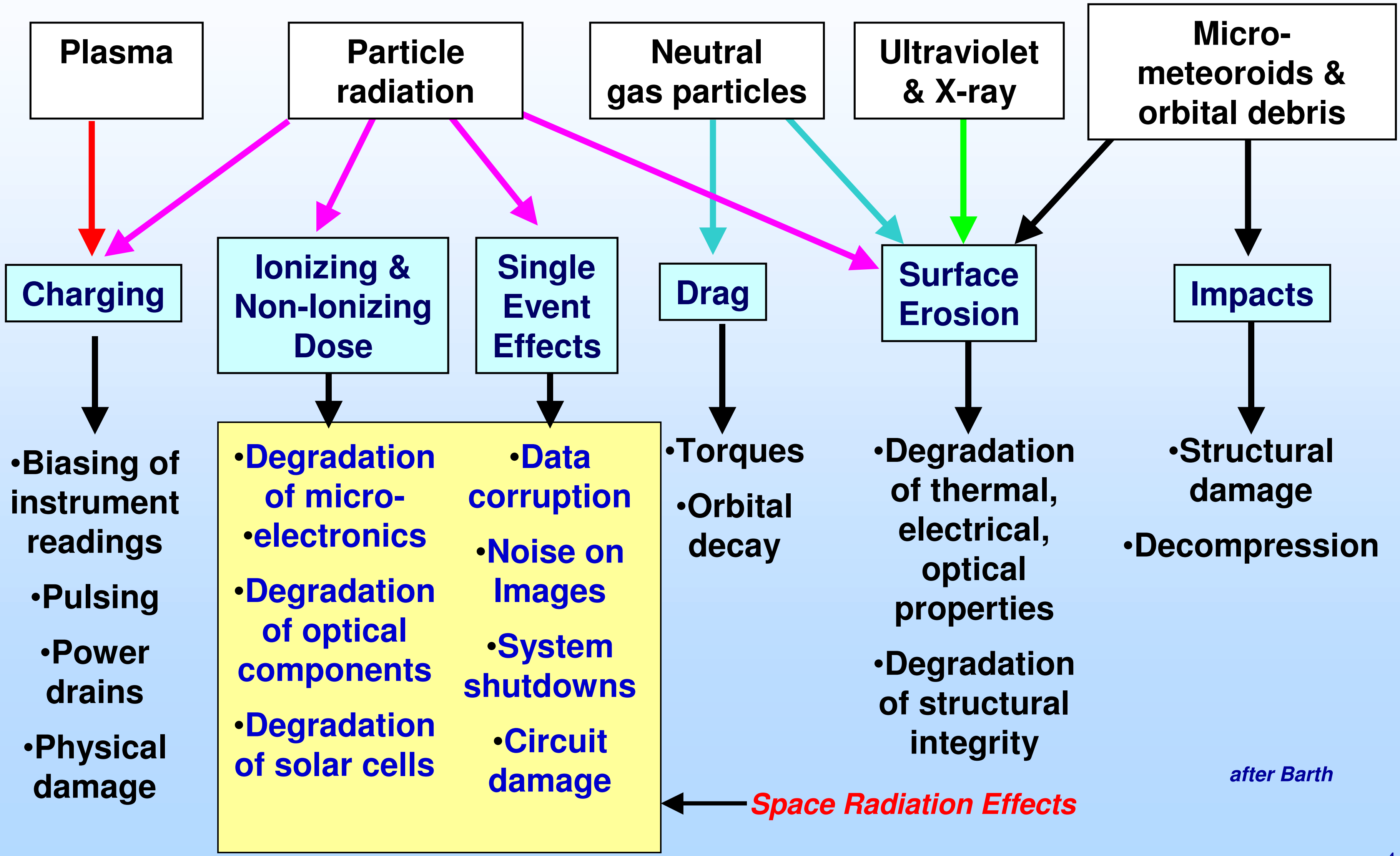
http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html

The Space Radiation Environment



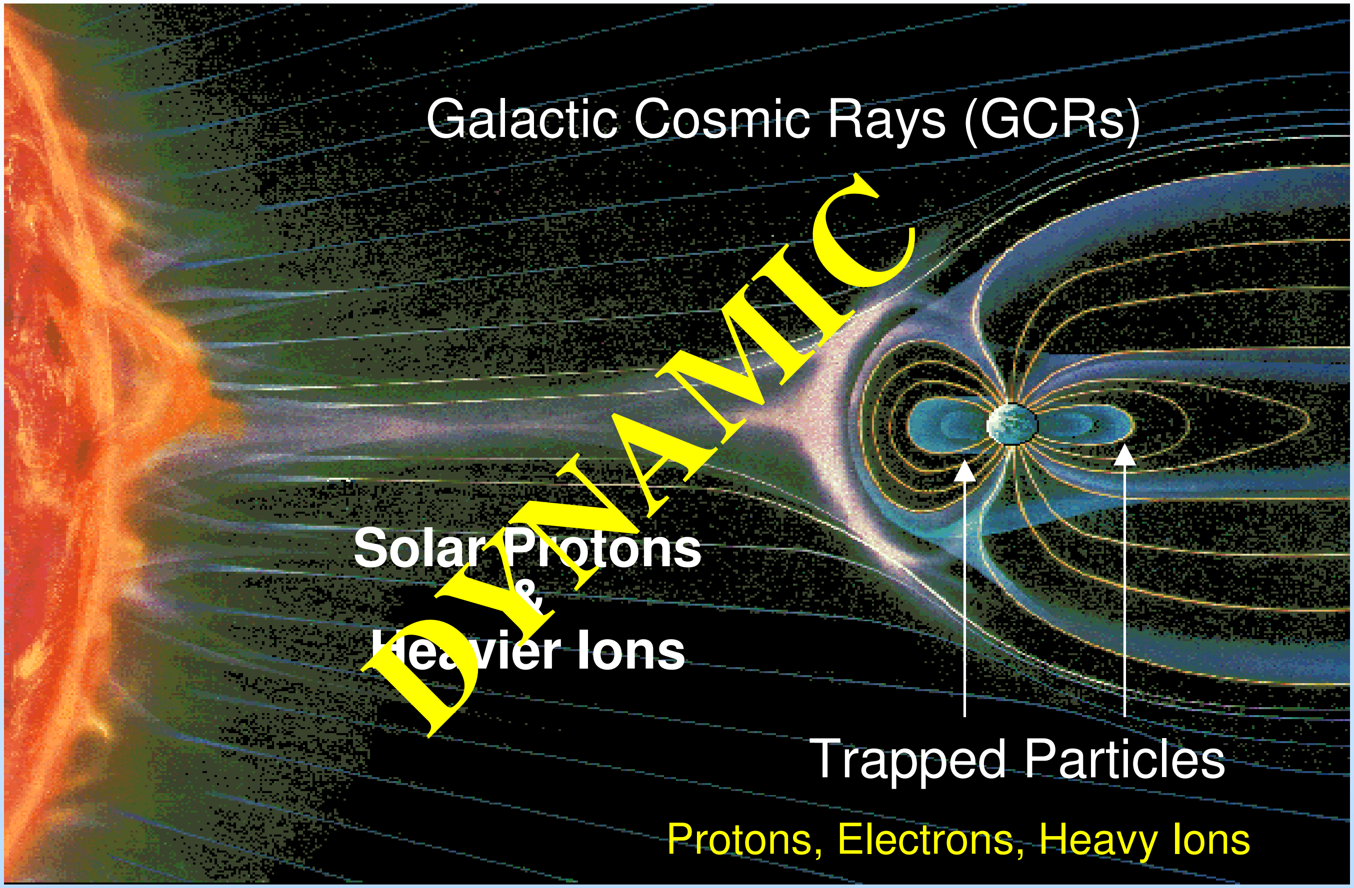
STARFISH detonation –
Nuclear attacks are not considered in this presentation

Space Environments and Related Effects



Space Radiation Environment

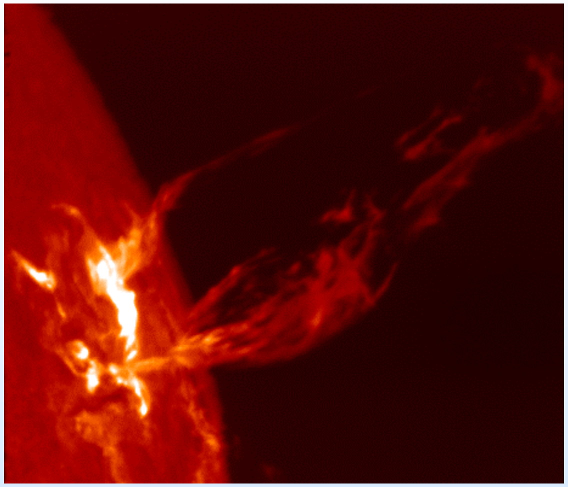
after
Nikkei Science, Inc.
of Japan, by K. Endo



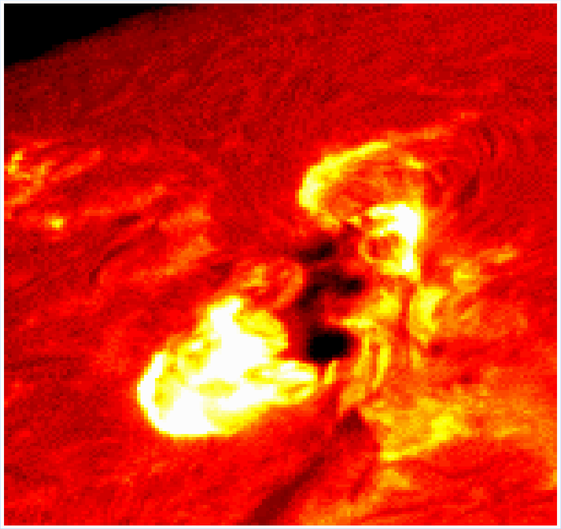
Deep-space missions may also see: neutrons from background or radioisotope thermal generators (RTGs) or other nuclear source
Atmosphere and terrestrial may see GCR and secondaries

Solar Particle Events

Holloman AFB/SOON

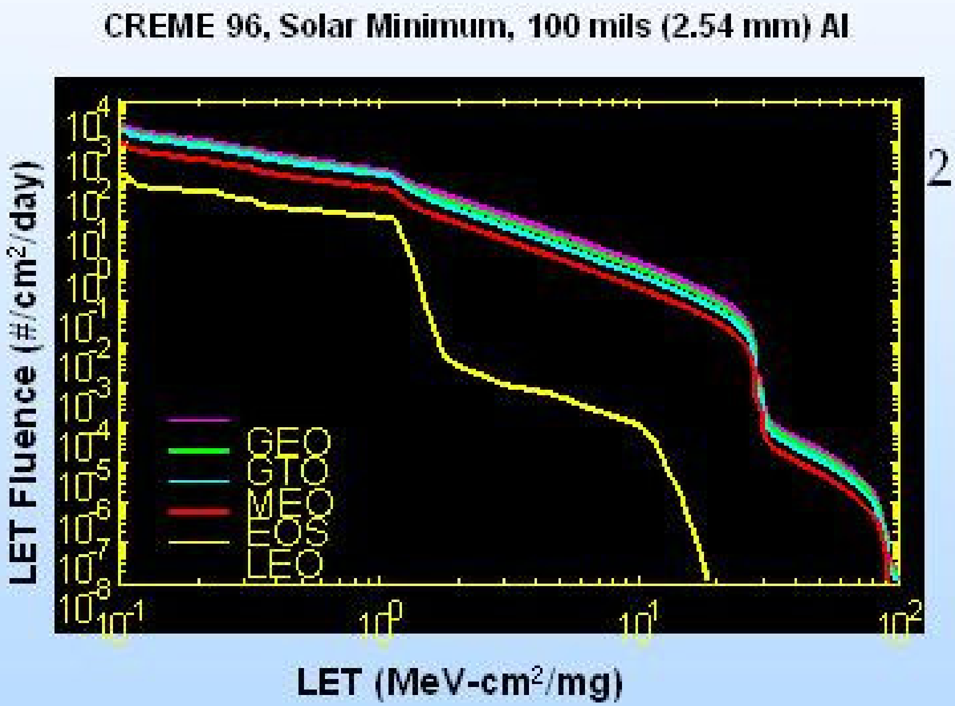


- Cyclical (Solar Max, Solar Min)
  - 11-year AVERAGE (9 to 13)
  - Solar Max is more active time period
- Two types of events
  - Gradual (Coronal Mass Ejections – CMEs)
    - Proton rich
  - Impulsive (Solar Flares)
    - Heavy ion rich
- Abundances Dependent on Radial Distance from Sun
- Particles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



Free-Space Particles: Galactic Cosmic Rays (GCRs) or Heavy Ions

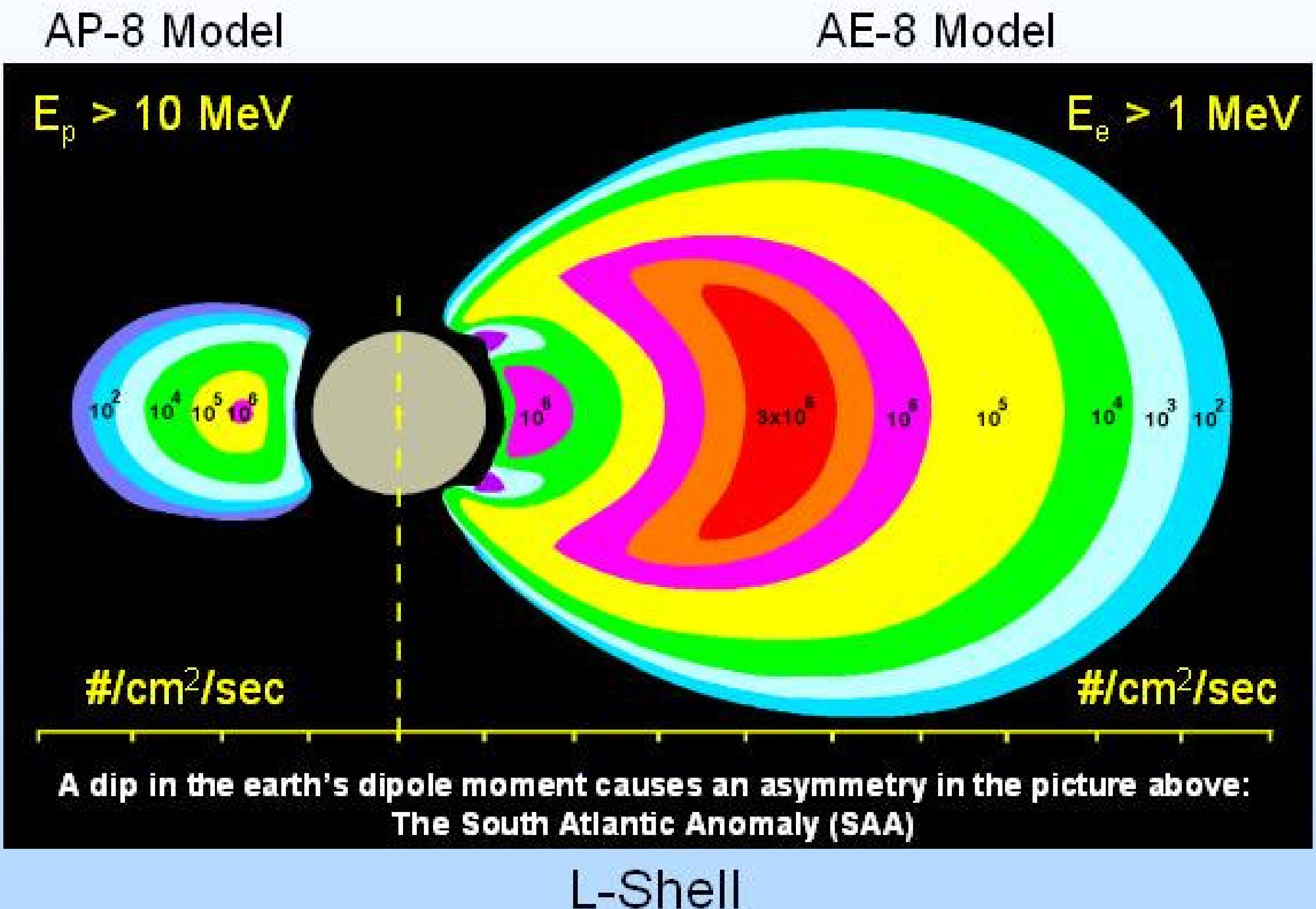
- **Definition**
  - A GCR ion is a charged particle (H, He, Fe, etc)
  - Typically found in free space (galactic cosmic rays or GCRs)
    - Energies range from MeV to GeVs for particles of concern for SEE
    - Origin is unknown
  - Important attribute for impact on electronics is how much energy is deposited by this particle as it passes through a semiconductor material. This is known as Linear Energy Transfer or LET (dE/dX).



Time

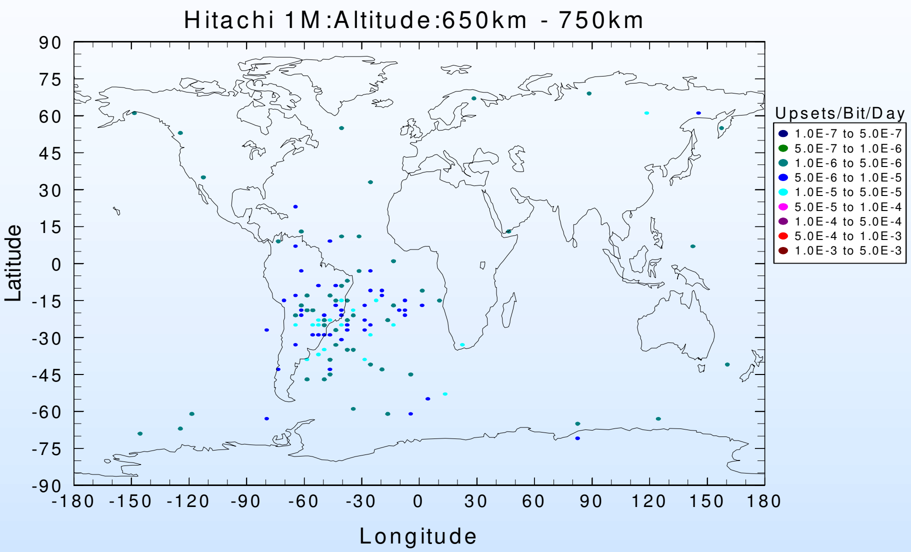
Commercial Technology Sensitivity

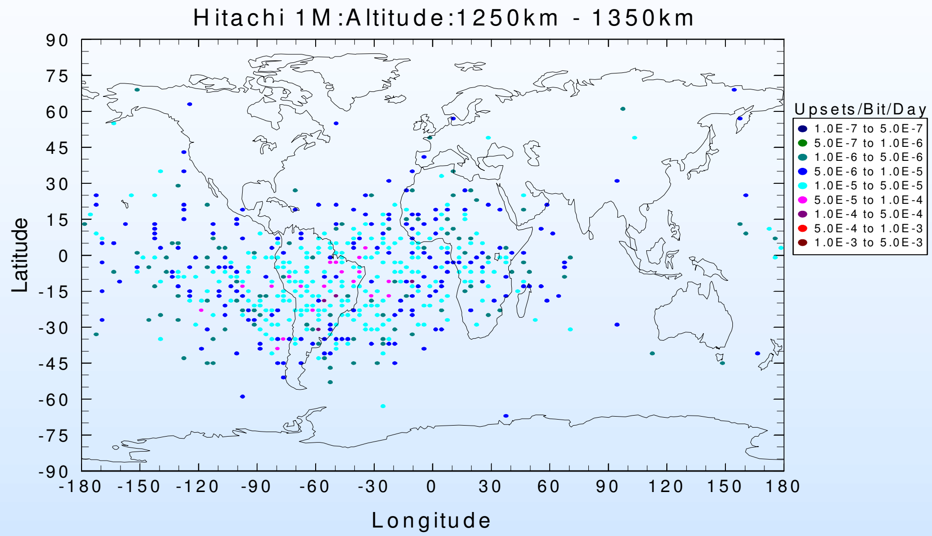
Trapped Particles in the Earth's Magnetic Field: Proton & Electron Intensities

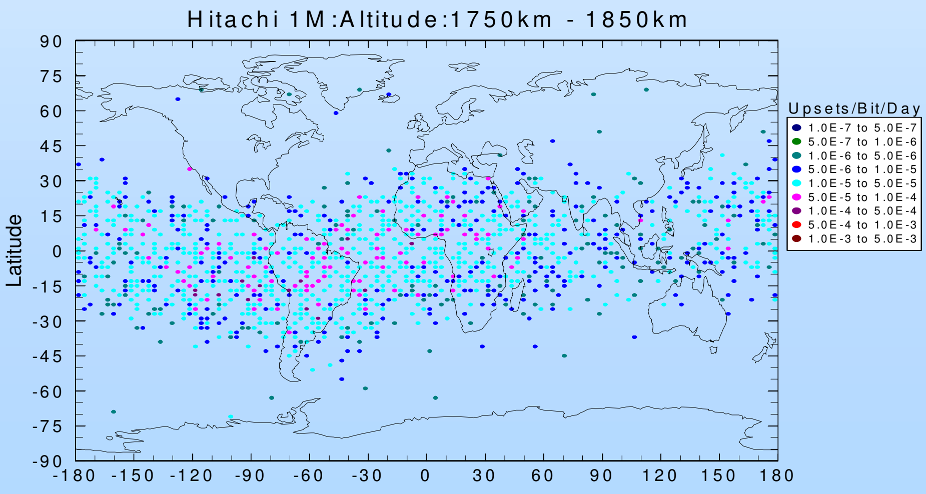


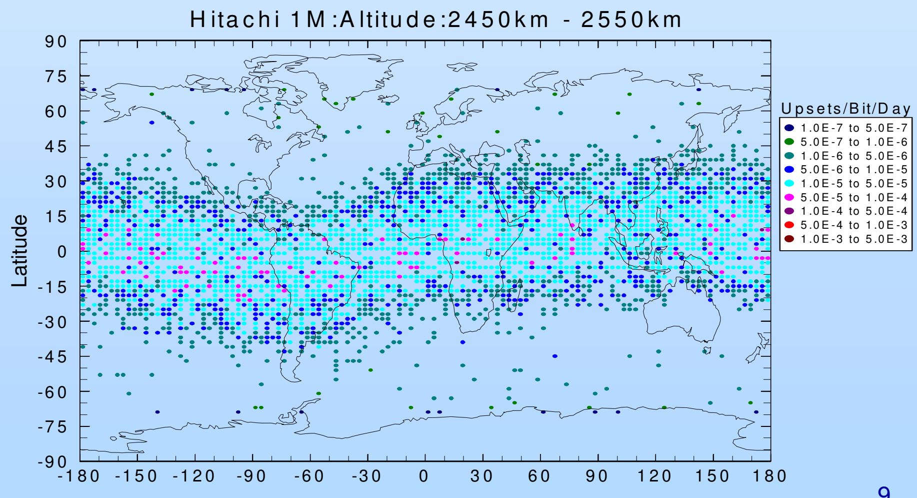
SAA and Trapped Protons:

Effects of the Asymmetry in the Proton Belts on SRAM Upset Rate at Varying Altitudes on CRUX/APEX

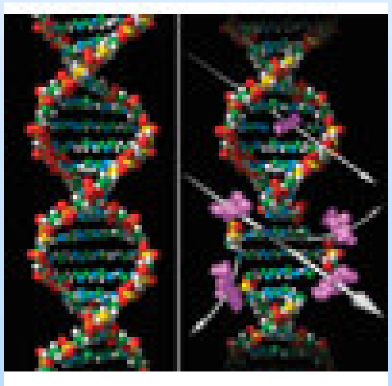








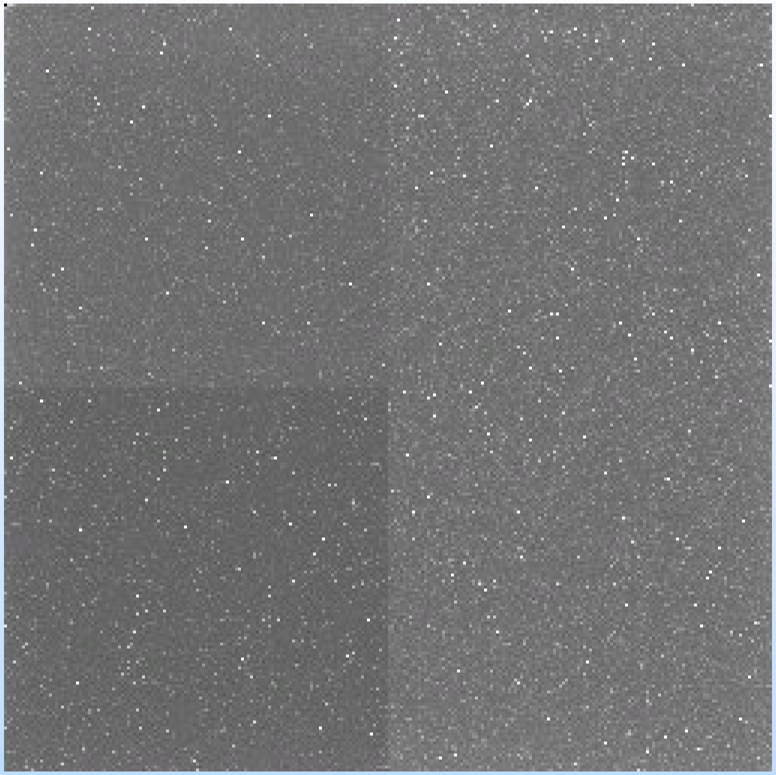
The Effects



DNA double helix
Pre and Post Irradiation
Biological effects are a key concern
for lunar and Mars missions

Radiation Effects and Spacecraft

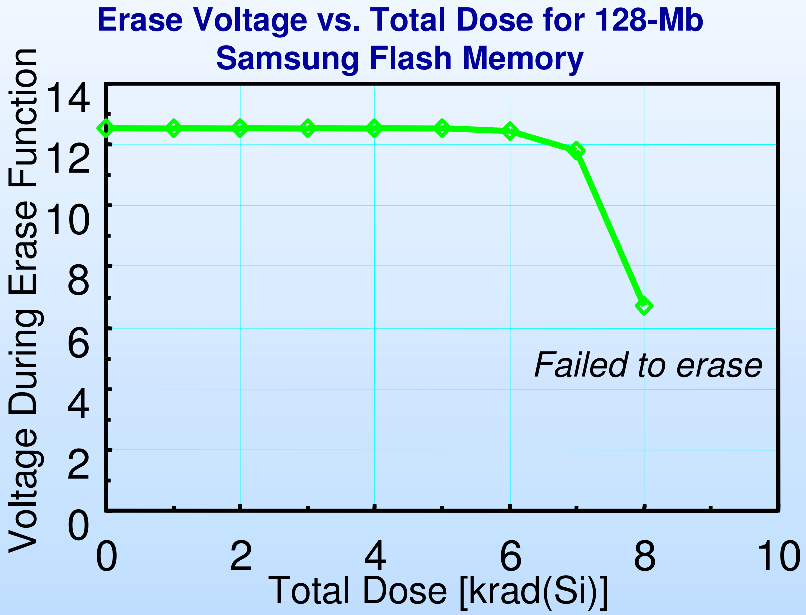
- **Critical areas for design in the natural space radiation environment**
  - **Long-term effects**
    - **Total ionizing dose (TID)**
    - **Displacement damage**
  - **Transient or single particle effects (Single event effects or SEE)**
    - **Soft or hard errors**
- **Mission requirements and philosophies vary to ensure mission performance**
  - ***What works for a shuttle mission may not apply to a deep-space mission***



An Active Pixel Sensor (APS) imager under irradiation with heavy ions at Texas A&M University Cyclotron

Total Ionizing Dose (TID)

- **Cumulative long term *ionizing* damage due to protons & electrons**
- **Effects**
  - **Threshold Shifts**
  - **Leakage Current**
  - **Timing Changes**
  - **Functional Failures**
- **Unit of interest is krads(material)**
- **Can *partially* mitigate with shielding**
  - **Low energy protons**
  - **Electrons**



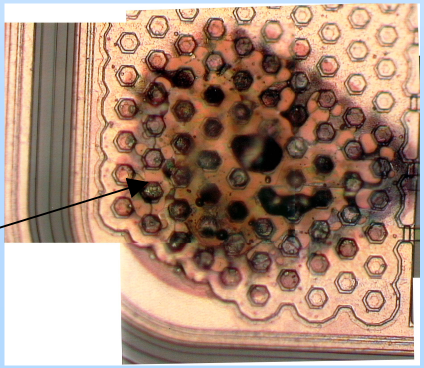
Displacement Damage (DD)

- Cumulative long term *non-ionizing* damage due to protons, electrons, and neutrons
- Effects
  - Production of defects which results in device degradation
  - May be similar to TID effects
  - Optocouplers, solar cells, CCDs, linear bipolar devices
- Unit of interest is particle fluence for each energy mapped to test energy
  - Non-ionizing energy loss (NIEL) is one means of discussing
- Shielding has some effect - depends on location of device
  - Reduce significant electron and some proton damage

Not particularly applicable to CMOS microelectronics

Single Event Effects (SEEs)

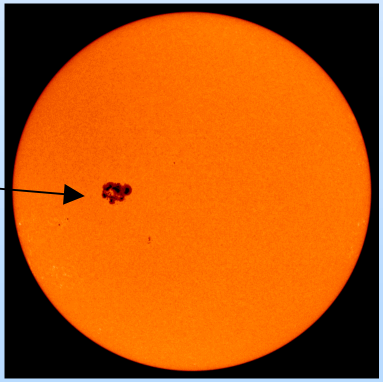
- **An SEE is caused by a *single charged particle* as it passes through a semiconductor material**
  - **Heavy ions**
    - **Direct ionization**
  - **Protons for sensitive devices**
    - **Nuclear reactions for standard devices**
- **Effects on electronics**
  - **If the LET of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen**
    - **Soft errors such as upsets (SEUs) or transients (SETs), or**
    - **Hard (destructive) 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

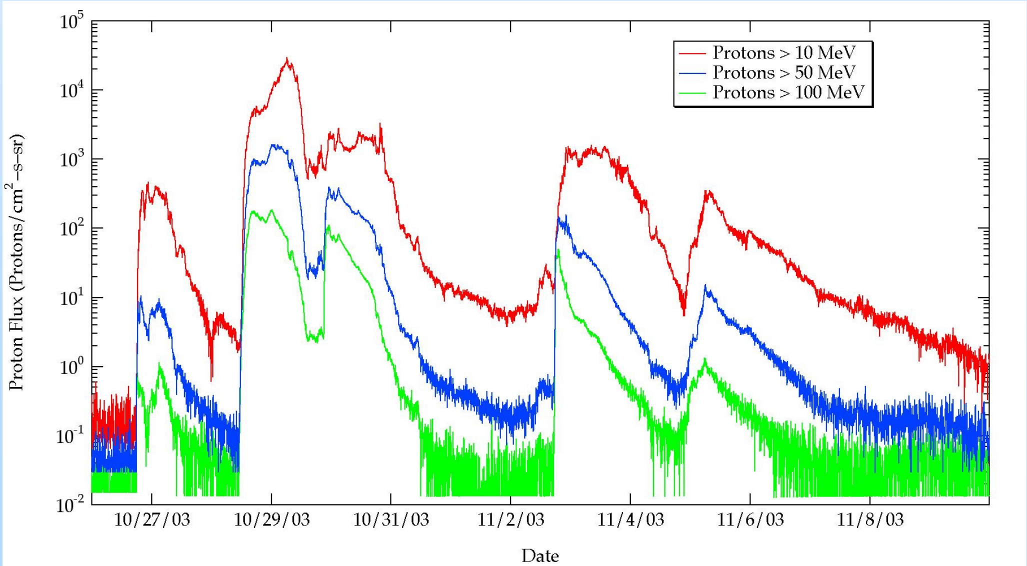
The Environment in Action

"There's a little black spot on the sun today"

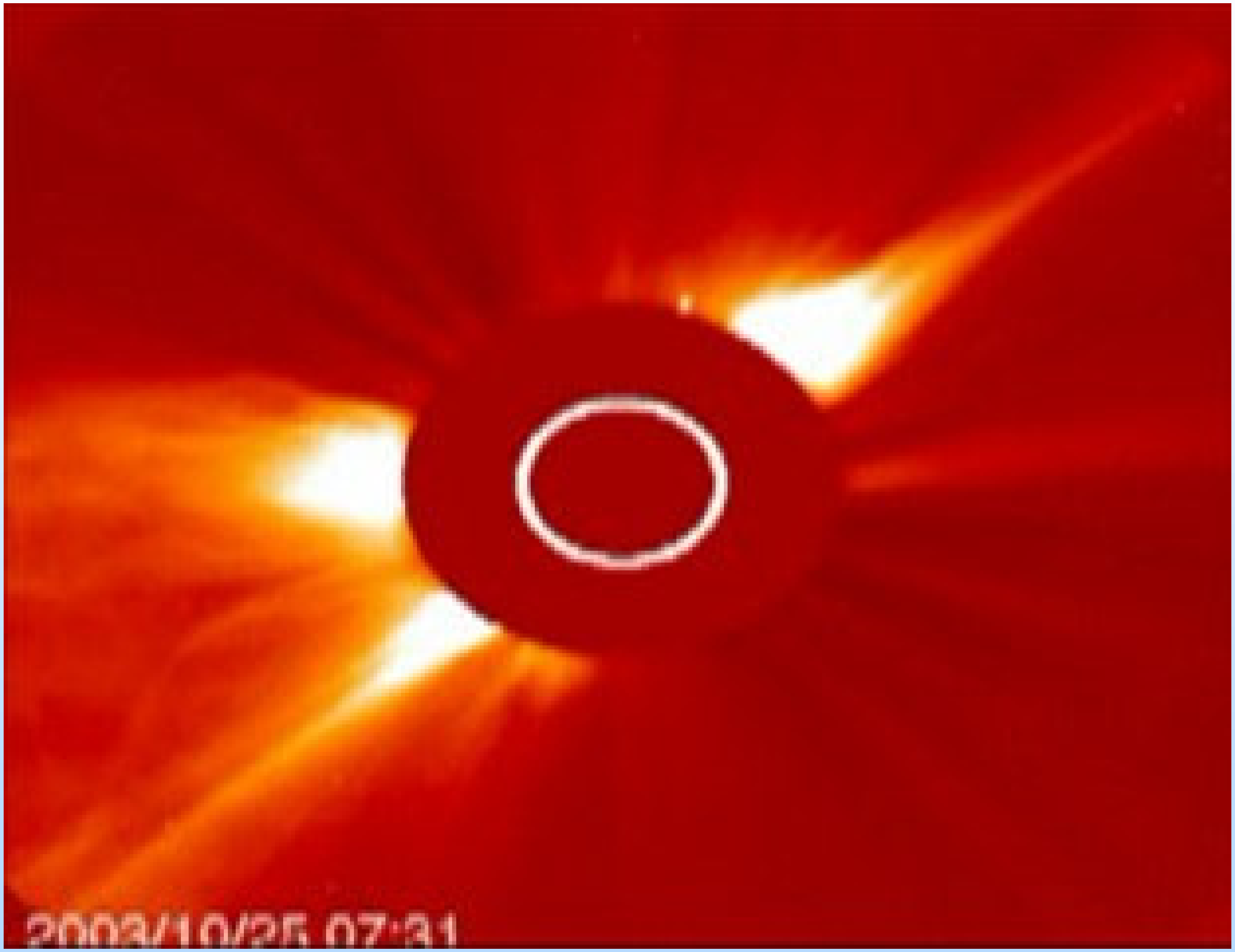


Recent Solar Events – A Few Notes and Implications

- In Oct-Nov of this year, a series of X-class (X-45!) solar events took place
  - High particle fluxes were noted
  - Many spacecraft performed safing maneuvers
  - Many systems experienced higher than normal (but correctable) data error rates
  - Several spacecraft had anomalies causing spacecraft safing
  - Increased noise seen in many instruments
  - Drag and heating issues noted
  - Instrument FAILURES occurred
  - Two known spacecraft FAILURES occurred
- Power grid systems affected, communication systems affected…

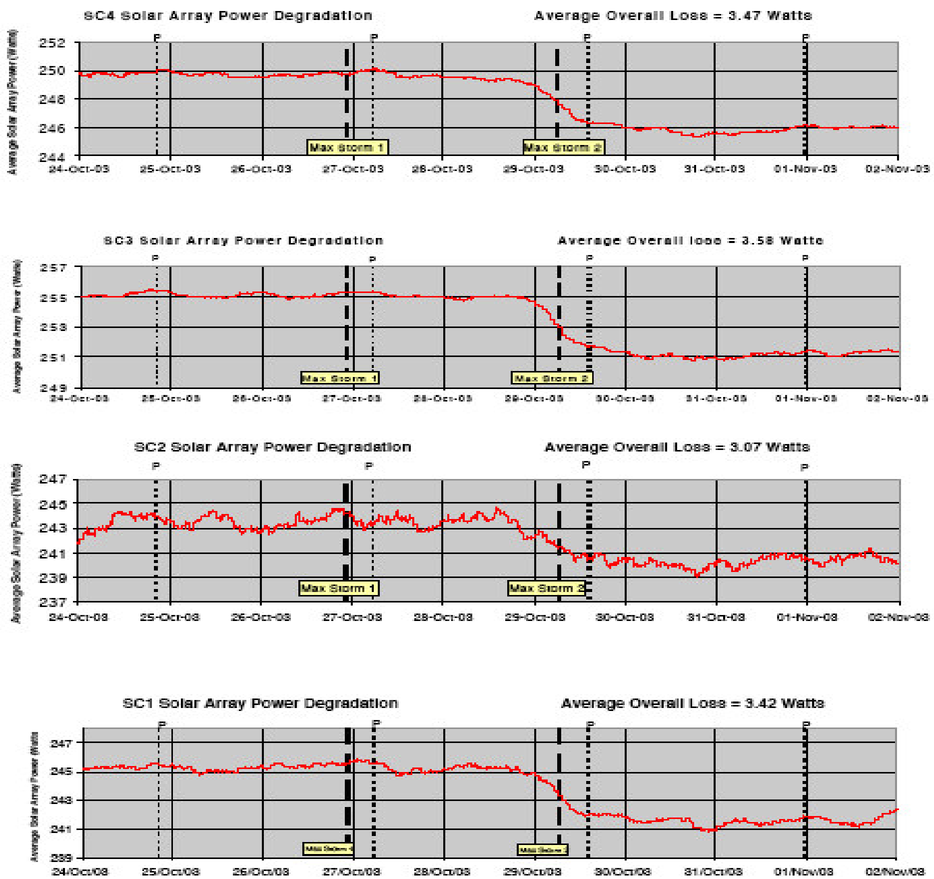


SOHO LASCO C2 of the Solar Event



Solar Event Effect - Solar Array Degradation on CLUSTER Spacecraft

ANNEX 1: Evolution of the Solar Array Power from 24-Oct to 02-Nov 2003 when two solar radiation storms occurred (the time of their maximum is indicated in the plot "---"). The degradation of the panels was about 1.4% and the average power loss is shown for each spacecraft.
The perigee passes are marked as "….." and labeled with "P"



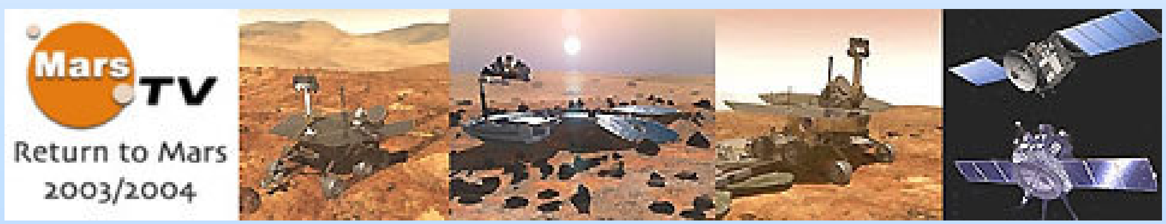
Many other spacecraft to noted degradation as well.

Selected Other Consequences

- Orbits affected on several spacecraft
- Power system failure
  - Malmo, Sweden
- High Current in power transmission lines
  - Wisconsin and New York
- Communication noise increase
- FAA issued a radiation dose alert for planes flying over 25,000 ft

A NASA-built radiation monitor that can aid anomaly resolution, lifetime degradation, protection alerts, etc.

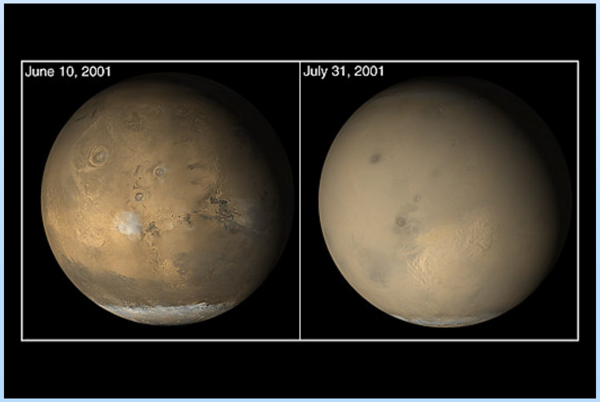
NASA Approaches to Electronics:
Flight Projects and Proactive Research



It doesn't matter where you go
as long as you follow a
programmatic assurance approach

NASA Missions –
A Wide Range of Needs

- **NASA typically has over 200 missions in some stage of development**
  - **Range from balloon and short-duration low-earth investigations to long-life deep space**
  - **Robotic to Human Presence**
- **Radiation and reliability needs vary commensurately**



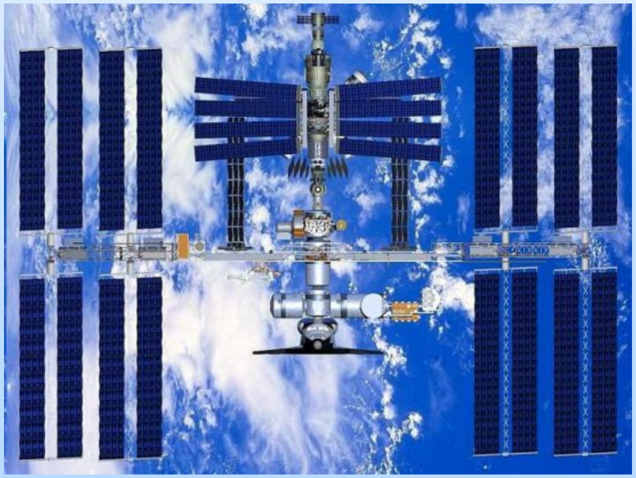
Mars Global Surveyor Dust Storms in 2001

Implications of NASA Mix

- **Prior to the U.S Vision for Space Exploration**
  - **>90% of NASA missions required 100 krad(Si) or less for device total ionizing dose (TID) tolerance**
    - **Single Event Effects (SEEs) were prime driver**
      - **Sensor hardness also a limiting factor**
    - **Many missions could accept risk of anomalies as long as recoverable over time**
- **Implications of the new vision are still TBD for radiation and reliability specifics, however,**
  - **Nuclear power/propulsion changes radiation issues (TID and displacement damage)**
  - **Long-duration missions such as permanent stations on the moon require long-life high-reliability for infrastructure**
    - **Human presence requires conservative approaches to reliability**
      - ***Drives stricter radiation tolerance requirements and fault tolerant architectures***

Lunar footprint
Courtesy of NASA archives

A Systematic Approach to Flight Project Radiation Hardness Assurance (RHA)

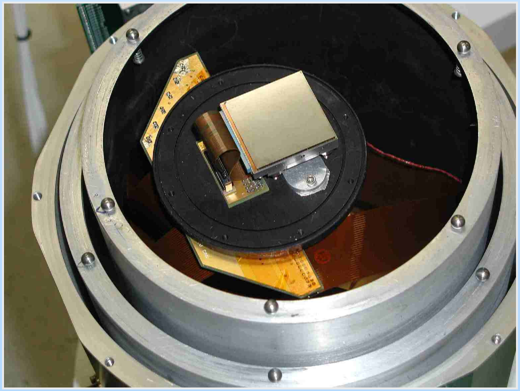


Size, complexity, and human presence are among the factors im deciding how RHA is to be implemented

NASA Approach to RHA

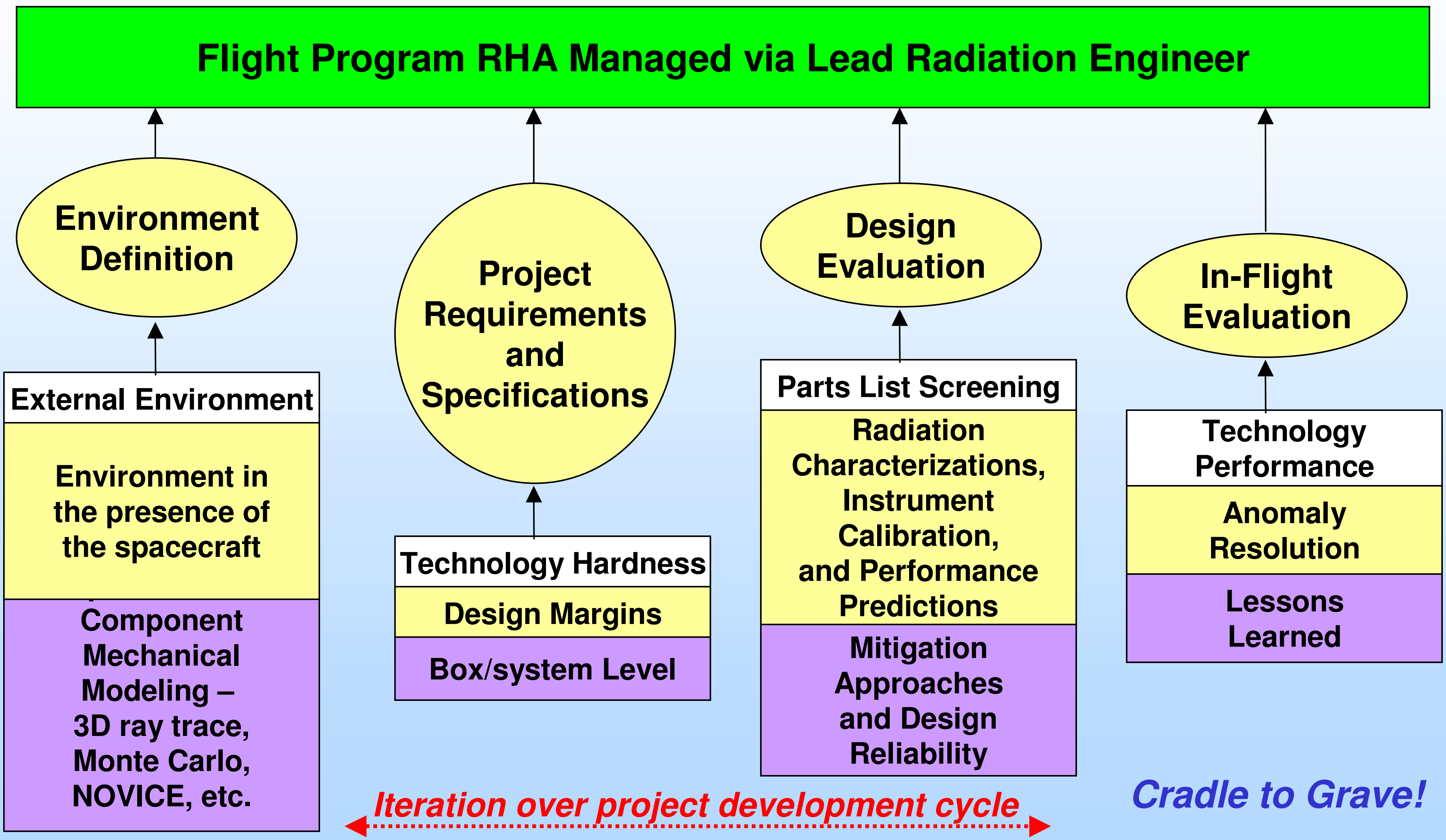
- **With commercial technology sensitivity to SEU increasing and limited radiation hardened offerings, a dual approach to RHA needs to be installed**
  - **A systems approach at the flight mission level, and**
  - **Proactive investigation into new technologies**

Rockwell/Hawaii 2048x2048
5µm HgCdTe NGST FPA (ARC)



Candidate James Webb Space Telescope (JWST) IR array preparing for rad tests. The ultra-low noise requirement of JWST is the driver.

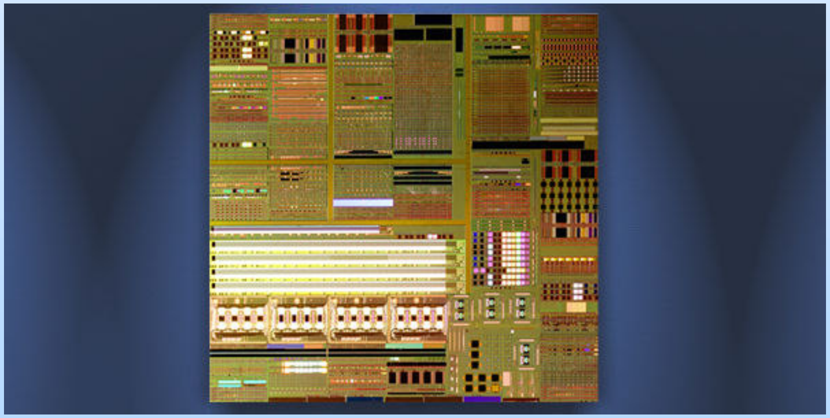
Flight Program Radiation Hardness Assurance (RHA) Flow



Radiation and Systems Engineering: A Rational Approach for Space Systems

- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
  - Existing data/Testing/Performance characteristics
- **“Engineer” with Designers**
  - Parts replacement/Mitigation schemes
- **Iterate Process**
  - Review parts list based on updated knowledge

Approach to Insertion of New Electronics

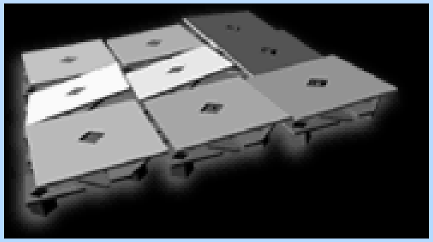


IBM CMOS 8SF ASIC

Microelectronics: Categories

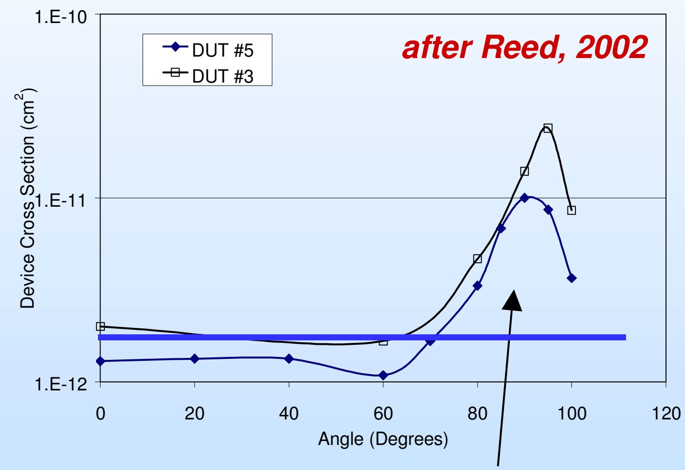
- Microelectronics can be split several ways
  - Digital, analog, mixed signal, other
  - Complementary Metal Oxide Semiconductor (CMOS), Bipolar, etc...
  - Function (microprocessor, memory, …)
- There are only two commercial foundries (where they build devices) in the US dedicated to building radiation hardened digital devices
  - Efforts within DoD to provide alternate means of developing hardened devices
    - Hardened-by-design (HBD)
    - Provides path for custom devices, but not necessarily off-the-shelf devices
  - Commercial devices can have great variance in radiation tolerance from device-to-device and even on multiple samples of same device
    - No guarantees!
  - Analog foundry situation is even worse
- New technologies have many unknowns
  - Ultra-high speed, nanotechnologies, microelectromechanical systems (MEMS and the optical versions – MOEMS), …

A MOEMS in action



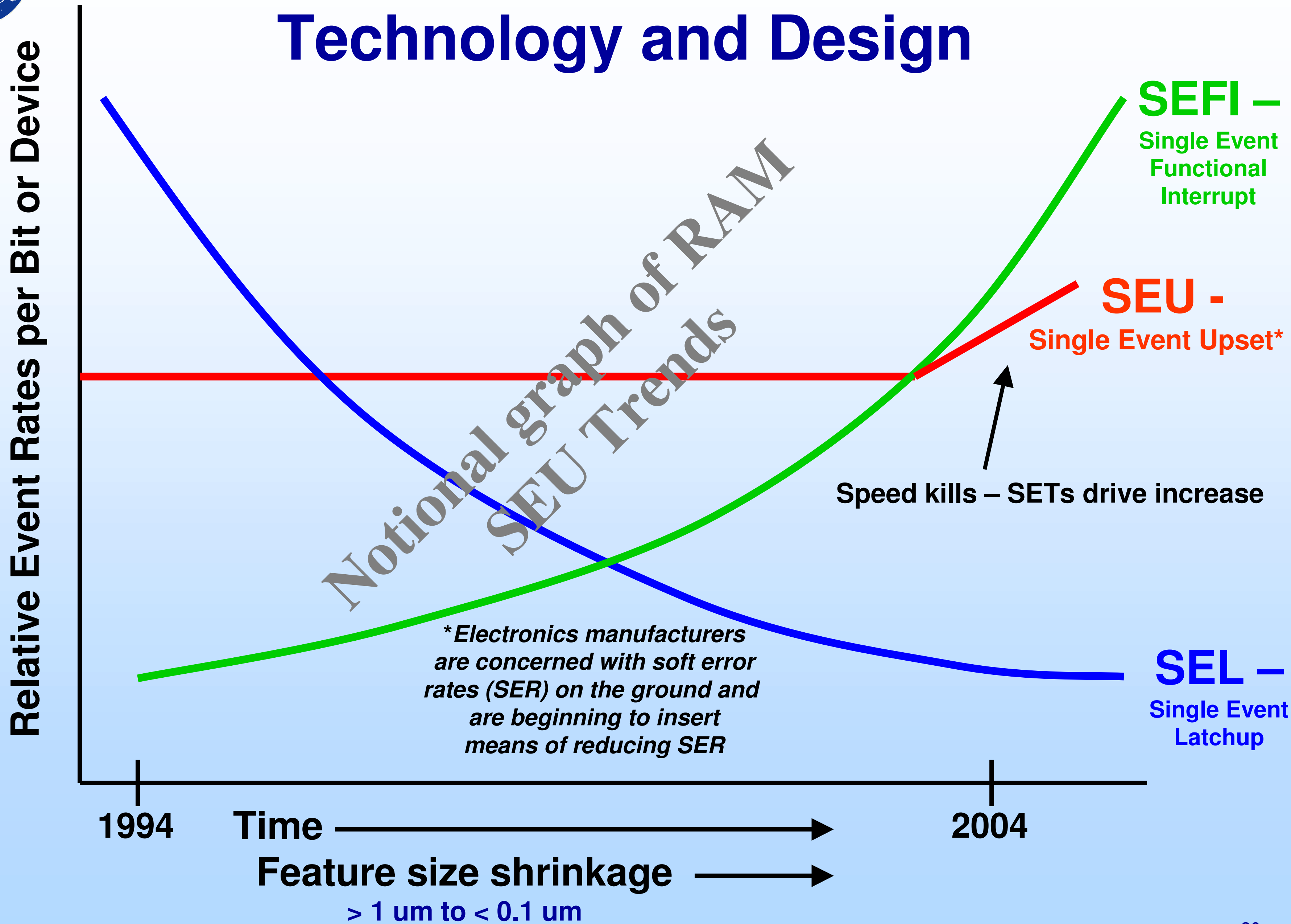
The Digital Logic Trends

- Standard CMOS
  - Feature sizes are scaling (shrinking) to sub-0.1 micron sizes
    - Faster devices, lower operating voltages
      - Reduced electrical margins within devices
  - New dielectrics are being used
  - Thickness of gate oxide is being diminished
  - Implications (general)
    - Improved TID tolerance
      - DD not an issue (except possibly at nuclear levels)
    - Improved SEL tolerance
    - Increased SEU sensitivity
      - Technology speed increase drives this issue (SETs in logic propagate)
    - Unknown effect of other technology changes
  - Increased use of silicon-on-insulator (SOI) substrates



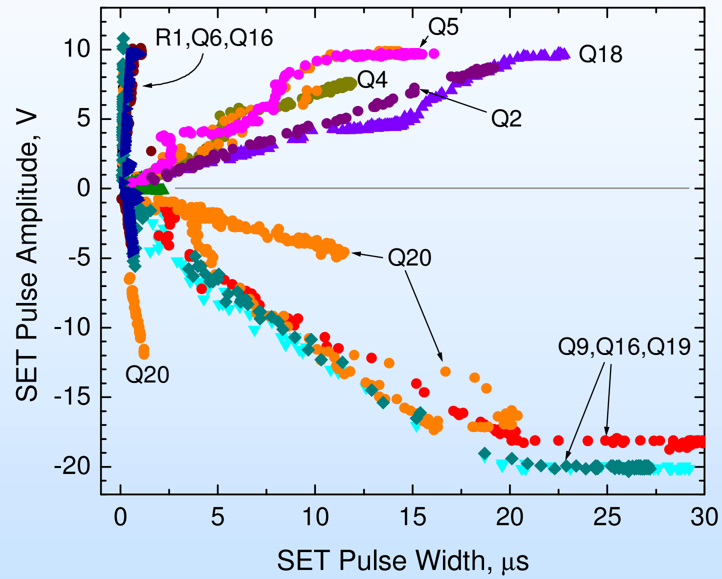
Effects of protons in SOI with varied angular direction of the particle; Blue line represents expected response with "standard" CMOS devices.

The New Challenge: Changes in CMOS Technology and Design



Analog/mixed signal

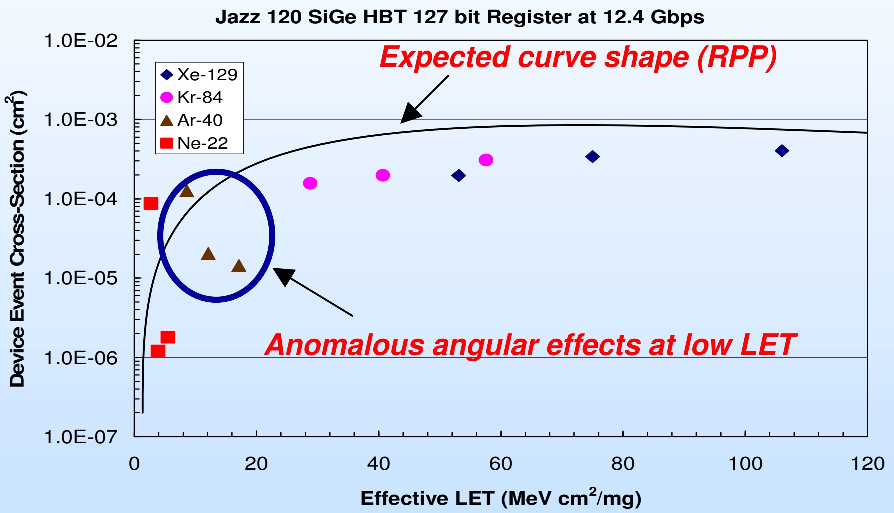
- **Not scaled as aggressively (need higher voltages to get analog range)**
  - **Efforts to improve electrical performance have reduced reliability and signal margins within the device**
  - **Increased sensitivity to**
    - **SETs (noise propagation that can be invasive to operations)**
      - **The higher the resolution or speed, the worse this becomes**
    - **TID and DD**
      - **Commercial device failure noted as low as 1 krad(Si)**
        - » **Even short duration missions would have concerns without test data**



LASER SEU tests on a LM124 Op Amp. Note the variety of transients generated depending on particle arrival point and circuit application

New Technologies – Sample Issues

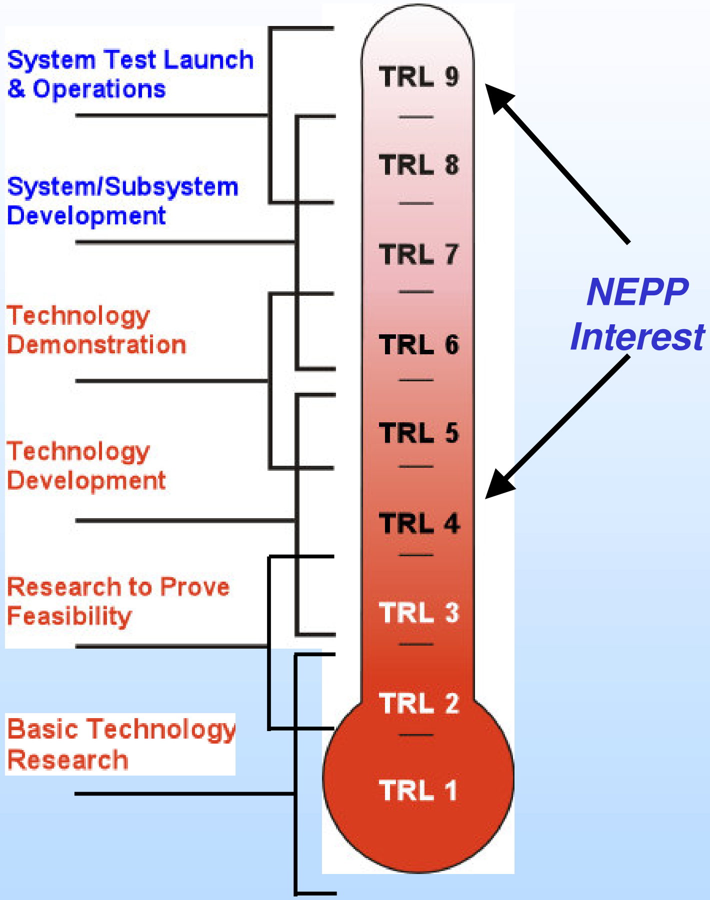
- **Ultra-high speed**
  - **Devices that may be relatively tolerant at low-speed (<100 MHz) have vastly increased SEU sensitivity at high-speeds (>1 GHz)**
    - **Speed can defeat HBD methods**
    - **New technologies don't fit old models**
- **Sensors**
  - **Noise, damage, etc. can limit device performance (such as an imager) and lifetime**
    - **Small effort at DoD to provide hardened solutions**
- **MEMS**
  - **Combined effects of electrical, optical, and mechanical degradation**
- **Nanotechnologies**
  - **A great unknown for radiation effects and protection**



Effects of heavy ions on SiGe devices at 12 GHz speeds; Drawn line represents expected response with "standard" models.

Insertion of New Technologies – A Mission Perspective

- **NASA mission timeframes rarely allow for a technology development path**
  - **For a 2008 launch, for example, technology freeze dates are likely 2005 or earlier**
    - **Technology must be moderately mature when a mission is being developed**
      - ***There may be time to qualify a device, but there may not be time to develop/validate a new technology solution!***
    - **Risk versus performance reward for using less mature or commercial off-the-shelf (COTS) technologies**
- **Technology development and evaluation programs need to be in place prior to mission design**
  - ***Strategic planning***



NASA Technology Readiness Levels (TRLs)

Final Comments and Future Considerations

Technology, Testing, and Flight

- Technology complicates the tests
  - Speed, Thermal, Fault Isolation, Packaging: die access!, etc
    - SETs are the "new" effect in digital devices
  - Ultra-low noise science instruments
- Future facility issues
  - Beam structure
    - Issue: At-speed testing
  - Microbeam
    - Issue: Isolation of errors / Identification of sensitive junctions
  - High energy heavy ions – Michigan State University (MSU) National Superconducting Cyclotron Labs (NSCL) now open for business
    - Issue: Increased fidelity to space environment
    - Issue: Improved ion penetration (packaging issues!)
    - Issue: Thermal (open air testing possible)
    - Issue: Speed (reduced cabling requirements)
- Nanotechnologies? MEMS?
- A proactive radiation test and modeling program is required to allow successful system RHA

Backup Slides

Details on RHA Approach for Flight Projects

Define the Hazard

- The radiation environment *external* to the spacecraft
  - Trapped particles
    - Protons
    - Electrons
  - Galactic cosmic rays (heavy ions)
  - Solar particles (protons and heavy ions)
- Based on
  - Time of launch and mission duration
  - Orbital parameters, …
- Provides
  - Nominal and worst-case trapped particle fluxes
  - Peak "operate-through" fluxes (solar or trapped)
  - Dose-depth curve of total ionizing dose (TID)

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

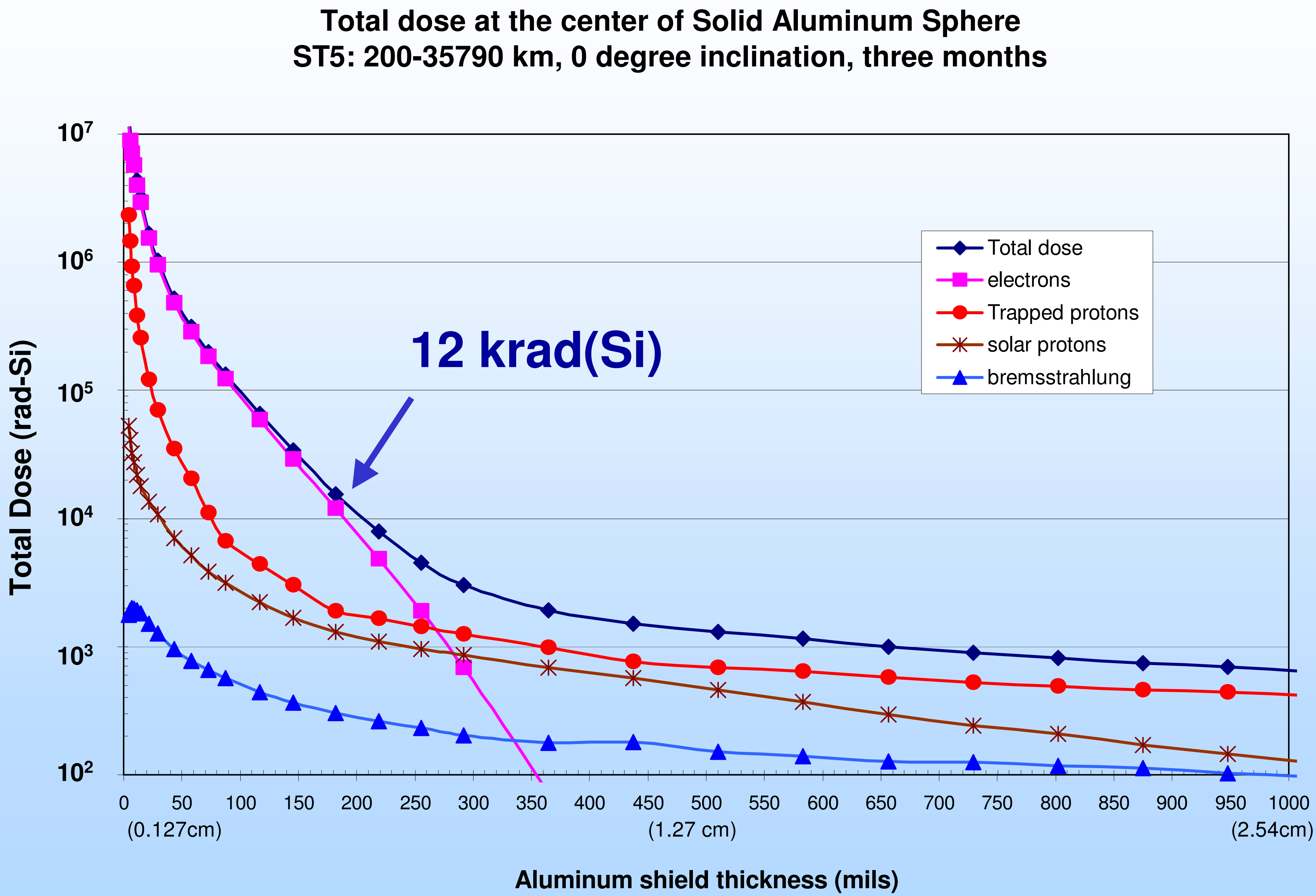
Evaluate the Hazard

- Utilize mission-specific geometry to determine particle fluxes and TID at locations *inside* the spacecraft
  - 3-D ray trace (geometric sectoring)
- Typically multiple steps
  - Basic geometry (empty boxes,…) or single electronics box
  - Detailed geometry
    - Include printed circuit boards (PCBs), cables, integrated circuits (ICs), thermal louvers, etc…
- Usually an iterative process
  - Initial spacecraft design
  - As spacecraft design changes
  - Mitigation by changing box location

Define Requirements

- **Environment usually based on hazard definition with "nominal shielding" or basic geometry**
  - **Using actual spacecraft geometry sometimes provides a "less harsh" radiation requirement**
- **Performance requirements for "nominal shielding" such as 70 mils of Al or actual spacecraft configuration**
  - **TID**
  - **DDD (protons, neutrons)**
  - **SEE**
    - **Specification is more complex**
    - **Often requires SEE criticality analysis (SEECA) method be invoked**
- Must **include radiation design margin (RDM)**
  - **At least a factor of 2**
  - **Often required to be higher due to device issues and environment uncertainties (enhanced low dose rate issues, for example)**

Sample TID Top Level Requirement : Dose-Depth Curve



System Requirements - SEE Specifications

- For TID, parts can be given A number (with margin)
  - SEE is much more application specific
- SEE is unlike TID
  - Probabilistic events, not long-term
    - Equal probabilities for 1st day of mission or last day of mission
      - Maybe by definition!

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*cm^2/mg	Cosmic Ray, Trapped Protons, Solar Proton Events
LET_{th} = 15*-100 MeV*cm^2/mg	Galactic Cosmic Ray Heavy Ions, Solar Heavy Ions
LET_{th} > 100 MeV*cm^2/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.

Notes on System Requirements

- Requirements do NOT have to be for piecepart reliability
  - For example, may be viewed as a “data loss” specification
    - Acceptable bit error rates or system outage
  - Mitigation and risk are system trade parameters
  - Environment needs to be defined for ***YOUR*** mission (can’t use prediction for different timeframe, orbit, etc…)

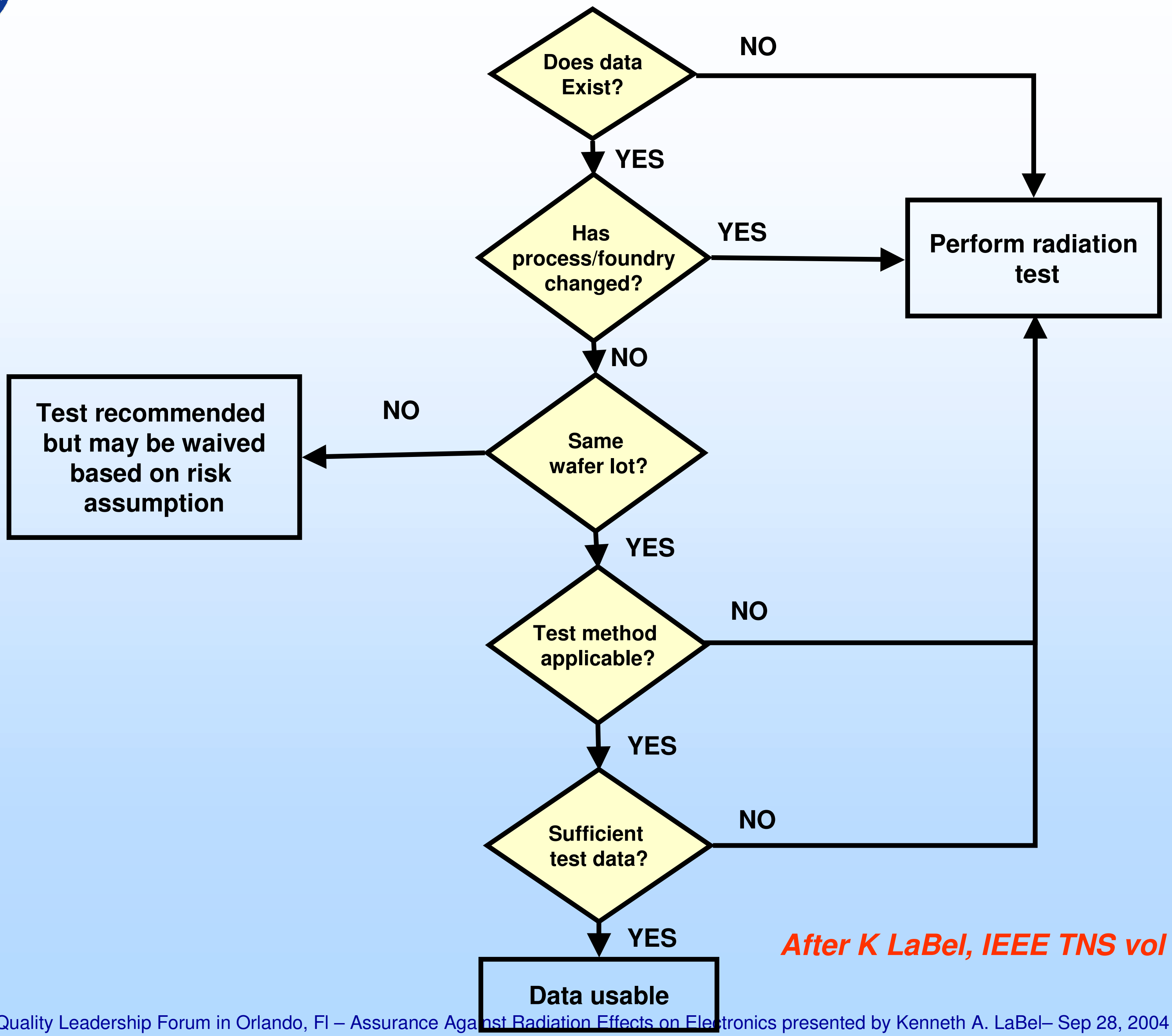
Radiation Design Margins (RDMs)

- How much risk does the project want to take?
- Uncertainties that must be considered
  - Dynamics of the environment
  - Test data
    - Applicability of test data
      - Does the test data reflect how the device is used in THIS design?
    - Device variances
      - Lot-to-lot, wafer-to-wafer, device-to-device
- Risk trade
  - Weigh RDM vs. cost/performance vs. probability of issue vs. system reliability etc…

Evaluate Design/Component Usage

- Screen parts list
  - Use existing databases
    - RADATA, REDEX, Radhome, IEEE TNS, IEEE Data Workshop Records, Proceedings of RADECS, etc.
    - Evaluate test data
  - Look for processes or products with known radiation tolerance (beware of SEE and displacement damage!)
    - BAE Systems, Honeywell Solid State Electronics, UTMC, Harris, etc.
- Radiation test unknowns or non-RH guaranteed devices
- Provide performance characteristics
  - Usually requires *application specific* information: understand the designer's sensitive parameters
    - SEE rates
    - TID/DDD

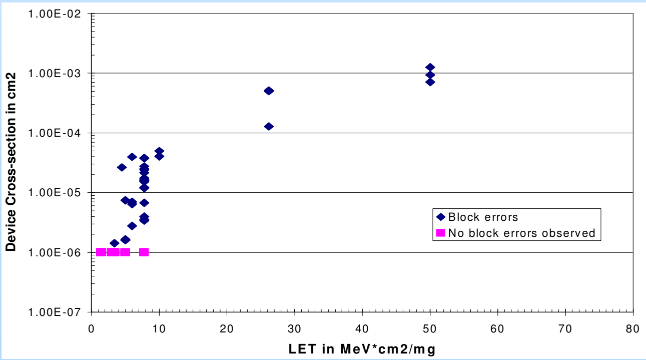
Data Search and Definition of Data Usability Flow



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

System Radiation Test Requirements

- All **devices with unknown characteristics should be ground radiation tested (TID and SEE)**
- **All testing should be performed on flight lot, if possible**
- **Testing should mimic or bound the flight usage, if possible**
  - **Beware of new technology issues…**



Sample Heavy Ion Test Results

Engineer with the Designer

- **Just because a device's radiation hardness may not meet requirements, does NOT necessarily make it unusable**
  - **Many concerns can be dealt with using mitigative approaches**
    - **Hardened by design (HBD) approaches**
    - **Circuit level tolerance such as error detection and correction (EDAC) on large memory arrays**
    - **Mechanical approaches (shielding)**
    - **Application-specific effects (ex., single bad telemetry point or device is only on once per day for 10 seconds or degradation of parameter is acceptable)**
    - **System tolerance such as 95% "up-time"**
  - **The key is what is the effect in THIS application**
  - **If mitigation is not an option, may have to replace device**

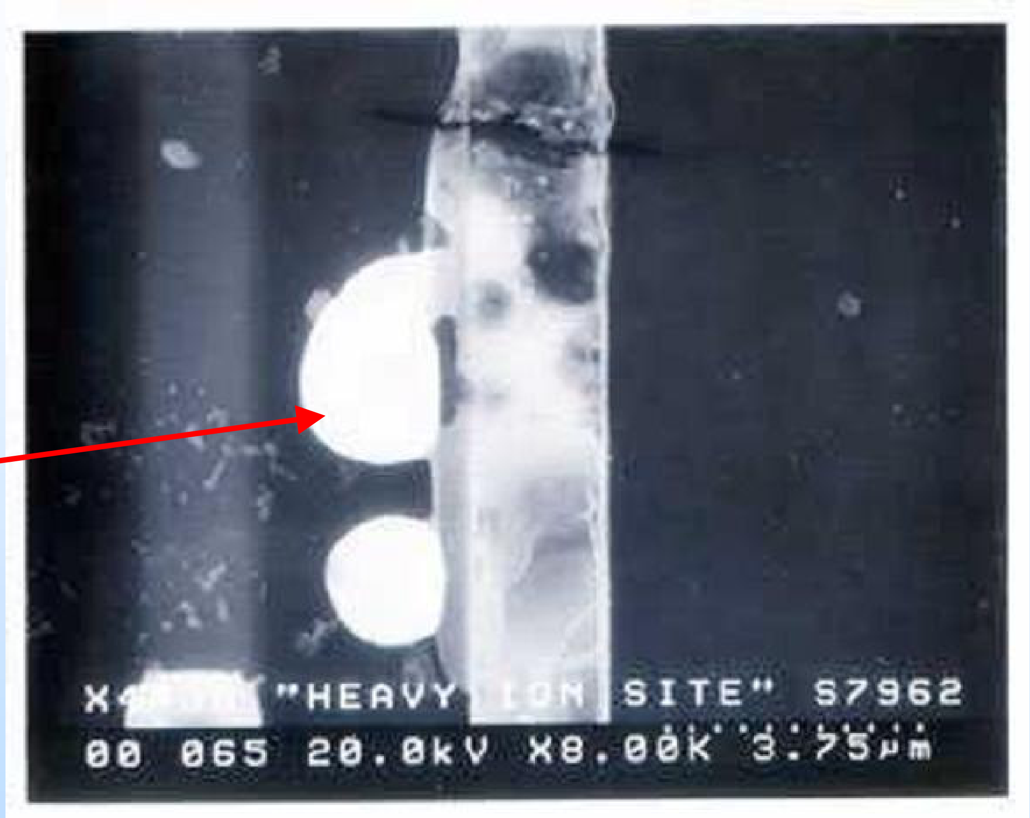
Warning: Not all effects can be mitigated safely

Destructive Conditions - 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 SELs may be difficult to detect
- 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!

Latent Damage: Implications to SEE

- SEL events are observed in some modern CMOS devices
  - Device may not fail immediately, but recover after a power cycling
- However, in some cases
  - Metal is ejected from thin metal lines that may fail catastrophically at some time after event occurrence



SEL test qualification methods need to take latent damage into consideration;
Post-SEL screening techniques required;
Mitigative approaches may not be effective