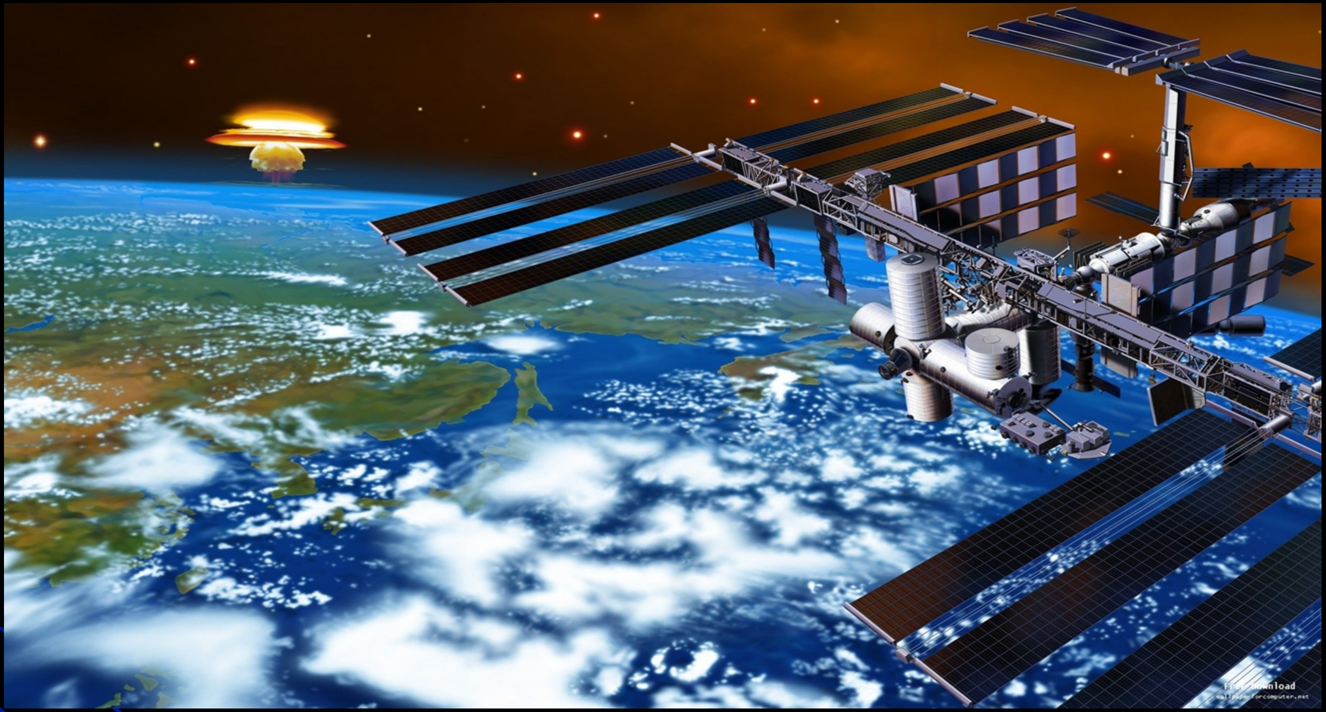
Understanding the Space Radiation Environment: Radiation Hardness Assurance (RHA) and Design for Space Systems



Amanda N. Bozovich

Jet Propulsion Laboratory (JPL)

Component Engineering Mission Assurance Office

Radiation Effects Engineering

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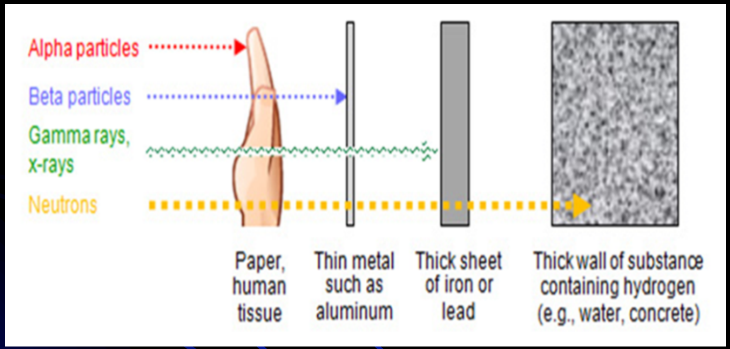
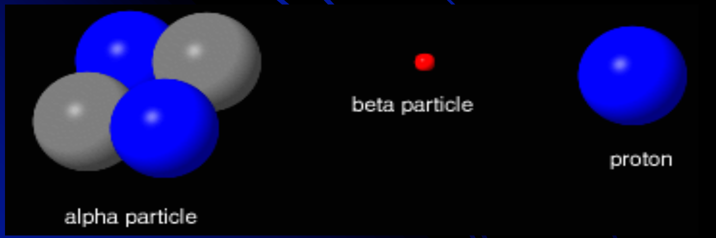
Agenda

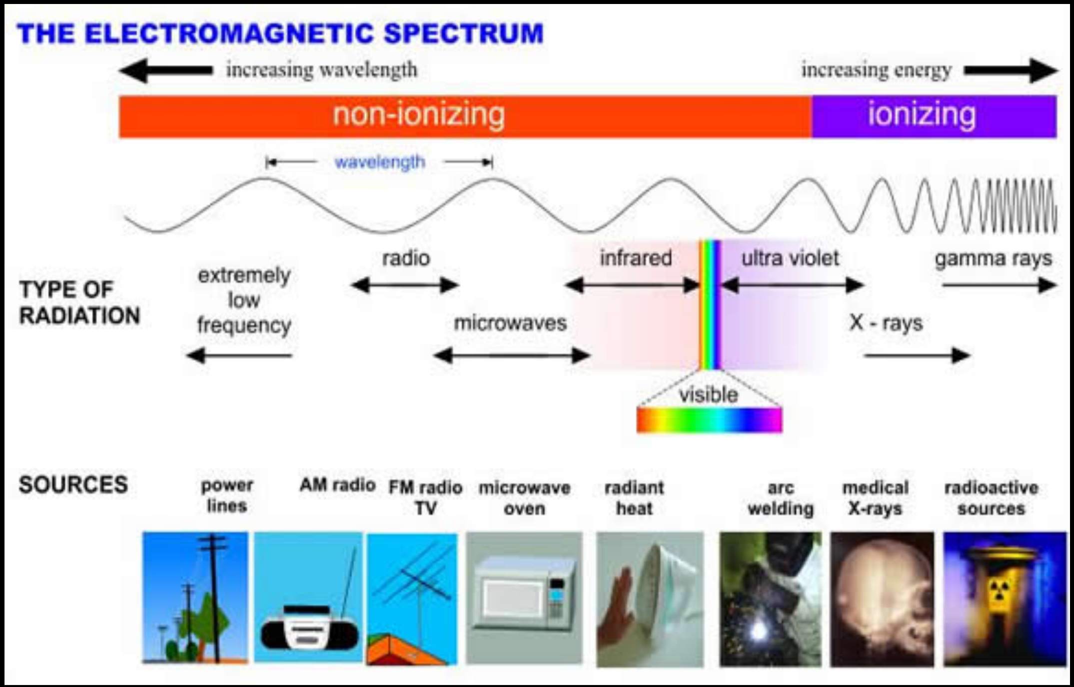
- **What is Space Radiation? Why do we care?**
- **Radiation Hardness Assurance (RHA) for Space System Design**
- Understanding the natural space radiation environment
- Radiation effects on satellite components and space systems
- Requirements definition, verification, validation and design considerations for hardening
- Radiation Testing Considerations
- Summary

What is Space Radiation?

- Electromagnetic spectrum: ionizing (charged particles i.e. alpha/beta, gamma rays, x-rays, neutron radiation) and non-ionizing radiation
- ***Space radiation***: flow of energy through space or material
  - Waves or ionizing particles (electrons, protons and heavy ions/charged particles consisting of elements in the Periodic Table)
  - Focus is on ionizing/ high energy charged particles (keV to TeV) – results in damaging radiation effects which severely impacts space system design







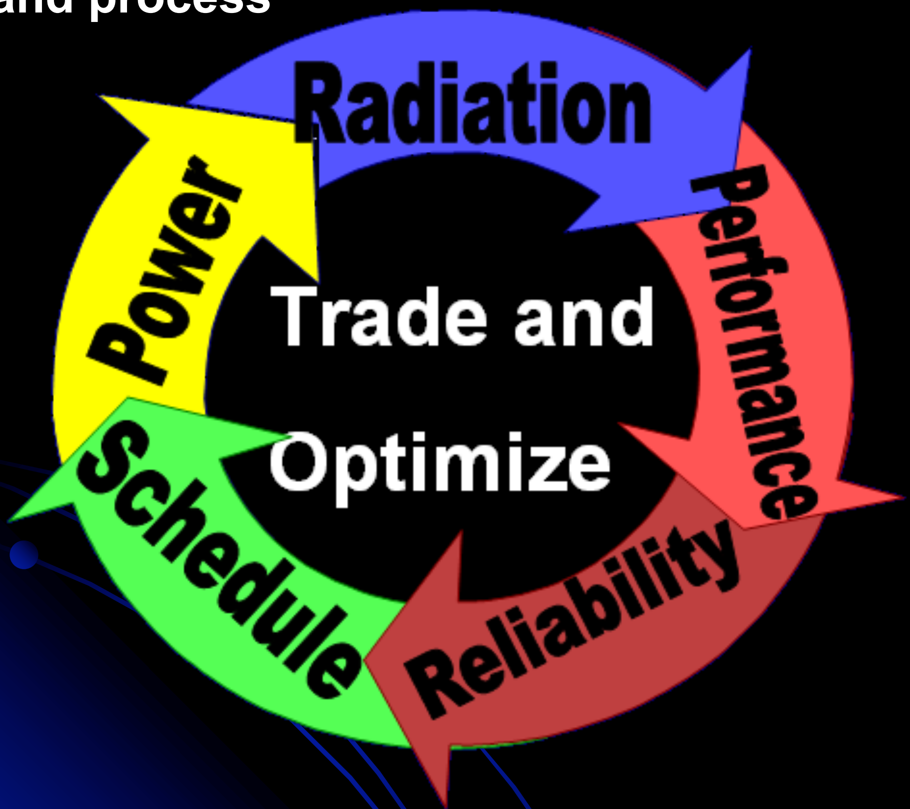
Critical Considerations for Radiation Hardness Assurance

- Space systems are subjected to harsh radiation environments – best approach to mitigate uncertainty factors is to define for mission
  - The severity is function of orbital environmental parameters (altitude, inclination, mission duration, start date) and shielding
  - Critical questions (***3 W's of space radiation***): <u>W</u>hen/ <u>W</u>here mission will fly? Are there design constraints (size, weight, etc.)? <u>W</u>hat systems/sub-systems must operate under worst case conditions? <u>W</u>hat systems are critical to mission success?
  - Three main radiation effects on satellite components and systems:
    - *Total Ionizing Dose (TID)*
    - *Displacement Damage Effects (DDE)*
    - *Single Event Effects (SEE)*

For space system design it is critical to understand the operating environment and types of radiation effects expected (including impact).

Critical Design Considerations for Radiation Risk Mitigation and Trade Space

<u>GOAL</u>: Meet end-of-life radiation requirements via mission + system design (including parts selection/ shielding), architecture, and hardening by design and process



Impact to speed, power, area, reliability, and schedule are important questions to address

- Continual trade to optimize and balance performance requirements, reliability, schedule risk, power efficiency, design complexity, radiation
- Will there be compromises?
  - Increased size (gate density)
  - Better performance
  - Improved speed
  - Lower power
  - Improved availability (schedule, program risk)
- Are you truly mitigating susceptible components?
- Reliability (is the circuit working and mitigating as expected)?

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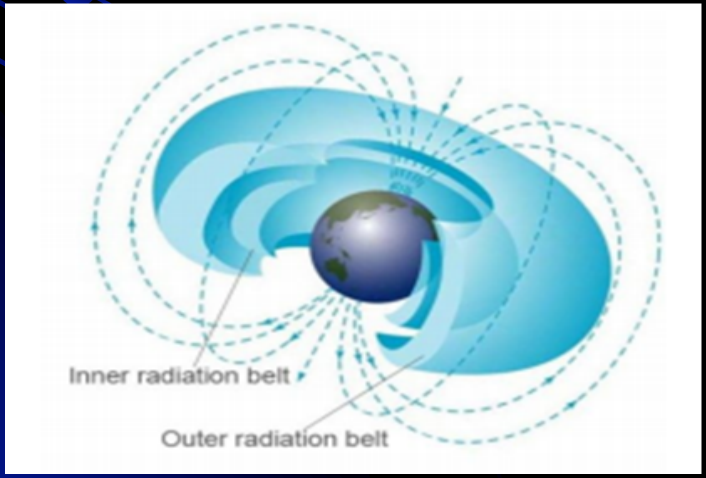
Main Sources of Radiation

- Main sources of energetic particles of concern to spacecraft designers:
  1) ***Trapped particles***: protons, electrons, heavy ions (Van Allen belts)
  2) ***Solar energetic particles (SEP)***: protons, electrons, heavy ions originating from Sun (solar flares and coronal mass ejections)
  3) ***Galactic Cosmic Rays (GCR)***: energetic protons, electrons, heavy ions of all elements in Periodic Table, highest GCR flux at solar min, cannot shield

MAXIMUM ENERGIES OF PARTICLES

Particle Type	Maximum Energy
Trapped Electrons	10s of MeV
Trapped Protons & Heavy Ions	100s of MeV
Solar Protons	GeV
Solar Heavy Ions	GeV
Galactic Cosmic Rays	TeV

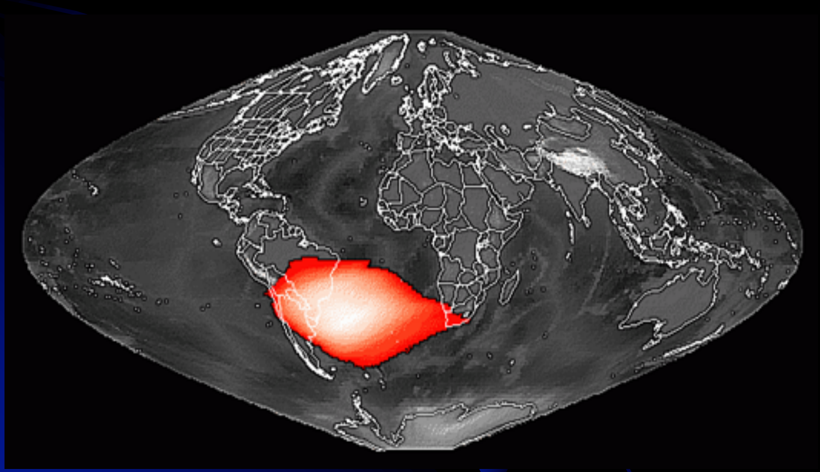
$$1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ J}$$



*Images from J. L. Barth et al., "Spaatmosphere, and terrestrial radiation environments", IEEE transaction on nuclear science, Vol. 50, No.3, 2003. Plasma and Space Physics and http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2012/07/space_radiation_affects_satellites/11258259-2-eng-GB/Space_radiation_affects_satellites.jpg

South Atlantic Anomaly (SAA)

- High density trapping zone at lower altitude, east of Brazil (South America)
- Inner Van Allen trapped radiation belt comes closest to Earth's surface (magnetic field is weakest)
- Formed as result of offset and tilt of Earth's geomagnetic axis with respect to rotation axis
- Area of intense, enhanced radiation exposure from high energy trapped protons, impacting LEO satellites (VIIRS BAE Single Board Computer)
- To mitigate effects: International Space Station requires extra shielding; Hubble Space Telescope doesn't make observations in SAA



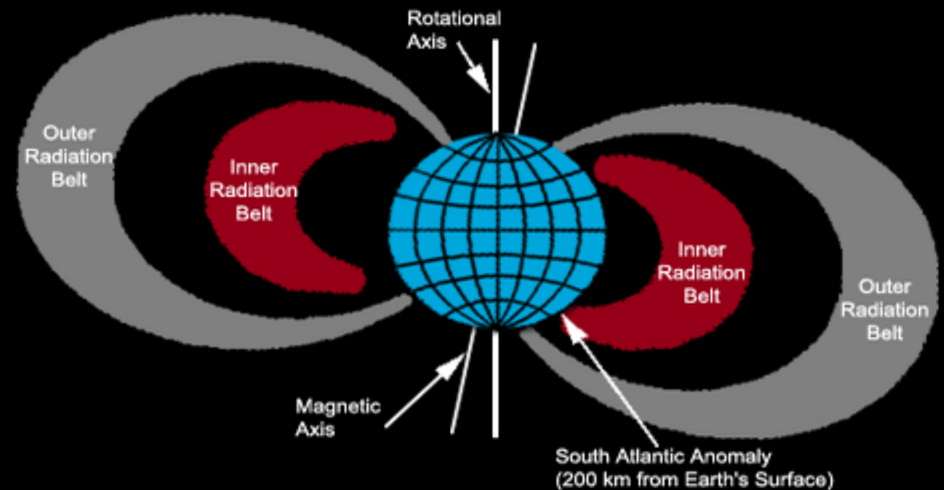
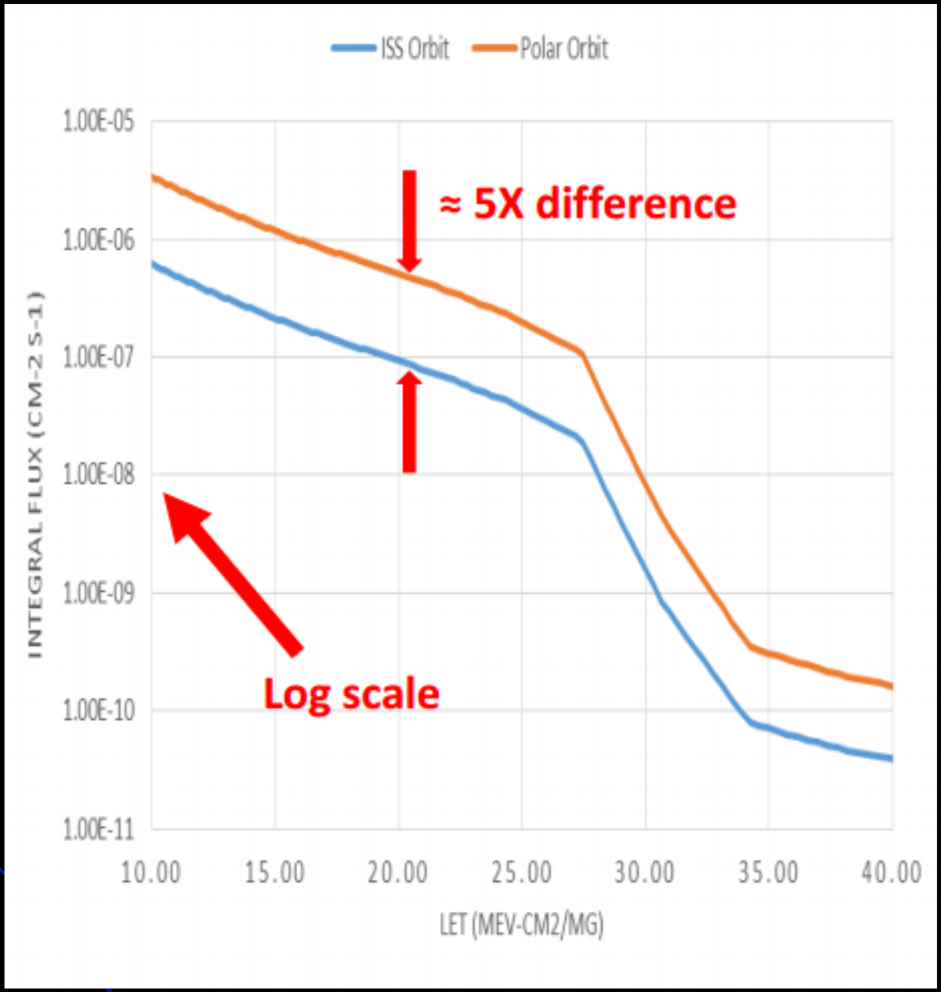


*Image from: reference 1

Example Orbit Flux Differences



LEO ISS orbit (400 km, 52º) 5X lower heavy ion integral flux compared to polar orbit (stronger magnetic field strength)

Image: Hadwin_Radiation_and_Reliability

Mission Dependent Environments

- **Low Earth Orbit (LEO):**
  - Pass Van Allen belts several times each day; level of flux depends on orbital inclination, altitude; location of peak flux depends on particle energy
  - As inclination, altitude increase, cosmic ray and solar flare particle flux increases until polar orbit (beyond geomagnetic field lines) where fully exposed to cosmic ray and solar flare particles for most of orbit
  - Inclinations below 45º completely shielded from solar flare protons (normal conditions)
- **Mid-Earth Orbit (MEO) and Highly Elliptical Orbit (HEO):**
  - Pass Van Allen belts each day, levels of trapped proton fluxes and TID levels depend on perigee position including altitude, latitude, and longitude
  - High altitude so long exposures to cosmic ray and solar flares regardless of inclination
- **Geosynchronous/Geostationary Orbit (GEO):**
  - Trapped protons negligible; trapped electrons cause significant total dose accumulation especially in areas of satellite lacking shielding
  - Fully exposed to galactic cosmic ray and solar flare particles

Understanding Radiation Effects in Different Orbits

Space hazard	Spacecraft charging		Single-event effects			Total radiation dose		Surface degradation		Plasma interference with communications	
Specific cause	Surface	Internal	Cosmic rays	Trapped radiation	Solar particle	Trapped radiation	Solar particle	Ion sputtering	O^+ erosion	Scintillation	Wave refraction
LEO <60°	Not applicable	Not applicable	Relevant	Important	Not applicable	Important	Relevant	Relevant	Important	Important	Important
LEO >60°	Relevant	Not applicable	Important	Important	Important	Important	Relevant	Relevant	Important	Important	Important
MEO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
GPS	Important	Important	Important	Not applicable	Important	Important	Important	Relevant	Not applicable	Important	Important
GTO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
GEO	Important	Important	Important	Not applicable	Important	Important	Important	Relevant	Not applicable	Important	Important
HEO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
Interplanetary	Not applicable	Not applicable	Important	Not applicable	Important	Not applicable	Important	Relevant	Not applicable	Relevant	Relevant

Legend: Important (red) — Relevant (yellow) — Not applicable (grey)

Source: *Crosslink*, The Aerospace Corp., Vol. 4, No. 2, Summer 2003.

Space Environment Summary

- Earth orbiting space systems are subjected to harsh radiation environment; severity of environment is function of location, mission duration (timing within solar cycle) and shielding.
  - *Large variations in particle fluxes depending on satellite trajectory.*
- MEO/GEO/HEO experience severe flux of high energy particles from cosmic rays and solar flare particles (intense single event effects and displacement damage environments).
- All orbits pass through Van Allen belts on a daily basis and are impacted by trapped radiation (total ionizing dose and displacement damage effects).

Radiation Source	Effects of Solar Cycle	Orbits Impacted	Primary Effect
Trapped Protons	Solar Min - Higher; Solar Max - Lower	LEO, MEO (severe), HEO	Total Dose Displacement Damage SEE
Trapped Electrons	Solar Min - Lower; Solar Max - Higher	LEO (moderate), MEO (severe), GEO (severe), HEO	Total Dose
Galactic Cosmic Rays (High Energy Charged Particles)	Solar Min - Higher; Solar Max - Lower	LEO, MEO, GEO, HEO	SEE
Solar Particles (Electrons, Protons, Heavy Ions)	During Solar Max Only	LEO (polar only), MEO, GEO, HEO	Total Dose Displacement Damage SEE

Experience has shown the best way to mitigate the uncertainty factors of the space radiation environment is to define and plan for the mission.

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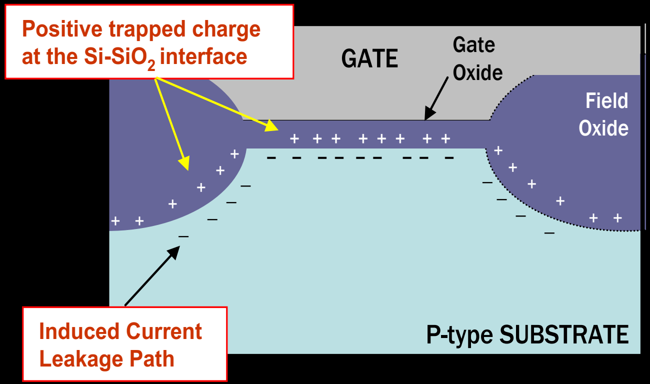
Ionizing Radiation – Total Ionizing Dose (TID)

- Cumulative damage mainly caused by trapped protons and electrons in Van Allen belts (SAA) or solar flare protons
- *<u>Ionizing energy deposition accumulated over time</u>*
- Results in generation of electron-hole (e-h) pairs in device
    - e-h pair generation leads to build-up of trapped charge, primarily of holes (positive '+' charge) due to their low mobility within insulator and oxide layers
    - Total trapped charge is related to total amount of ionizing energy deposited over time (TID)
    - Parametric degradation: threshold voltage shifts, leakage current, timing shifts

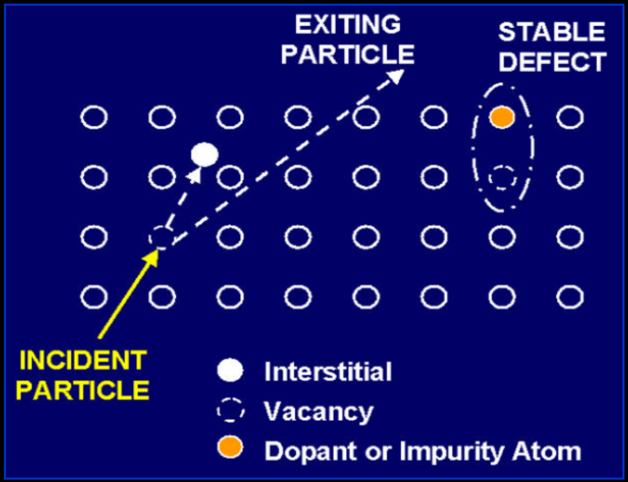
- Circuit parameters are changed
- Ultimately, the circuit ceases to function properly



Non-Ionizing Radiation– Displacement Damage Effects (DDE)

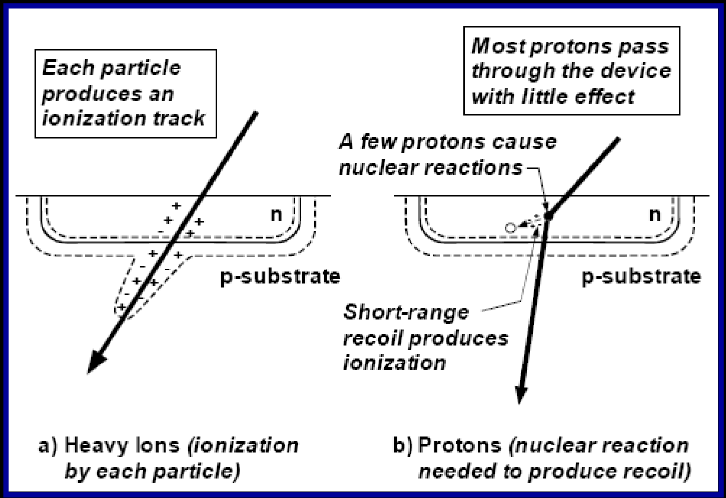
- Cumulative, permanent, *non-ionizing* damage due to highly energetic protons/ions and, to a lesser extent, electrons and neutrons
- Produces crystal lattice defects (vacancies and interstitials) that result in device degradation through decrease in charge carrier lifetime, carrier removal or charge trapping
- Device parametric degradation: reduced gain, leakage current, increased "ON" resistance, reduced charge transfer efficiency in CCDs, reduced LED output current

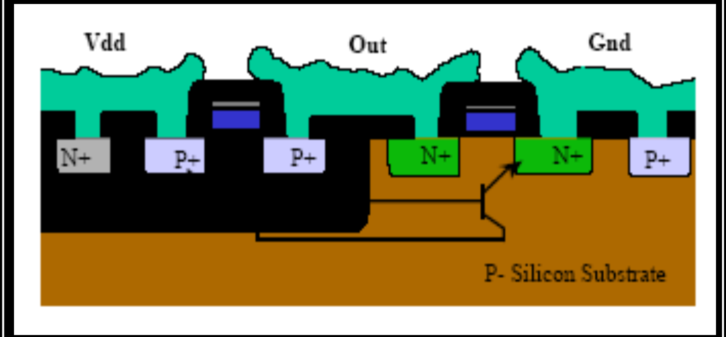
Technology	Lifetime Degradation	Carrier Removal	Charge Trapping
CCD	✓		✓
Si Bipolar	✓	✓	
Photodetectors	✓		
LED, Laser Diode	✓		
JFET		✓	✓
GaAs		✓	



Single Event Effects (SEE)

- Caused by charge deposition from *single high energy particle* (proton or cosmic ray) striking sensitive region
  - Heavy ions – direct ionization
  - Protons – indirect ionization from nuclear reactions
- Effects on electronics – if Linear Energy Transfer (LET) of particle is greater than critical charge required $LET_{threshold}$:
  - Non-destructive (soft errors):
    - Upsets (SEU): bit-flip in memory, change of state in logic circuit
    - Transients (SET): current/voltage spike causes output error
    - Correctable (reset device, rewrite data)
  - Destructive (hard errors)
    - Latchup (SEL): corruption of signal path, high current regenerative logic state or permanent bit-flip destroys devices
    - Burnout (SEB): highly localized device destruction from high current flow (includes SEGR,SEDR)





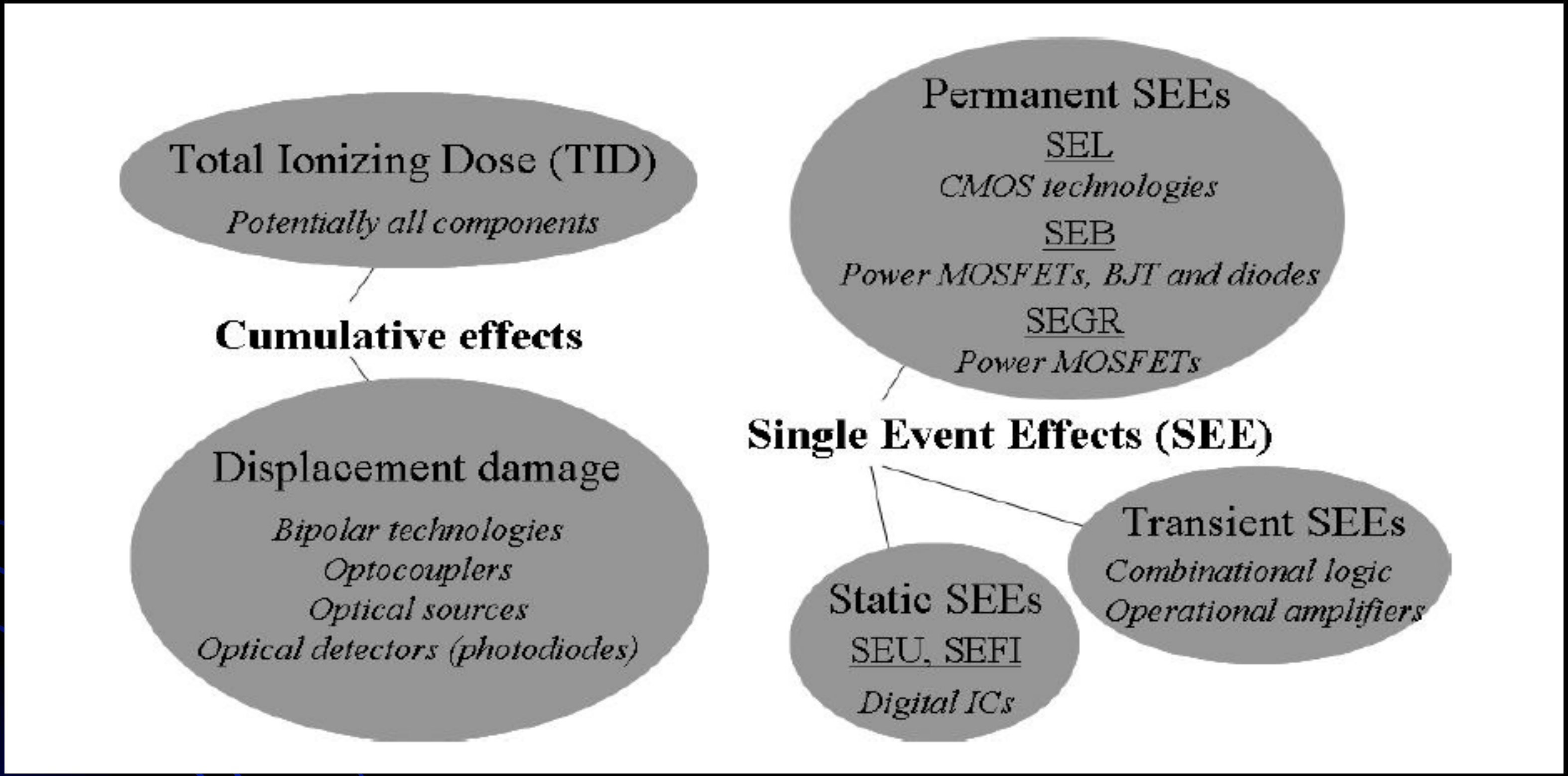
Latchup occurs when energetic particle turns on parasitic elements resulting in alternate current path. Device becomes inoperable. Non-destructive SELs can be cleared with power reset.

NOTE: LET_{th}, or LET Threshold, defines minimum LET value to cause an effect

Types of SEE

Acronym	Definition	Description
MBU	Multiple Bit Upset	More than one memory bit is upset by passage of a single charged particle.
SEB	Single Event Burnout	Any SEE-induced failure resulting in device destruction due to high current flow. Encompasses SEDR, SEGR, destructive SEL.
SEDR	Single Event Dielectric Rupture	Rupture of a dielectric structure within a semiconductor device due to high current flow
SEFI	Single Event Functional Interrupt	Corruption of functional control path
SEGR	Single Event Gate Rupture	Rupture of gate dielectric in a POWER MOS device caused by high current flow
SEL	Single Event Latchup	Loss of device functionality due to corruption of signal path through activation of parasitic path. High current regenerative state can occur, resulting in damage or destruction of device. Low current states, or "micro-latches", can also occur. Power reset can clear a non-destructive SEL condition.
SET	Single Event Transient	Current transient induced bypassage of a particle, canpropagate to cause output error incombinational logic
SEU	Single Event Upset	Change of information stored

Summary


Total Ionizing Dose (TID)
Potentially all components
Cumulative effects
Displacement damage
Bipolar technologies
Optocouplers
Optical sources
Optical detectors (photodiodes)
Permanent SEEs
SEL
CMOS technologies
SEB
Power MOSFETs, BJT and diodes
SEGR
Power MOSFETs
Single Event Effects (SEE)
Transient SEEs
Combinational logic
Operational amplifiers
Static SEEs
SEU, SEFI
Digital ICs

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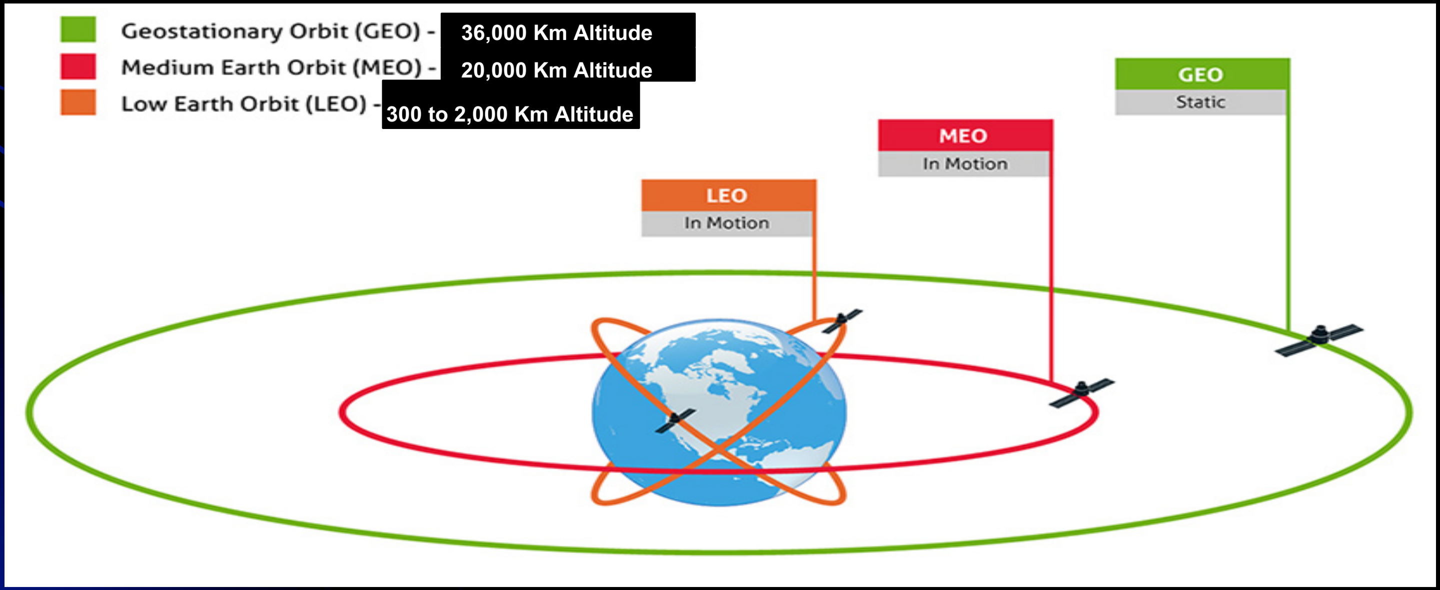
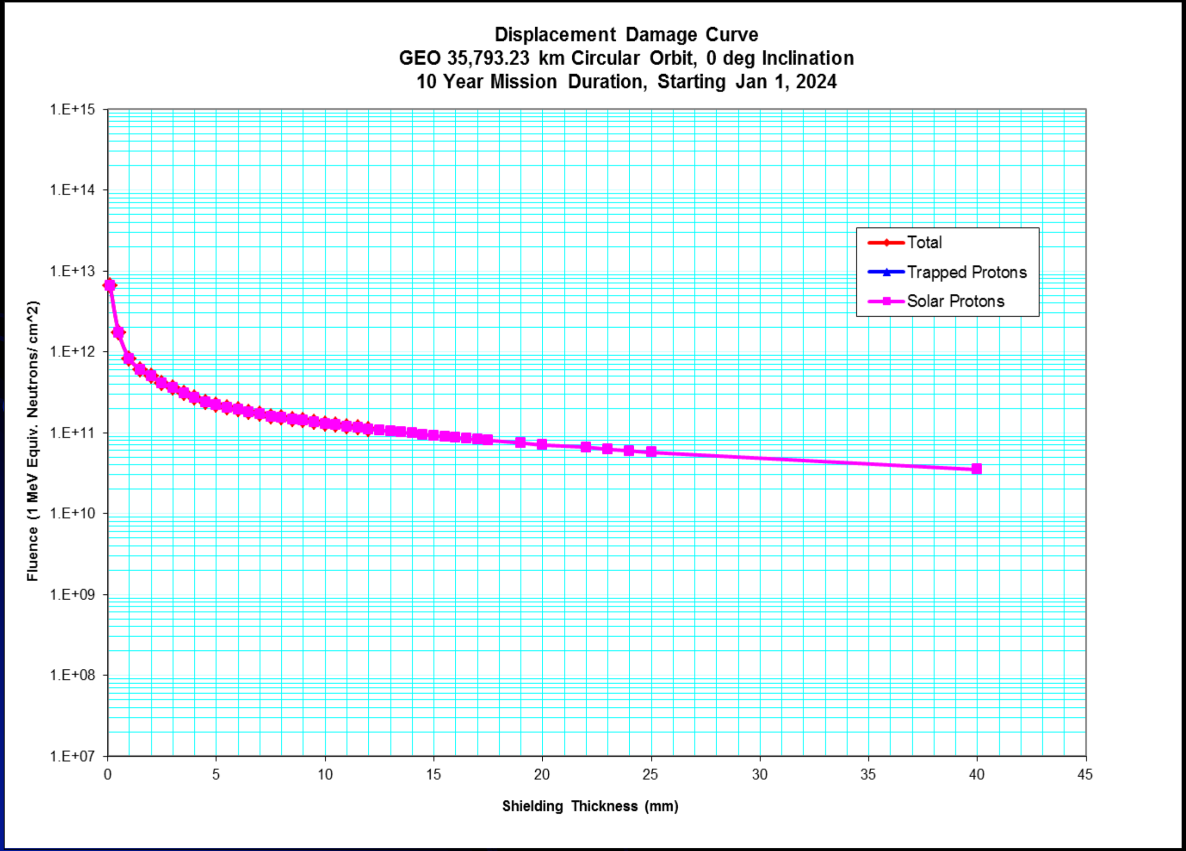
TID Requirements in Space Systems

- Example mission requirements (100 mil equivalent aluminum shielding)
  - LEO – 5 year mission (science satellite)
    - Located below edge of belt, primary concerns protons from SAA and heavy ions
    - 10 krad to 20 krad(Si)
  - MEO – 15 year mission (navigation satellite)
    - Located in inner proton belt, primary concern protons from belts, heavy ions
    - Typically 300 krad(Si)
  - Geosynchronous orbit – 20 year mission (communications satellite)
    - Located in outer electron belt, primary concern electrons from belts, heavy ions
    - Typically 100 krad(Si)



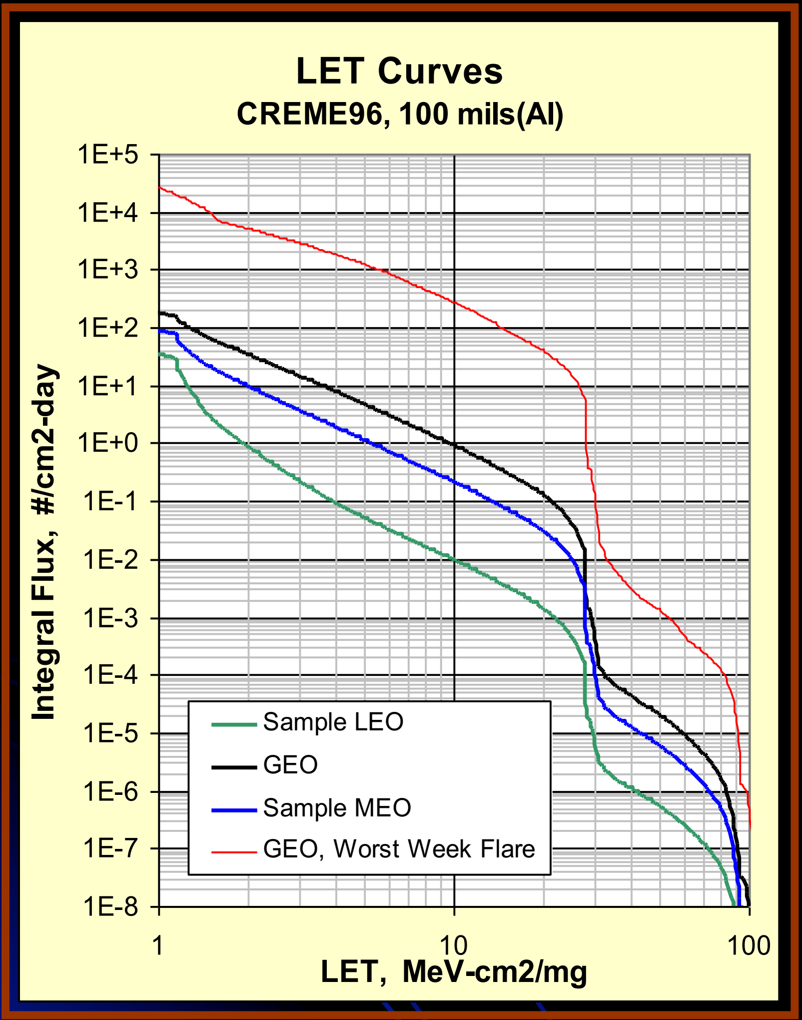
DDE Environment Requirement

- Displacement Damage Effects (DDE) Curve (generated in SPENVIS) providing worst case estimate of neutron fluence as function of shield thickness for representative GEO mission
- Derived from specified proton and electron fluence environments and converted to 1 MeV-equivalent neutron fluence (NOTE: neutrons are a convenient and inexpensive method to test for DD effects in electronics)



- For High LEO, MEO, GEO, HEO missions, DD requirement dominated by intense, high energy solar protons, shielding not effective mitigation methodology
- Low LEO missions have low DDE environments

SEE Environment Requirement



High altitude missions have intense SEE environments

- **"Heinrich" LET curves generated in CRÈME-MC**
- **Curves depend on:**
  - Orbital parameters
    - Geomagnetic shielding and Earth shadowing effects
  - Solar conditions (average and peak)
    - "Quiet Model" for evaluating typical and long-term average particle fluxes and SEE rates
    - "Flare Model" for evaluating worst case and peak particle fluxes and SEE rates
- Includes galactic cosmic ray and solar heavy ions (LET spectra); solar and trapped protons (energy spectra)

Device TID Radiation Regimes

- **Low**
  - < 10 krad (Si)
  - May have
    - short mission duration
    - low altitude/ low inclination
    - moderate SEE environment
    - low DD environment

Examples:
Hubble Space Telescope (HST), Space Shuttle, VIIRS
Type of device needed:
COTS with SEE mitigation

- **Moderate**
  - 10-100 krad (Si)
  - May have
    - medium mission duration
    - low altitude/ high inclination
    - intense SEE environment
    - moderate DD environment

Examples:
Earth Observing System (EOS), high LEO, ISSA (weather)
Type of device needed:
Rad Tolerant (RT)

- **High**
  - ≥ 100 krad (Si)
  - May have
    - long mission duration
    - high altitude
    - intense SEE environment
    - intense DD environment

Examples:
Europa (NASA), Geostationary Transfer Orbit (GTO), MEO
Type of device needed:
Rad Hard (RH)

Designing for Total Ionizing Dose (TID)

- *Shielding can mitigate TID effects*: spot or box level shielding
- A major consideration for satellite hardening philosophy is parts selection
- First choice should always be QML or Space Grade components if available (rad-hard or rad-tolerant)

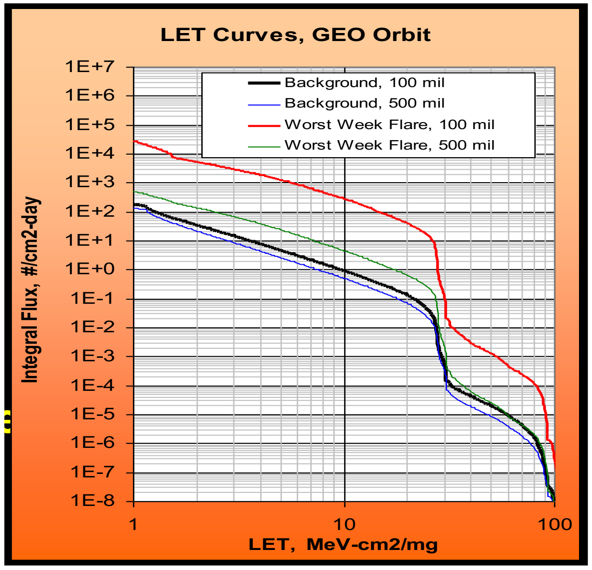
	PROs	CONs
RAD-HARD	• Guaranteed hardness capability (~100 krad-Mrad) • Low Risk	• Very high cost • Schedule (long lead) • Performance (size, power, density, speed)
RAD-TOLERANT	• Hardness capability is generally known (historical radiation data available)	• Hardness capability less than Rad-Hard equivalent, and hardness often not guaranteed • In-house radiation acceptance testing sometimes required
COTS (Commercial-Off-the-Shelf)	• Availability (schedule impact) • Low Cost • Complexity of Functions • Performance (size, power, density, speed)	• Characterization testing is often required, and lot-to-lot variability is often an issue • In-house radiation acceptance testing often required (marginal ~3-30 krad performance) • No configuration control • Obsolescence • Often no radiation data in databases • Often only available in plastic

Designing for Displacement Damage Effects (DDE)

- DDE mainly concern for bipolar technologies and electro-optics
- **CMOS process technology** generally rad hard to DDE
- High LEO and MEO missions shielding not effective to mitigate DDE
- Parts selection important, however few suppliers fabricate devices with DD hardness in mind
  - Supplier claims of “Rad-Hard” or “Rad-Tolerant” generally DON’T address DDE
  - ***Testing is often required (including BiCMOS devices)***
- Circuit design – important factor in determining impact of DDE
  - Account for gain degradation
    - Low input offset voltage and/or input offset and bias current, or low noise
      - e.g. currents in transistor pairs within a differential amplifier must match within 0.04% in order to maintain offset voltage of 10 µV.
    - Devices that use substrate or lateral pnp devices as direct inputs or as output stages generally most susceptible
      - large base width leads to minority carrier lifetime degradation, gain loss

Designing for Single Event Effects (SEE)

- **Requirement: no SEE may cause permanent damage to a system or subsystem**
- **Parts Selection is key:**
  - *Choose parts not susceptible to destructive SEE (SEL,SEB) (LETth > 75 MeV-cm^2/mg)*
  - Procure SEE-hardened Power MOSFETs to mitigate SEGR concerns
  - Select parts with high LET_{th} values for transient SEE (SEU, SET): look for “knee” of LET curve – where particle flux drops several orders of magnitude, usually LET of 30 to 40
- **Implement SEE Circuit Design Mitigation – Radiation Hardening by Design:**
  - **SET**: filtering, over-sampling, place high speed device with slow response time following circuit
  - **SEL**: current limit and power cycle, use SOS/SOI technology
  - **SEU**: redundancy, watchdog timers, EDAC, memory scrubbing, high refresh rates for SEU-susceptible memory
  - **SEGR**: derate Power MOSFETs, stay within specified SOAs for rad-hard parts and non-SEE hardened devices derate to 35% of max rated V_{DSS}
- **Shielding is NOT an effective mitigation method for SEE:**
  - **If system is required to operate through solar flare condition then (significant) shielding can help reduce damage, not cost-effective. Difficult to impleme within size, weight, cost constraints.**



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Radiation Testing Overview

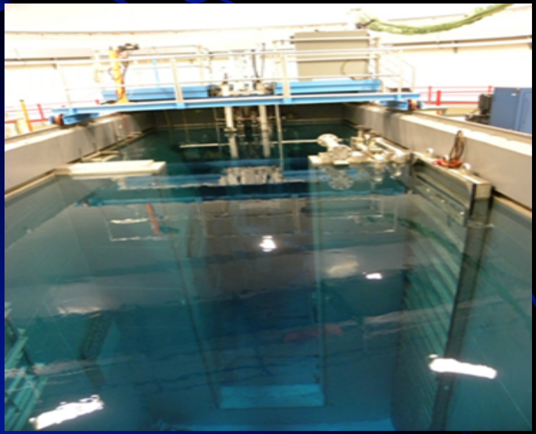
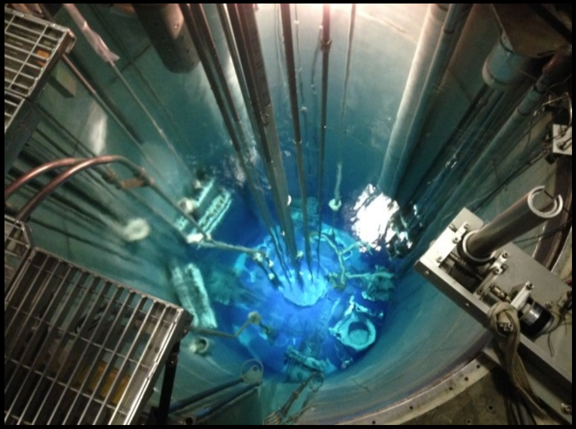
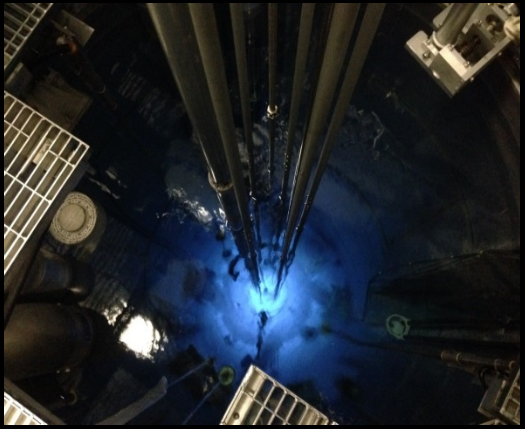
- All devices with unknown performance characteristics should be ground radiation tested
  - Total Ionizing Dose (TID), Displacement Damage Effects (DDE), and Single Event Effects (SEE)
- All testing should be performed on flight lot samples, if possible, or from the same product line that flight parts will be purchased from
- Determine type of testing needed (mission specific) – test bias conditions should simulate or bound flight application
  - This includes "unbiased" conditions as with cold spares
  - Test plan should include appropriate test levels, sample size, choice of radiation source, electric parameters for pre- and post-characterization (specs and standards)

Total Ionizing Dose (TID) Testing

- TID data generally required for electronic, optical, electro-optic devices
- Radiation Lot Acceptance Testing (RLAT) required for all flight lots that fail to meet project RDM for RLAT exemption
  - MIL-STD-883, Method 1019
  - High dose rate and low dose rate testing capability
  - Test-to-failure is common practice for characterization tests
  - Step-stress model commonly used for RLAT (cumulative dose effect)
- Pre- and post- electrical characterization performed in-house at JPL

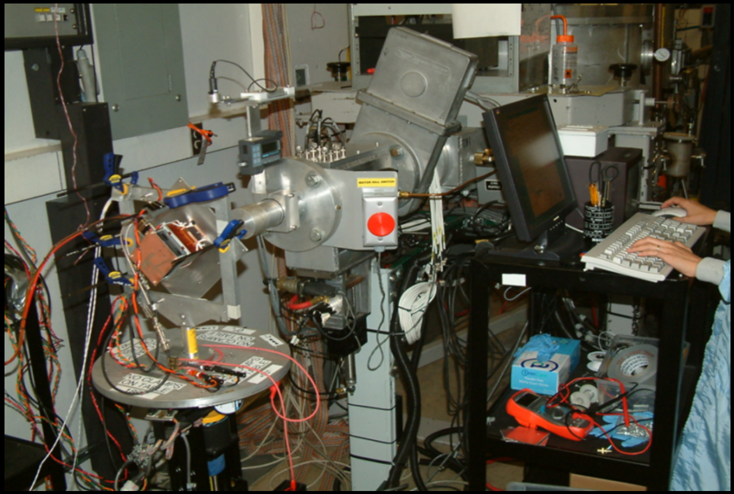
Displacement Damage Effects (DDE) Testing

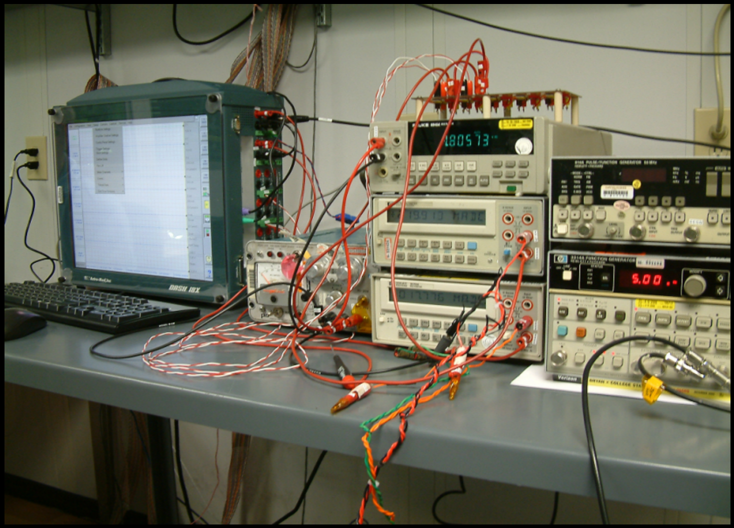
- Most susceptible electronic devices may be evaluated for DD effects using neutron irradiation
  - **Very inexpensive (~$5K per device)** and usually involves shipping test samples to neutron irradiation facility for unbiased "brown-bag" irradiation, perform pre- and post-test electrical measurements in-house (El Segundo)
  - In space environment protons are prime source of DDE, however neutrons are generated when protons interacts with spacecraft materials
- Optics and electro-optics better evaluated for DD effects by using proton irradiation
  - Charged particles better simulate space environment and are important in formation of damage to optical components

Single Event Effects (SEE) Testing

- Performed off-site at various heavy ion and proton test facilities (U.C. Berkeley and Texas A&M Cyclotrons)
- SEE tests require experienced test team (cabling, DUT setup, biasing, data collection, beam alignment)
- SEE test planning requires good understanding of device under test and intended applications
  - Design engineering support is required for test planning
  - Special Test Equipment (STE) is often required





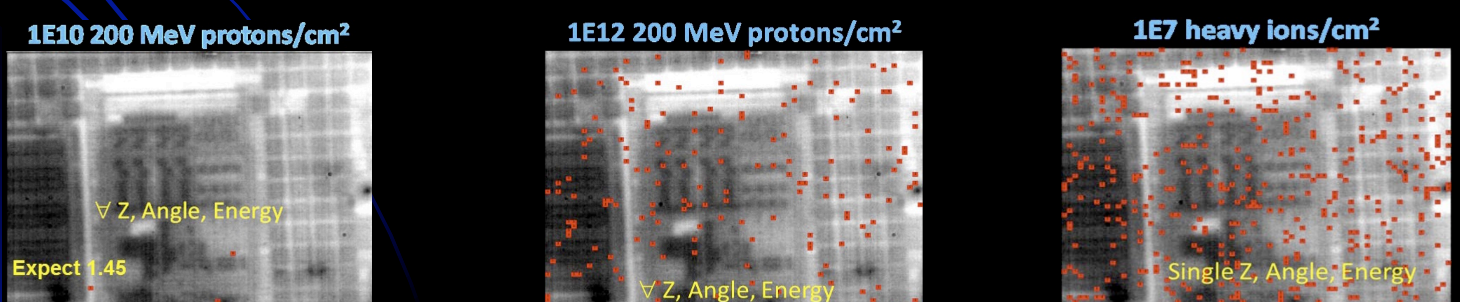
Current SEE Testing Trends and Risks (Proton Only Testing)

- ***Aggressive commercial, higher risk missions performing board and box level assembly SEE tests with only protons***
- **Proton SEE testing:**
  - Causes SEE via indirect ionization – recoil ions ($3 \leq Z \leq 15$)
  - Tested in air, no need for de-lidding (allows for module level test)
  - Produces ions reaching sensitive volumes even in difficult parts
  - Less expensive to test – cost and time savings (board box level tests)
  - Suitable for LEO missions (abundance of protons) where proton upset rates are critical and could be more abundant than heavy ion upset rates
- **Heavy Ion Single Event Effects (SEE) testing:**
  - Expensive and time consuming, difficult to schedule beam time
  - Requires de-lidding of parts to expose active area
  - Some parts may be nearly impossible to test w/ normal accelerator ions
  - Very difficult to test boards and boxes

Can heavy ion SEE rates be bounded with proton data?

Important Considerations for SEE Testing in the CubeSat Era

- **Natural space environment does not consist of protons only…heavy ions exist**
- Limitations with protons:
  - Do not know Z, energy, angle, or LET of an ion that causes SEE (random)
  - Proton recoils low energy/short range, ion range limited to 10 μm, heavy ions have much higher LETs and deposit more energy in sensitive volumes
  - Very few proton recoil ions w/ LET>10 MeVcm^2/mg, low LET ions must hit much smaller device cross-section to cause SEE
  - Testing coverage key to whether test reveals all SEE susceptibilities (proton testing coverage not as good as heavy ion, depends on particle fluence)
  - Proton testing worst for assessing SEL, SEB, SEGR effects (worst coverage)
  - Heavy ion tests allow exploration of angular sensitivity
- Proton SEE data does marginally constrain heavy ion SEE performance (in LEO) but not entirely (constraints weak due to energy deposition and testing coverage differences)
- Critical to perform heavy ion SEE testing to distinguish between transient effects (soft errors) and catastrophic effects (hard errors) which pose most risk



Reference: Ladbury and Laurenstein NASA Goddard, presented at NSREC, Portland, Oregon, July 11-15, 2016

Is Testing Always Required?

- *Exceptions for testing may include:*
  - *Operational*: device is only powered on once per orbit and sensitive time window for SEE is minimal – based on SEE rates)
  - *Acceptable data loss*: system level error rate set so data gathered 95% of time, given physical device volume and assuming every ion causes an upset, worst case rates might be manageable
  - *Negligible effect*: example – for a two-week mission TID testing of a flash memory could be waived if levels are low or device is not powered on for large majority of time)

Agenda

- What is Space Radiation? Why do we care?
- Radiation Hardness Assurance (RHA) for Space System Design
- Understanding the natural space radiation environment
- Radiation effects on satellite components and space systems
- Requirements definition, verification, validation and design considerations for hardening
- Radiation Testing Considerations
- **Summary**

Summary

1. Define environment (external to spacecraft)
2. Evaluate environment (internal to spacecraft)
3. Define and refine requirements
4. Evaluate design/components (existing data/testing/performance characteristics)
5. Work with designers (parts replacement/mitigation schemes)
6. Iterate process (review parts list based on updated knowledge)

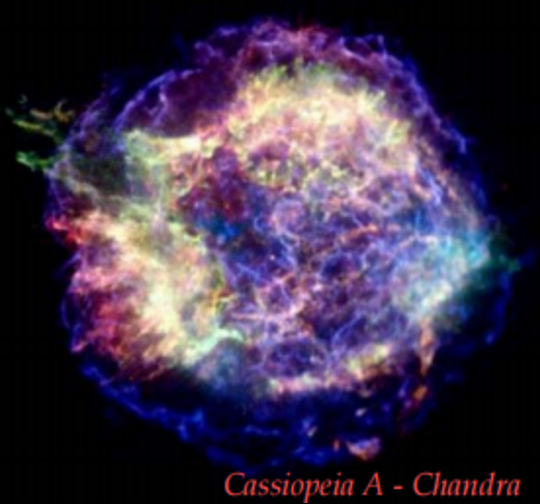
- Critical questions: When/where will mission fly? Are there design constraints (size, weight, etc.)? What systems/sub-systems must operate under worst case conditions? What systems are critical to mission success?
- RHA approach on space systems is based on risk management and not on risk avoidance
- RHA should be taken into account in early phases of program development, including proposal and feasibility analysis phases

Radiation Hardness Assurance goes beyond the piece part level!

BACK-UP

Galactic Cosmic Ray (GCR) Ions

- Found everywhere in interplanetary space and omnidirectional
- Originate from outside solar system and are affected by Earth's magnetic field
- Consist of ions from several elements in Periodic Table (energetic 14% alpha particles, **85% protons** and 1% heavy ions)
- Energies in TeV range (highest energy of all space radiation sources)
- Single Event Effects (SEE) hazard – difficult to shield (issue for International Space Station)
- Cyclic variation in GCR flux levels (11-year solar cycle)
  - Highest levels = lowest point in solar minimum
  - Lowest levels = solar maximum peak

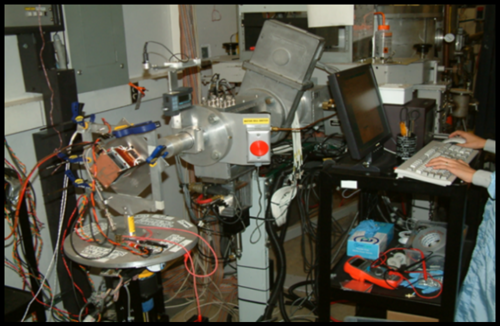


NASA/CXC/MIT/UMass Amherst/M.D.Stage et al.

Risks with COTS Board Level Radiation Testing

- Inability to trace die heritage or in some cases lack of vendor information
  - Bill-of-materials (BOM) often does NOT include lot date codes or manufacturer info
  - Parts lists and process technology info can be proprietary
- Limited testability of boards due to complex circuitry and packaging issues ("visibility" issues)
- Parts variability
  - Possibility of "board-to-board" IC variances for "copies" of the "same" boards – no parts control
- Limited statistics
  - Easier to purchase and test 10 components than 10 boards (impacts cost and schedule), reducing test sample size

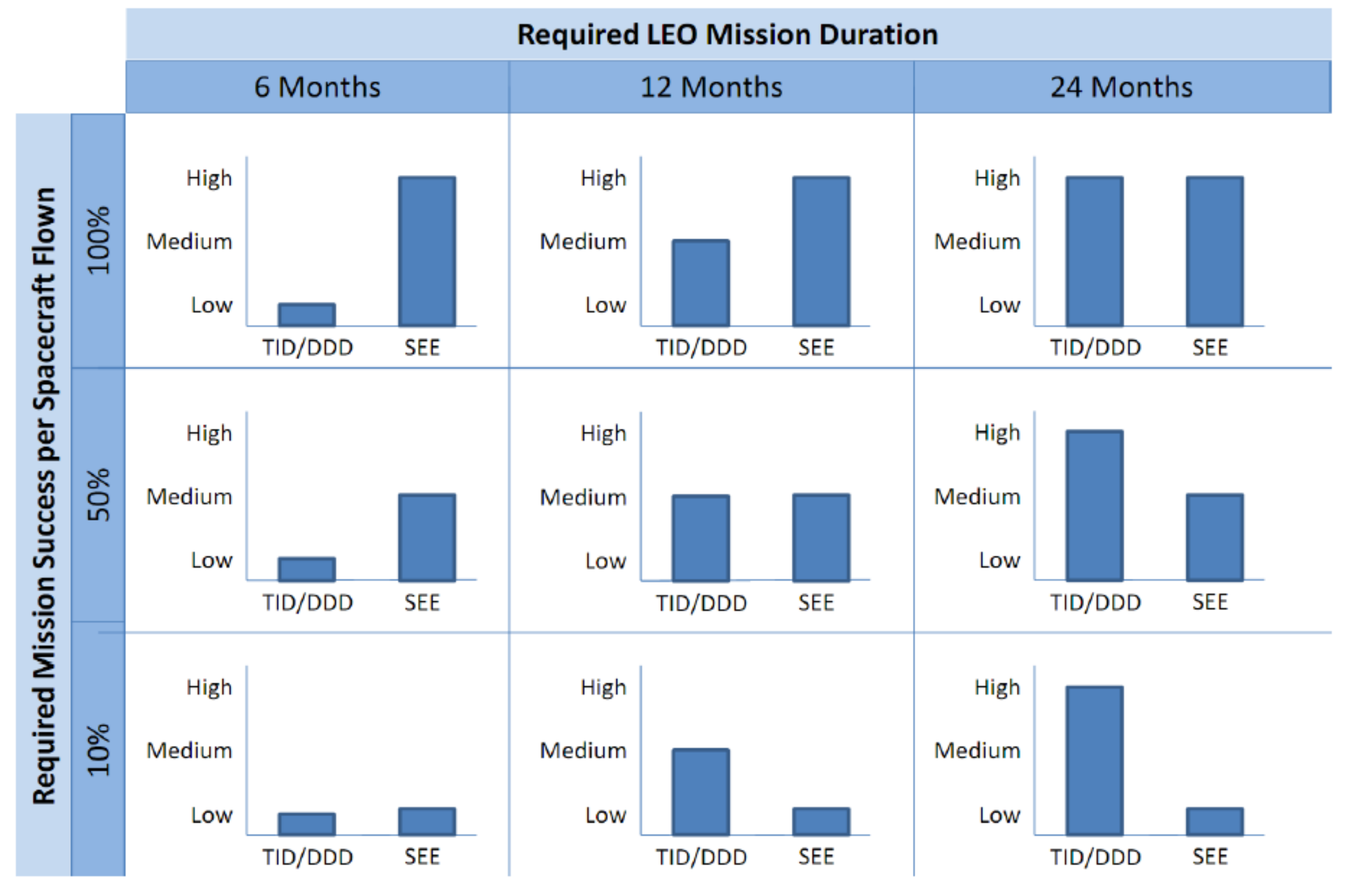
- ***Board level testing irradiates many parts with diverse technologies***
- ***Saves money, but different SV depths mean parts see different coverage distributions***
- ***Proton test may vary in effectiveness for every device on board***
- ***Need to know as much as possible about technology of each device to make sense of proton data***



CubeSat Test Success Evaluation

- Design can be considered radiation tolerant IF:
  - No destructive SEEs observed
  - SEE rate is manageable (in context of overall system and data availability)
  - Unit functional up to expected mission dose
  - Unit functional following annealing after 2X expected mission dose
- Marginal success:
  - No destructive SEEs, manageable SEE rates, unit functional following annealing after expected mission dose
  - Reduce design life by 50% and/or apply shielding to reduce reqs
- Failure:
  - Destructive SEEs observed *AND* SEE rate is unmanageable
  - Unit is not functional following annealing after expected mission dose
  - Susceptible components must be identified and replaced (drop-in replacements needed)

SEE Risk Assessment – Mission Success vs Required LEO Duration



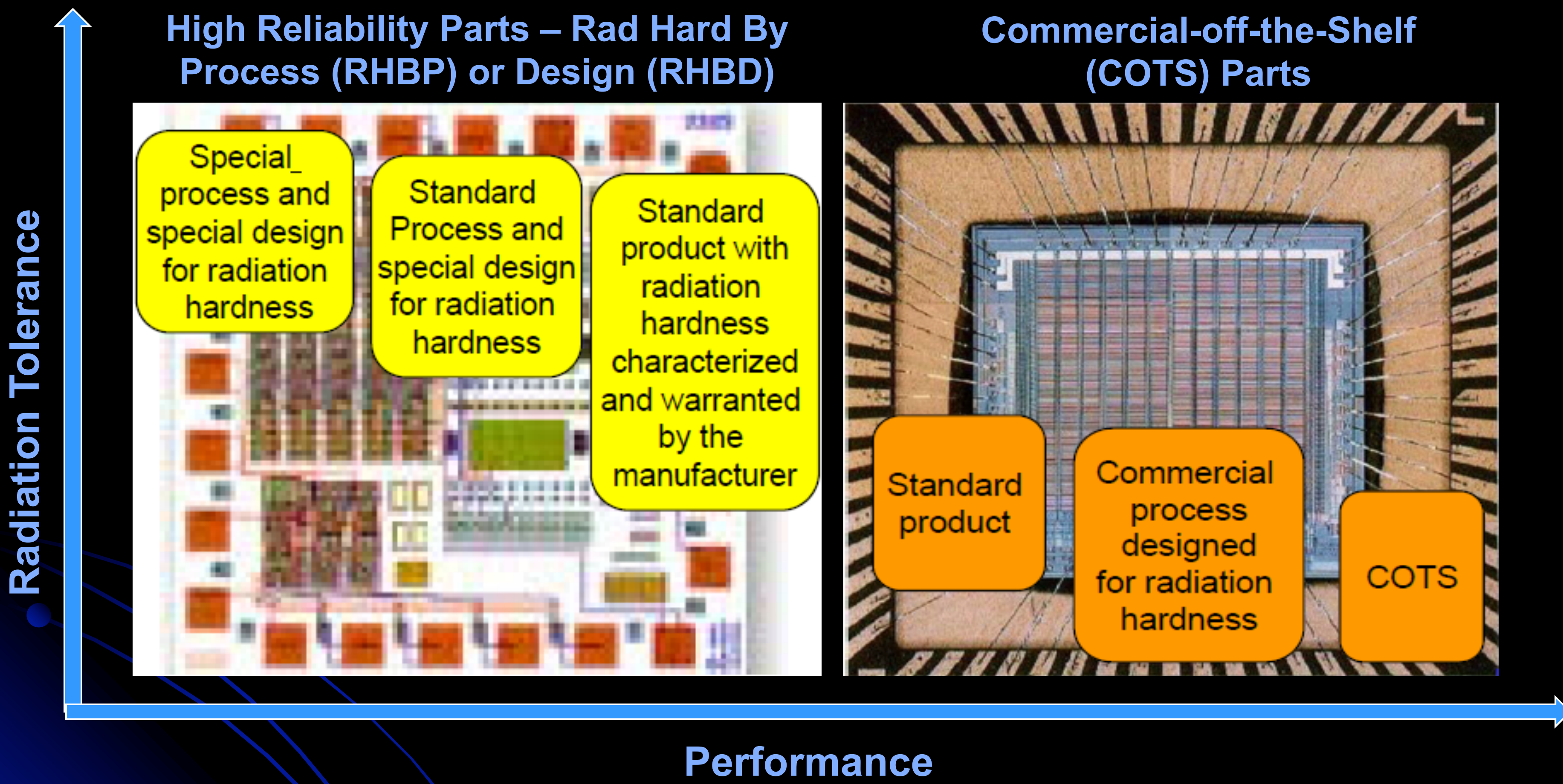
Single Event Effects Analysis

- Determine criticality of each possible SEE to system:
  - *Catastrophic* – results in mission loss
  - *Critical* – loss of control or functionality, possible damage or degraded performance; may require ground intervention to recover
  - *Marginal* – Acceptable error rates or correctable via design mitigation
- Damaging SEE Analysis (SEL,SEB)
  - Determine probability of damaging SEE for each component and incorporate into system reliability assessment if necessary
- Transient SEE Analysis (SEU, SET)
  - Demonstrate no SEE will propagate through system causing damage
  - Demonstrate compliance to SEE reqs at subsystem and system level

SEE LET Threshold	Analysis Requirement
> 60 $MeVcm^2/mg$	SEE risk negligible, no further analysis needed
15 $MeVcm^2/mg < LET_{threshold} < 60$ $MeVcm^2/mg$	SEE risk, heavy ion induced SEE rates to be analyzed
$LET_{threshold} < 15$ $MeVcm^2/mg$	SEE risk high, heavy ion and proton induced SEE rates to be analyzed

*Image from reference 12: Radiation Hardness Assurance (RHA) for Space Systems

Parts Selection is Critical – Component Level Hardening



Parts selection is generally based on function and performance. However, more challenging mission objectives coupled with increase in complexity of radiation response of technologies, choosing high reliability parts is critical. Use of RHA devices reduces cost, improves reliability, and ensures system's radiation hardware requirements will be met.

Generic Satellite Orbits

- Natural space radiation environment will vary depending on orbit
- **Low Earth Orbit (LEO)** – 160 km to 2,000 km, varying inclination
  - Most common orbit: *LEO/Sun-synchronous, polar (600-850 km, 90° inc)*
- **Middle Earth Orbit (MEO)** – 2,000 km to 35, 780 km, varying inclination
- **Geosynchronous/Geostationary Orbit (GEO)** – ≥35,780 km , 0° inclination
- **Highly Elliptical Orbit (HEO)** – perigee in LEO, apogee near GEO
  - **MEO/GEO/HEO environments most severe radiation fluxes**

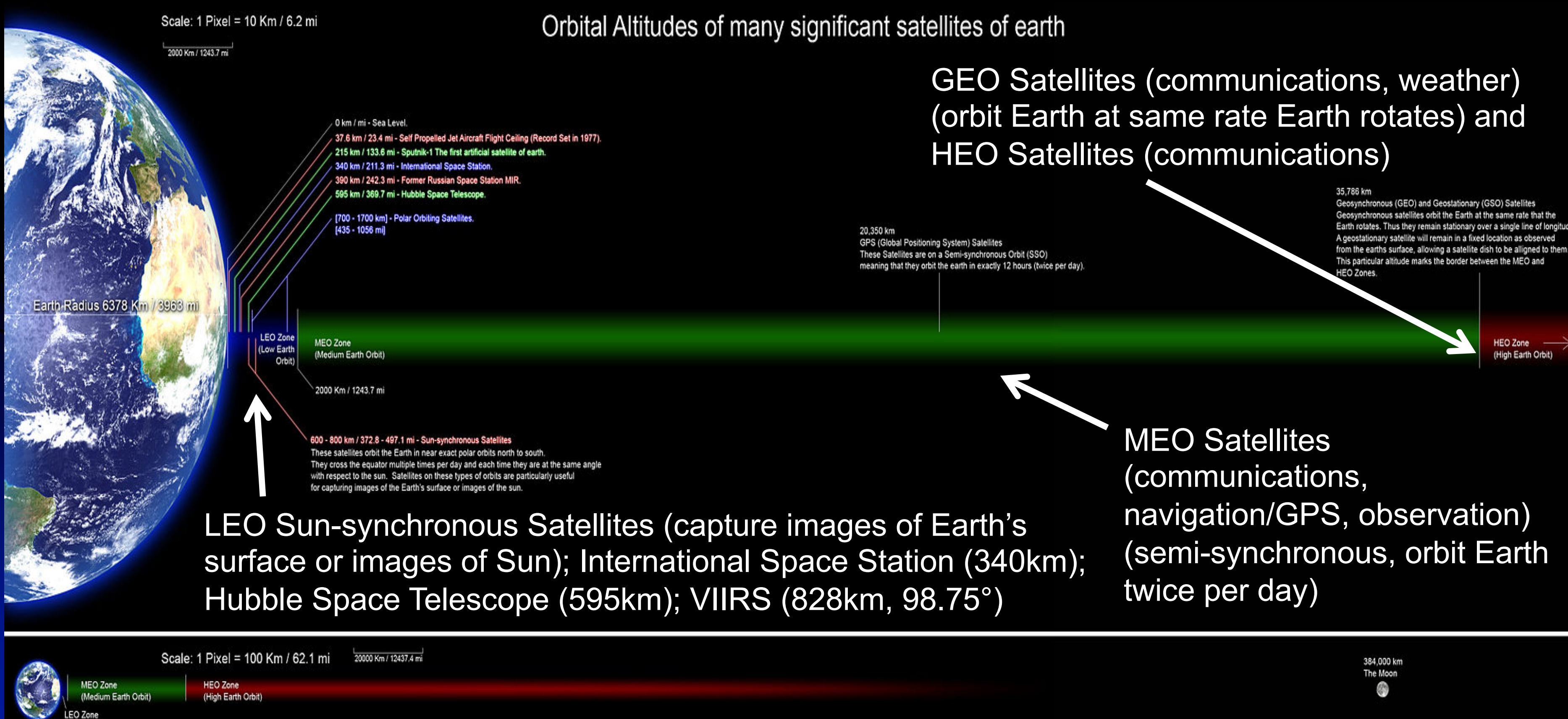
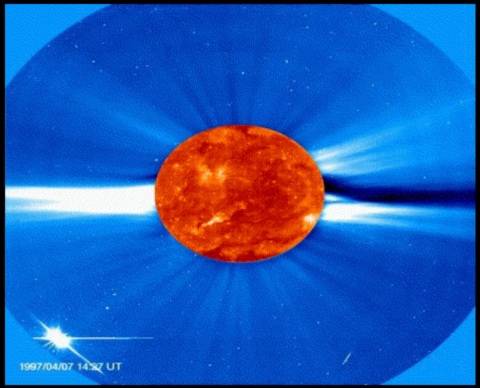
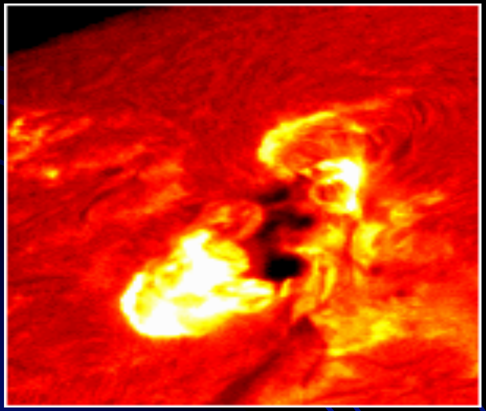


*Image from: http://en.wikipedia.org/wiki/Satellite#mediaviewer/File:Orbitalaltitudes.jpg

Solar Energetic Particle (SEP) Events



Gradual Events – Coronal Mass Ejections (CMEs)



Impulsive Events – Solar Flares

- Magnetic activity heats corona of Sun and forms active regions
- CMEs fast moving burst of plasma ejected from Sun over several hours
  - CMEs disrupt flow of solar wind and eject billions of particles to Earth
  - Largest proton events
- Solar flares are sudden, huge explosions on surface of Sun (few mins in duration)
  - Occur near sunspots and release energy equivalent to millions of hydrogen bombs
  - Ionized particles (GeV energy) guided to Earth along solar magnetic field lines (can move quickly up to 80% speed of light)
- Difficult to predict but seem to occur around first and last year of solar maximum

*Images from: http://solarscience.msfc.nasa.gov/CMEs.shtml and Holloman AFB/SOON

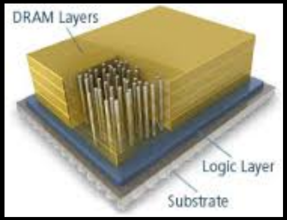
Summary of Radiation Effects Impact on Space System Design

Area of Spacecraft Design	Type of Impact	Radiation Effects
Generic Electrical Architecture (including optics, electronics)	• Equipment failure • Parametric degradation • Self switch-off. Disjunction, reset, reboot, redundancy, swapping	Total Dose, Displacement Damage, Single Event Effects (SEE) (Transient, Upset, Latchup)
On-board energy	• Solar panel degradation	Total Dose, Displacement Damage
Altitude and Orbit Control System	• Possible altitude loss • Star tracker out of loop • Inertia wheel disturbances • Switch off ion thruster	SEE Proton transients
On-board Management	• Disturbances of on-board computer, resets, mode refusal , safe-hold mode • Mass memory	Single Event Upset (SEU)
Imaging System	• UFOs • Hot pixels, Real-time strategy (RTS) • Dark current, non-linearity, etc.	Total Dose, Displacement Damage Proton transients
Time References	• Frequency jumps	Total Dose (SAA passes or flares)

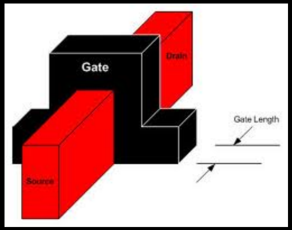
Technology Forecast – Where We Are Headed

DRIVING REQUIREMENTS:

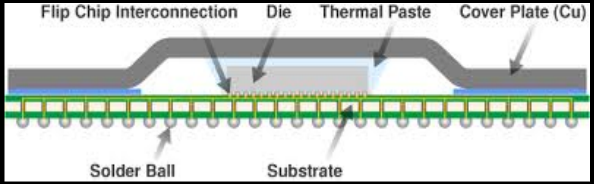
- 2.5D/3D integration (e.g., Micron Hybrid Memory Cube)
- Complexity (System-on--Chip, Mixed Signal Devices, Hybrids)
- Smaller feature sizes, higher levels of integration
  - 10 and 7 nm nodes coming
- Novel transistor structures (e.g., FINFETs, nanowire FETs)
- Novel technologies (Spintronics, Spin Torque Transfer NVM)
- Novel materials, heterogeneous integration with CMOS
  - III-Vs, II-VIs
  - Dielectrics, high-Z materials
  - Graphene, other 2D materials
  - Carbon nanotubes, quantum dots
- Higher frequency devices
  - HEMTs, HBTS, etc
- Increased operating speeds to >> GHz (CMOS, SiGe, InP, ABCS)
- Synergistic effects
- Package complexity (flip-chip, area array)
- Importance of specific usage to radiation performance
- Thermal effects
- Software/Hardware interaction



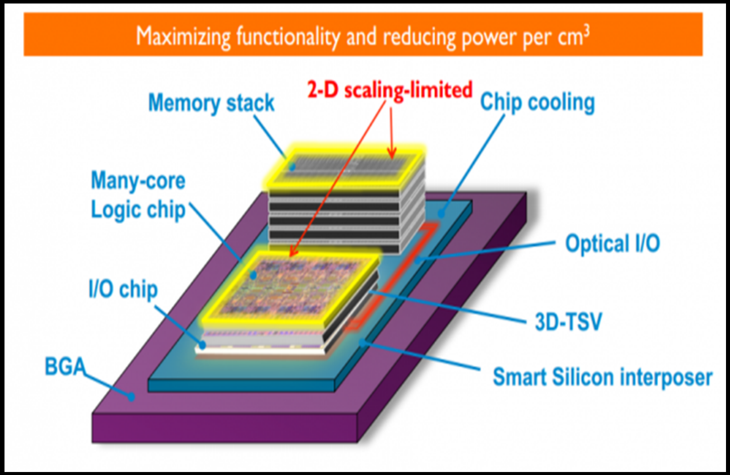
www.enterprisetech.com



nextbigfuture.com

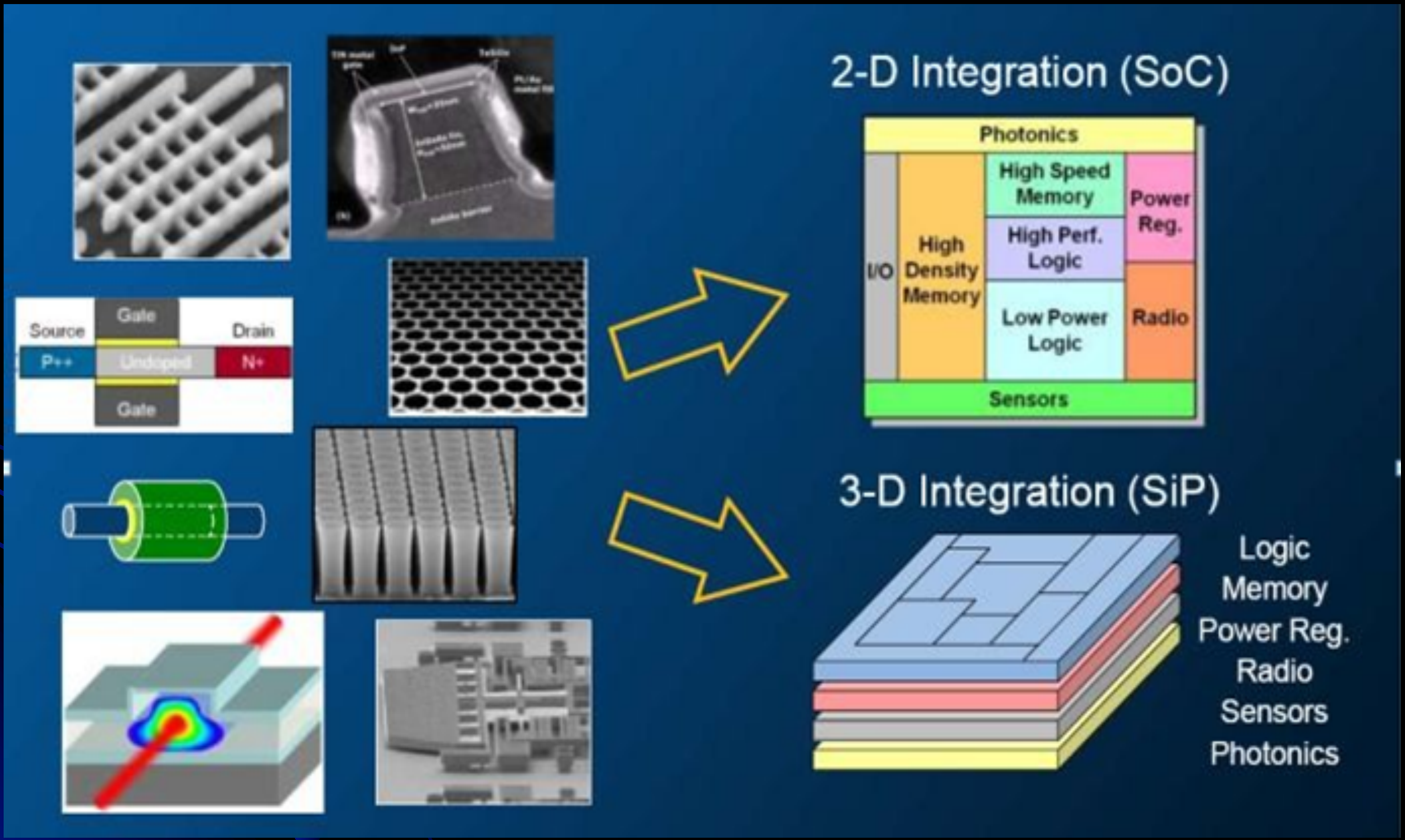


Toshiba Semiconductor



Heterogeneous System Integration of the Future

Future systems will integrate much wider variety of materials and device structures. Evolution of System-on-Chip (SoC) to System-in-Package (SiP).

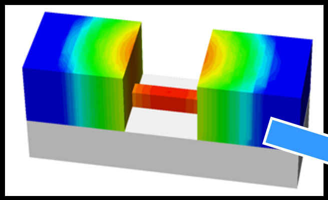


Source: IEDM 2011 – The Evolution of Scaling from the Homogeneous Era to the Hetereogeneous Era, M. Bohr

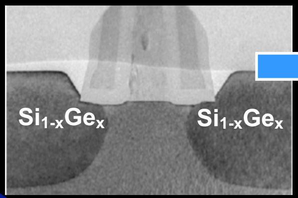
Radiation Effects on Emerging Electronic Materials and Devices

- More changes in IC technology and materials in past five years than previous forty years
  - SiGe, SOI, strained Si, alternative dielectrics, new metallization systems, ultra-small devices…
- Future space and defense systems require identification and understanding of radiation effects to develop hardening approaches for advanced technologies (numerous failure modes). Changes in device geometry and materials effect energy deposition, charge collection, circuit upset, parametric degradation…

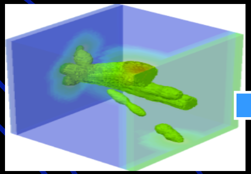
New Device Technology (complex charge collection vols)



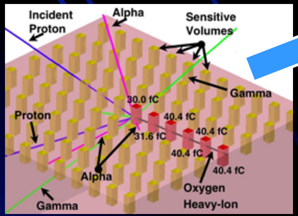
New Materials effect device response to rad



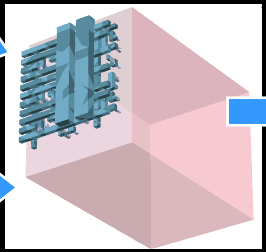
Energy Deposition (ion tracks larger than device size)



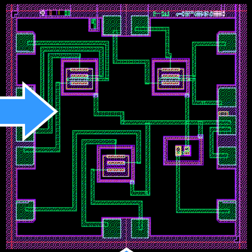
One event effects multiple cells

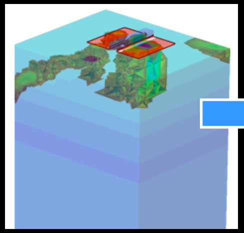


Device Structure

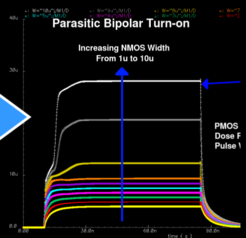


IC Design





Device Response



Circuit Response

Technology Scaling (smaller feature size, closer layouts, increased gate/ cell density per unit area)

- **Thinner gate oxides: less vol for creation, trapping, collection of rad induced charge**
- **SEU increases with scaling (takes less energy to produce SEU)**
- **Minimization of spacecraft size/ composite structures (effective shielding reduction) – using more rad sensitive devices with less protection**
- **Circuit speeds increase – SEUs increase; SETs more critical**

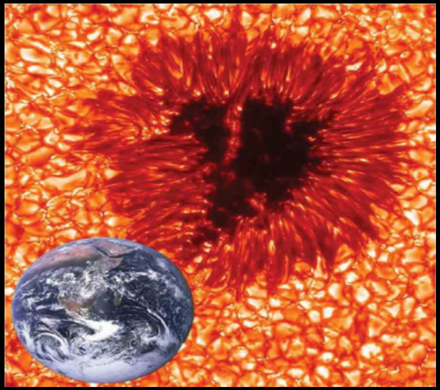
What is Radiation Hardness Assurance (RHA)?

- Activities to ensure electronics and materials of space systems will perform to intended design specifications and will survive specified ***external*** and ***internal*** operational radiation environment
- **Three-stage process**:
  - 1. Top level radiation environmental requirements (“A”-spec) flowed down from customer defines worst case, ***external*** radiation environment (mission definition of orbital environmental parameters)
  - 2. Evaluation of radiation environmental effects on design (component level hardness assessment, rad tolerant design, transport shielding analysis and spacecraft layout, ***internal*** operational requirements definition, radiation design margins)
  - 3. Evaluate usability of design and characterize performance of susceptible areas (part selection, component and/or system/circuit level testing, replacement or redesign if necessary, impact analysis)

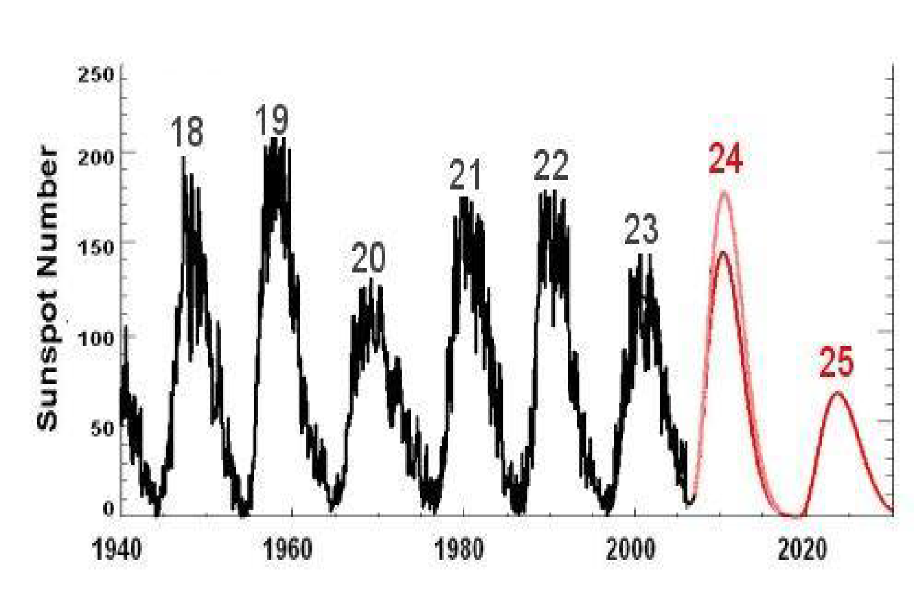
Deals with environment definition, component selection, part testing, spacecraft layout, rad hard design, and mission/system requirements. RHA goes beyond the piece part level!

The Sun – Sunspots and Solar Cycle

- Sun is major source of space radiation and shield to Earth (solar particle events – energetic protons, electrons and heavy ions)
- Solar activity and solar wind significantly impact shape of Earth's magnetosphere and magnitude/ type of radiation Earth orbiting satellites encounter
- Number of sunspots (dark regions of lower surface temp caused by intense magnetic activity) not constant over **11 year solar cycle**



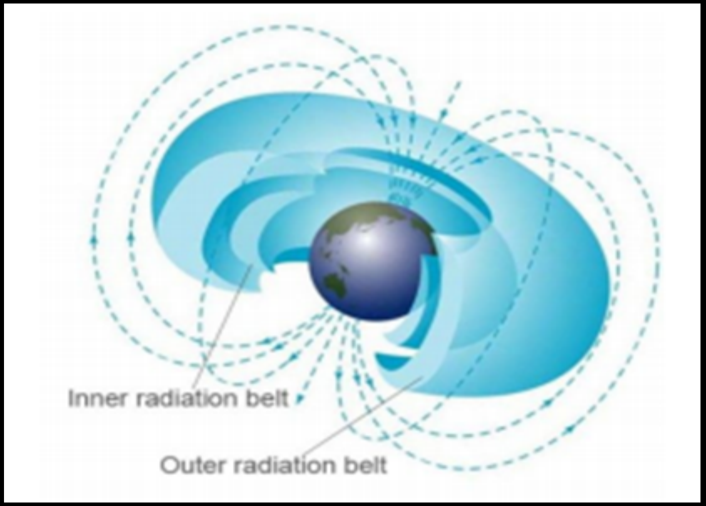
Small sunspot same size as Earth



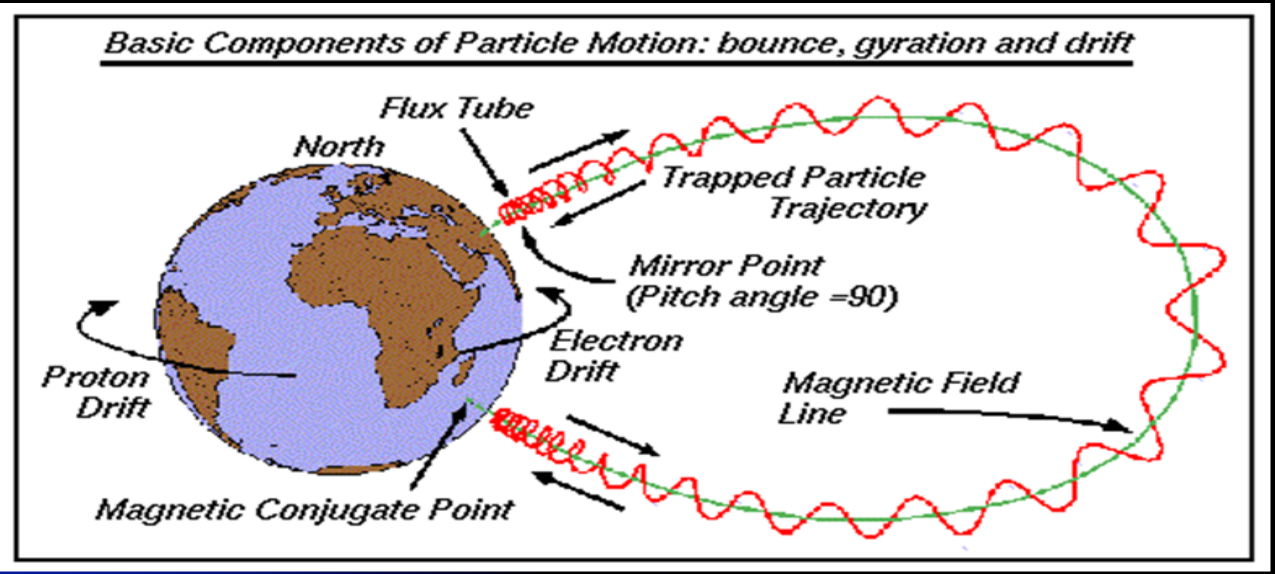
- **Solar Minimum** (**Quiet**, **4 years**) – lower SEP contribution, fewer sunspots with less intensity, less solar wind (higher trapped proton and GCR flux levels)
- **Solar Maximum** (**Active**, **7 years**) – higher SEP contribution, more sunspots with greater intensity, strong solar wind to shield Earth's magnetosphere (lower trapped proton and GCR flux levels)

Trapped Particles - Van Allen Belts (1958)

- Electrons and protons trapped by Earth's magnetic field form Van Allen belts
- Components (omnidirectional):
  - <u>Outer belt</u> – lower energy **electrons** **~ 1 keV – 10 MeV**
  - <u>Inner belt</u> – highly energetic **protons** **~ 1 keV – 500 MeV** (can penetrate up to 143 mm lead)



- Beta radiation levels potentially dangerous to humans if exposed for extended period of time (Apollo first time humans travel thru region)
- Impacts all orbits in terms of radiation effects



- <u>Bounce or mirroring</u> - particles travel from one hemisphere to other and back
- <u>Gyration</u> - particles rotate helically around magnetic field lines
- <u>Drift</u> – longitudinal motion around Earth (electrons drift east and protons west)

*Images from: reference 1

Enhanced Low Dose Rate Sensitivity (ELDRS)

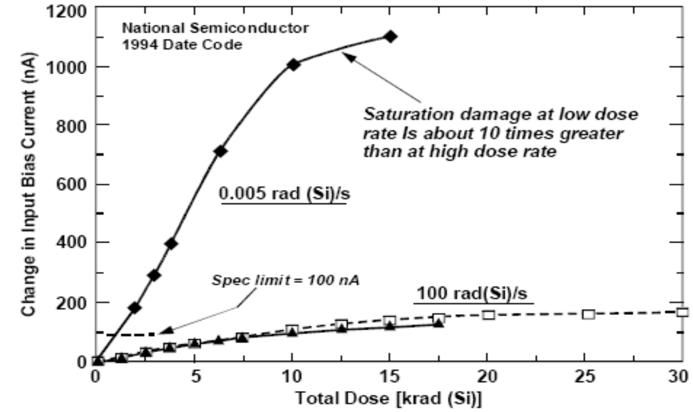


Figure 1. Increased degradation of a bipolar comparator when it is irradiated at very low dose rate.

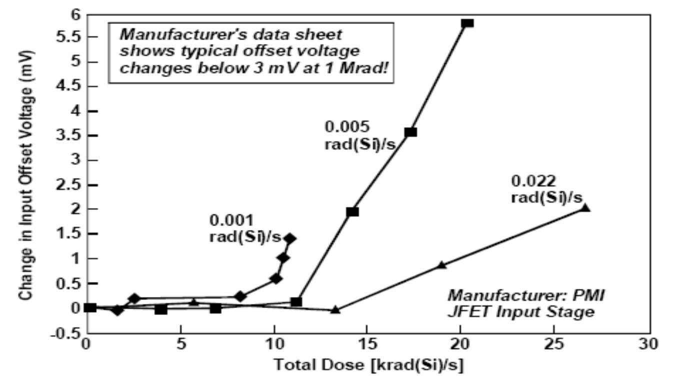
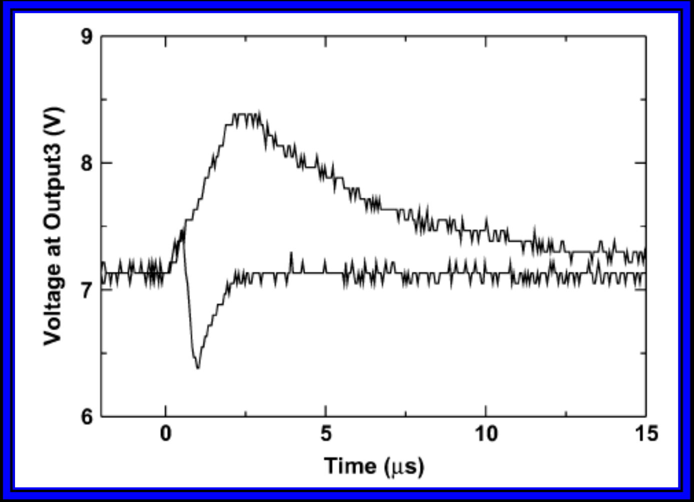


Figure 2. Degradation of input offset voltage of the OP42 bipolar op-amp when the device is irradiated at different dose rate.

- Typical bipolar ICs exhibit significantly more parameter degradation at low dose rates (0.01 rad/s) encountered in space (all environments)
- Watch for disclaimers in supplier data sheets or Standard Military Drawings:
  - *"Rad-Hard to 100 krad(Si) [dose rate 50 to 300 rad(Si)/second]. These parts may be dose rate sensitive in a space environment and may demonstrate enhanced low dose rate effects."*
  - This is the supplier's way of saying that the part is NOT rad-hard guaranteed in a space environment! Testing may be required.

SET Design Mitigation Techniques

- SET is an increasingly important issue for space systems
- SET susceptible components:
  - Analog and Linear Circuits
  - Optical Links
- SET mitigation techniques include:
  - Filtering
  - Over-sampling
  - High speed device with a slow response following circuit



SEU Design Mitigation Techniques

- Redundancy
- Voting (e.g. TMR, or Triple Mode Redundancy)
- Watchdog timers
- "Robust Design", Good Engineering Design Practices
  - Store critical commands and data in SEU-immune technology
  - Memory scrubbing, high re-fresh rates for SEU-susceptible memory, improved noise margins, ….
  - **E**rror **D**etection **A**nd **C**orrection (EDAC)

EDAC METHOD	EDAC Capability
Parity	Single bit error detect
Cyclic Redundancy Check	Detects if any errors have occurred
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

Some On-Orbit Examples

Table 1. Selected Missions with Associated Radiation Issues

Mission	Launch Date	Purpose	Radiation Issue(s)
Galileo	10-18-89	Planetary exploration (Jupiter)	Safe-holds; analog switches may fail due to total dose (has already exceeded its design requirement)
TOPEX-Poseidon	8-10-92	Earth observation (oceanography); 1336 km, 66°)	Permanent failure of optocouplers
Mars Pathfinder	12-4-96	Mars surface exploration	Modem anomaly on surface of Mars; later concluded unlikely to be caused by radiation.
Cassini	10-15-97	Planetary exploration (Saturn and its moon, Titan)	Transients in comparators Solid-state recorder errors
Deep Space 1	10-24-98	Technology demonstrations, ion propulsion, interplanetary exploration (comet)	Latchup in stellar reference unit, upset in solar panel control electronics, safe-hold.
QuikScat	6-19-99	Earth observation (oceanography)	GPS receiver failure, 1553 bus lockups
Mars Odyssey	4-7-01	Map chemicals & minerals, look for hydrogen/water	Entered Safe mode, due to processor reset caused by latch upset in DRAM.
GRACE	3-17-02	Gravity mapping (~485 km, 89°)	Resets, reboots, double-bit errors in MMU-A, some GPS errors and A-ICU failure (possible)

- Many of the on-orbit anomalies and "failures" listed here occurred long after the intended design life
- When component or system "failures" are observed, even if beyond their design life, this information can be useful for future designs, some of which may have even longer life or higher radiation requirements