Radiation Hardness Drivers for Mission Success – What We Have Learned

Michael J. Campola,
NASA Goddard Space Flight Center (GSFC)

To be presented by Michael J. Campola at the NASA Ames Research Center Webinar, January 19, 2021.

Acronyms

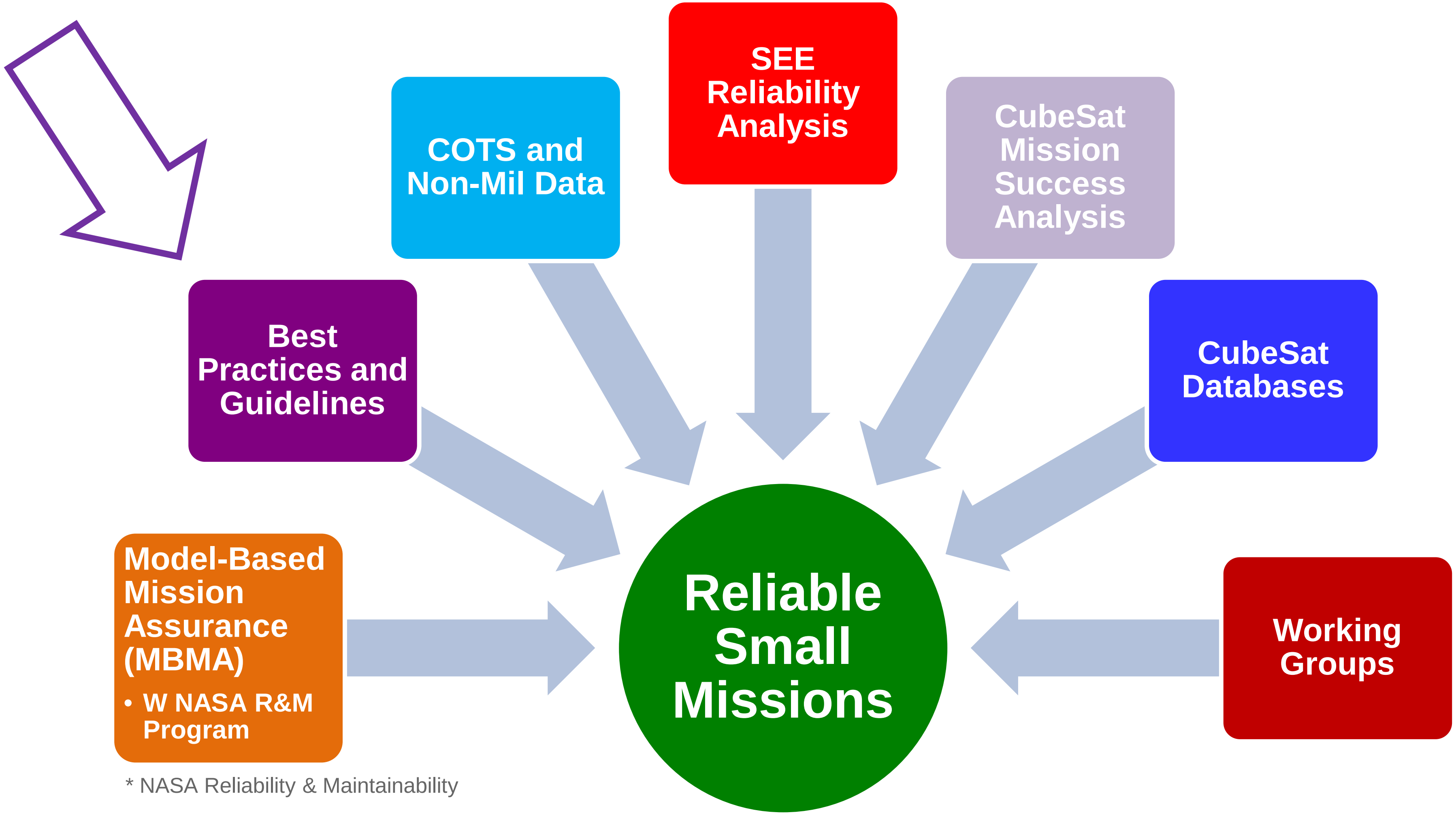
CME	Coronal Mass Ejection
COTS	Commercial Off The Shelf
DDD	Displacement Damage Dose
EEE	Electrical, Electronic, and Electromechanical
ELDRS	Enhanced Low Dose Rate Sensitivity
EP	Enhanced Performance
ESA	European Space Agency
GCR	Galactic Cosmic Ray
GOMAC	Government Microcircuits Applications and Critical Technologies Conference
GSFC	Goddard Space Flight Center
GSN	Goal Structuring Notation
HEART	Hardened Electronics and Radiation Technology
LEO	low earth orbit
LET	Linear Energy Transfer
MBMA	model based mission assurance
MRQW	Microelectronics Reliability and Qualification Workshop
NAND	Negated AND or NOT AND
NASA	National Aeronautics and Space Administration
NEPP	NASA Electronic Parts and Packaging
NEPP ETW	NASA Electronic Parts and Packaging (NEPP) Program Electronics Technology Workshop
NSREC	Nuclear and Space Radiation Effects Conference

RADECS	Radiation Effects on Components and Systems
RHA	Radiation Hardeness Assurance
SAA	South Atlantic Anomaly
SEE	Single Event Effects
SEE/MAPLD	SEE-MAPLD Single Event Effects (SEE) Symposium/
	Military and Aerospace Programmable Logic Devices (MAPLD) Workshop
SEGR	Single Event Gate Rupture
SEL	Single Event Latchup
SEP	Single Event Effects Phenomena (includes SEU, SEL, SEGR and SET)
SERESSA	School on the Effects of Radiation on Embedded Systems for Space Applications
SET	Single Event Transient
SEU	Single Event Upset
SLU	Saint Louis University
SwaP	Size, weight, and power
TID	Total Ionizing Dose
TID	Total Ionizing Dose
TMR	triple-modular redundancy
TNID	Total Non-Ionizing Dose
UV	Ultra-Violet

Introduction

- Embry-Riddle Aeronautical University
  - Bachelor's Engineering Physics, Space Physics Research Lab
- Arizona State University
  - Master's Electrical Engineering, Separation of Radiation and Temperature Effects, Enhanced Low Dose Rate Sensitivity
- NASA GSFC
  - Started in 2007 From Test Engineer to Radiation Lead, MMS, Juno, ICESat-2, TESS, LandSat8, DSCOVR, SMAP
  - REAG Group Lead

NEPP Program (OSMA)- Small Mission Efforts



SEE Reliability Analysis

COTS and Non-Mil Data

CubeSat Mission Success Analysis

Best Practices and Guidelines

CubeSat Databases

Model-Based Mission Assurance (MBMA)
- **W NASA R&M Program**

Reliable Small Missions

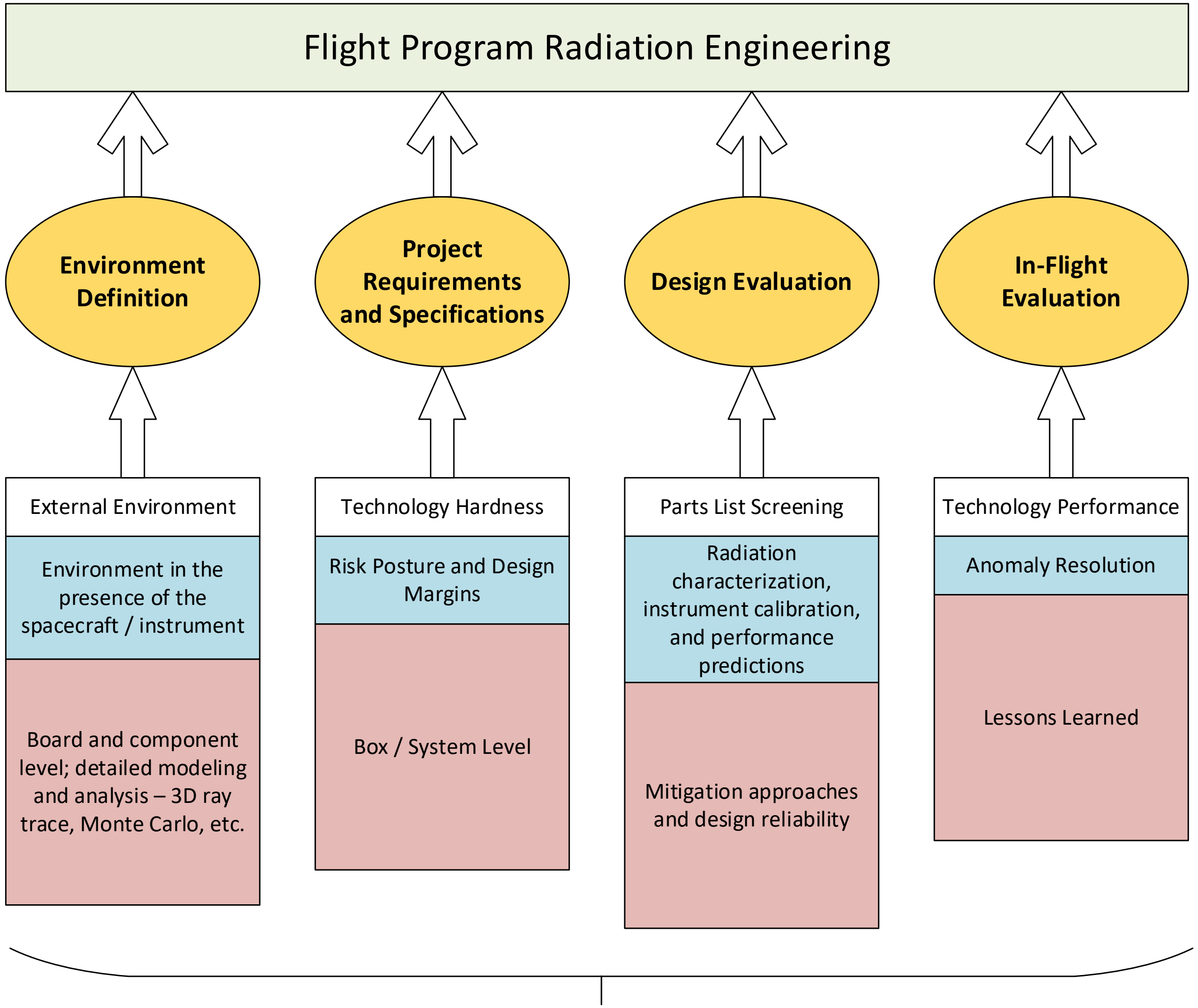
Working Groups

* NASA Reliability & Maintainability

Radiation Hardness Assurance (RHA) Overview

RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their *design* specifications throughout exposure to the mission space environment

(After Poivey 2007)



Flight Program Radiation Engineering

Environment Definition

Project Requirements and Specifications

Design Evaluation

In-Flight Evaluation

External Environment	Technology Hardness	Parts List Screening	Technology Performance
Environment in the presence of the spacecraft / instrument	Risk Posture and Design Margins	Radiation characterization, instrument calibration, and performance predictions	Anomaly Resolution
Board and component level; detailed modeling and analysis – 3D ray trace, Monte Carlo, etc.	Box / System Level	Mitigation approaches and design reliability	Lessons Learned

(After LaBel 2004) *Iteration over project development cycle*

Questions to Keep in Mind

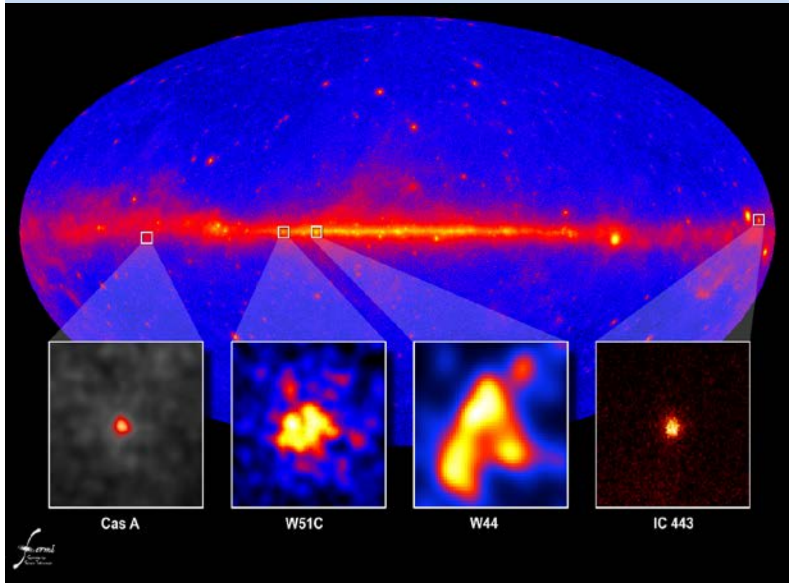
- What are radiation risks:
  - What is the hazard?
  - What are the challenges?
- What can you do to reduce risk for a given hazard?
- What does changing a radiation environment mean for success?
- Need reliability or availability throughout the mission? or just at specific times?
- What basic steps can we do that help to achieve mission success?

Outline

- **The Natural Space Radiation Environment Hazard**
- **Radiation Effects on Micro-Electronics**
- **New Space and SmallSat Considerations**
- **Hardness Assurance, as a Discipline, What We are Learning**
  - **New Technologies**
  - **New Architectures**
  - **Unbound Risks**
- **Risk Acceptance and Guidance**
- **RHA @ GSFC**

Natural Space Radiation Environment

Galactic Cosmic Rays

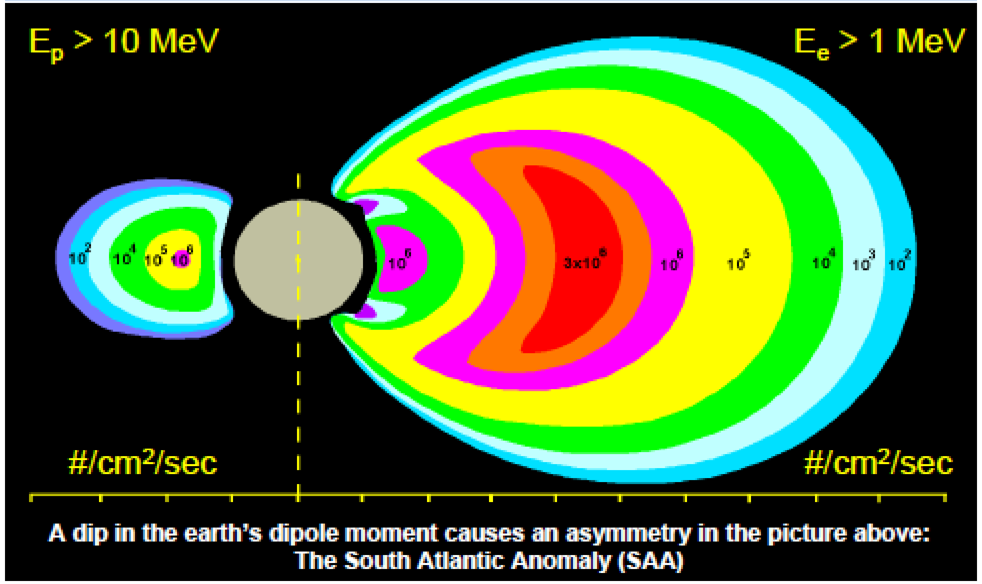


Energetic supernovae remnants (~GeV, Z=1-92)
Originate outside of our solar system

Solar Activity

Solar Wind, Solar Cycle
CMEs (proton rich)
Flares (heavy ion rich)

Trapped Particles in Planetary Magnetic Fields



A dip in the earth's dipole moment causes an asymmetry in the picture above: The South Atlantic Anomaly (SAA)

Fluctuate with Solar Activity and Events
Not a perfect dipole
Protons and Electrons trapped at different L-shell values and energies

Images from left to right – NASA FERMI X-ray telescope, Solar Dynamics Observatory, Janet Barth (radhome.gsfc.nasa.gov)

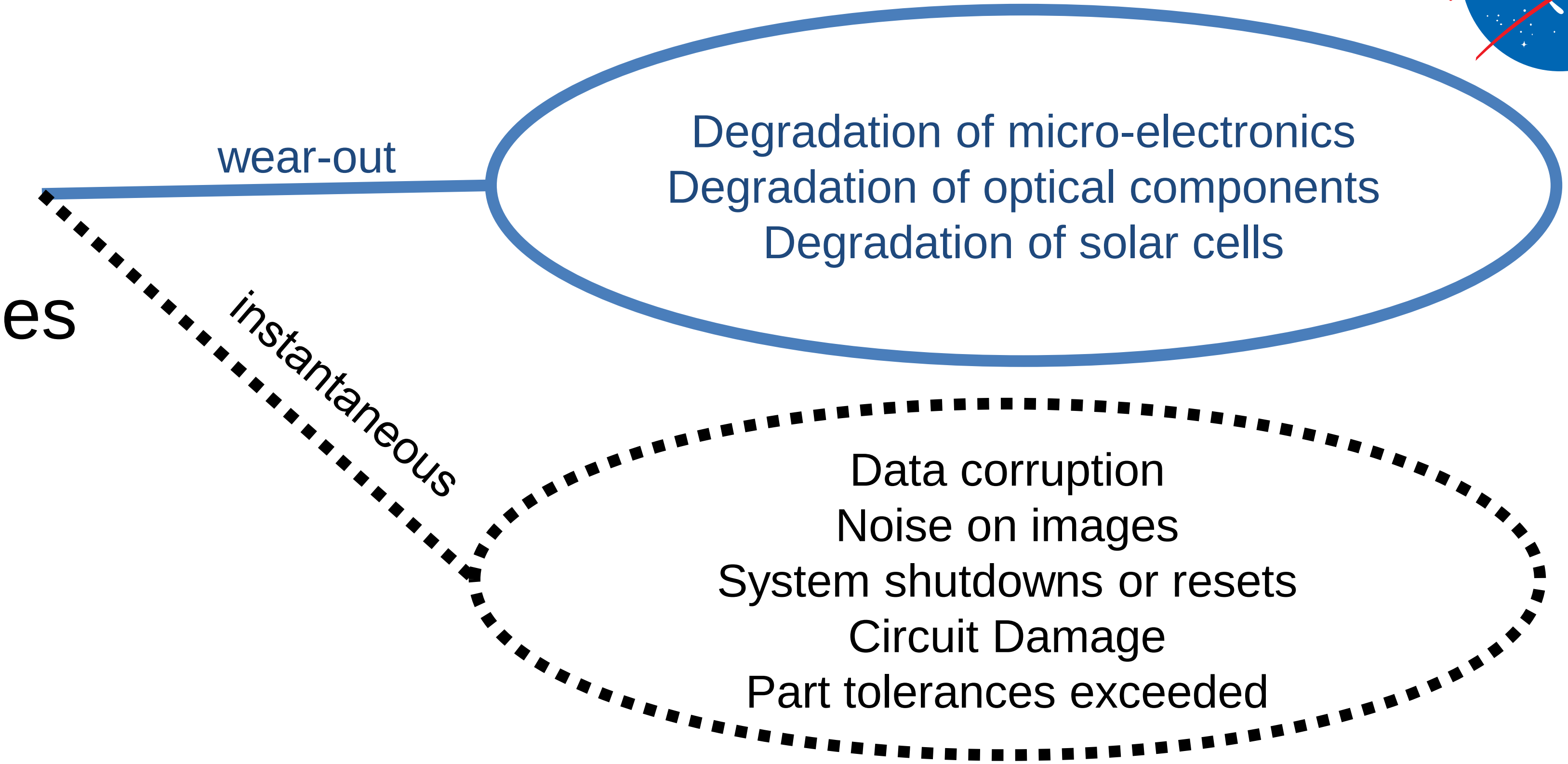
Summary of Environmental Hazards (Reference)

	Plasma (charging)	Trapped Protons	Trapped Electrons	Solar Particles	Cosmic Rays	Human Presence	Long Lifetime (>10 years)	Nuclear Exposure	Repeated Launch	Extreme Temperature	Planetary Contaminates (Dust, etc)
GEO	Yes	No	Severe	Yes	Yes	No	Yes	No	No	No	No
LEO (low-incl)	No	Yes	Moderate	No	No	No	Not usual	No	No	No	No
LEO Polar	No	Yes	Moderate	Yes	Yes	No	Not usual	No	No	No	No
International Space Station	No	Yes	Moderate	Yes - partial	Minimal	Yes	Yes	No	Yes	No	No
Interplanetary	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	Yes	Yes	No	Yes	Maybe	No	Yes	Maybe
Exploration – Lunar, Mars, Jupiter	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Possibly	Yes	Maybe	No	Yes	Yes

https://radhome.gsfc.nasa.gov/radhome/papers/SSPVSE05_LaBel.pdf

Natural Space Radiation Environment

- Plasma
- **Particle Radiation**
- Neutral Gas Particles
- UV and X-Ray
- Orbital Debris



Degradation of micro-electronics
Degradation of optical components
Degradation of solar cells

Data corruption
Noise on images
System shutdowns or resets
Circuit Damage
Part tolerances exceeded

(After Barth)

Spacecraft Charging, Ionizing Dose, Non-Ionizing Dose, Single Event Effects, Drag, Surface Erosion, Debris/Micro-Meteoroid Impacts, Thermal Cycles

Natural Space Radiation Environment

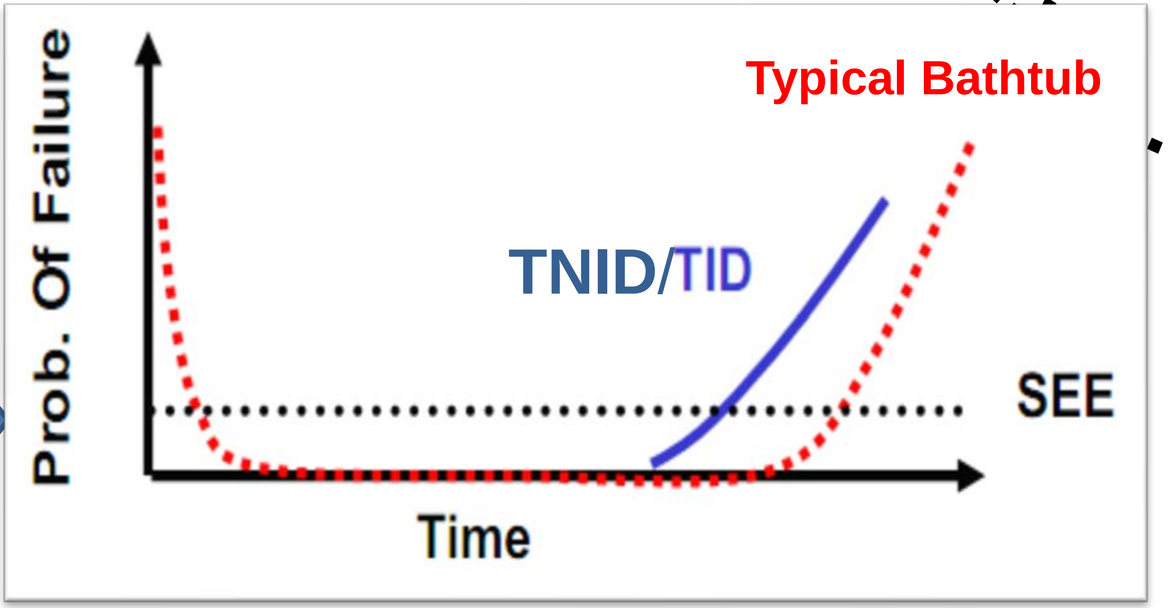
- **Particle Radiation**

wear-out

Degradation of micro-electronics
Degradation of optical components
Degradation of solar cells

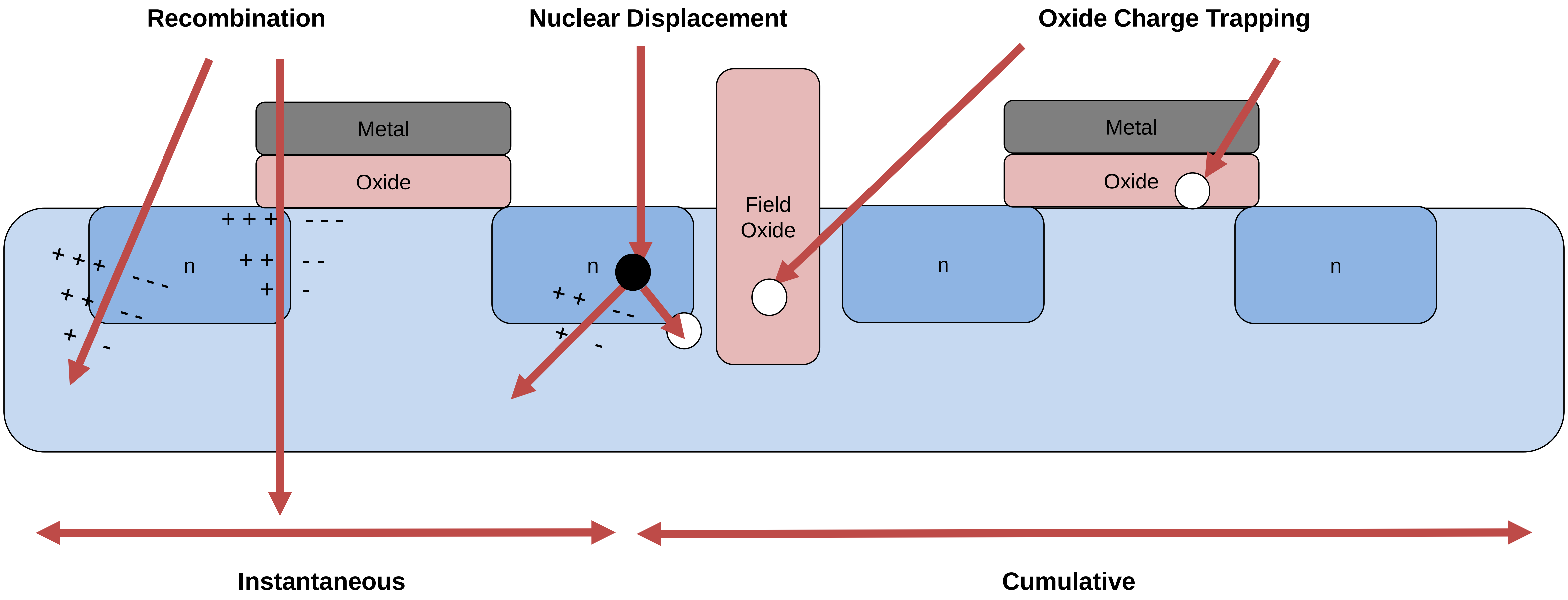
instantaneous

Data corruption
Noise on images
System shutdowns or resets
Circuit Damage
Part tolerances exceeded



(After Buchner)

Device and Particle Interaction



Brock J. LaMeres, Colin Delaney, Matt Johnson, Connor Julien, Kevin Zack, Ben Cunningham Todd Kaiser, Larry Springer, David Klumpar, "Next on the Pad: RadSat – A Radiation Tolerant Computer System," Proceedings of the 31st Annual AIAA/USU Conference on Small Satellites, Logan UT, USA, Aug. 5-10, 2017, paper: SSC17-III-11,
URL: http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3618&context=smallsat

Conventional Units Explanation

Degradation

- **Total Ionizing Dose (TID)**
  - Absorbed dose (rad(Si))

    1 rad = 100 erg/g = 0.01 J/kg; 100 rad = 1 Gy
  - Always specified for a particular material

    1 rad(SiO_2), 10 krad(Si), 100 Gy(H_2O)
  - This is not exposure (R), or dose equivalent (Sv)
- **Total Non-Ionizing Dose (TNID)**
  - Fluence (particles/cm^2)

    Number of particles per unit area
  - Displacement Damage Dose (DDD)

    Specified at a given incident particle energy - e.g., 10 MeV p+, 50 MeV p+, 1 MeV eq. neutrons, etc.

Single Event

- **Linear Energy Transfer (LET)**
  - Stopping power normalized to target material

$$S = -\frac{dE}{dx} \Rightarrow \mathrm{LET} = -\frac{1}{\rho}\frac{dE}{dx}$$

  - Units are MeV·cm^2/mg
- **Cross Section (σ)**
  - Device particle interaction (cm^2)
  - Used in calculation of rate

    Can be /device or /bit per time interval

Degradation Contributors vs. Single Event

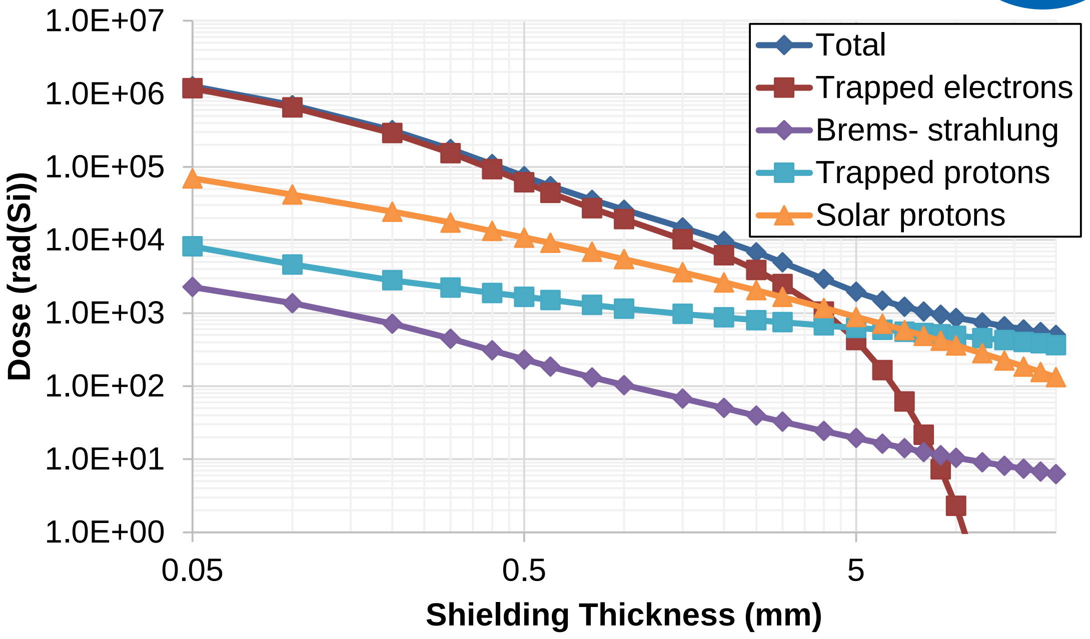
- **Cumulative effects**
  - Depend highly on which contributors and duration in their presence
  - Mimic wear-out/aging
  - TNID and TID must be accounted for

- **Typical destinations (LEO, GEO)**
  - LEO at low altitude/inclination is more protected by the Geomagnetic field
  - Proximity to the poles & SAA show a large variability in dose despite short mission durations
  - Electrons and their braking radiation are the big offender in Geostationary orbits (don't forget about spacecraft charging…)

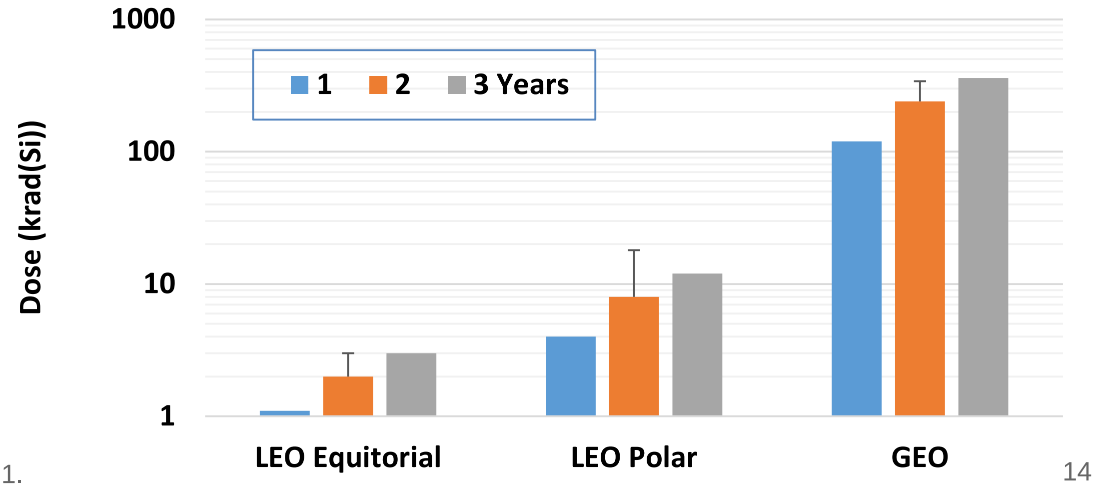
- **Note that**
  - A little bit of shielding goes a long way
  - Altitude plays a huge role when in/near the radiation belts (even transiting)
  - Beyond Geomagnetic field, highly variable solar environment contributions (Solar cycle)

Degradation has a strong dependence on where you go, not just how long you are on orbit

Total Ionizing Dose vs. Shielding



Approximate Dose Behind ~2.5mm Al



Degradation vs. **Single Event Contributors**

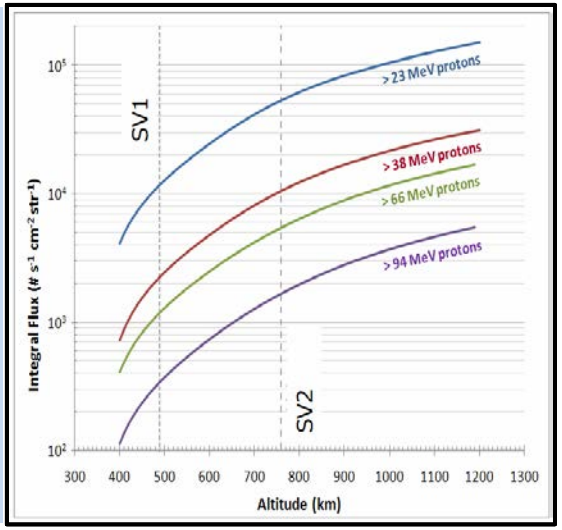
- **One particle causes the effect**
  - Random in nature, particle must traverse sensitive structure within device and have sufficient charge creation along its path
  - Shielding doesn’t do so much for highly energetic particles
  - Device technology can be dependent on particle species

- **Typical Destinations (LEO, GEO)**
  - Again altitude plays a role; for some devices that is a direct threat
  - You are exposed to more GCR + Solar contribution as geomagnetic protection is reduced
  - Natural phenomena like the South Atlantic Anomaly (SAA), magnetic poles, are temporal drivers

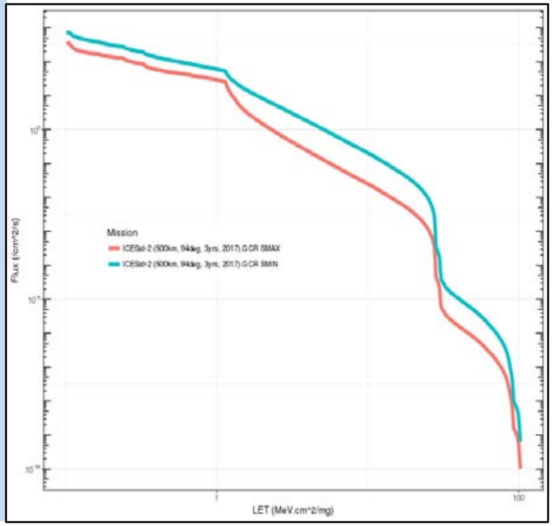
- **Note that**
  - There will be a background rate, solar cycle dependence, solar event rate, increased rate for poles or SAA – **not just one rate to consider**

Single event contributors benefit very little from shielding, have dependence on where you are

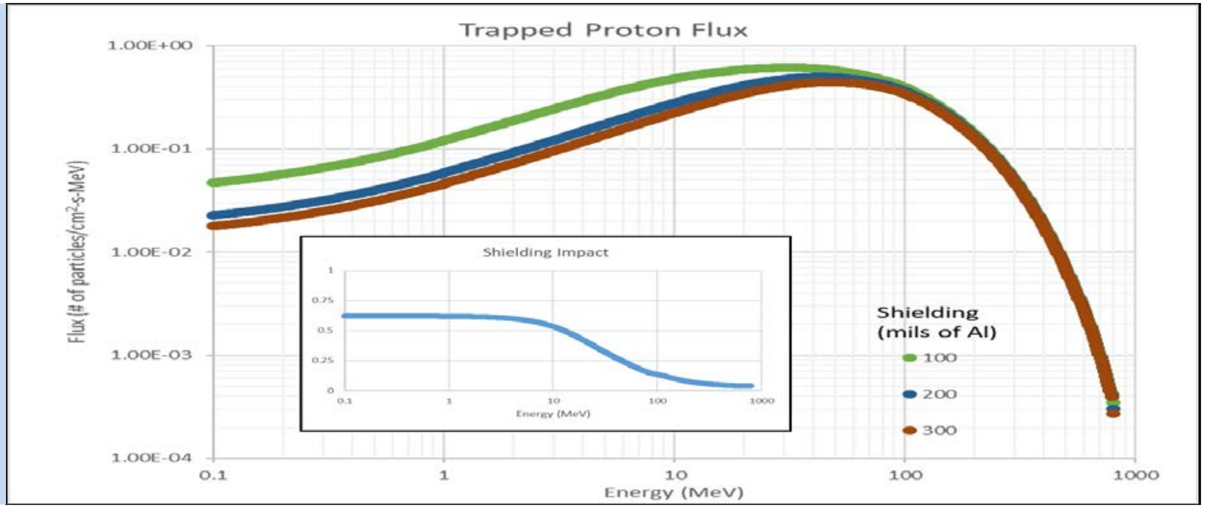
Altitude and Orbit



GCR – Solar Cycle



Shielding Effectiveness



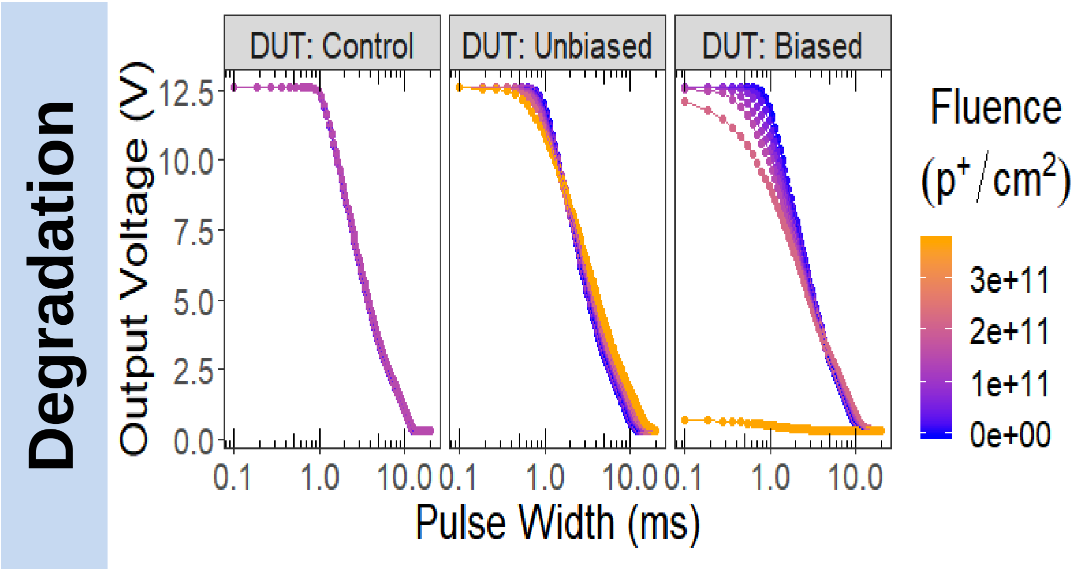
Radiation Effects on Active Microelectronic Devices

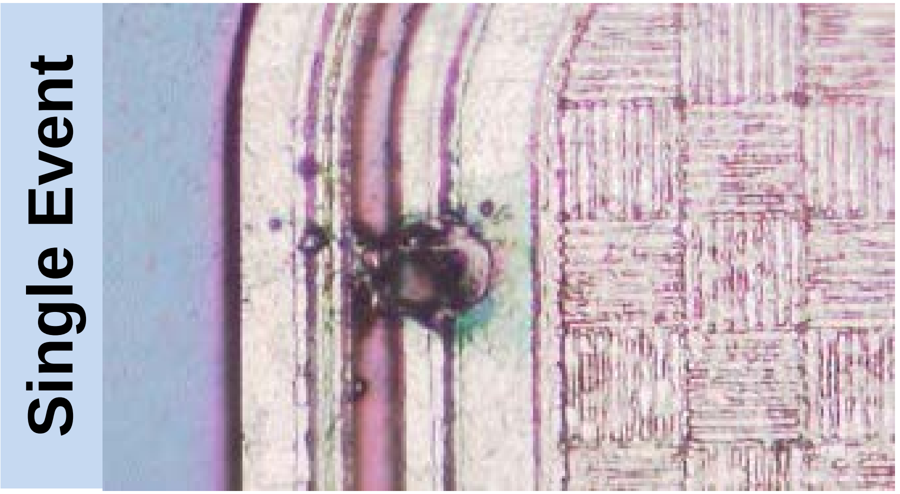
- **Cumulative effects and single event effects can <u>both</u> be permanently damaging**
  - TID/DDD lead to wear-out of device operation and degrade devices beyond acceptable operations internally and externally
  - Single Event Effects can be catastrophic instantaneously by turning on parasitic devices within the semiconductor or inducing electric field across dielectrics that eventually break down
  - Synergistic effects can make ground based testing very difficult

- **Destructive Single Event Effects (SEEs)**
  - Irreversible processes
  - Terms: Latchup, Burnout, Gate Rupture

- **Non-Destructive SEEs**
  - Lead to interruptions in operation and/or errors leading to unknown state spaces or loss of science / mission if not accounted for
  - Terms: Functional Interrupt, Transients, Upsets

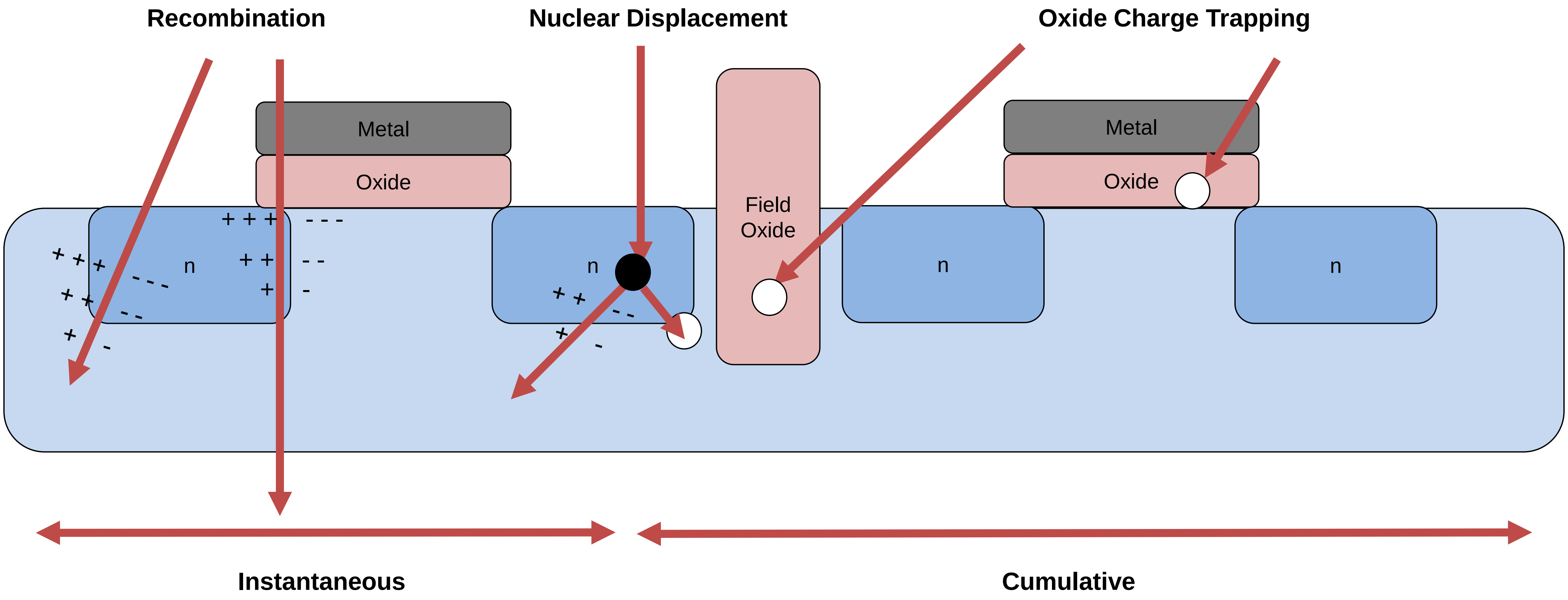
- **IEEE / Papers / Short Courses / Presentations**
  - GOMAC, HEART, MRQW, NEPP ETW, NSREC, RADECS, SEE/MAPLD, SERESSA, SPWG





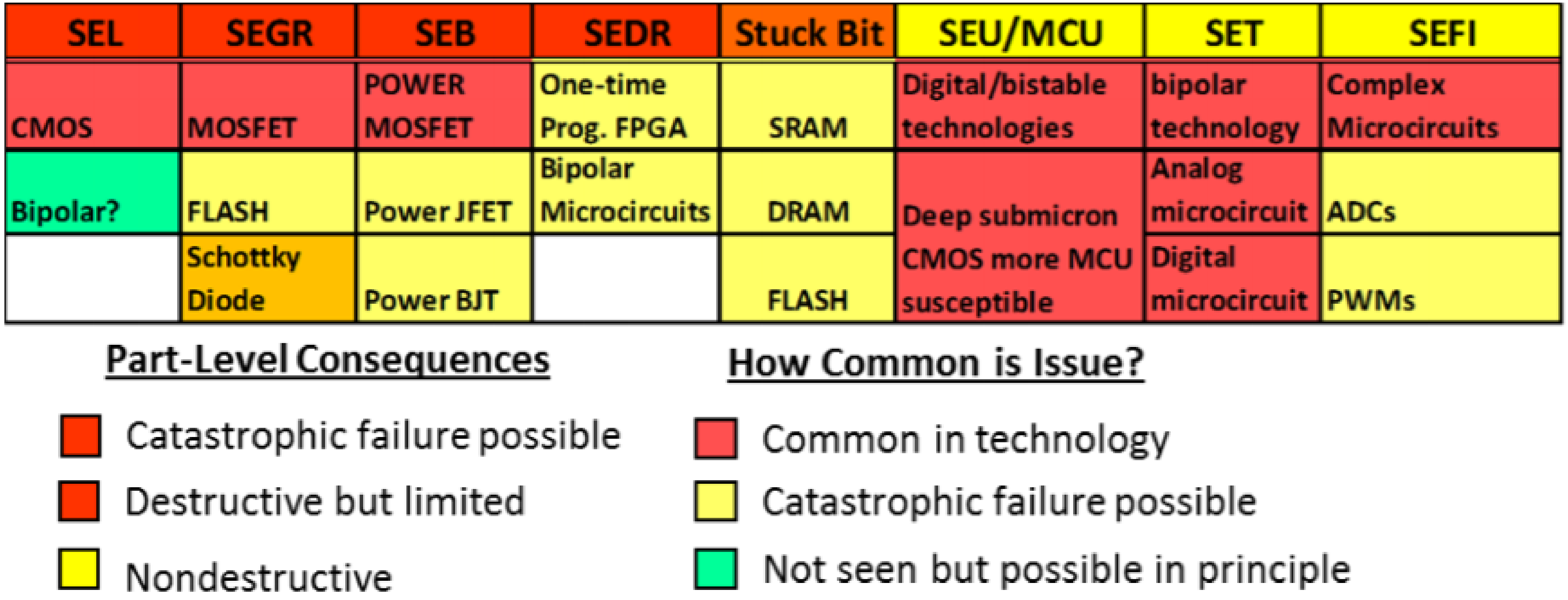
Megan Casey - https://nepp.nasa.gov/files/26196/2014-561-Casey-Final-Web-Pres-ETW-Diodes-TN16278_v2.pdf

Device and Particle Interaction



Brock J. LaMeres, Colin Delaney, Matt Johnson, Connor Julien, Kevin Zack, Ben Cunningham Todd Kaiser, Larry Springer, David Klumpar, "Next on the Pad: RadSat – A Radiation Tolerant Computer System," Proceedings of the 31st Annual AIAA/USU Conference on Small Satellites, Logan UT, USA, Aug. 5-10, 2017, paper: SSC17-III-11,
URL: http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3618&context=smallsat

Table of SEE Susceptibility



SEL	SEGR	SEB	SEDR	Stuck Bit	SEU/MCU	SET	SEFI
CMOS	MOSFET	POWER MOSFET	One-time Prog. FPGA	SRAM	Digital/bistable technologies	bipolar technology	Complex Microcircuits
Bipolar?	FLASH	Power JFET	Bipolar Microcircuits	DRAM	Deep submicron CMOS more MCU susceptible	Analog microcircuit	ADCs
	Schottky Diode	Power BJT		FLASH		Digital microcircuit	PWMs

Part-Level Consequences

- 🟥 Catastrophic failure possible
- 🟧 Destructive but limited
- 🟨 Nondestructive

How Common is Issue?

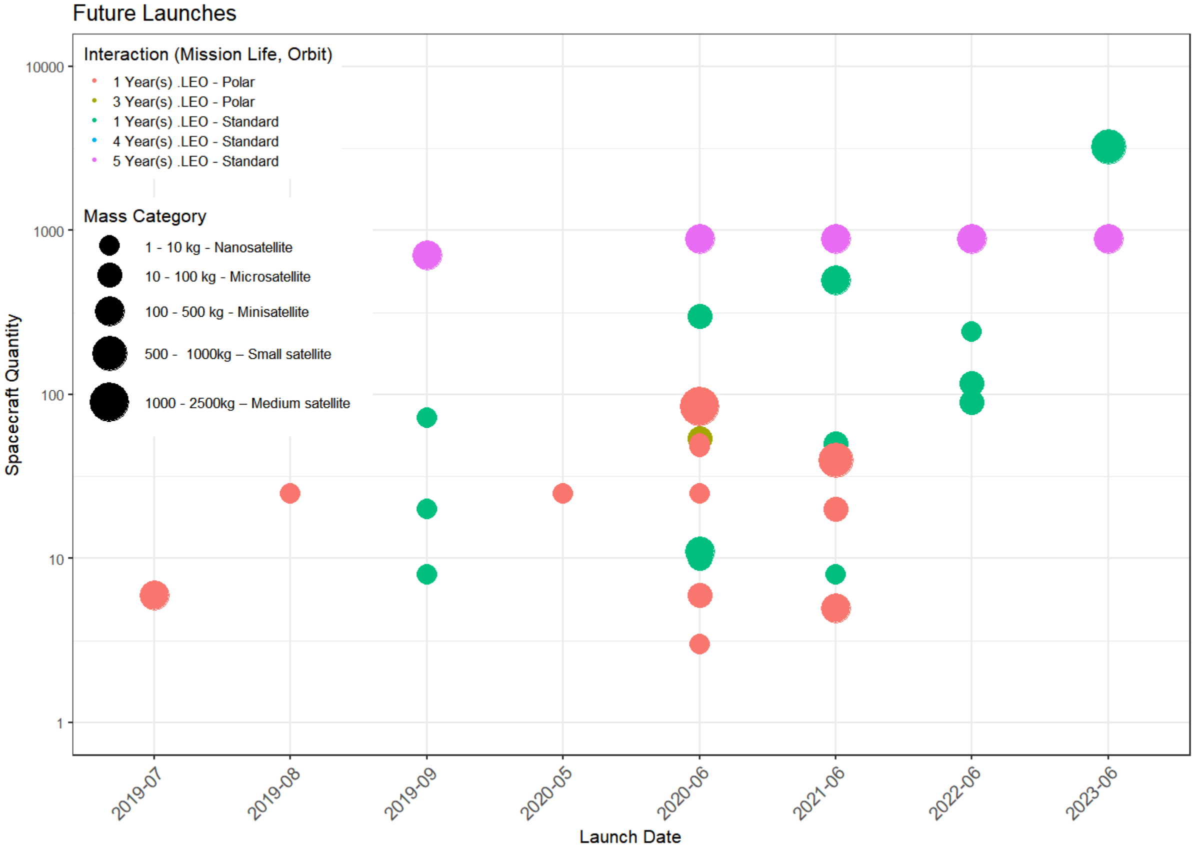
- 🟥 Common in technology
- 🟨 Catastrophic failure possible
- 🟩 Not seen but possible in principle

Ray Ladbury, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006865.pdf

List is not exhaustive, but new failure modes are found in new devices, so it would not be possible to capture all

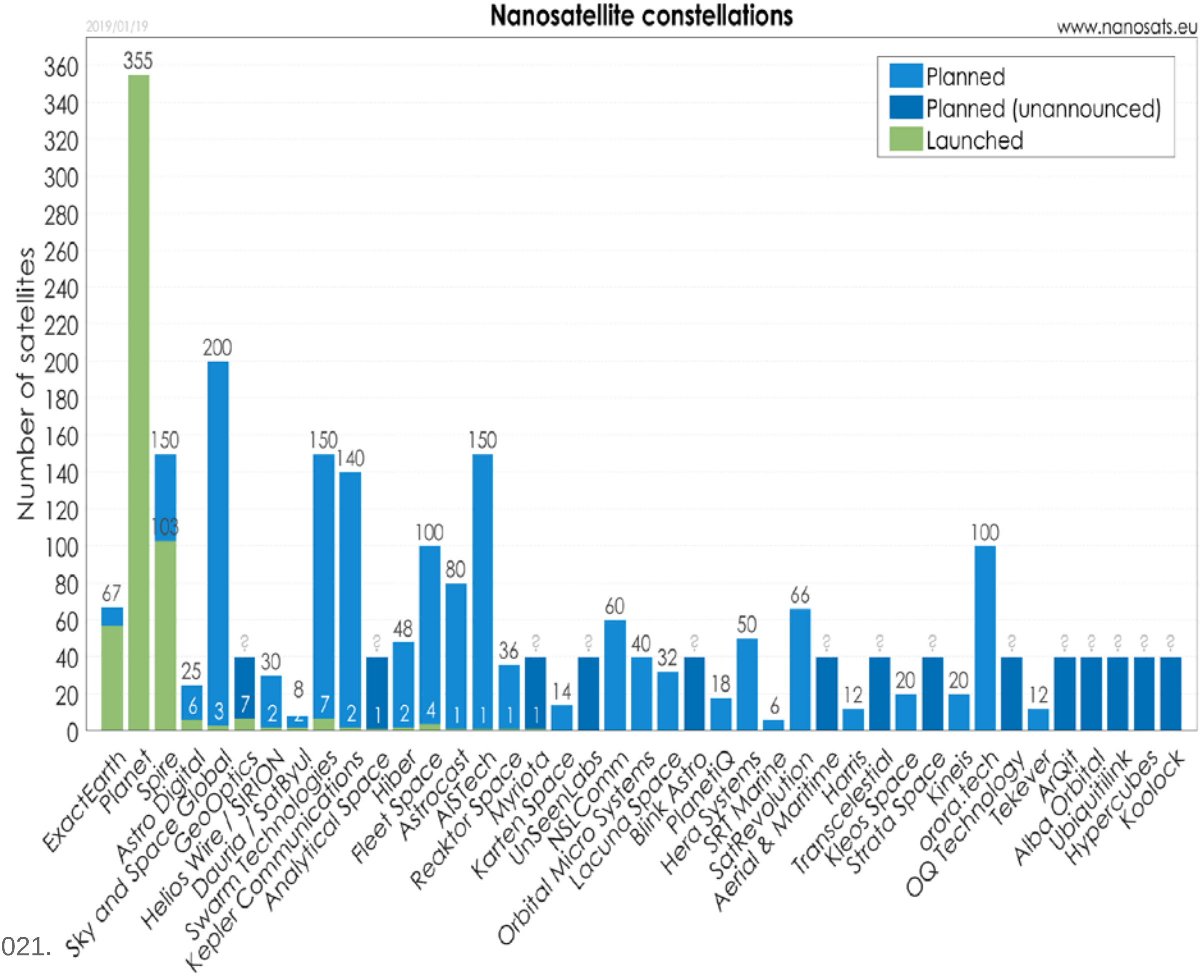
New Space – Looking Ahead

Constellations and Swarms



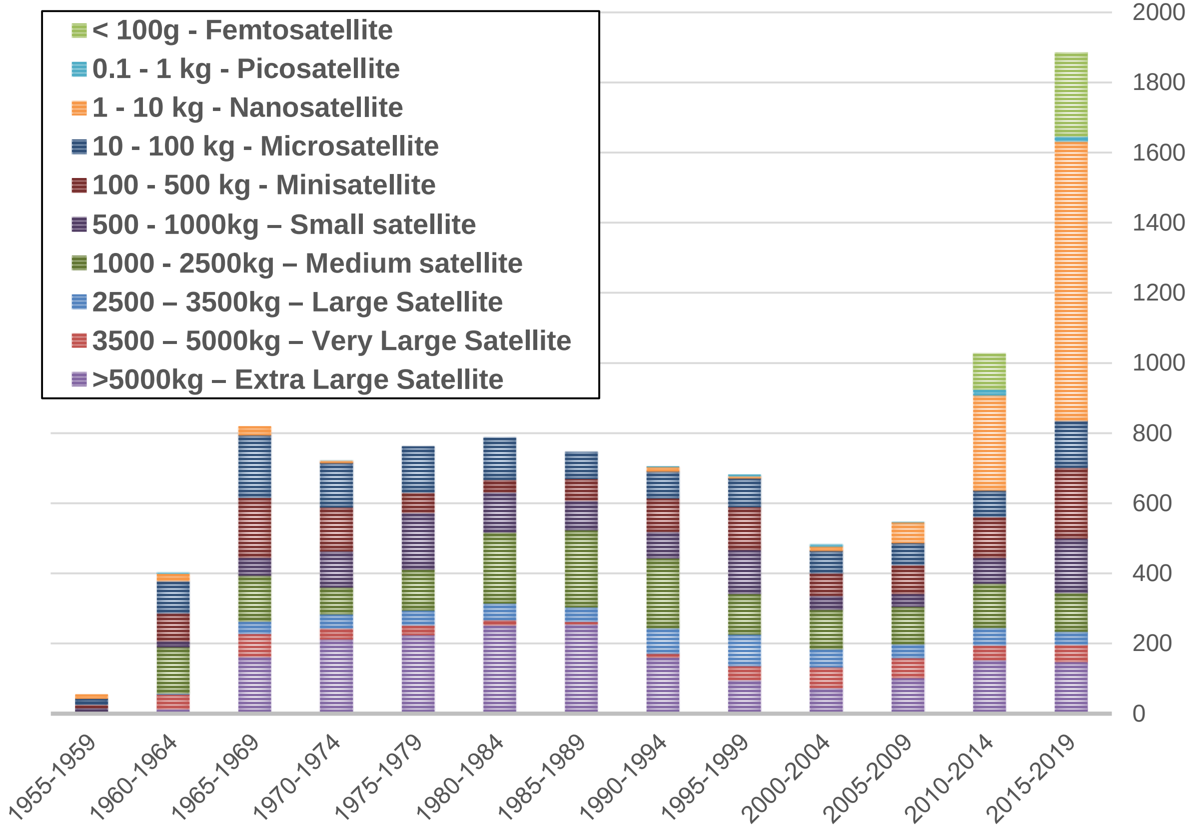
Seradata SpaceTrak Data (Notional Launches)

New Space = New Companies



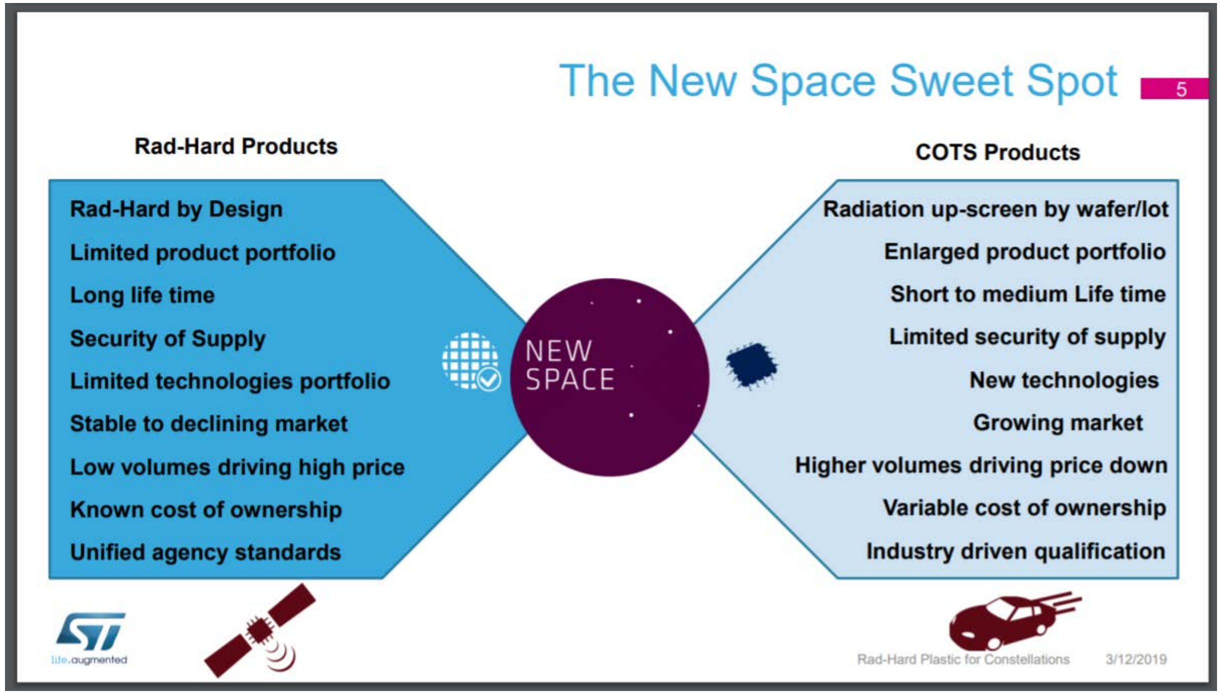
New Space – New Point of View

SmallSats Come in Many Sizes



Seradata SpaceTrak Data

Component Grades are Merging



The New Space Sweet Spot

5

Rad-Hard Products	COTS Products
Rad-Hard by Design	Radiation up-screen by wafer/lot
Limited product portfolio	Enlarged product portfolio
Long life time	Short to medium Life time
Security of Supply	Limited security of supply
Limited technologies portfolio	New technologies
Stable to declining market	Growing market
Low volumes driving high price	Higher volumes driving price down
Known cost of ownership	Variable cost of ownership
Unified agency standards	Industry driven qualification

NEW SPACE

life.augmented

Rad-Hard Plastic for Constellations 3/12/2019

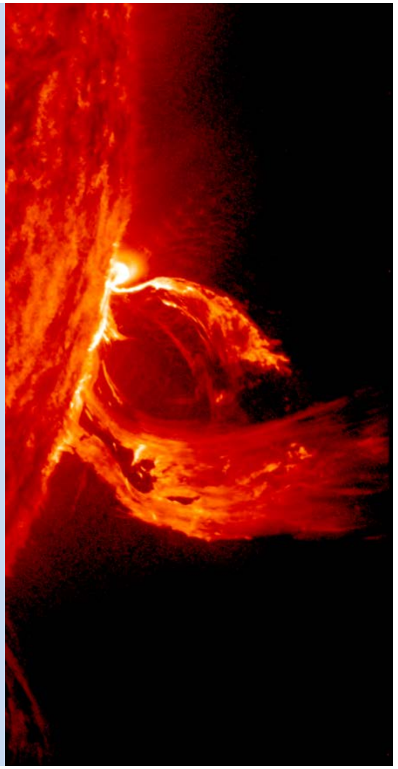
ESSCON : Eccofet

Risk acceptance is being used as a means to enable innovation

New Space – Same Old Radiation

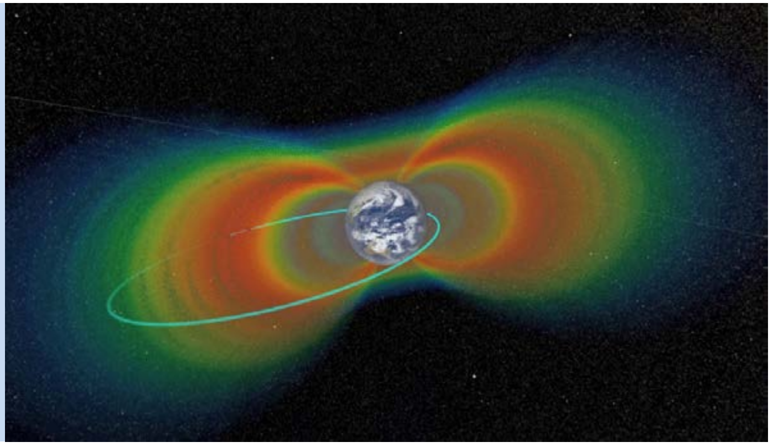
- **New mission concepts and SmallSat paradigm**
  - Radiation challenges identified in the past are here to stay; adoption of new technologies are often the risk driver
  - Commercial Space, Constellations, Small missions, etc. will benefit from detailed hazard definition and mission specific requirements
- **The need for Radiation Hardness Assurance (RHA)**
  - Radiation effects are a mix of disciplines, evolve with technologies and techniques
  - Misinterpretation of failure modes / misuse of available data can lead to over/under design
  - RHA flow doesn't change, risk acceptance needs to be tailored
- **Some Top Level Resources**
  - NPR-7120.5 – NASA Agency Program Management
  - GPR-8705.4 – NASA Goddard Risk Classification Guidelines
  - NASA-STD-8739.10 – NASA Parts Assurance Standard

Solar Events & Activity



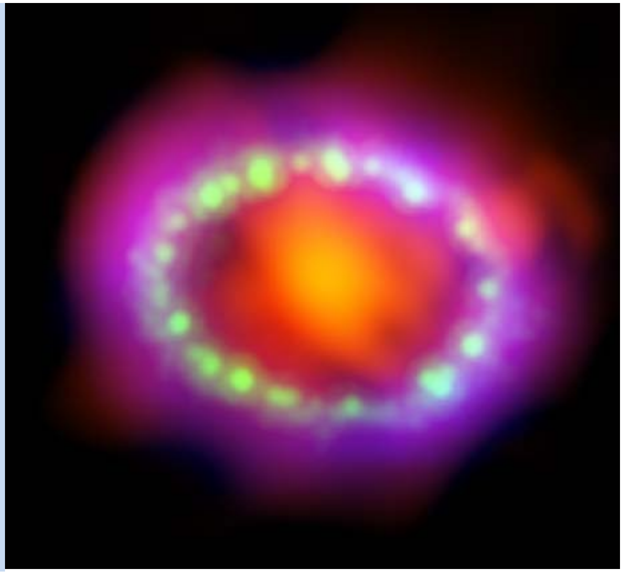
https://sdo.gsfc.nasa.gov

Trapped Radiation



https://www.nasa.gov/van-allen-probes

Supernovae

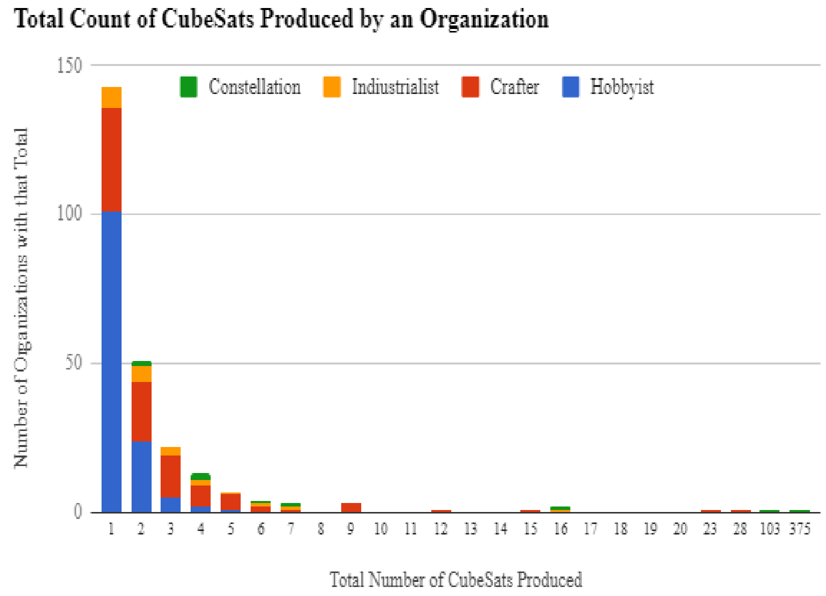


NASA, ESA, and L. Hustak (STScI)

Who Needs This Guidance?

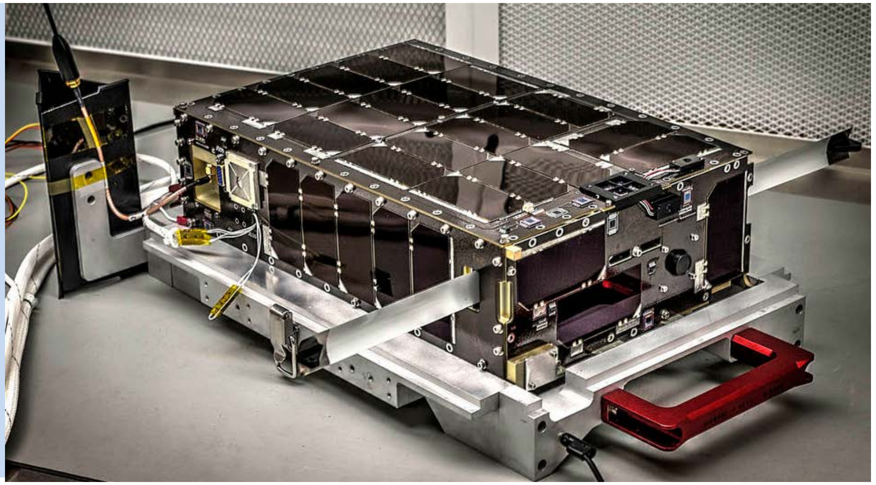
- **Universities / CubeSats**
    - May be first-time designers, or previous missions did not have requirements
    - Schedule driven, limited time for development
    - Rideshares – could end up in multiple environments
- **Space Agencies / Government**
    - More compact designs in new destinations
    - Cost savings of SmallSat platform, with more reliable outcome
    - More willing to trade risk for capability
- **Device / Subsystem Manufacturers**
    - Product / Device offerings: Space Plastic, EP, LeanRel, radiation tolerant, modified HiRel, etc.
    - Fault tolerance in designs

CubeSat Metrics



Michael Swartwout, SLU CubeSat Database

Dellingr



NASA's Goddard Space Flight Center/Bill Hrybyk

Outline

- The Natural Space Radiation Environment Hazard
- Radiation Effects on Micro-Electronics
- New Space and SmallSat Considerations
- **Hardness Assurance, as a Discipline, with its Challenges**
  - **New Technologies**
  - **New Architectures**
  - **Unbound Risks**
- **Risk Acceptance and Guidance**
- **RHA @ GSFC**

The Job: Watch For the ‘ilities

Survivability

- Must survive until needed
- Entire mission?
- Screening for early failures in components

Availability

- Must perform when necessary
- Subset of time on orbit
- Operational modes
- Environmental response

Criticality

- Impact to the system
- Part or subsystem function
- Mission objectives

Reliability

- Resultant of all
- Many aspects and disciplines
- Known unknowns

The People: Radiation Effects Engineers

Materials

- Material Property degradations with radiation
- Energy loss in materials

Device Physics

- Charge transport
- Device Process Dependencies
- Charge dependency of device operation

Electrical Engineering

- Part to part interconnections
- Understanding circuit response
- Device functions and taxonomy

Systems Engineering

- Requirements
- System Level Impacts
- Understanding interconnections
- Understanding functionality

Space Physics

- Space weather
- Environment models/modeling
- Radiation Sources and variability

Paths to Space Radiation

Space Radiation Ecosystem

Systems Engineering Background

- Radiation Reqs. Definition
- SPENVIS, OMERE, Fastrad, etc.
- Radiation Testing Management

Device Physics / Electrical Engineering Background

- Radiation Testing + Qualification
- EEE Parts Programs

Space Weather Physics Background

- Mission Scientists / PIs
- Model Developers (e.g. AP9/AE9)
- Often University + Research Lab based

After Whitney Lohmeyer, presented at JPL meeting 2019

RHA Challenges… Not So Small

- **Always in a *<u>dynamic</u>* environment**
- **New Technologies**
  - Device Topology / Speed / Power
  - Increased COTS parts / subsystem usage
- **New Mission Architectures**
  - Profiles of mission life, objective, and cost are evolving
  - Oversight gives way to insight in some mission classifications
  - Ground systems, do no harm, hosted payloads
  - Similarity and heritage data requirements widening
- **Quantifying Risk**
  - Translation of system requirements to radiation trades can be problematic
  - Determining appropriate mitigation level (operational, system, circuit/software, device, material, etc.)

Unbound radiation risks are likely

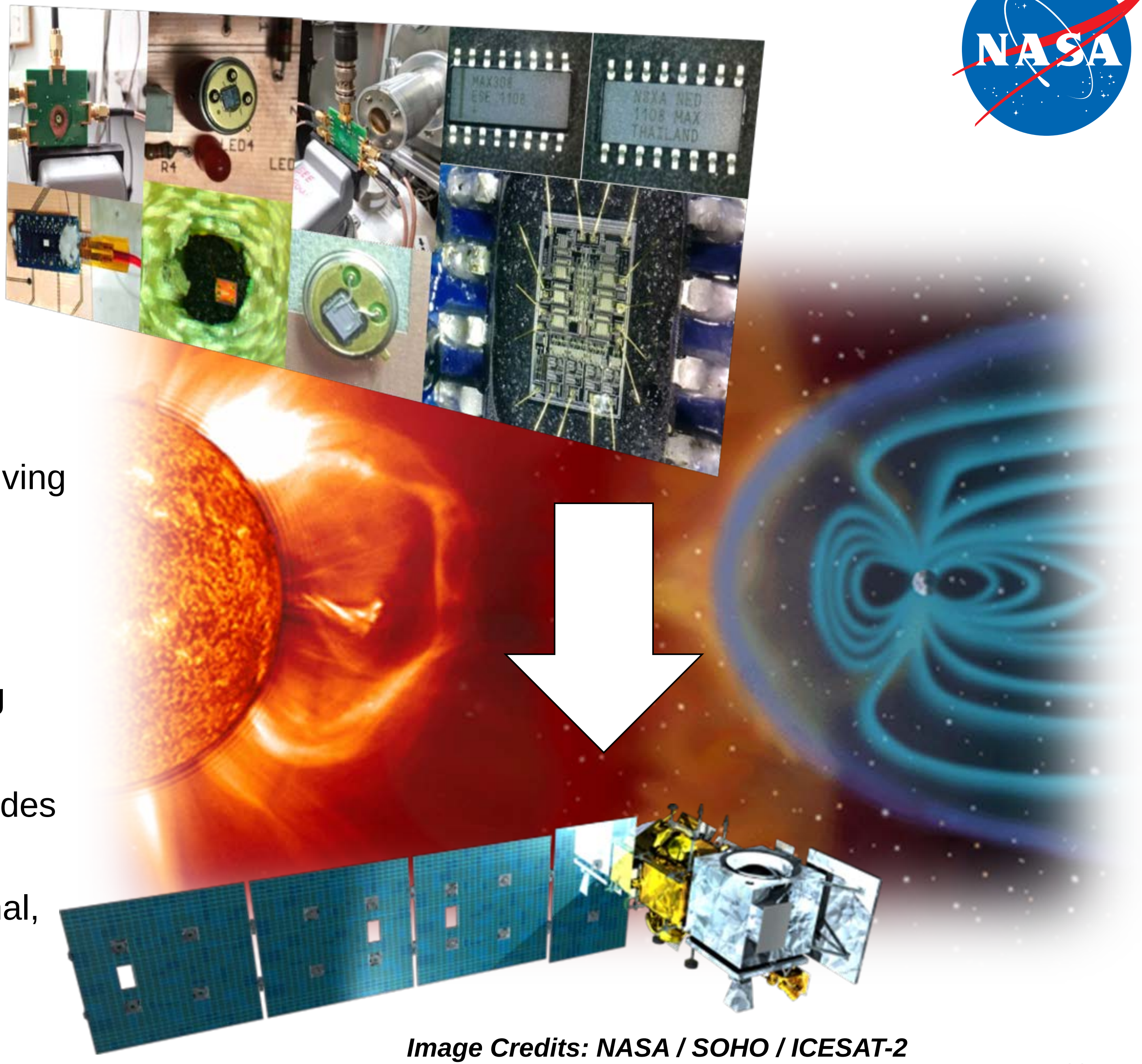
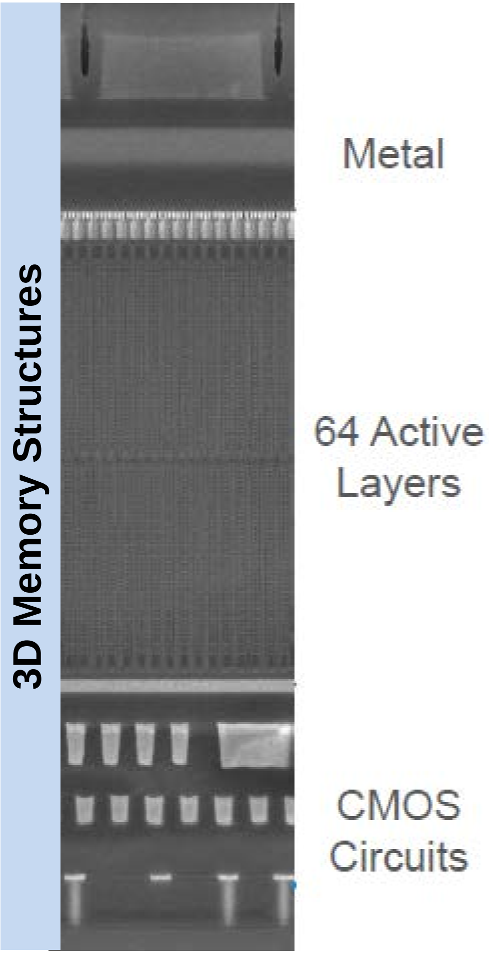


Image Credits: NASA / SOHO / ICESAT-2

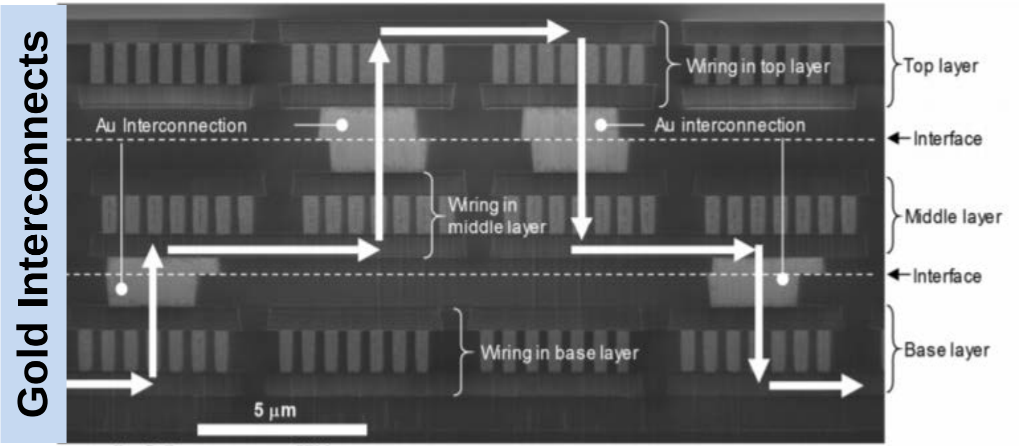
New Technologies - New Susceptibilities

- **Feature Size / Critical Charge**
  - Sensitivity to muons? Low energy protons?
- **3D Stacking / Structures**
  - Deep sensitive volumes
  - New materials within structure
- **Testing Challenges**
  - Complexity (e.g., Systems-on-a-Chip)
    - Speed of interfaces
    - Obfuscation of state-space
  - Flux / range of beam at facilities
- **Function**
  - Integrated Photonics, MEMS, Hybrids

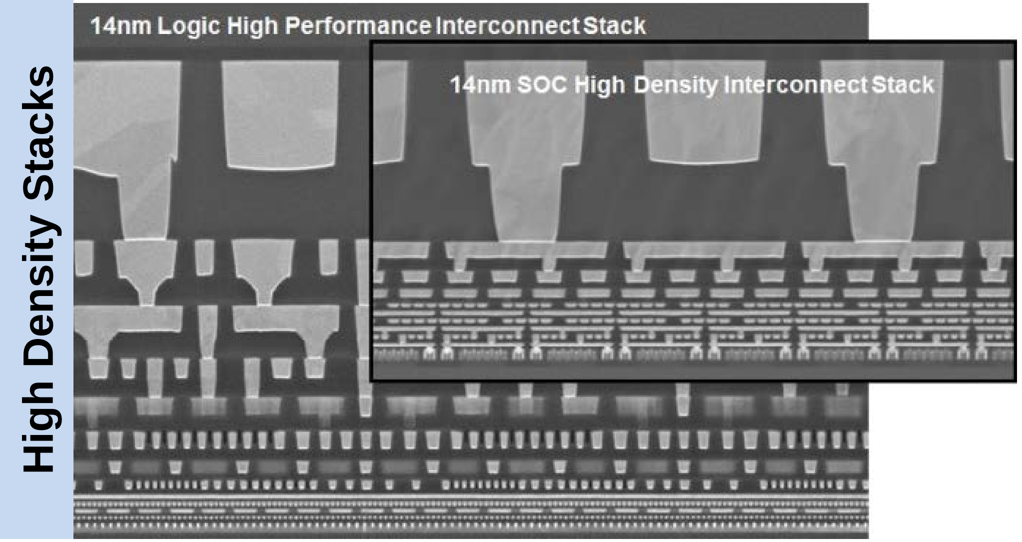
Without detailed part information you do not have certainty of the radiation threats



www.micron.com



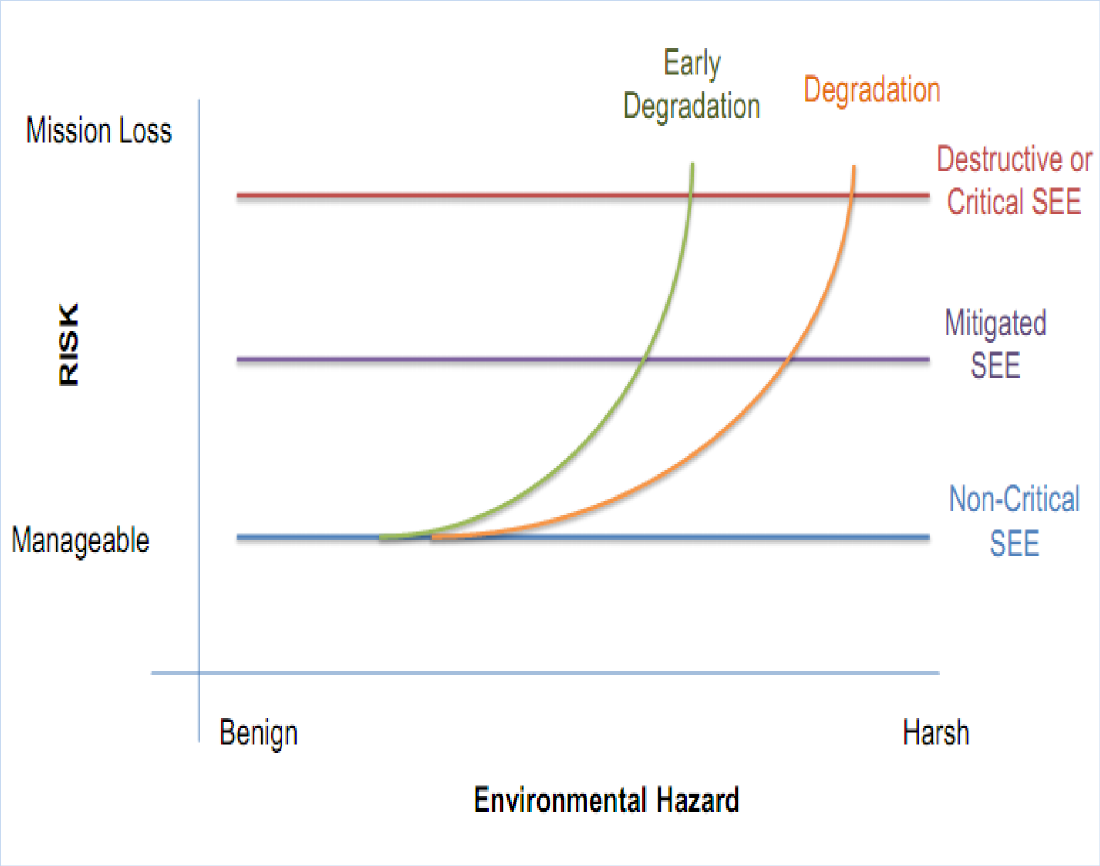
IEEE/DOI: 10.1109/TCPMT.2019.2910863



IEEE/DOI:10.1109/IITC-AMC.2016.7507637

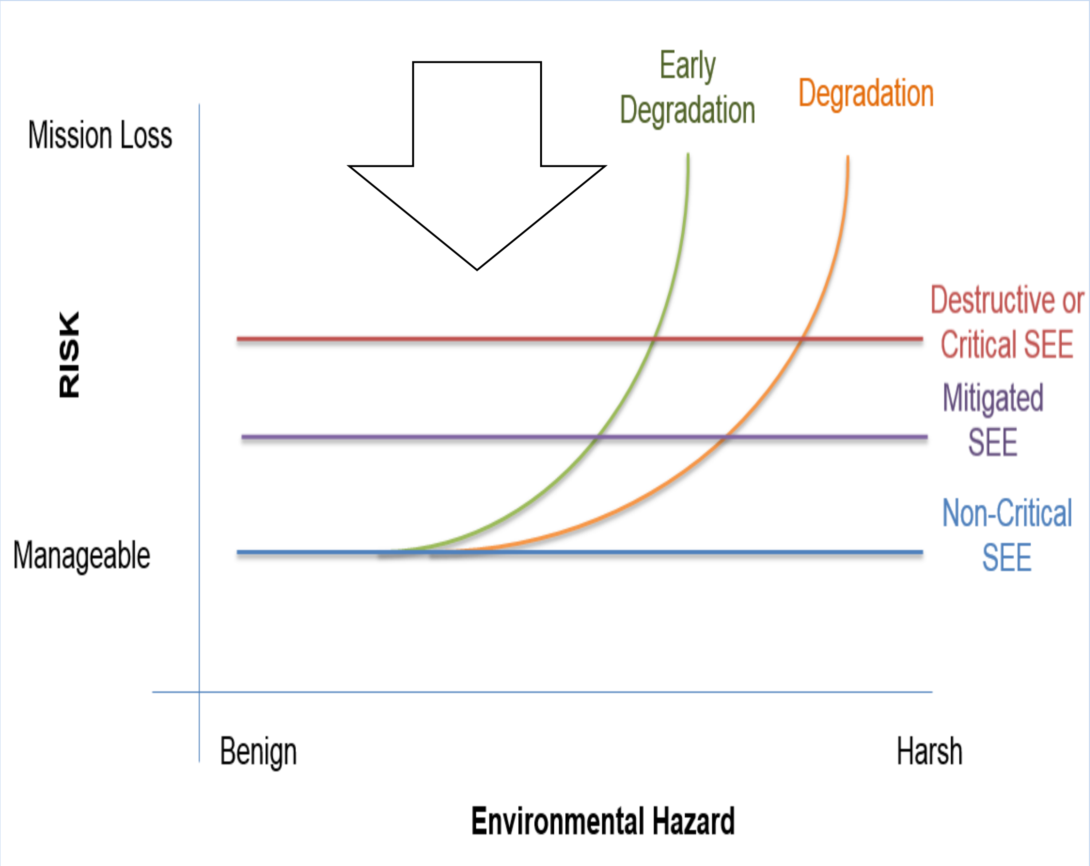
New Mission Architectures - How Many to Succeed?

Single String



vs

Allowable Losses

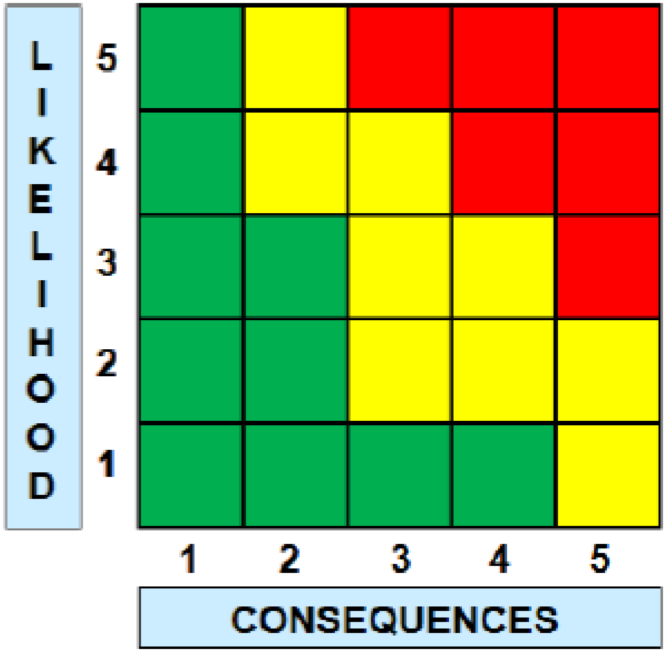


Redundancy alone does not remove the threat, adds complexity

New Challenges in Quantifying Risk

From Risk Assessment section of NASA Program Management 7120.5

Likelihood	**Safety** Estimated likelihood of Safety event occurrence	**Technical** Estimated likelihood of not meeting performance requirements	**Cost Schedule** Estimated likelihood of not meeting cost or schedule commitment
5 Very High	$(P_{SE} > 10^{-1})$	$(P_T > 50\%)$	$(P_{CS} > 75\%)$
4 High	$(10^{-2} < P_{SE} \leq 10^{-1})$	$(25\% < P_T \leq 50\%)$	$(50\% < P_{CS} \leq 75\%)$
3 Moderate	$(10^{-3} < P_{SE} \leq 10^{-2})$	$(15\% < P_T \leq 25\%)$	$(25\% < P_{CS} \leq 50\%)$
2 Low	$(10^{-5} < P_{SE} \leq 10^{-3})$	$(2\% < P_T \leq 15\%)$	$(10\% < P_{CS} \leq 25\%)$
1 Very Low	$(10^{-6} < P_{SE} \leq 10^{-5})$	$(0.1\% < P_T \leq 2\%)$	$(2\% < P_{CS} \leq 10\%)$



LIKELIHOOD	1	2	3	4	5
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩	🟨	🟨	🟥
2	🟩	🟩	🟨	🟨	🟨
1	🟩	🟩	🟩	🟩	🟨

CONSEQUENCES

Can only get there with enough information about the system or the chosen device, need to have a known hazard and a known response

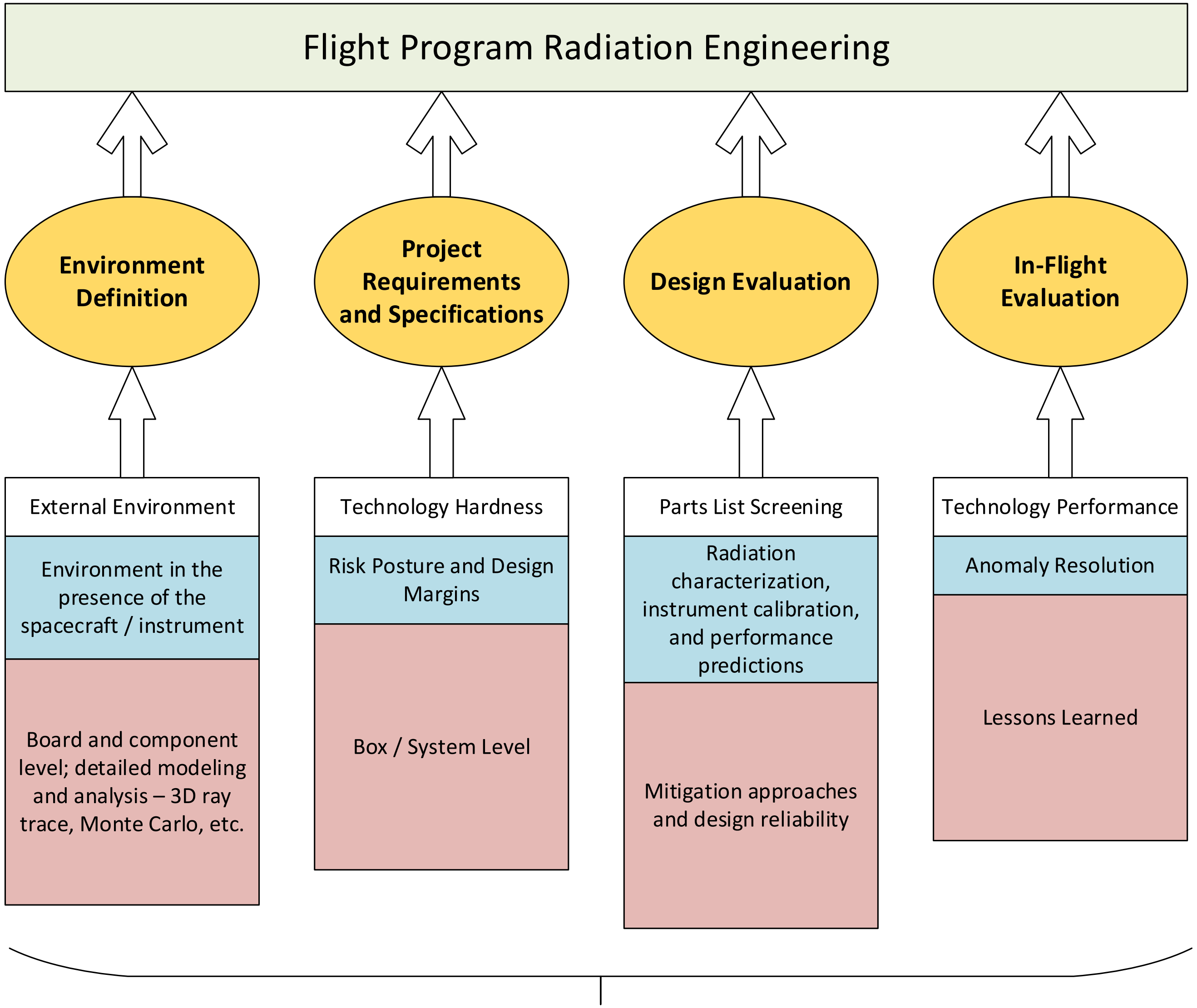
That Seems Difficult, Now What?

- We know we have challenges, but:
  - New technologies enable progress
  - New architectures enable solutions to problems with past missions
  - Quantifying the risk helps communicate across disciplines
- What can we do if we know there are going to be clear and present risks?
- How can we verify that our requirements have been met?

Radiation Hardness Assurance (RHA) Overview

RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their *design* specifications throughout exposure to the mission space environment

(After Poivey 2007)



Flight Program Radiation Engineering

Environment Definition

Project Requirements and Specifications

Design Evaluation

In-Flight Evaluation

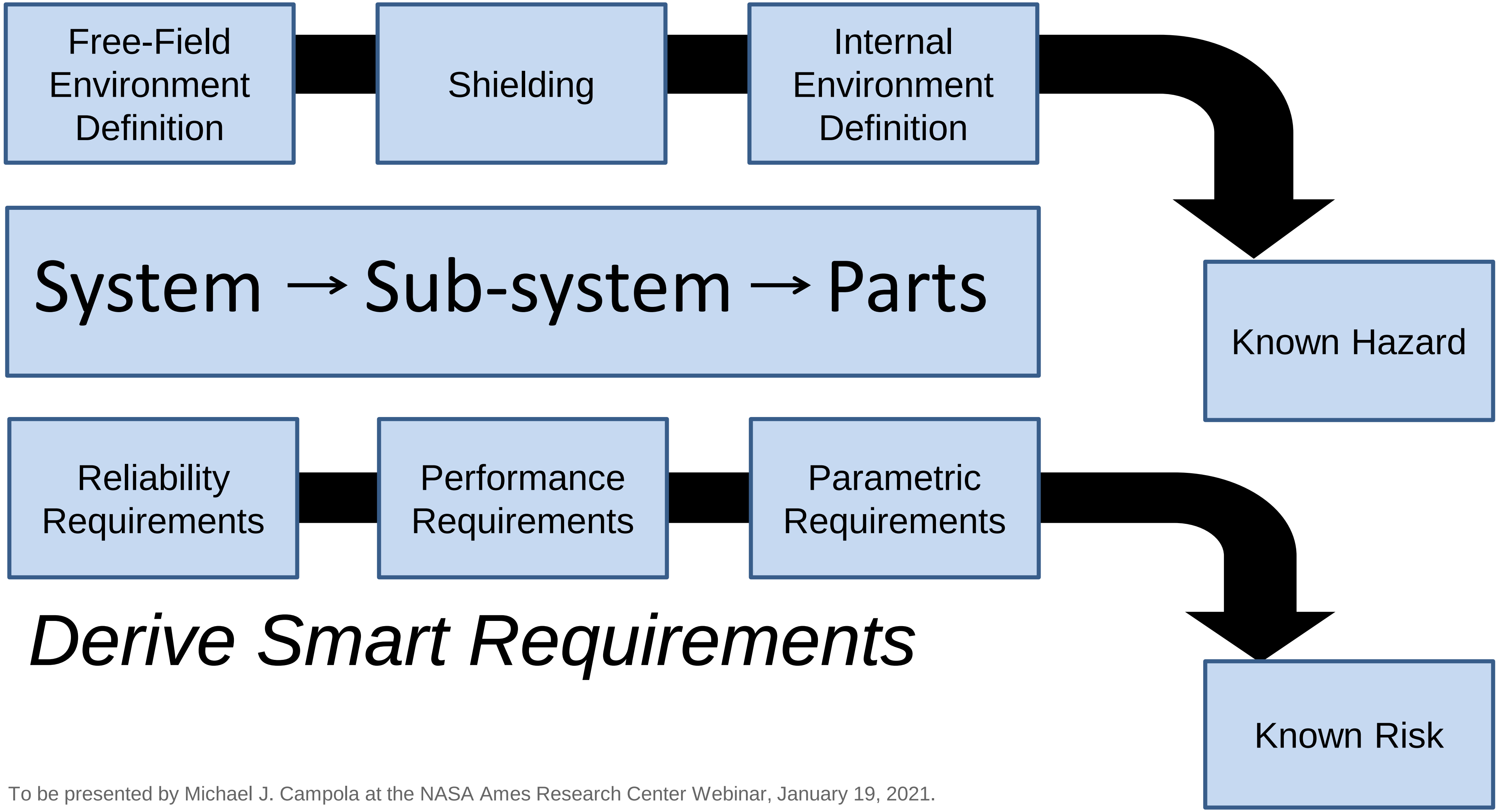
External Environment	Technology Hardness	Parts List Screening	Technology Performance
Environment in the presence of the spacecraft / instrument	Risk Posture and Design Margins	Radiation characterization, instrument calibration, and performance predictions	Anomaly Resolution
Board and component level; detailed modeling and analysis – 3D ray trace, Monte Carlo, etc.	Box / System Level	Mitigation approaches and design reliability	Lessons Learned

Iteration over project development cycle

(After LaBel 2004)

RHA Building Blocks

Define and Evaluate the Hazard



Free-Field Environment Definition

Shielding

Internal Environment Definition

Known Hazard

System → Sub-system → Parts

Reliability Requirements

Performance Requirements

Parametric Requirements

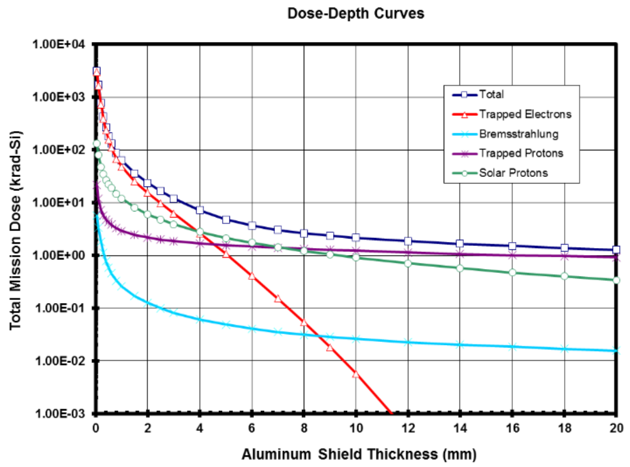
Known Risk

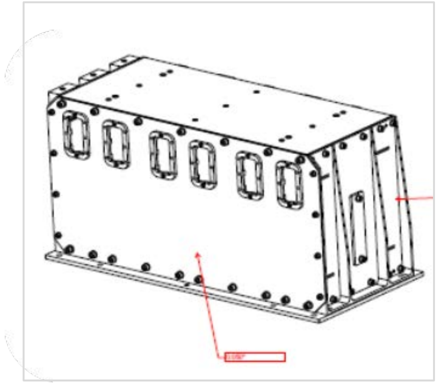
Derive Smart Requirements

RHA Step-by-Step

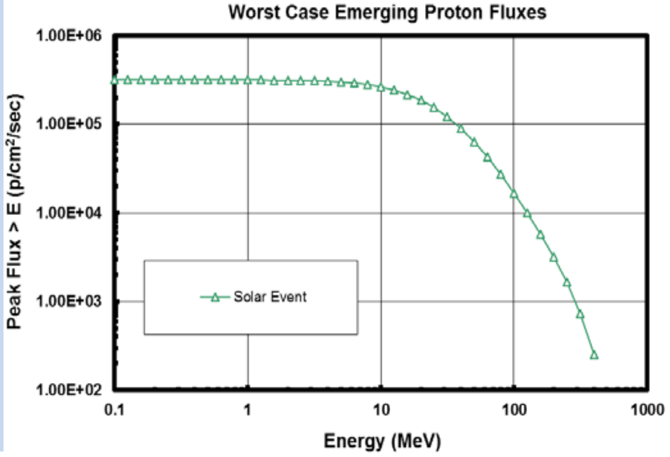
- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
  - Existing data/Testing
  - Performance characteristics
- **“Engineer” with Designers**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

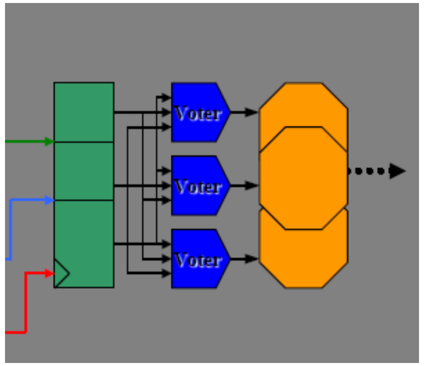
Degradation





Single Event

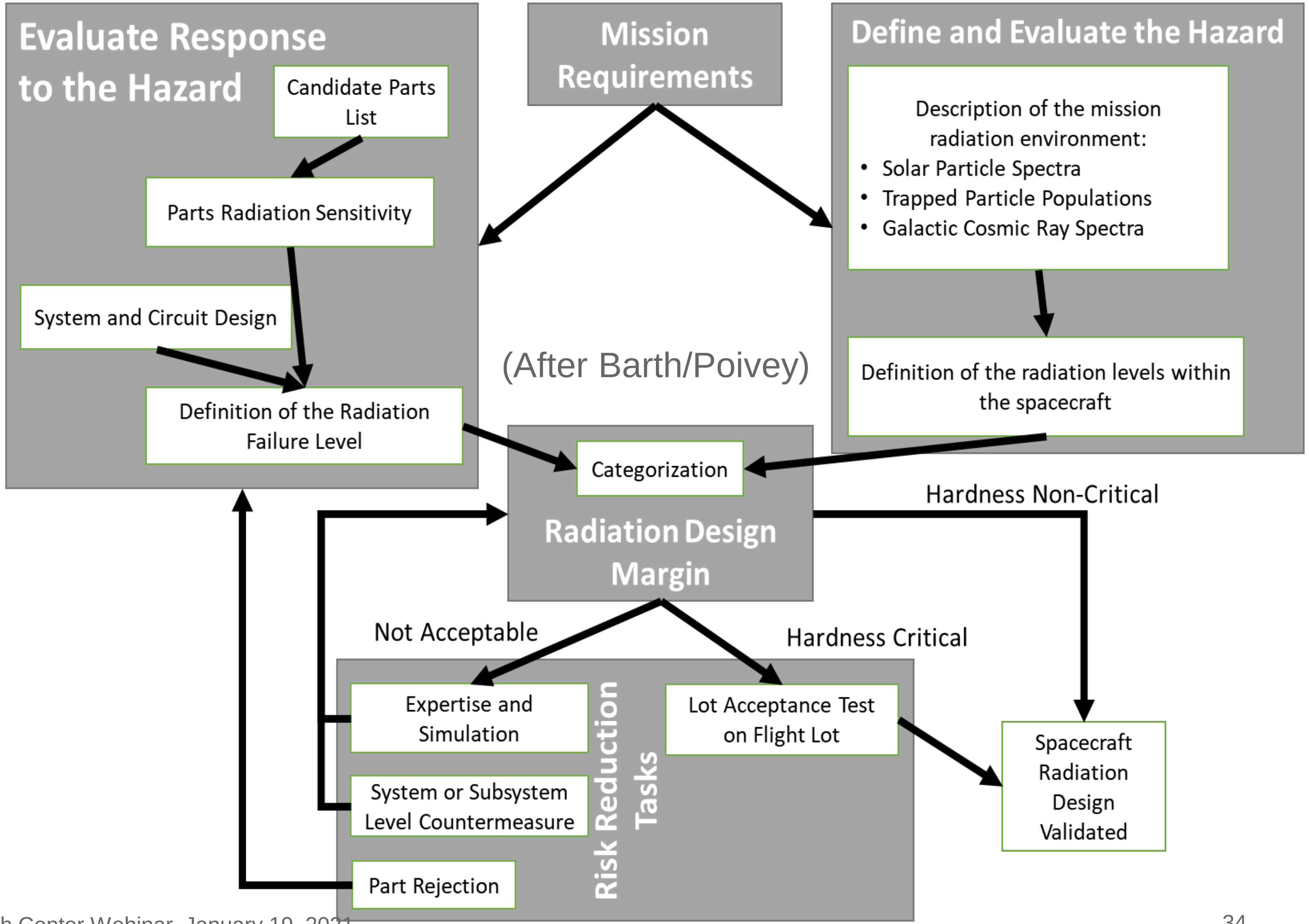




K.A. LaBel, A.H. Johnston, J.L. Barth, R.A. Reed, C.E. Barnes, “Emerging Radiation Hardness Assurance (RHA) issues: A NASA approach for space flight programs,” IEEE Trans. Nucl. Sci., pp. 2727-2736, Dec. 1998.

RHA Flow Doesn’t Change With Accepted Risk

- **Hardness Assurance is the practice of designing for radiation effects**
- **What it takes to overcome the radiation challenges**
- **Competing failure modes**



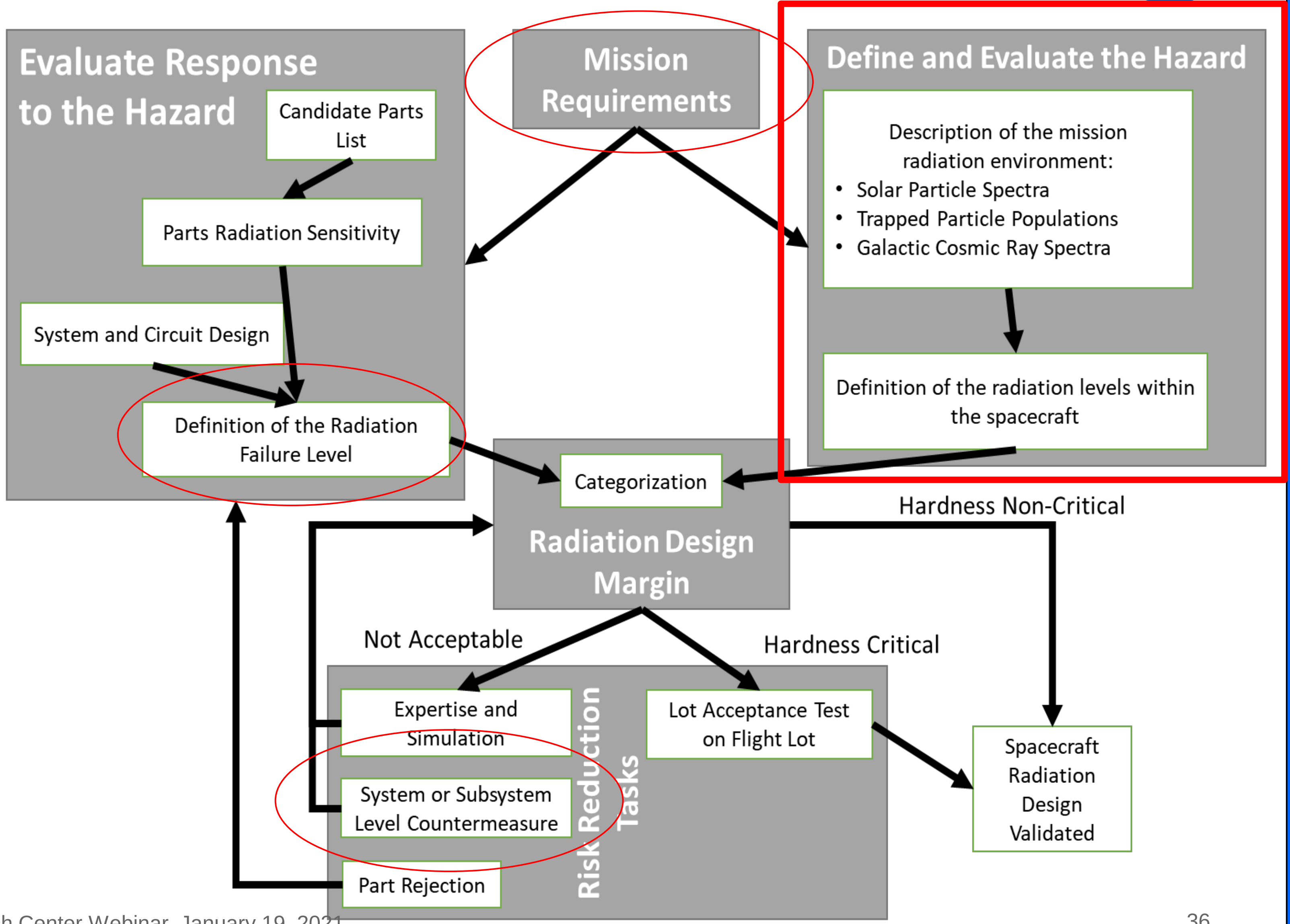
(After Barth/Poivey)

Focus For Risk Acceptance

- **Failure Awareness**
  - Know your hazard from the natural environment
  - Know your devices potential failure mechanisms or response (data)
- **Countermeasures and Mitigation**
  - Where are they necessary?
  - At what level (part, card, box, mission)
- **Smart Requirements – and Eventually Smart Trades**

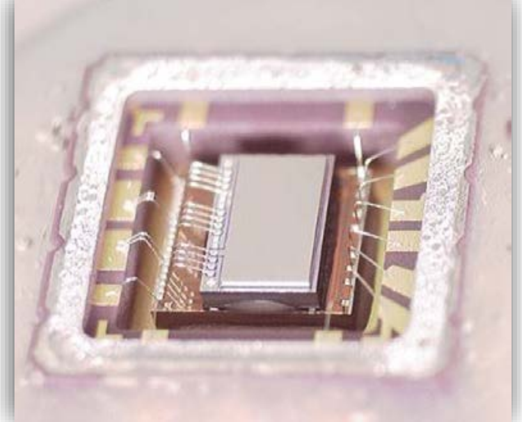
RHA Flow Doesn’t Change With Accepted Risk

- **Hardness Assurance is the practice of designing for radiation effects**
- **What it takes to overcome the radiation challenges**
- **Competing failure modes**
- **Focus for impact on risk acceptance:**
  - Failure Awareness
  - Countermeasures/Mitigation
  - Mission Requirements



Risks Abound, What is Critical?

- **Parts**
  - Parametric degradation and leakage currents allowable in application?
  - Downstream/peripheral circuits considered?
  - Reset/refresh capability?
  - Mitigation within too complex?
  - Predicted radiation response unknown– loss of part functionality critical?
- **Subsystem**
  - Functionally required to mission that the subsystem work?
  - Interfaces allow you to get to a known state if all goes wrong?
- **System**
  - Increased power dissipation a mission ender?
  - Availability outweighed by error circumvention?
  - Data retention through reboots? What if there is science data loss?
  - Communications interruptions overwhelm?
  - Navigation or Attitude determination unable to deal with faults?

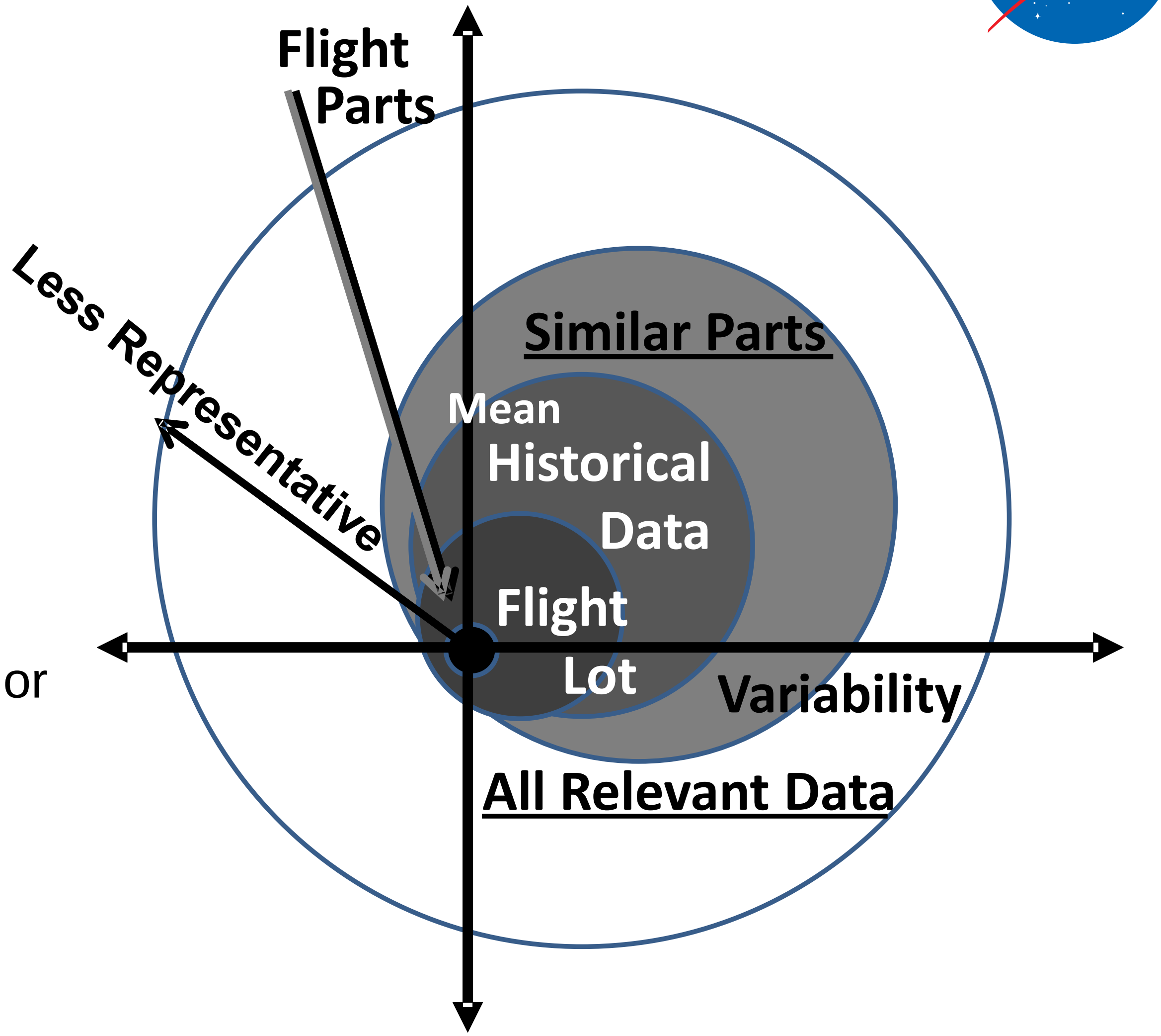


vs.

Risk Acceptance – Data Available?

- **Part Classifications Growing**
  - Mil/Aero vs. Industrial vs. Medical
  - Automotive vs. Commercial vs. Modified HiRel
- **Substitute COTS in this diagram**
  - Now you have another degree of separation
  - Failure modes not fully understood
  - Unlikely to have historical data
  - Similarity data no applicable due to fab, process, or design rules
  - Cost of testing usually too high

Without traceability you may be depending on non-representative data.



Ray Ladbury, NSREC2017 SC, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006865.pdf

Test Costs Grow With Complexity

Pulled from the NAS Study: Testing at the Speed of Light

The State of U.S. Electronic Parts Space Radiation Testing Infrastructure

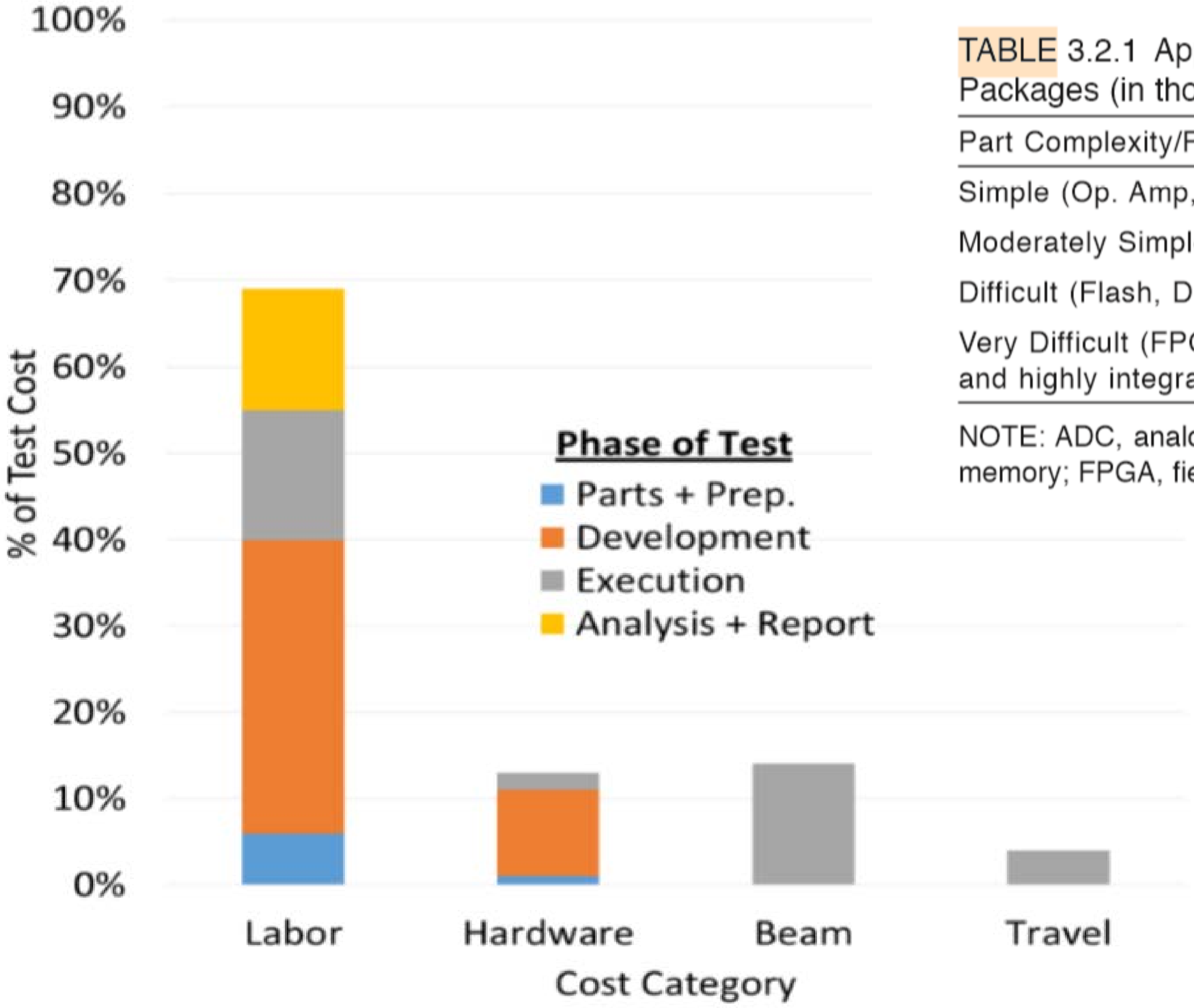


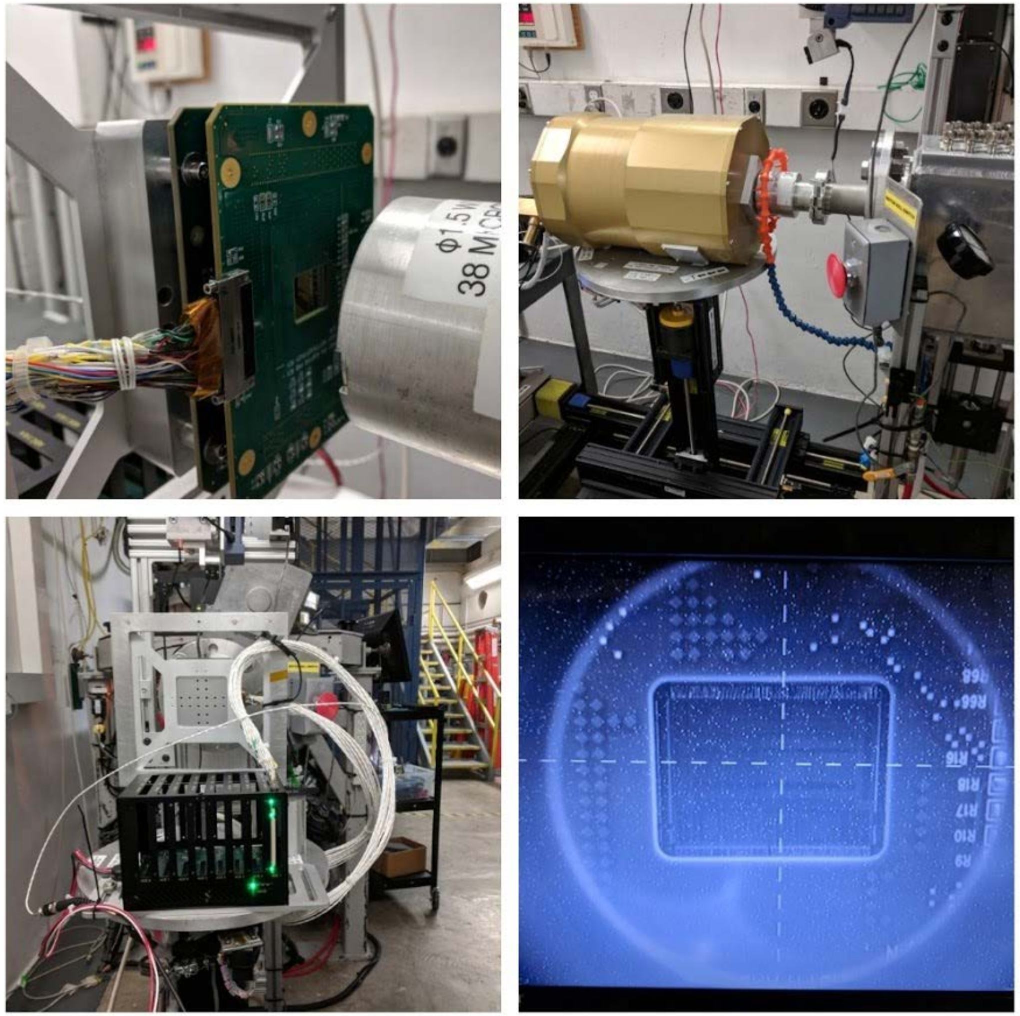
TABLE 3.2.1 Approximate Single-Event Effects Test Cost for Various Part Complexities and Packages (in thousands of dollars)

Part Complexity/Package Difficulty	Easy	Moderate	Difficult
Simple (Op. Amp, Comparator, etc.)	25–35	35–45	>50
Moderately Simple (ADC, DAC, SRAM, etc.)	40–75	50–85	>100
Difficult (Flash, DRAM, Simple Processor, etc.)	85–150	100–200	>250
Very Difficult (FPGA, Complex Processor, other highly complex and highly integrated components)	>500	>550	>600

NOTE: ADC, analog-to-digital converter; DAC, digital-to-analog converter; DRAM, dynamic random-access memory; FPGA, field-programmable gate array; SRAM, static random-access memory.

When Do You Test? When Do You Model?

- **Divine your risk threshold**
    - There’s a doc coming for that… radhome.gsfc.nasa.gov/nepp.nasa.gov
- **Unknown failure modes that would not be acceptable to the mission**
    - Known unknowns can be carried as a risk if you already know that the outcome is mitigated at the board or box level
    - New technologies should be identified early on
- **Fault propagation may be the problem you wish to mitigate**
    - This can include cumulative effects!
    - Fault injection may not be able to cover the state space
- **Destructive single event effects are an obvious target**
- **Can you tolerate a part replacement in your design cycle?**
    - Lead times, board re-spins, etc.

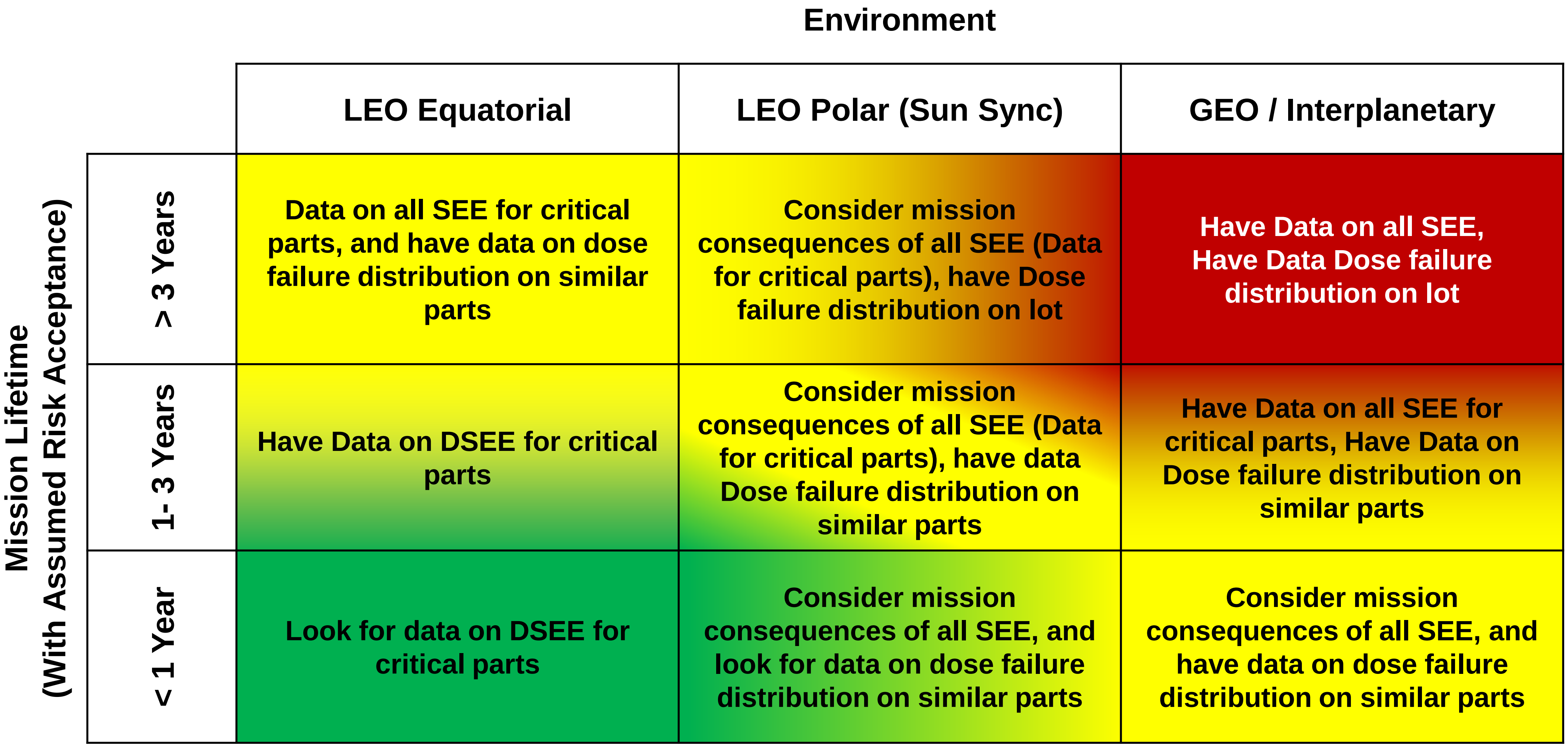


Radiation Hazard Contributors for Dose and SEE

Environment

Mission Lifetime	LEO Equatorial	LEO Polar (Sun Sync)	GEO / Interplanetary
> 3 Years	Moderate Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	High Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
1- 3 Years	Manageable Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
< 1 Year	Manageable Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	Moderate Dose / High GCR, High Solar Proton Variability

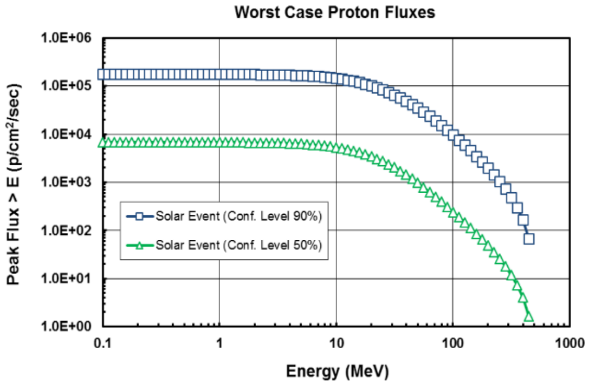
Notional Radiation Data Collection Guidelines

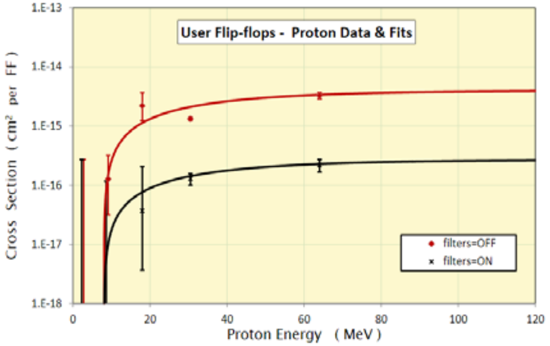


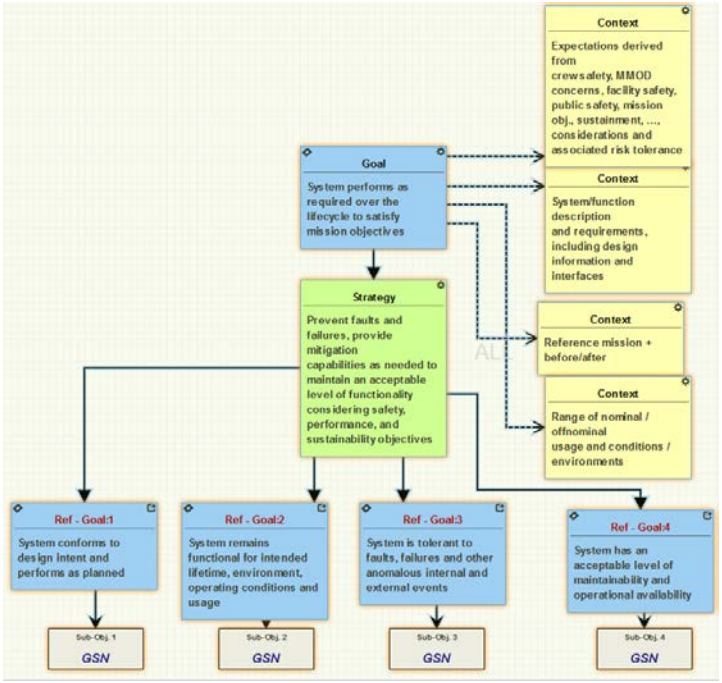
Environment

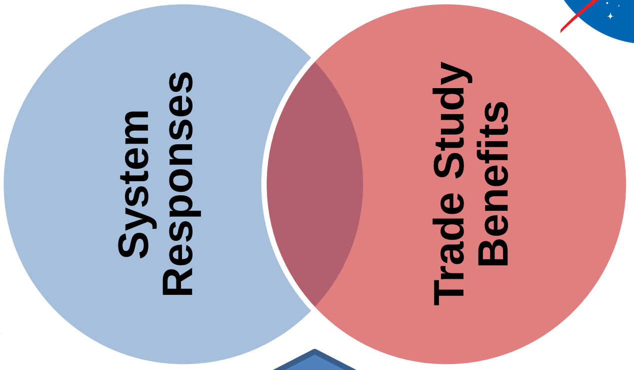
Mission Lifetime (With Assumed Risk Acceptance)	**LEO Equatorial**	**LEO Polar (Sun Sync)**	**GEO / Interplanetary**
> 3 Years	**Data on all SEE for critical parts, and have data on dose failure distribution on similar parts**	**Consider mission consequences of all SEE (Data for critical parts), have Dose failure distribution on lot**	**Have Data on all SEE, Have Data Dose failure distribution on lot**
1- 3 Years	**Have Data on DSEE for critical parts**	**Consider mission consequences of all SEE (Data for critical parts), have data Dose failure distribution on similar parts**	**Have Data on all SEE for critical parts, Have Data on Dose failure distribution on similar parts**
< 1 Year	**Look for data on DSEE for critical parts**	**Consider mission consequences of all SEE, and look for data on dose failure distribution on similar parts**	**Consider mission consequences of all SEE, and have data on dose failure distribution on similar parts**

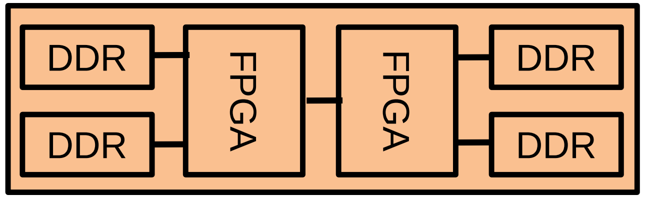
Model Based Mission Assurance (MBMA) as a Tool











Environment, Device, & Design

- ***Models and Test Data*** are brought together to get rates of upset / failure distributions
- ***Resources and Utilization*** are the scaling factors with criticality

Goal Structuring Notation (GSN)

- Concept of operations
- ***Requirements and Availability*** are fed down correctly to subsystem
- Evidence is presented
- Assumptions are tracked

Systems Modeling Language

- Description of System Connections and Dependencies
- Receives GSN readily
- ***Fault propagation*** can be identified

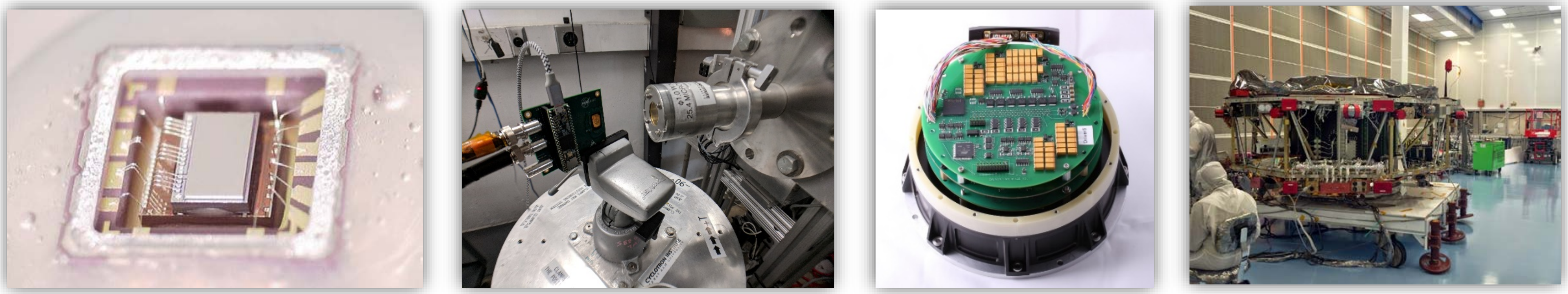
RHA @ GSFC

- **Assign a lead radiation engineer to each spaceflight project**
  - **Treat radiation like other engineering disciplines**
    - **Parts, thermal,...**
  - **Provides a single point of contact for all radiation issues**
    - **Environment, parts evaluation, testing, cost/budget…**
- **Each program follows a systematic approach to RHA**
  - **Develop a comprehensive RHA plan**
  - **RHA active early in program reduces cost in the long run**
    - **Issues discovered late in programs can be expensive and stressful**
      - **What is the cost of reworking a flight board if a device has RHA issues?**

PG exists for customer interface: 561-PG-8700.2.2C

Key Takeaways

- Systematic Approach is a MUST
- Early Integration with spacecraft/instrument teams
- Report to Systems Engineer or Assurance
  - Document all studies, reports, reviews
- Coordinate with Parts Engineer
- Don’t be afraid to ask if you don’t know
  - Don’t go forward without expertise
  - Don’t throw it over the fence completely
- *All work must be funded*
- Hopefully track successful performance in-flight



michael.j.campola@nasa.gov

THANK YOU