CUBESAT ARCHITECTURE FOR RELIABLE ON-ORBIT COTS PARTS USE

Space Micro Inc.

Cal Poly CubeSat Developers Workshop

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www.spacemicro.com

Outline

- **The Threat – Space Radiation Effects**
  - The Environment
  - Satellites do fail in orbit
- **The Response**
  - Rad Hard Parts vs. COTS
  - Hardening Techniques
- **The Solutions - Case Studies in Radiation Hardening**
  - The CubeSat Space Processor (CSP)
  - Alternative approaches

September 18, 1941

vs.

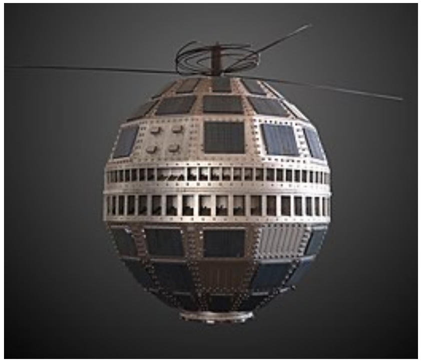
With the score tied 0-0 in the 4th inning the broadcast was lost for 15 minutes ...

…when the broadcast resumed, the Pirates had 4 runs.

Irate Brooklyn fans found "little satisfaction" with the explanation that sunspots were to blame

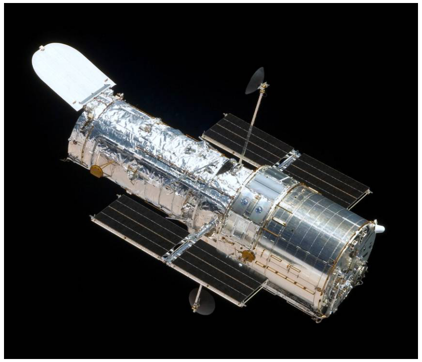
https://eos.org/features/the-geomagnetic-blitz-of-september-1941

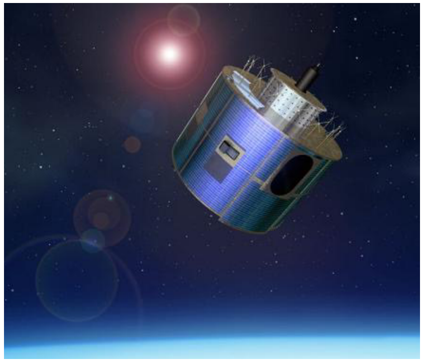
Radiation Induced Failures



Telstar I (1962) – First Satellite to fail due to radiation (Total Dose)

Hubble Space Telescope (1990) - Six status monitors fail in the South Atlantic Anomaly



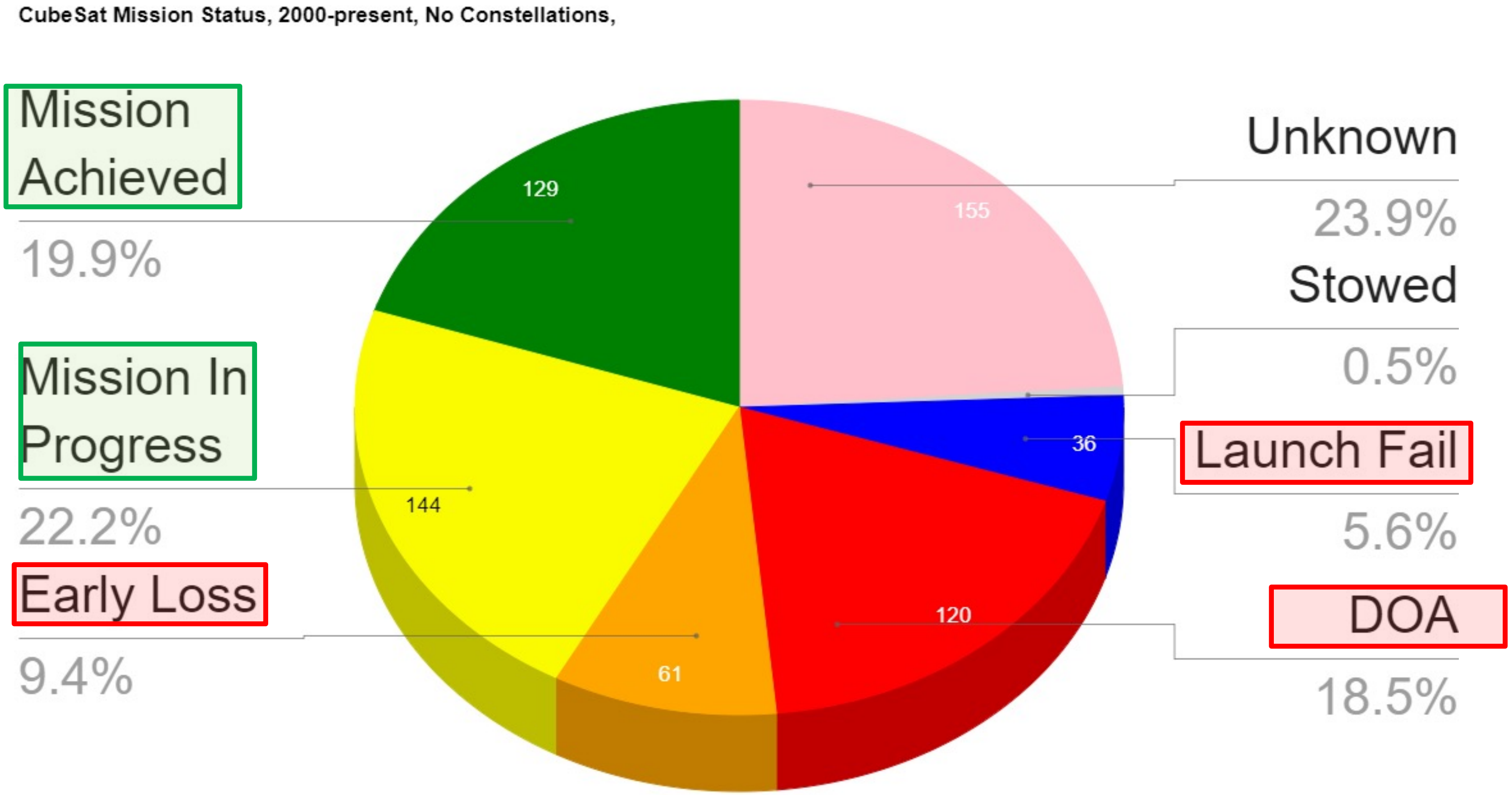


Meteosat (2006) – Satellite enters safe mode after single event upset

Radiation has been an issue for satellites since the beginning of the Space Age

CubeSat Failure Rates

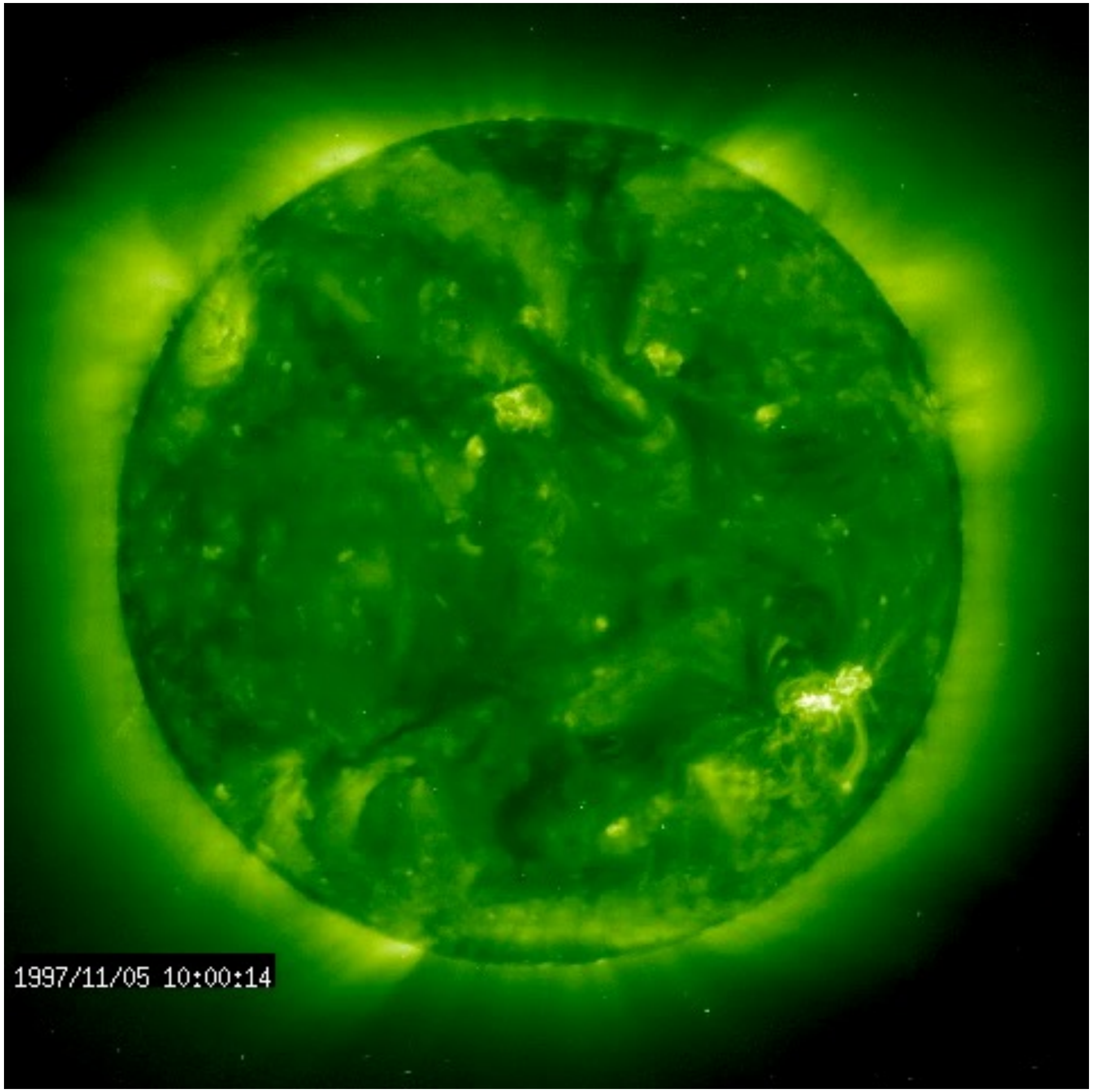
2019 Data from Michael Swartwout (St. Louis University)



CubeSats: historically have very high failure rates; Need cost effective radiation solution.

https://sites.google.com/a/slu.edu/swartwout/

SOHO Satellite

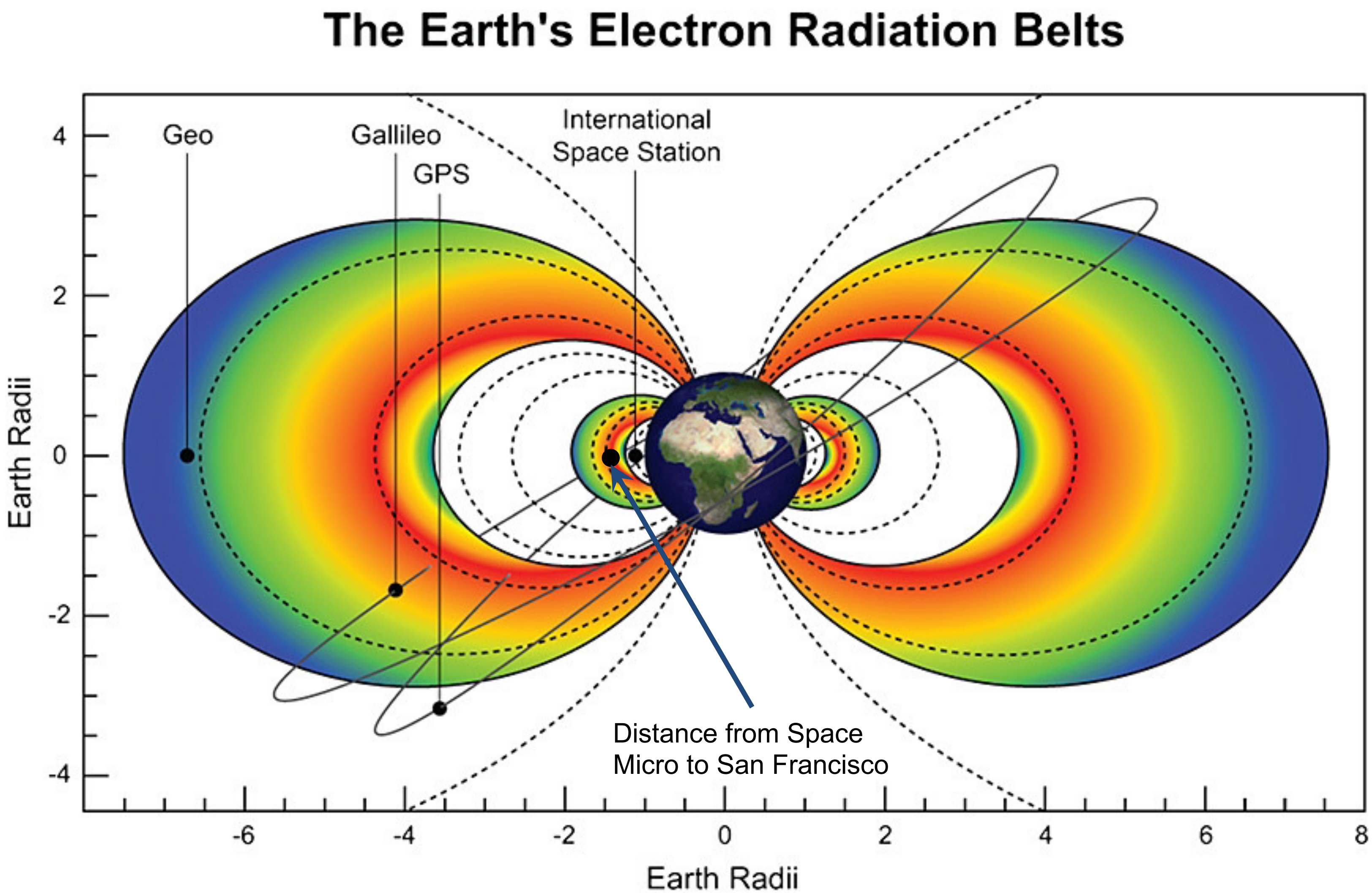


- EIT 195Å Imager
- Flare
  - "White" Flash
- Coronal Mass Ejection
  - "Scratches" on the image
  - Due to ejected ions (mostly protons)

Solar protons upset the imager following a solar flare

https://sohowww.nascom.nasa.gov/bestofsoho/Movies/flares.html

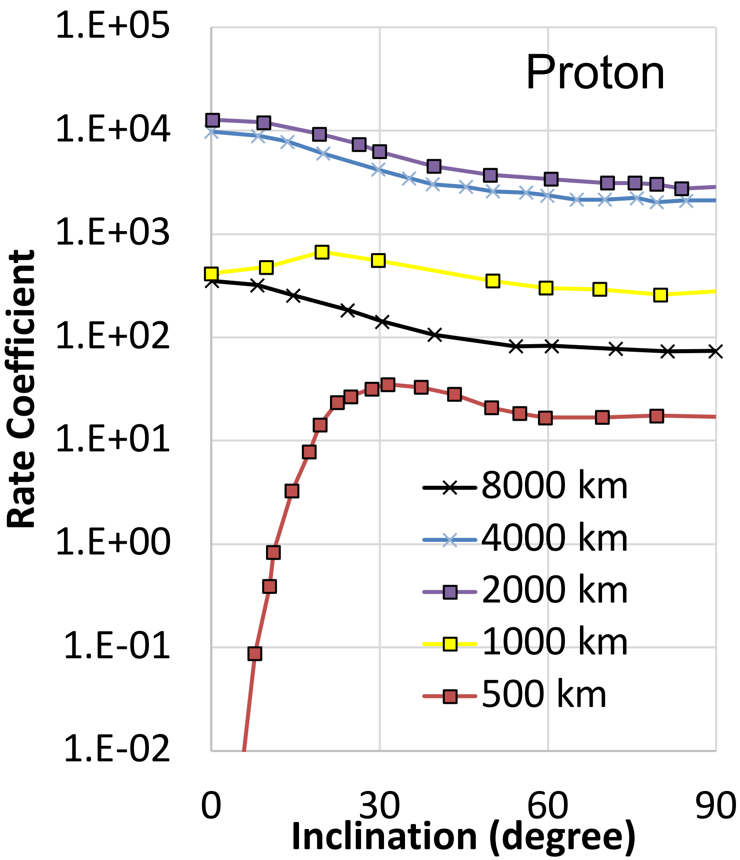
Orbit and Radiation

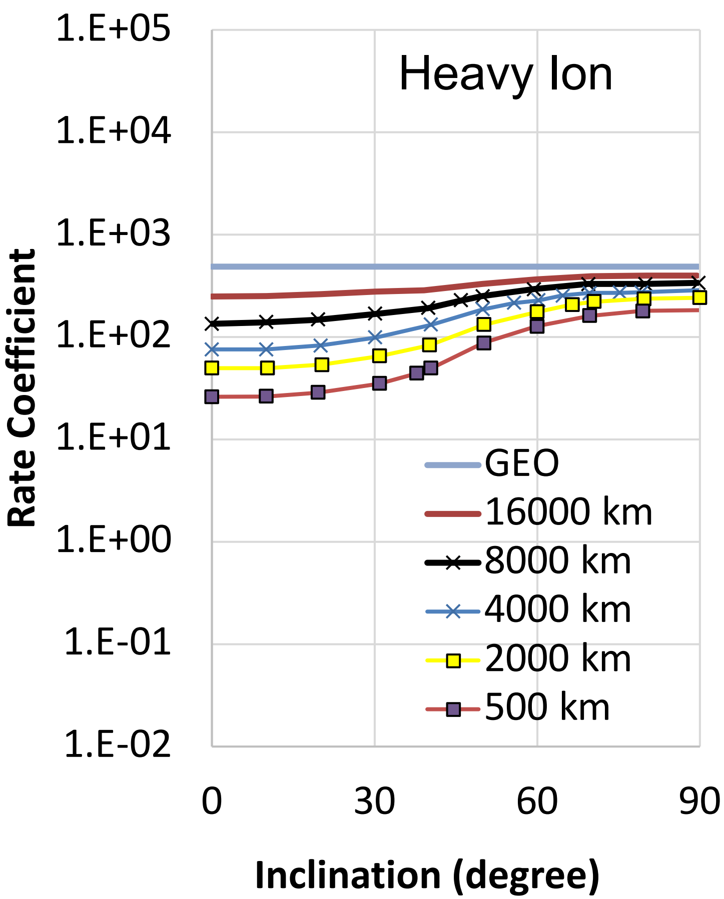


Radiation Belts are More Severe for Navigational Orbits

Space Weather, Volume: 11, Issue: 4, Pages: 169-186, First published: 22 January 2013, DOI: (10.1002/swe.20023)

Orbit Severity

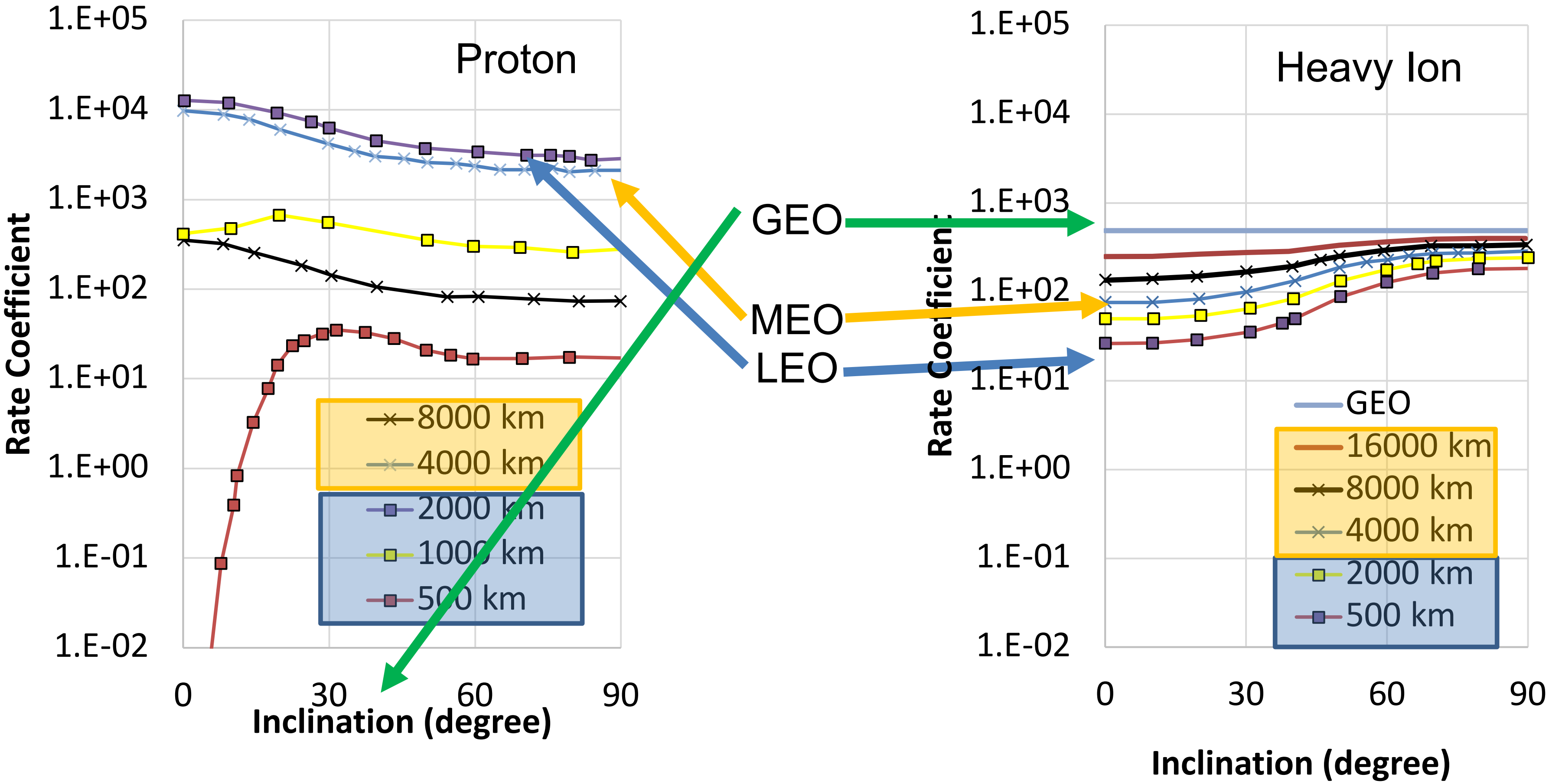




Radiation Type and Severity Changes with Orbit

Petersen 1998 IEEE Trans. Nucl. Science

How Bad is it?



LEO, MEO – "Mostly" Protons = Lightly Ionizing

GEO – Heavy Ions = Highly Ionizing

Petersen 1998 IEEE Trans. Nucl. Science

Part Selection

Part Class	Quality / Reliability	Radiation	Cost	Capability	Availability
QMLV – Space Grade	Screen + Test	Rad Hard	Expensive	Old Tech	Later
QMLQ – MIL Grade					
Enhanced products	Quality / Reliability	Radiation	Cost	Capability	Availability
Automotive					
Commercial	Low FIT	Good Luck!	Cheap	Modern	Now

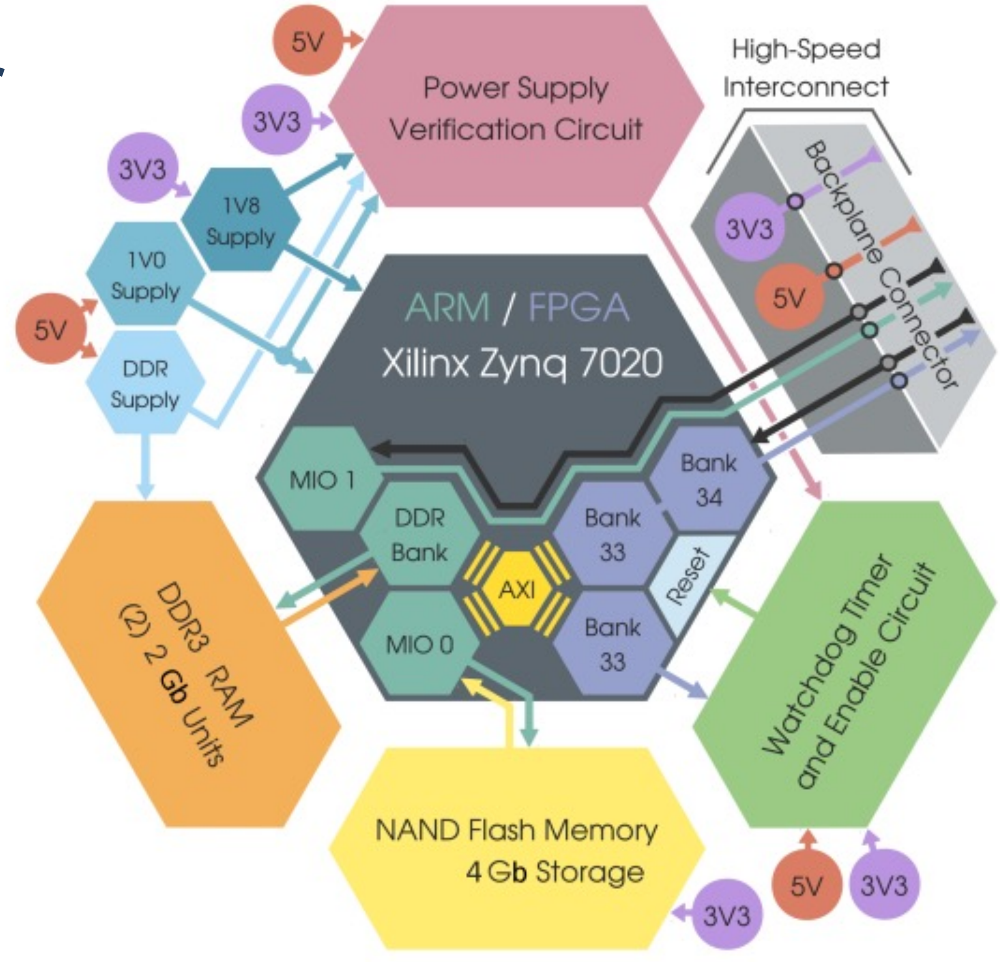
Architecture can Mitigate Risks of Lower Grade Parts

Baumann SEE Symposium 2016

The Cubesat Space Processor

Cubesat Space Processor (CSP)

- Single board computer
  - Xilinx's Zynq 7020 SoC
  - reconfigurable I/O
  - 32 Gbit NAND Flash
- Small form factor (1U)
- Radiation-tolerant



C.M. Wilson, Dissertation U. Florida, 2018

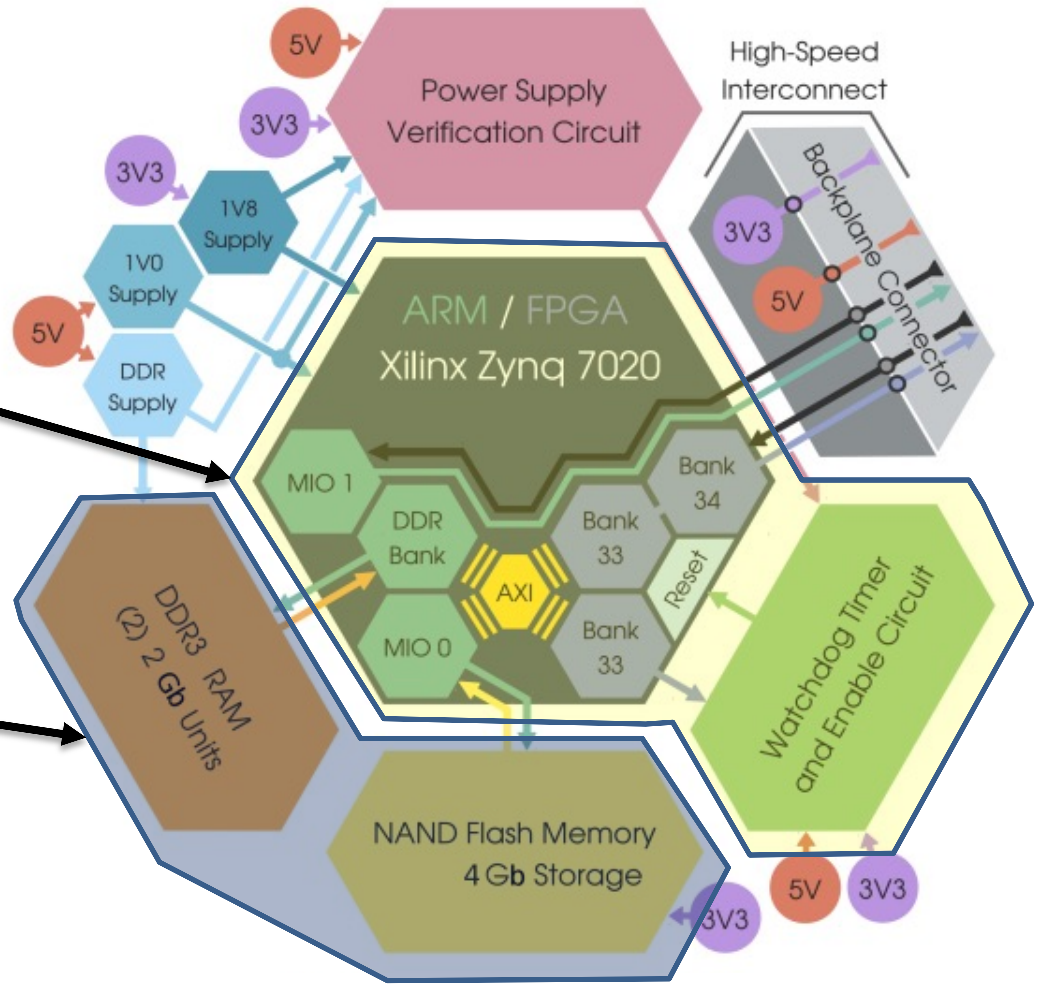
Multiple Systems, Multiple Modes of hardening

The Case Study

Mitigation

Unhardened
RH Component

Unhardened
TMR
ECC



Case Study Will Look at Consequences of Different Radiation Hardening Choices

Memory

- Bit Errors
  - Manufacturing "Weak" bits
  - Radiation
    - Total Dose
    - Single Events

Protons

Heavy Ions

- Device Level Failure
  - Functional Interrupt
  - Latchup

Heavy Ions

Smaller heavy ion threat in LEO/MEO missions makes device level failure modes less likely

Part Class	Qual / Rel	Radiation	Cost	Capability	Availability
"Space Grade"	Upscreen	Same	$10,000	2-10 year lag	Months
Unhardened	--	Same	$100	Same	Days

No Rad-Hard, Modern Memory

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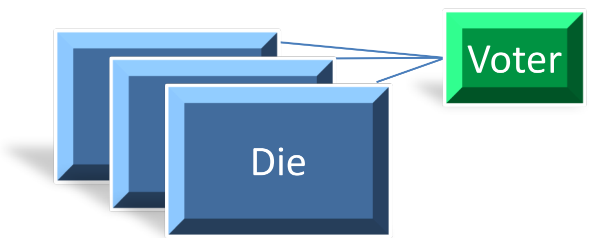
Memory – The Solutions

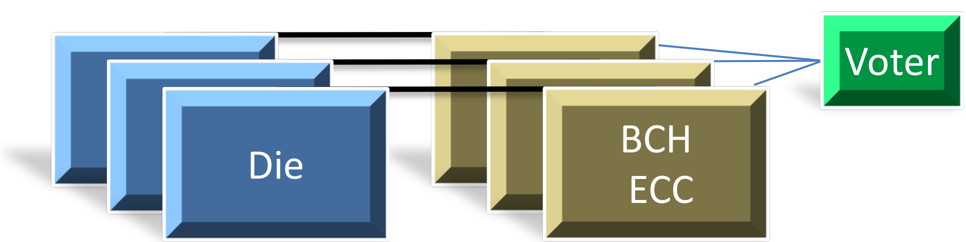
BCH Error Correction Code (ECC)

- 95% Memory Density
- 10^{-8} better upset rate
- Same Device level effects



Triple Mode Redundancy (TMR)

- 1/3 Memory Density
- $1/10^{-5}$ better upset rate
- Same Device level effects



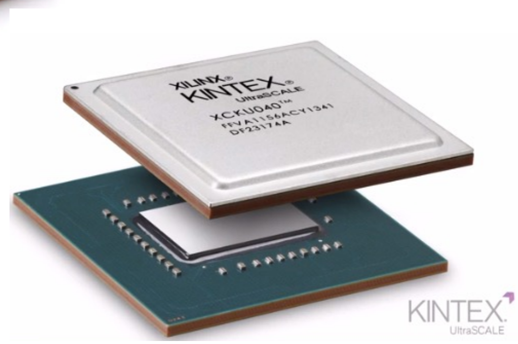
TMR + ECC

- 1/3 Memory Density
- 10^{-8} better upset rate
- 10^{-6} Device level effects

Hansen et al., 2017 Radiation Effects Data Workshop
Allen et al., 2010 IEEE Trans. Nucl. Sci.

Using Modern Memory Requires Hardening by Architecture

FPGA



Lee, SAND2017-5703C, “Commercial Field-Programmable Gate Arrays”

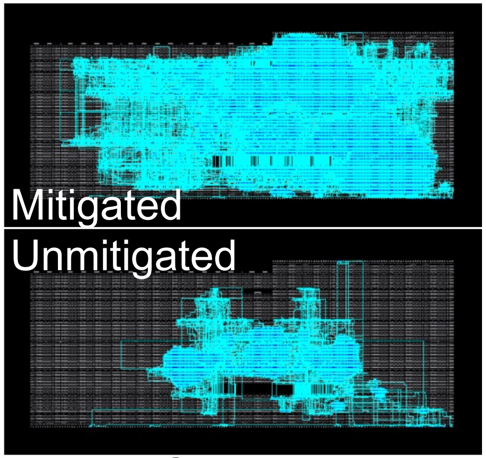
Device	Node	SEU Rate Improvement
Virtex-II	130 nm	1.0
Virtex-4	90 nm	1.5
Virtex-7	28 nm	28.3
UltraScale	20 nm	52.8
Virtex -5Q	65 nm	1000

Part Class	Qual / Rel	Radiation	Cost	Capability	Availability
Space Grade	QML-V Rugedized	1Mrad / No SEL	$20,000-$200,000	Old Technology	6-8 Months
Unhardened	--	30 krad / SEL LET= 15	$2000	Lower power Better tools	Weeks

Available FPGAs Span a Range of Rad Requirements

FPGAs – The Solutions

Internal TMR



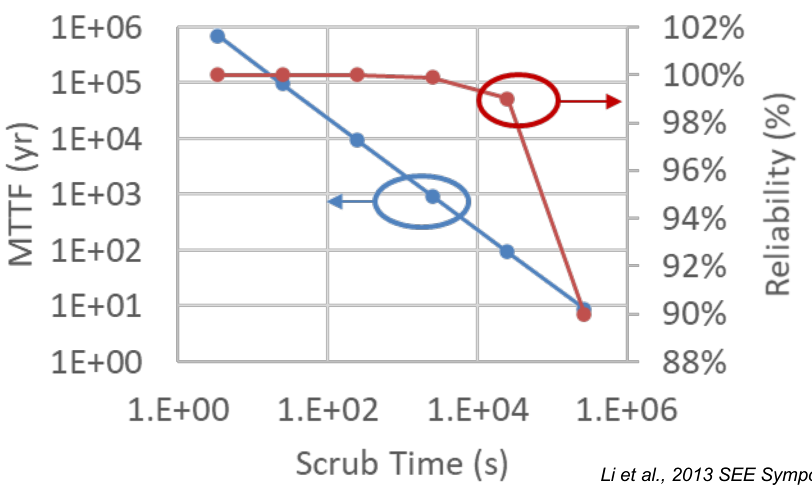
FPGA Layout

M. Wirthlin, et al., SEU Mitigation and Validation of the LEON3 Soft Processor Using Triple Modular Redundancy for Space Processing

Lee, SAND2017-5703C, "Commercial Field-Programmable Gate Arrays"

- 3x Resource Penalty
- 100x better upset rate
- No Device Level Mitigation

Scrubbing



Li et al., 2013 SEE Symposium

- Tuneable Hardness
- Trade Upset Rate for Resource and Dead Time Penalty
- No Device Level Mitigation

Internal Architecture Provides Tunable Hardening but Doesn't Address Device Level Effects

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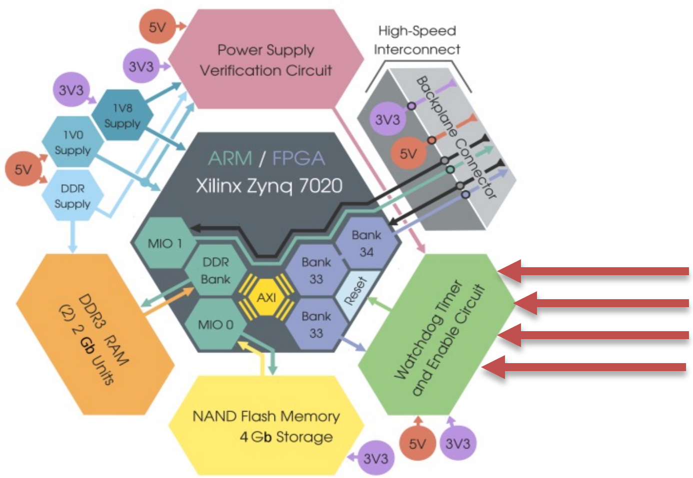
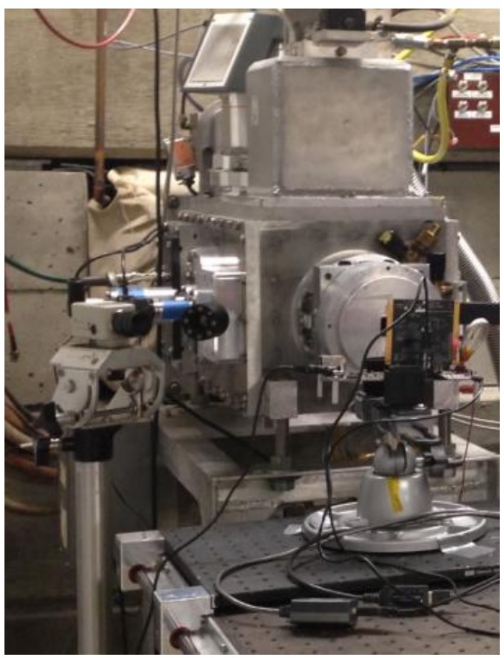
Watchdog Timer





- External to FPGA
  - Monitors FPGA "heartbeat"
  - Resets the processor to an operational state following a "hang"
- Built with Rad-Hard Parts
  - SEL threshold LET=86 MeV cm2/mg
  - Cheaper than Rad-Hard FPGA

FPGA Hardness is outsourced to External Circuitry

Mitigated with Watchdog for ARM Cores (Patent Number 7,237,148 plus ReExamination Certificate number RE42,314 C1)

Conclusion

- The Cubesat Space Processor provides a useful case study in how to apply architectural hardening to satellite electronics
- Satellite radiation requirements are highly dependent on the mission profile
  - LEO – Low dose, proton rich, short duration
  - MEO – High dose, proton rich, long duration
  - GEO – Mid dose, heavy ion rich, long duration
- There are a variety of different approaches to achieve circuit hardness
  - ECC
  - TMR
  - Scrubbing
  - Watchdog Timer
- The best approach trades reliability, cost and function.