Moving Toward a More Capable Small Satellite Bus for Interplanetary Missions

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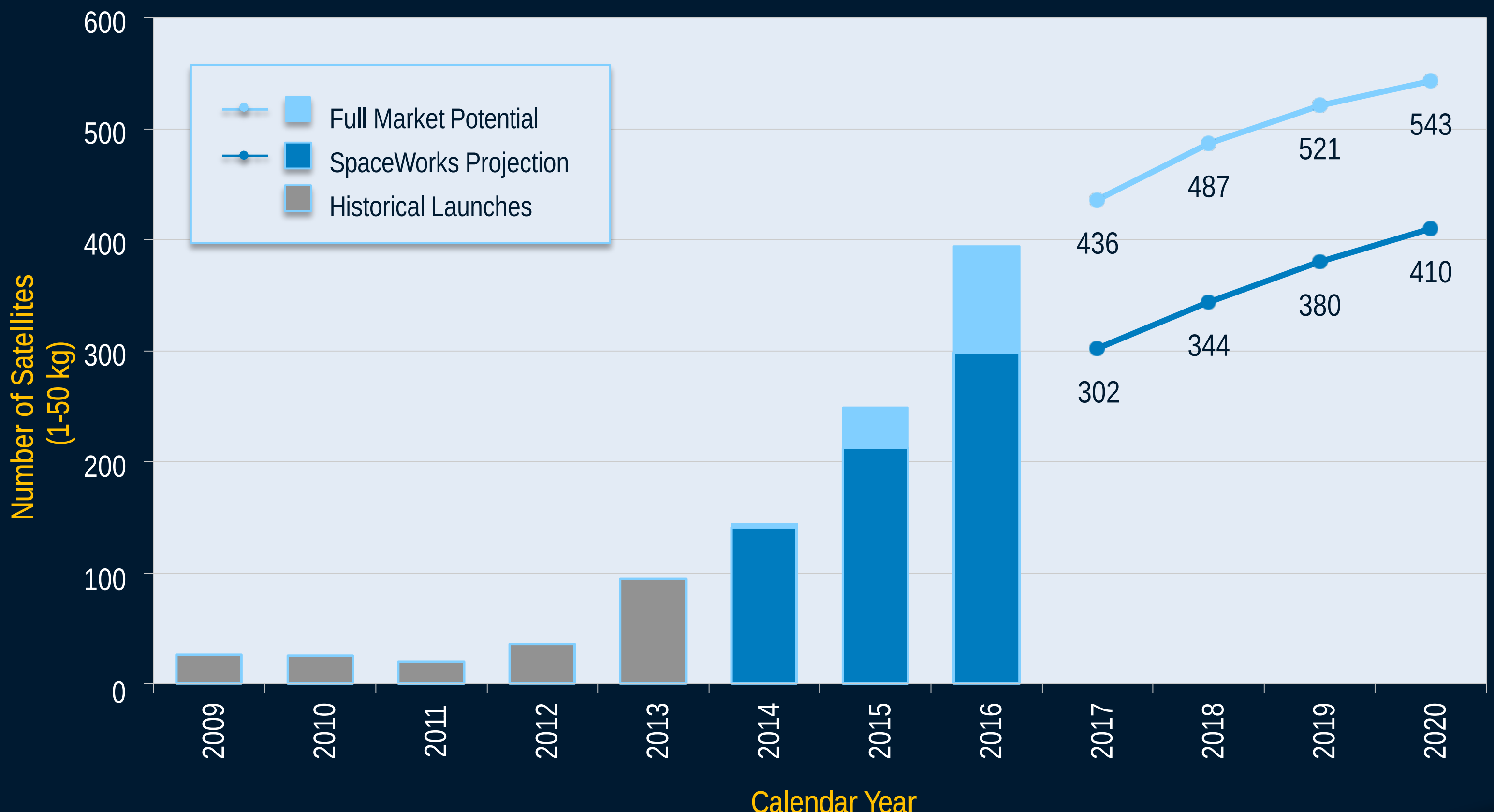
Projections based on announced and future plans of developers and programs indicate between 2,000 and 2,750 nano/microsatellites will require a launch from 2014 through 2020



The Full Market Potential dataset is a combination of publically announced launch intentions, market research, and qualitative/quantitative assessments to account for future activities and programs. The SpaceWorks Projection dataset reflects SpaceWorks' expert value judgment on the likely market outcome.

Small Satellites To Scale

Mars Curiosity Rover in Aeroshell

Image: NASA

4.5 m, 3900 kg (9000 lbs)

3U CubeSat

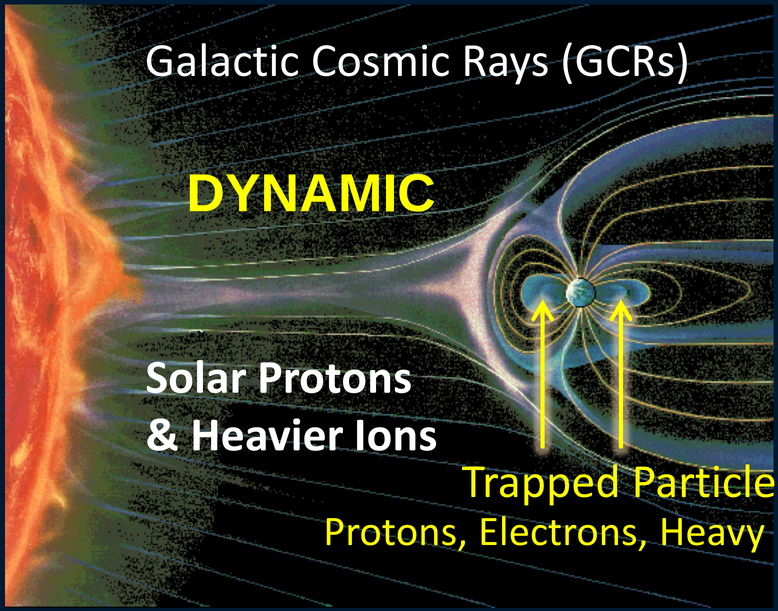
Image: Texas Spacecraft Lab

30 cm,
4.5 kg
(10 lbs)

Can We Leverage LEO Small Satellites for Interplanetary Missions?

- Possibly, but there are important differences
- Most LEO Small Satellites would not survive an interplanetary mission for many reasons
- Selective technology development and demonstration is necessary to create a small satellite *intended for* interplanetary missions

Space Radiation Environment



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

Image: K. Label, NASA

Flight Opportunities Are Relatively Scarce: Histogram of Interplanetary Missions vs. Time

- Average 2 interplanetary missions per year
- Small satellites will likely travel as ride shares and value added targets of opportunity
- Significance and visibility of interplanetary missions means that quality control and fault tolerance of such missions will be characteristically different than LEO small satellite missions

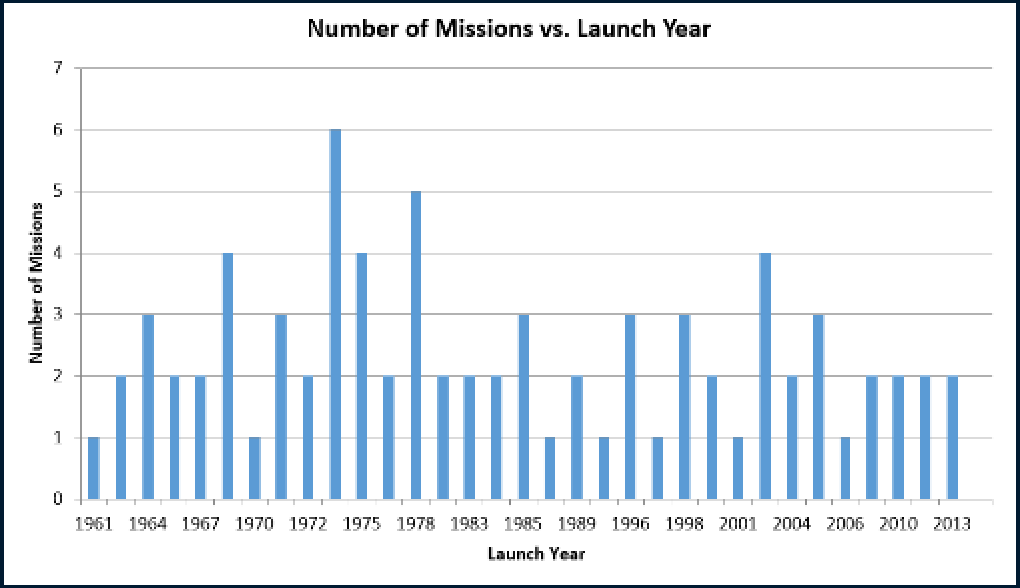


Image: R. Selvaratnam, GIT

Historical Survey Of Mission Travel Times and Lifetimes Based on Destination

Location	Number	Transit Time (yrs)	Total Life (yrs)
LEO – 450 km	1000s	0	1 (orbit)
LEO – 650 km	100s	0	1-25 (orbit)
GEO – 42164 km	100s (419 active)	0	10-20
Mercury	2	3.5	6.1
Venus	23	0.4	1.7
Mars	28	0.8	3.8
Jupiter	6	2.4	27.2
Saturn	4	5.1	29.5
Uranus	1	8.4	38.6
Neptune	1	12.0	38.6
Pluto	1	9.5	10.2

MARIE Radiation Instrument Data Aboard Mars Odyssey (2002-2003)

- Measured average dose rate of 25 mrad/day (9 rad/yr) at Mars
- Although dose rate is low, GCR energetic particle effects are not dependent on total dose
- Solar events measured have dose rates 100 times the normal average
- Ironically the MARIE instrument failed during the solar event of October 2003

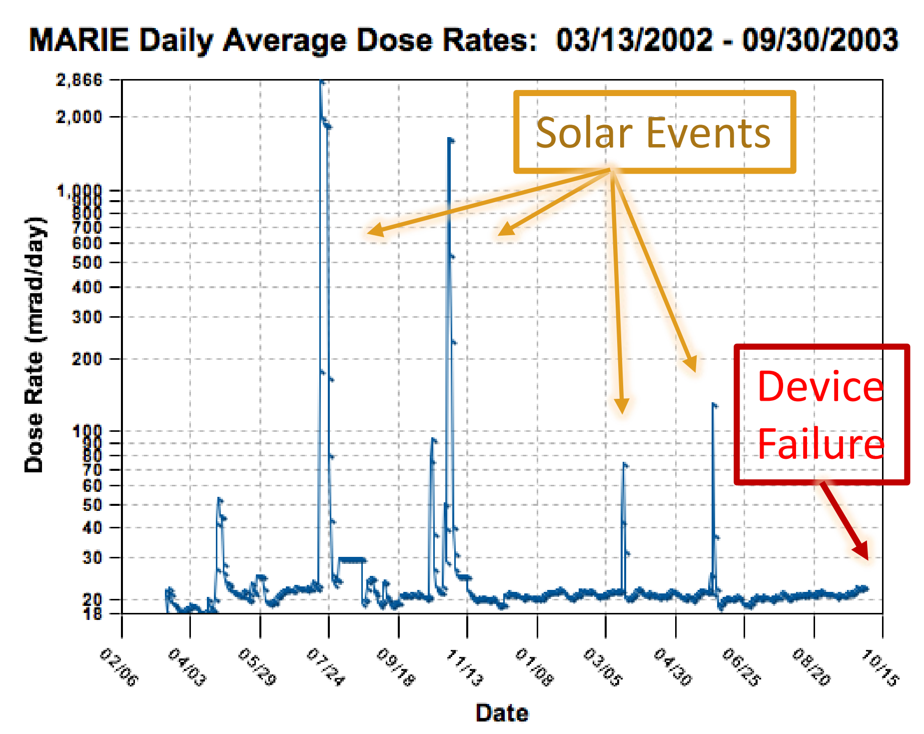


Image: NASA/wiki

MARIE measured ionizing dose rates in Mars orbit

Radiation Hardening or Radiation Tolerance?

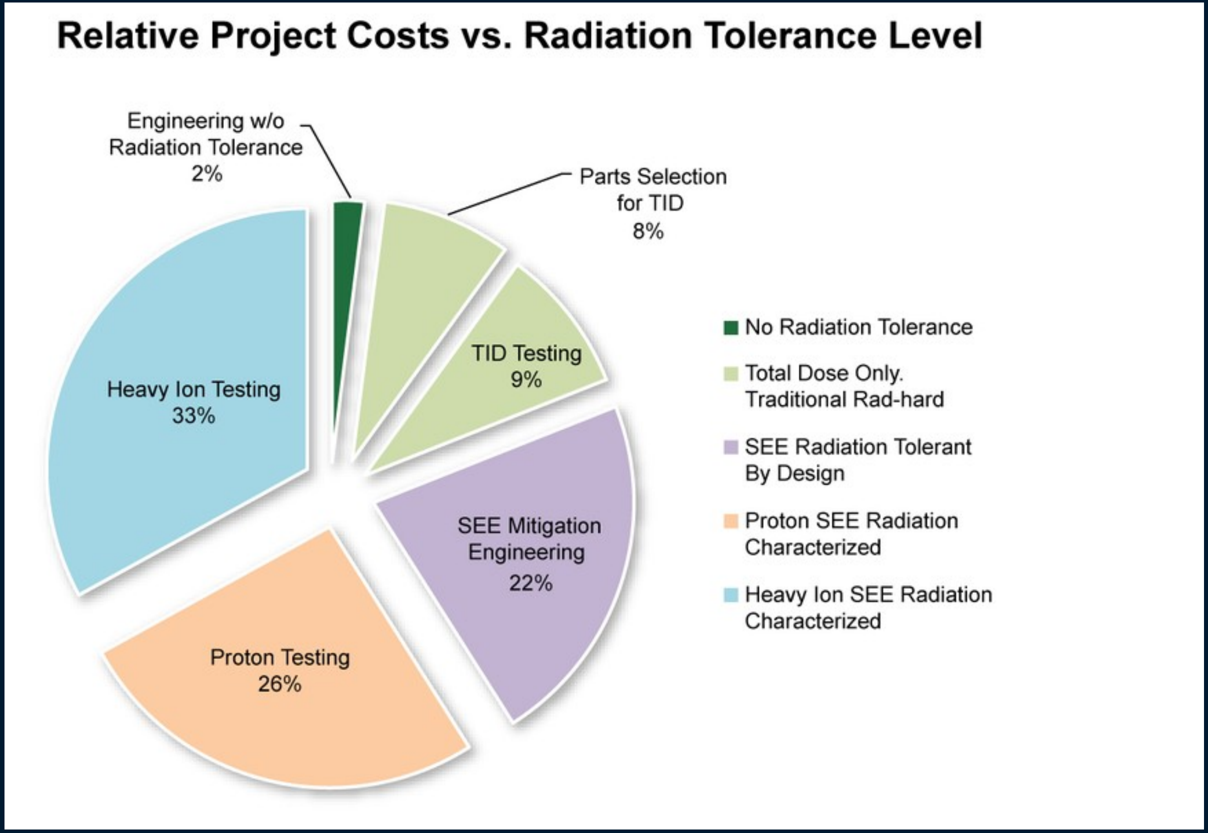
- Radiation Hardened By Process (RHBP)
- Radiation Hardening By Design (RHBD)

More NRE
Lower Quantities
Probably not feasible for lower cost missions

- Radiation Hardening By Stochastics/ Serendipity (RHBS)
- Radiation Tolerant By Design

Potentially Less NRE
Uses Commercial Parts
Possibly feasible for lower cost missions

Relative Cost of Parts Qualification vs. Radiation Tolerance Level

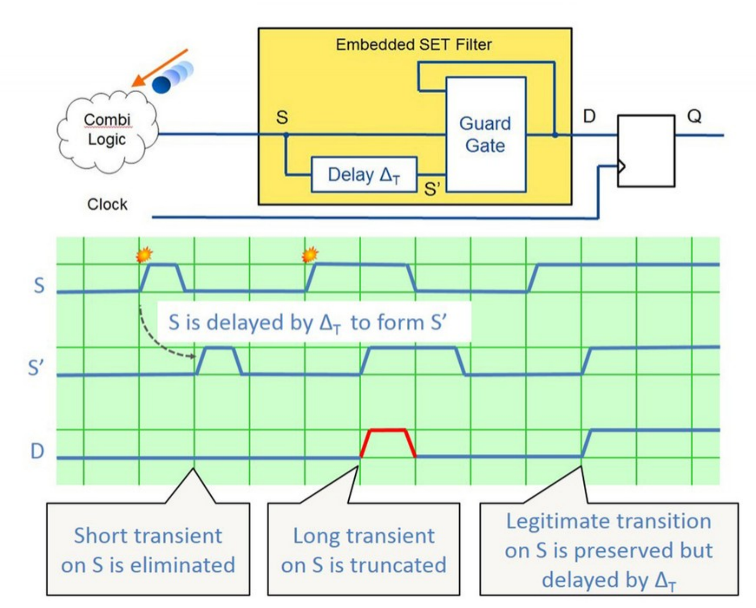


What level of risk tolerance (vs. cost) is acceptable
for an interplanetary small satellite mission?

For *your* interplanetary small satellite mission?

Fault Tolerance and Redundancy Strategies for Interplanetary Small Satellite Missions

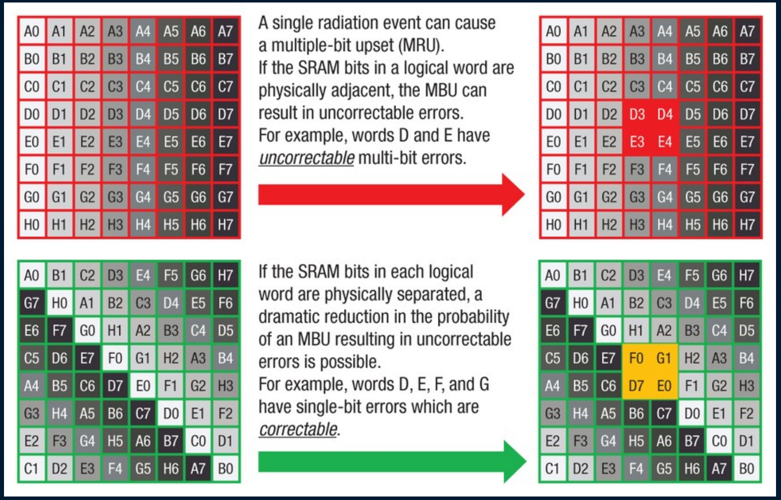
- Watchdog timers
- Current monitors
- Selective parts upgrades
- Selective parts redundancy
- Triple module redundancy
- Memory integrity checks
- Satellite redundnacy
- A matter of cost, size, power



Circuit latchup protection reduces risk of hardware failure

Software Redundancy for Long Duration Missions

- Multiple code copies
- Memory scrubbing
- Process replication and process mirroring
- Multi-core processing if hardware supports
- What is possible depends on hardware processing and power capabilities



Memory interleaving reduces impact of SEU memory effects

Mission Operations
Fault Tolerance By Design

- Design spacecraft mission concept and software to operate in presence of hardware and software resets
- Mission should not require long periods of uninterrupted operation to succeed
- Incomplete tasks may be autonomously resumed after reset
- For example, program counter, stack data are in non-volatile memory preserved through reset

Image: JPL

JPL Mission Control Center employs fault tolerant satellite operations

The Effects of Temperature on Spacecraft Electronics

- Electronics vary considerably with the temperature range they can operate in.
  - Standard Military Grade is -55C to +125C
  - Standard Commercial is 0 to 70C
- Extremes for space can go below and above even Military Grade for interplanetary
- Thermal cycling will occur due to shadowing, vehicle rotation, and orbit eclipse
- Operating an IC out of its range can sometimes work, but not always

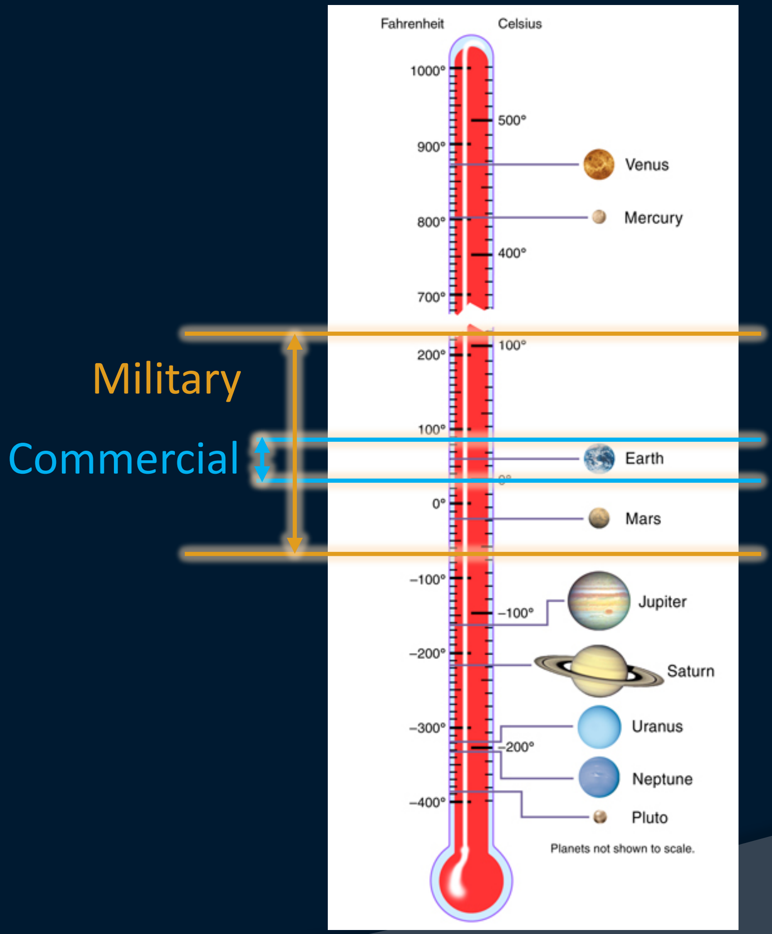
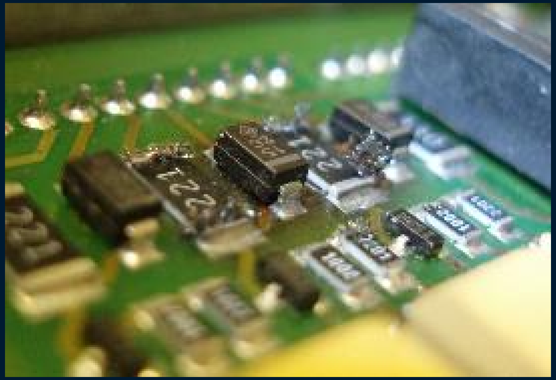


Image: NASA

Slide Credit: K. Label, NASA

Thermal Failure Mechanisms for Low Cost Electronics

- Commercial devices may have design processes (e.g. metal whiskers) and workmanship limits (e.g. low quality solder joints) that lead to temperature related sensitivities and failures
- If possible, test devices in the same environmental conditions as flown



Metal whiskering

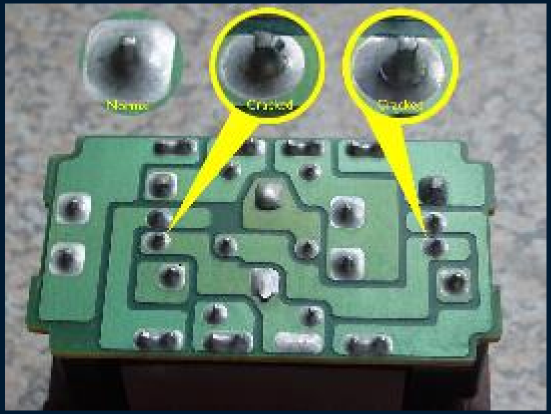


Image: tegger.com

Stress Induced Solder Failures

Potential Solutions for Thermal Effects on Small Satellites

- On a ride share, the carrier vehicle may provide a thermally controlled environment during the transfer journey
- On/off power cycling can give some thermal control, provided it can be accommodated operationally
- Smart placement of components may provide conductive heat paths and thermal isolation as needed
- For cold extremes, a heated box may thermally regulate sensitive devices
  - Requires power to operate
- For hot extremes, a refrigerated section (e.g. dewar) may provide a finite time of acceptable temperatures
- Deployables (e.g. solar panels and antennas) may double as radiative surfaces
- Thermally stable locations may be created using heat storage reservoirs (e.g. phase change materials)
- Technology development and demonstration is needed for most of these concepts

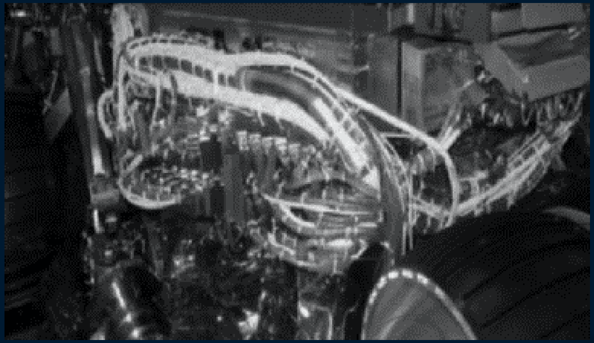


Image: NASA

Mars Exploration Rover heated electronics box

Mission Autonomy: Navigation, Control, On-Board Processing, Communications

- Most interplanetary small satellites will travel as rideshares
- Relative navigation, control, and communications strategies should be pursued with respect to the mother ship/formation
- Remote location motivates on-board processing to reduce data transmission and increase vehicle autonomy
- Small satellite deep space communication is needed area of further technology development

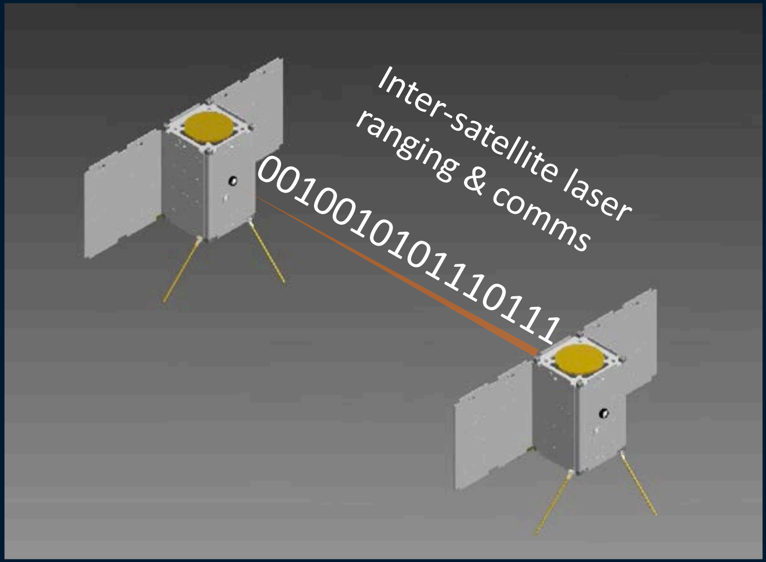
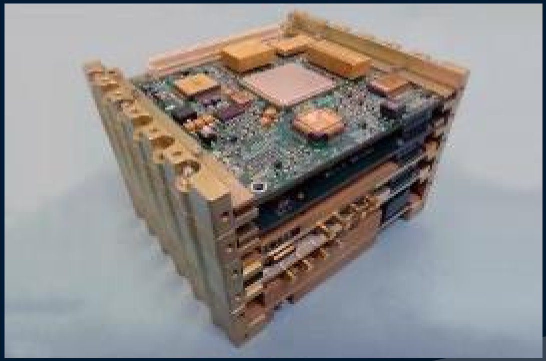


Image: B. Gunter, GIT



IRIS CubeSat Deep Space Network transponder (26W)

Image: C. Duncan, JPL

Notional Electronics Usage Matrix

Criticality	Environment/Lifetime: Low	Medium	High
Low	COTS upscreening/ testing optional; do no harm (to others)	COTS upscreening/ testing recommended; fault-tolerance suggested; do no harm (to others)	Rad hard suggested. COTS upscreening/ testing recommended; fault tolerance recommended
Medium	COTS upscreening/ testing recommended; fault-tolerance suggested	COTS upscreening/ testing recommended; fault-tolerance recommended	Level 1 or 2, rad hard suggested. Full upscreening for COTS. Fault tolerant designs for COTS.
High	Level 1 or 2 suggested. COTS upscreening/ testing recommended. Fault tolerant designs for COTS.	Level 1 or 2, rad hard suggested. Full upscreening for COTS. Fault tolerant designs for COTS.	Level 1 or 2, rad hard recommended. Full upscreening for COTS. Fault tolerant designs for COTS.

Standard LEO CubeSats Here

Most Interplanetary SmallSats Will Be Here

Traditional High Profile Missions

Slide Credit: K. Label, NASA

Considerations using Commercial Parts

- Full documentation (e.g., radiation) is not usually available for low cost commercial devices
- Commercial production processes can change without notice to customers
- Manufacturers source their parts from several facilities – behavior can be different for each
- Low cost methods means variable performance may exist between lots, even within lots
- Product is sold "as is" – caveat emptor

Space Qualified Hardware?

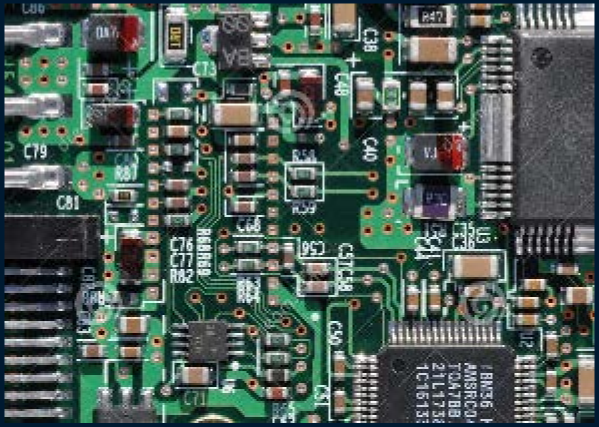


Image: dreamstream.com

Slide Credit: P. Dugan, NASA

Techniques to Improve Chances of Success with Commercial Parts

- Design with redundancy (component level, system level, and satellite level)
- Use higher rated parts where single point failures exist
- Use manufacturers' high reliability, automotive or telecommunication grade components
- Use manufacturers that are ISO certified for quality management
- Test under the same conditions as you fly
- Use LEO pre-screening demonstration flights of new components to raise TRL and mitigate risk

Slide Credit: P. Dugan, NASA

An Acceptable Interplanetary Bus Design Will Combine Solution Modalities

- For example, a safe box may provide radiation shielding and thermal control
- Radiation tolerance will require hardware and software mitigation strategies
- An integrated design is needed to address all spaceflight objectives to an acceptable level of risk for a small satellite mission

TID radiation reduction achieved by increased wall thickness

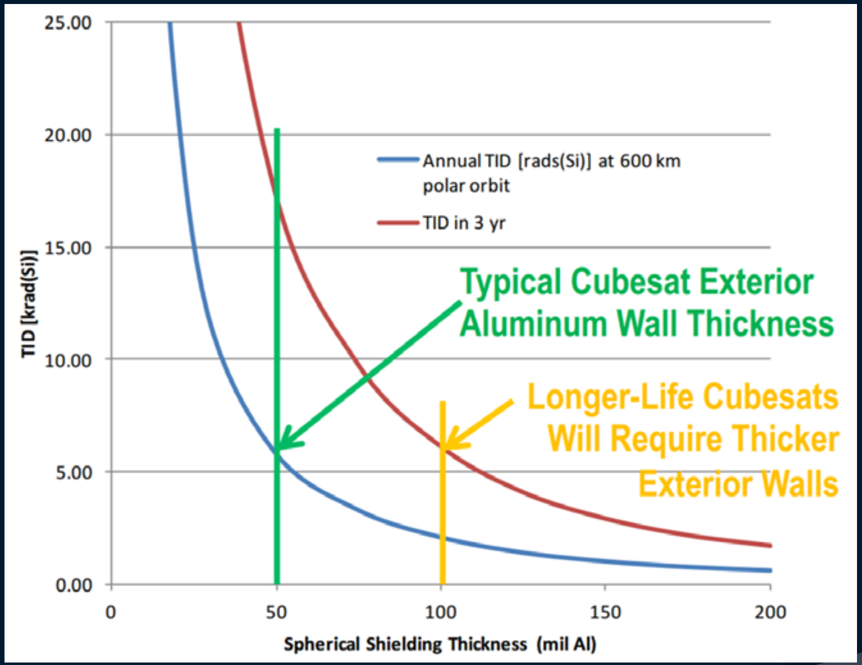


Image: Ball Aersospace

Takeaway Points From Today's Talk

- Interplanetary small satellites can potentially add value and enable space science missions at very affordable budgets
- Current small satellite technology is targeted for LEO applications and will likely not survive in an interplanetary environment
- A focused technology development and design activity could produce a small satellite bus suitable for interplanetary missions with acceptable reliability and risk
- Higher reliability small satellites could also be used for HEO and GEO Earth orbits and high value missions
- Prediction: Small satellites will be used within 5 years to enhance a planetary exploration mission

Acknowledgments and References

- *Extreme Environment Electronics,* 2012, eds. Cressler and Mantooth
- *2014 NEPP EEE Parts for Small Missions Workshop,* especially presentations by Label and Dugan
- *Crosslink* magazine published by the Aerospace Corporation
- Spacecraft histogram images by Roshan Selvaratnam at Georgia Tech

Image: wallpapers-xs.blogspot.com

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Value Added Science of Small Satellites for Interplanetary Missions

- Low altitude surveyors, impacters, landers
- Atmosphere, plume sniffers
- Multipoint observations
- Distributed instruments
- Field and particle measurements
- Lightning sensing
- 3D imaging
- Extrasolar planets and dim objects
- Full sky coverage astronomy
- Deep space science: helio and astrophysics
- Communication relay, network

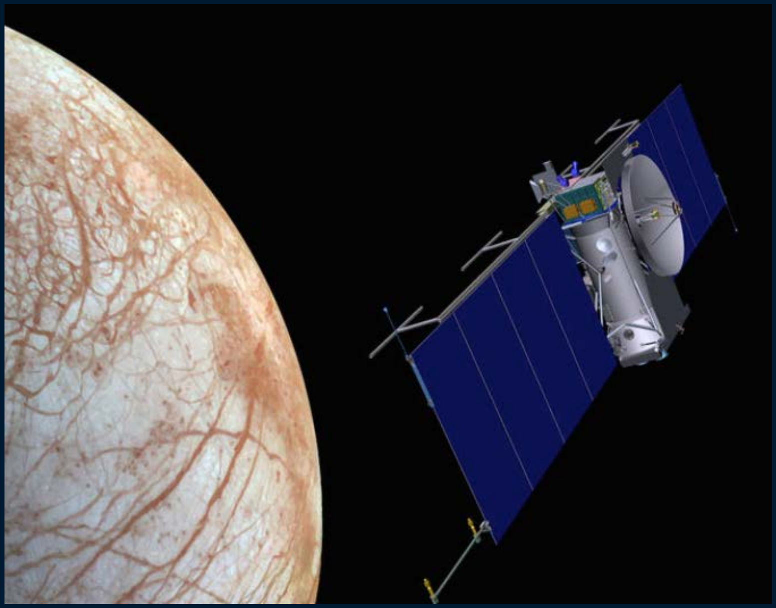
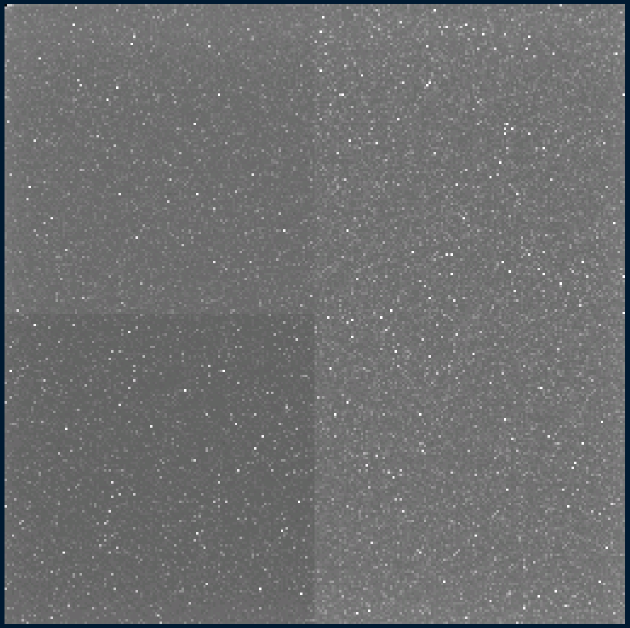


Image: NASA

Numerous NRC Decadal Survey Space Exploration Objectives

Radiation Effects on Spacecraft

- Long term effects causing parametric and/or functional failures
  - Total Ionizing Dose (TID)
  - Displacement Damage
- Transient and Single Particle Effects causing temporary and/or permanent damage
  - Single Event Effects (SEE)

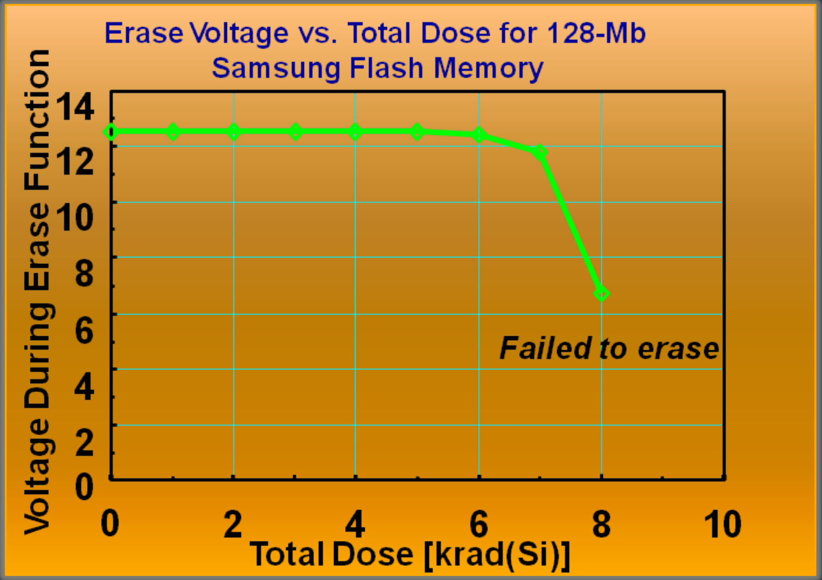


An active pixel sensor (APS) imager experiencing irradiation at the Texas A&M University Cyclotron

Slide Credit: K. Label, NASA

Total Ionizing Dose

- Cumulative long term ionizing damage due to protons and electrons
- Effects
  - Threshold Shifts
  - Leakage Current
  - Timing Changes
  - Functional Failures
- Unit of relevance is rads (material)
- Can partially mitigate with shielding, reduces low energy particles
- Total allowed astronaut career dose: 1 Sv = 100 rads



TID Failure of Flash Memory Device

Slide Credit: K. Label, NASA

Displacement Damage

- Cumulative long term non-ionizing damage due to protons, electrons, and neutrons
- Effects
  - Device degradation
  - Similar to TID effects
  - Optocouplers, solar cells, CCDs, linear bipolar devices
- Unit of relevance is particle fluence at sensitive energies
- Device dependent
- Can partially mitigate with shielding, reduces low energy particles

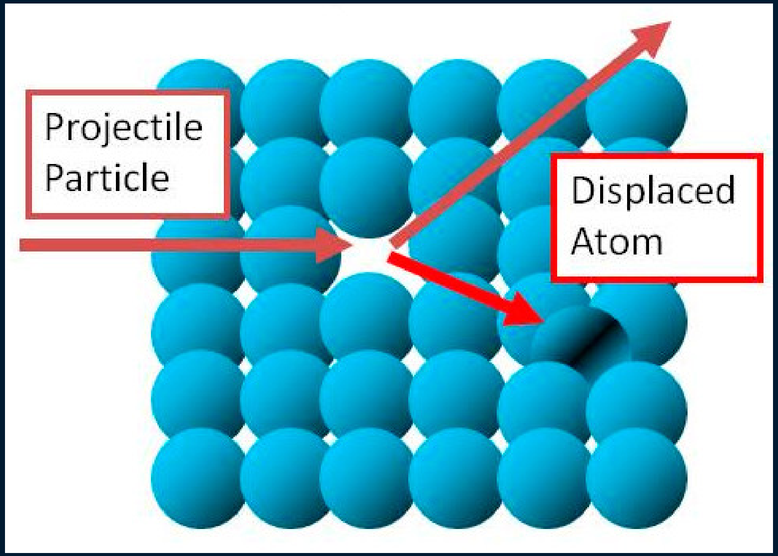


Image: wpo.altertechnology.com

Crystal lattice disruption due to displacement damage

Slide Credit: K. Label, NASA

Single Event Effects (SEEs)

- Caused by a single charged particle passing through material
  - Heavy ions (GCRs and solar)
  - Protons (solar >10MeV)
- Effects
  - Single Event Upsets (SEUs)
  - Circuit latchup
  - Burnout
- Unit of relevance is linear energy transfer (LET)
- Severity depends on type of effect and component criticality
- Shielding not as effective due to limited blockage of high energy particles

Cosmic Ray Damage Mechanism

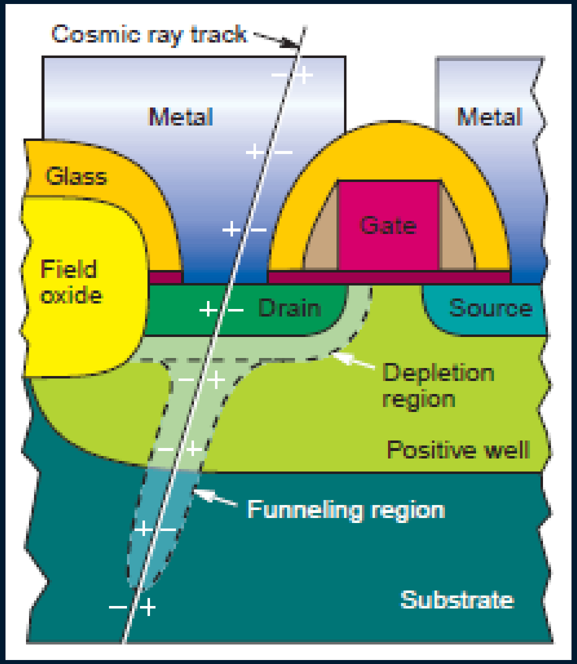


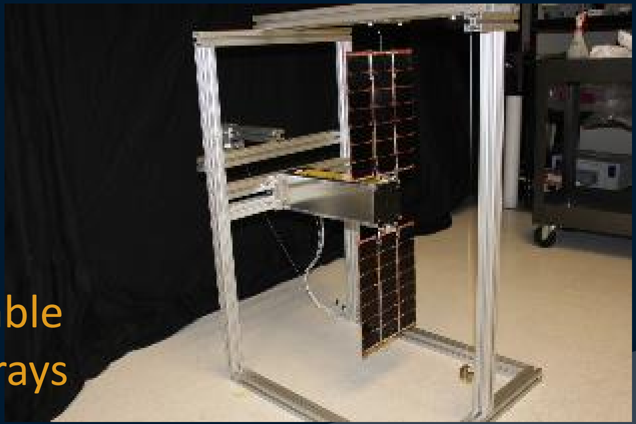
Image: *Crosslink*

Slide Credit: K. Label, NASA

Solar Energy Implications for Small Satellite Exploration of Outer Planets

- Current art is 45W orbit average power (OAP) deployable solar panel at Earth orbit
- Same panel area gives 20W OAP at Mars and 2W OAP at Jupiter
- Solution will likely rely on batteries (rechargeable or primary) to handle peak loads depending on mission power profile
- Technology development needed in larger deployable solar arrays, more efficient batteries and lower power spacecraft systems

Image: NASA



Example deployable CubeSat solar arrays

Image: MMADesign

NASA Mission Classifications

What is the appropriate classification for an interplanetary CubeSat mission?

Class A: Qualification testing & screening required to produce highest reliability and lowest risk, radiation hardness testing required. Duration: greater than 5 years

NASA Flagship Interplanetary Missions

Class B: Reliable parts, low risk, radiation hardness testing required. Mission duration: 2 to 5 years

Class C: No formal reliability assessment, medium risk, radiation assessment, no additional testing. Mission duration: less than 2 years

Interplanetary CubeSat Mission?

Class D: Highest risk level, low cost & shorter schedule outweigh risks. Mission duration: less than 1 year

Traditional LEO CubeSat Missions

[Refer to NPR 8705.4 for additional details on risk class]

Slide Credit: P. Dugan, NASA