Shielding Considerations for CubeSat Structures During Solar Maximum

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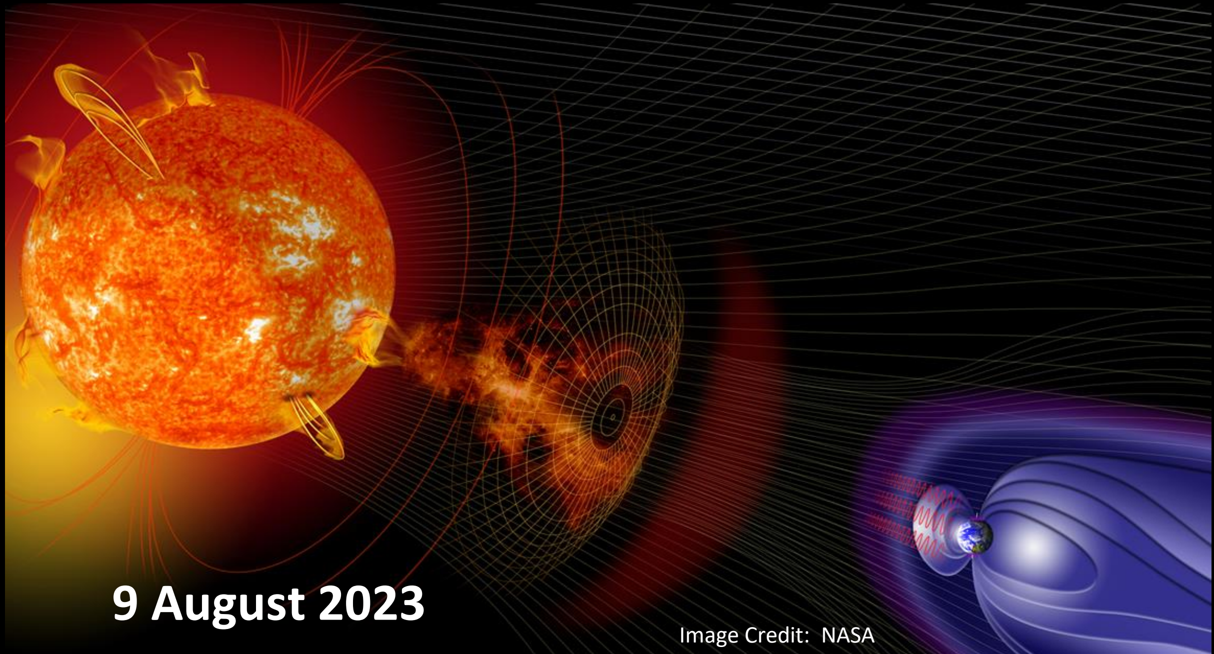
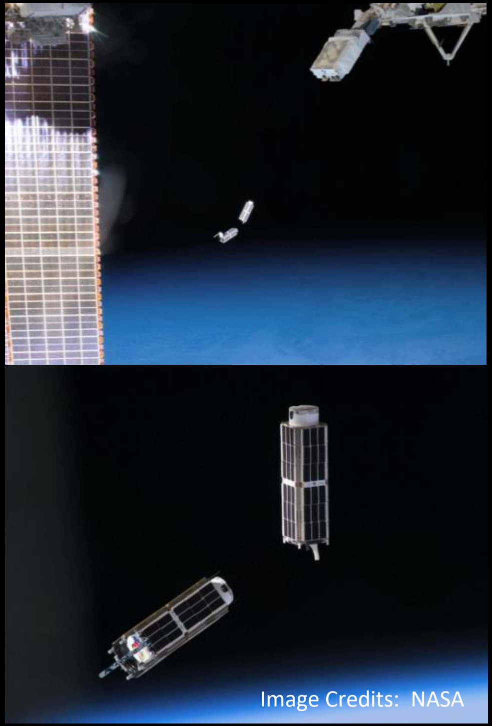


9 August 2023

Image Credit: NASA

Reliability has a Price: Enabling Missions, Return on Investment

- CubeSat Market: $0.5B-1B over 3 yr
- Over 1700 small satellites forecasted for 2017-2023 (www.spaceworksforecast.com)
- More than 500 over next 3 yr into polar low-Earth orbit (PLEO) (www.spaceworksforecast.com)
- Typical 6U CubeSat costs $6-9M (https://esto.nasa.gov/techval_space.html)
- CubeSat value at risk: $0.5-1B in the past 3 yr alone

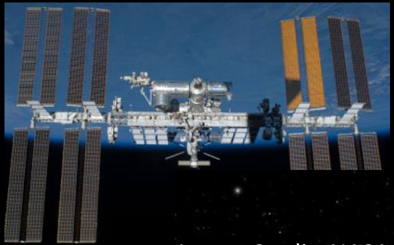


ISS CubeSat Deployment, one of many space launch service methods

1 unit (U) = 10 cm x 10 cm x 10 cm

Reliability Engineering for Mission Assurance

- **NASA Preferred Reliability Series, 1258, “Space Radiation Effects on Electronic Components in Low Earth Orbit,” August 1996.**
  - **Typical Commercial parts hardness:**
    - Total Dose: 2 to 10 kRAD (typical)
    - SEU Threshold LET: 5 MeV/mg/cm2
    - SEU Error Rate: 10E-5 errors/bit-day (typical)
- **NASA Preferred Reliability Series, 1260, "Radiation Design Margin Requirement", May 1996.**
    - Radiation Design Margin 2 or 3
- **NASA Handbook 4002A, “Mitigating In-Space Charging Effects —a Guideline”, 19 October 2017.**
    - 0.284-cm Aluminum equivalent minimum thickness to reduce internal discharge risk in Earth Orbit, upcoming revision.
- **NASA-STD-8729.1A, “NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems”, 13 June 2017.**



ISS

Image Credit: NASA

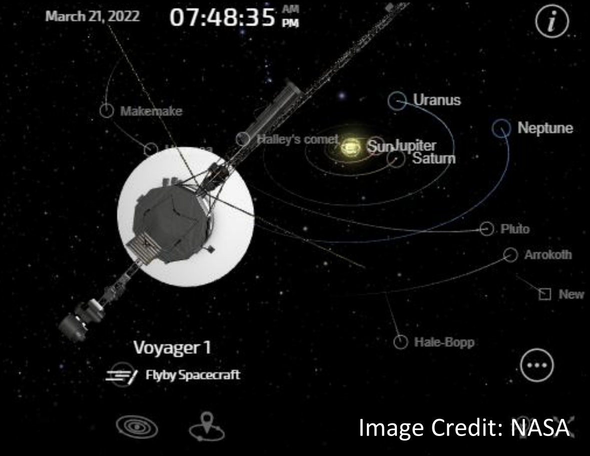


Image Credit: NASA

Voyager 1

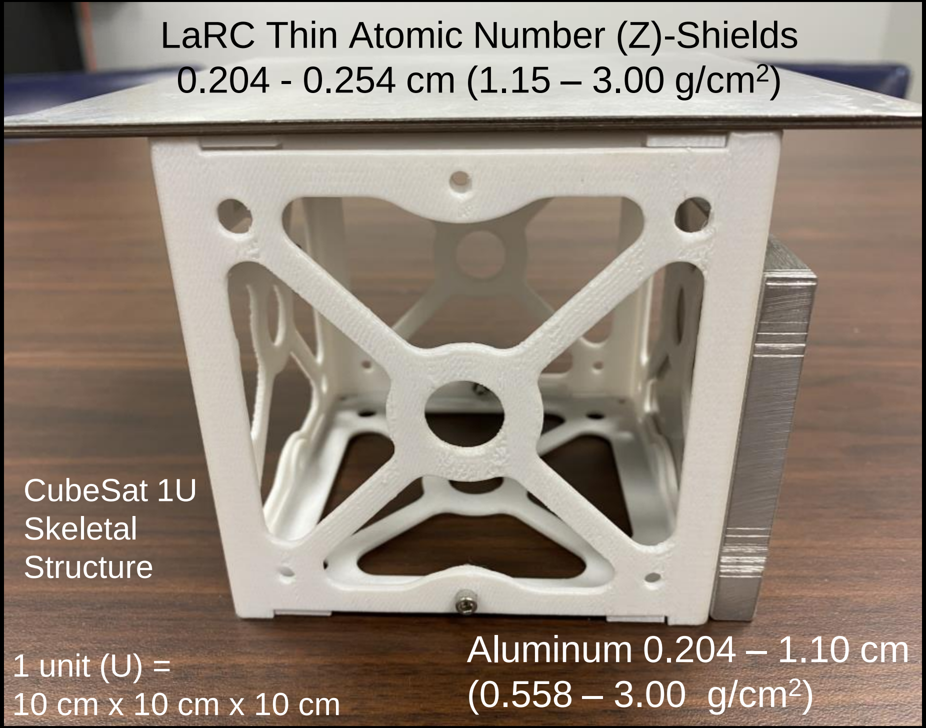
Image Credit: USAF

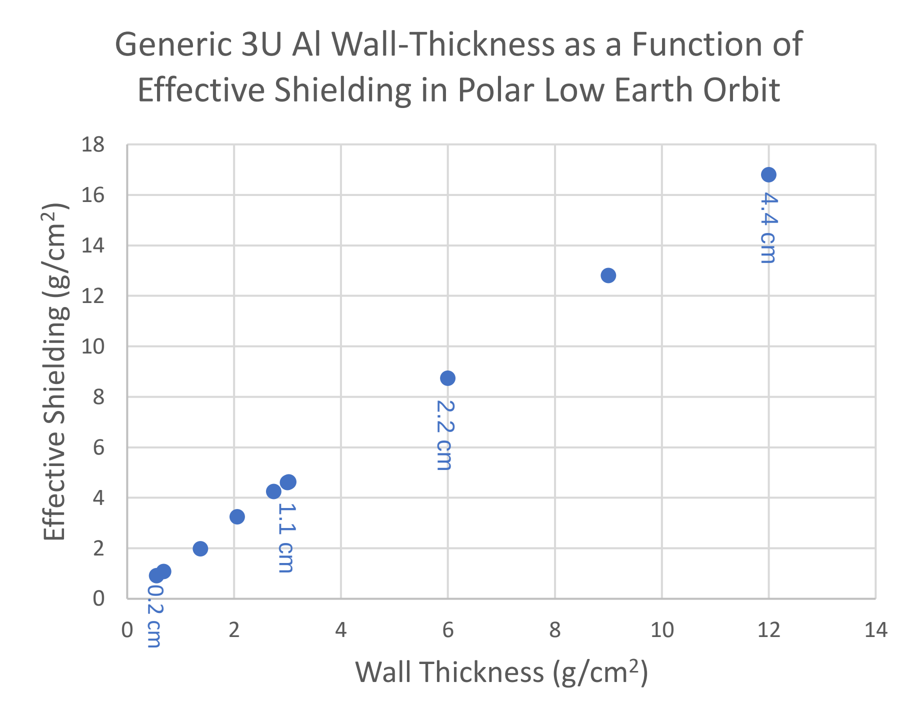
SCATHA (Spacecraft Charging at High Altitude)

Standards, Design, Testing, and Guidelines Improve Reliability in the Radiation Environment

Single Event Upset = SEU, LET = Linear Energy Transfer

The Problem of Radiation Shielding of CubeSats is Putting Mass into the Walls of Thin Structures

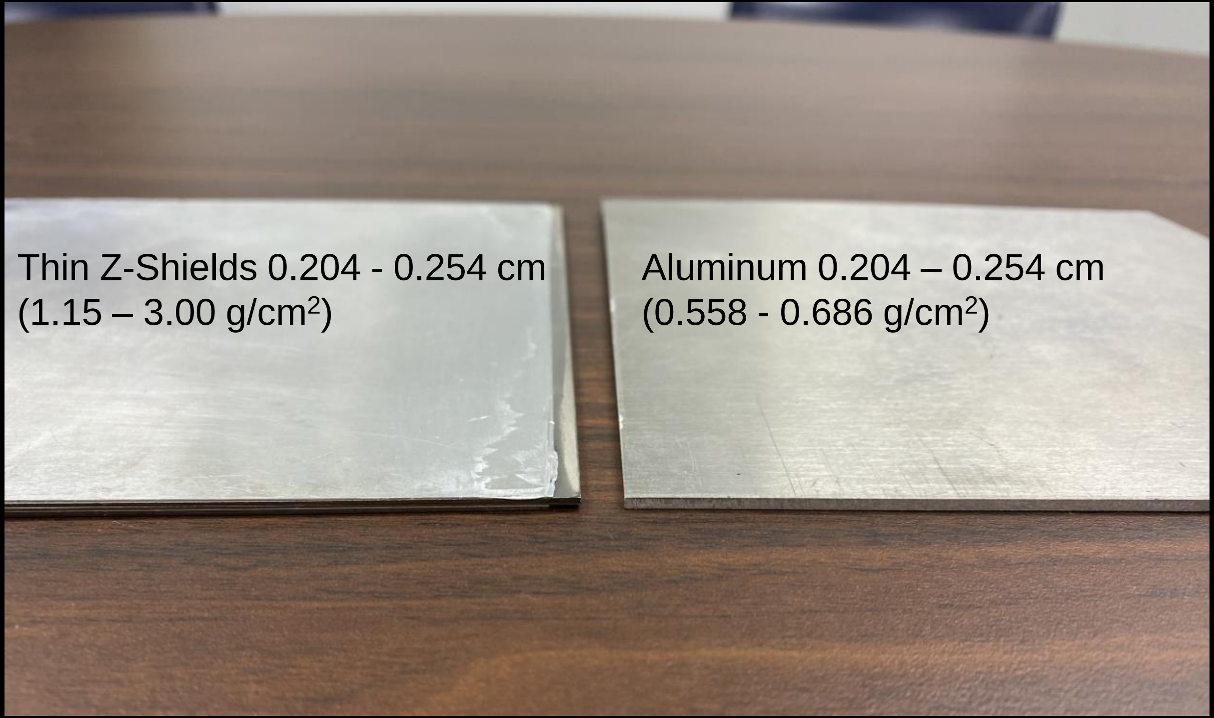




Effective Shielding determined using NOVICE SIGMA, 3-D Ray Tracing Sector Analysis, Estimates with Aerospace Corporation Proton (AP)8 Solar Minimum Model for a 500-km altitude and 85^o inclination orbit.

Aluminum CubeSat Structural Wall Thicknesses Limit Shielding

Shielding = mass thickness, areal density = g/cm^2 = thickness (cm) x density (g/cm^3)



Total Ionizing Dose (TID) and Proton Single Event Effects (SEEs) Impact Mission Reliability Over Time

In most cases, shielding amounts reduce the dose rate, reduce particle fluence and energies

Radiation Shielding: Like a wear rate, a 20,000 mile versus 100,000 mile tire tread life
If need new tires though no one available to change in space, yet……

Shields-1 (Z-Shield Vault): Performing over 4 Years in Polar Low-Earth Orbit

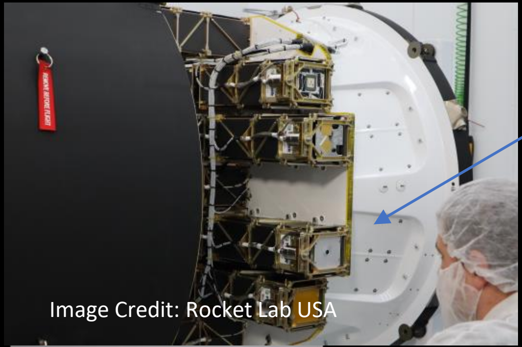


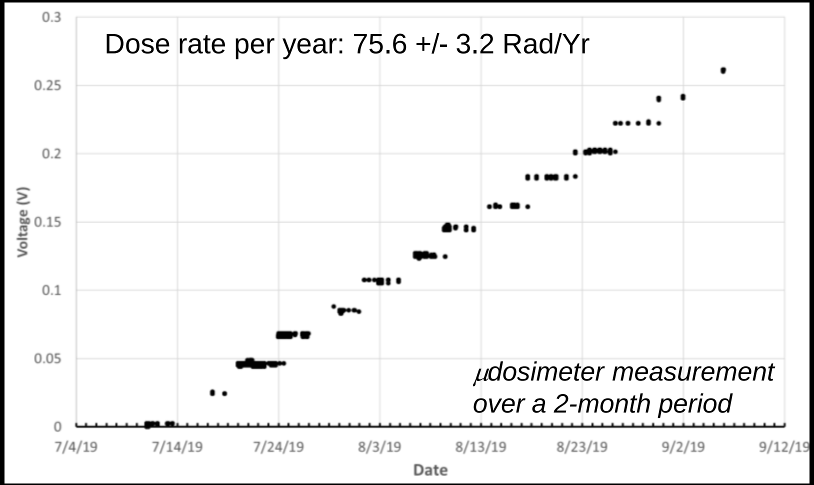
Image Credit: Rocket Lab USA

Shields-1 onboard Rocket Lab USA, Electron Rocket, NASA ELaNaXIX Mission, 16 December 2018 Launch

Space Heritage
NORAD ID 43850

Image Credit: NASA

Z-Shield Vault Performance in Polar Low-Earth Orbit



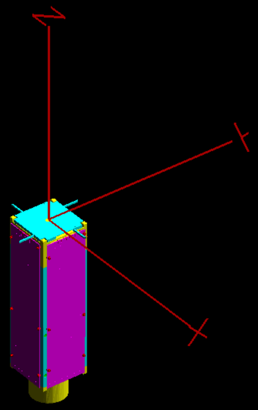
North American Aerospace Defense Command = NORAD

TID, Effective Shielding, and Minimum Proton Threshold Approximations by NOVICE

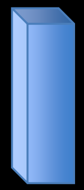
- Polar Low-Earth Orbit (LEO):
  - 85º Inclination
  - 500-km apogee/ perigee
- 1-yr mission, AP8 Radiation Belt Model, Solar Protons, SOLPRO (King) Model, 95% Confidence
- NOVICE ADJOINT Fluence and SIGMA Effective Shielding measurements at Shields-1 μDosimeter location in Electronics Enclosure (vault) and inside a generic 3U CubeSat containing four electronic boards
- *Minimum particle proton energy threshold for a detector is the minimum proton particle energy that transmits through spacecraft shielding to the detector.*
- *Minimum particle proton energy threshold for a detector is determined from the space environment integral fluence and the integral fluence at each detector.*

NOVICE Software calculates and models radiation transport methods and effects. It uses ADJOINT Monte Carlo Code and SIGMA, a ray-tracing sector analysis tool. SOLPRO is a NASA developed code for estimated solar proton radiation effects.

Shields-1 CAD Model

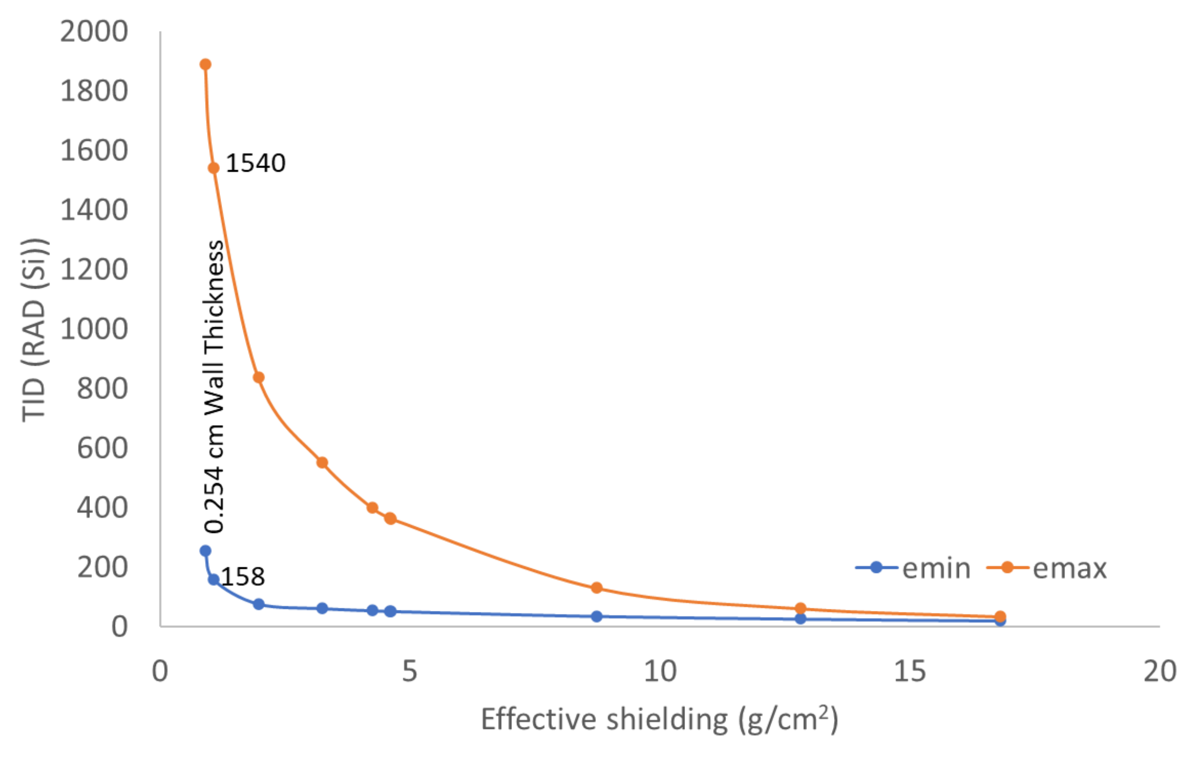


Thin-Walled (0.204 cm) Generic 3U CubeSat with Four Electronic Boards Inside



Modeled CAD structures for this study

TID Increases during Solar Maximum for Thin-Walled Shielding



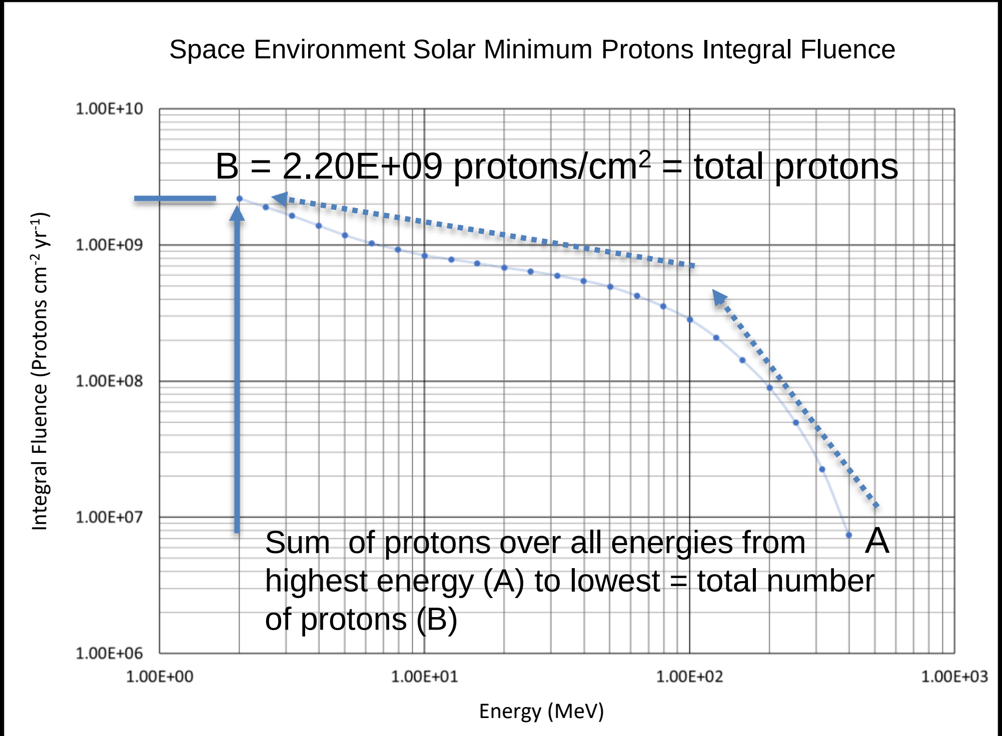
- For thin-walled shielding, TID 10x difference solar minimum to solar maximum
- With a Radiation Design Margin (RDM) of 2 or 3, (3 kRAD or 4.5 kRAD), at limits of commercial part hardness range of 2 to 10 kRAD.

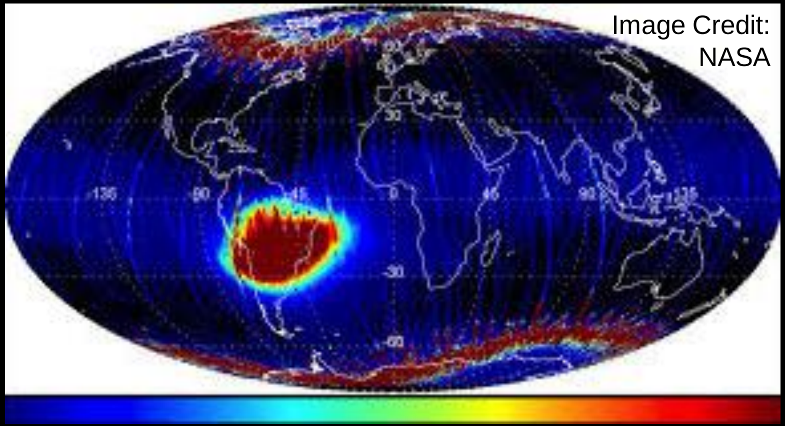
solar minimum = emin, solar maximum = emax

NASA Preferred Reliability Series, 1260, "Radiation Design Margin Requirement", May 1996.

NASA Preferred Reliability Series, 1258, “Space Radiation Effects on Electronic Components in Low Earth Orbit,” August 1996.

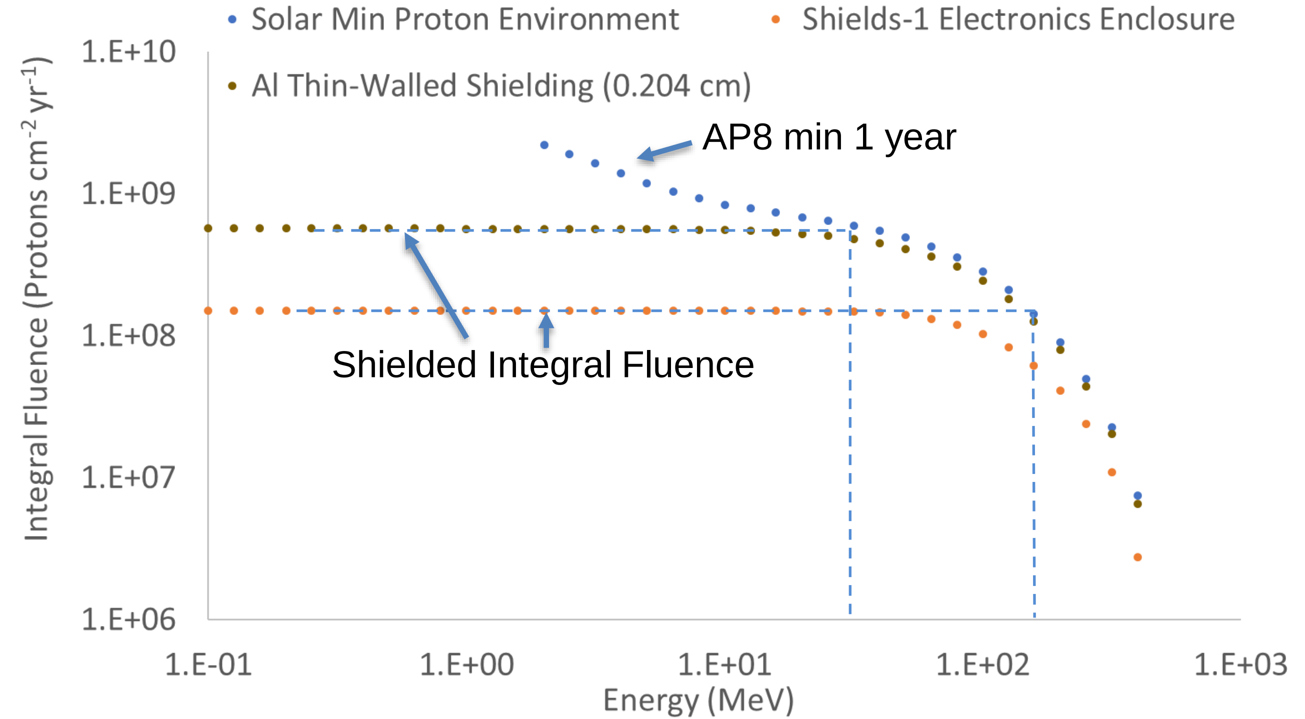
Shields-1 NOVICE Model Fluence (Solar minimum)





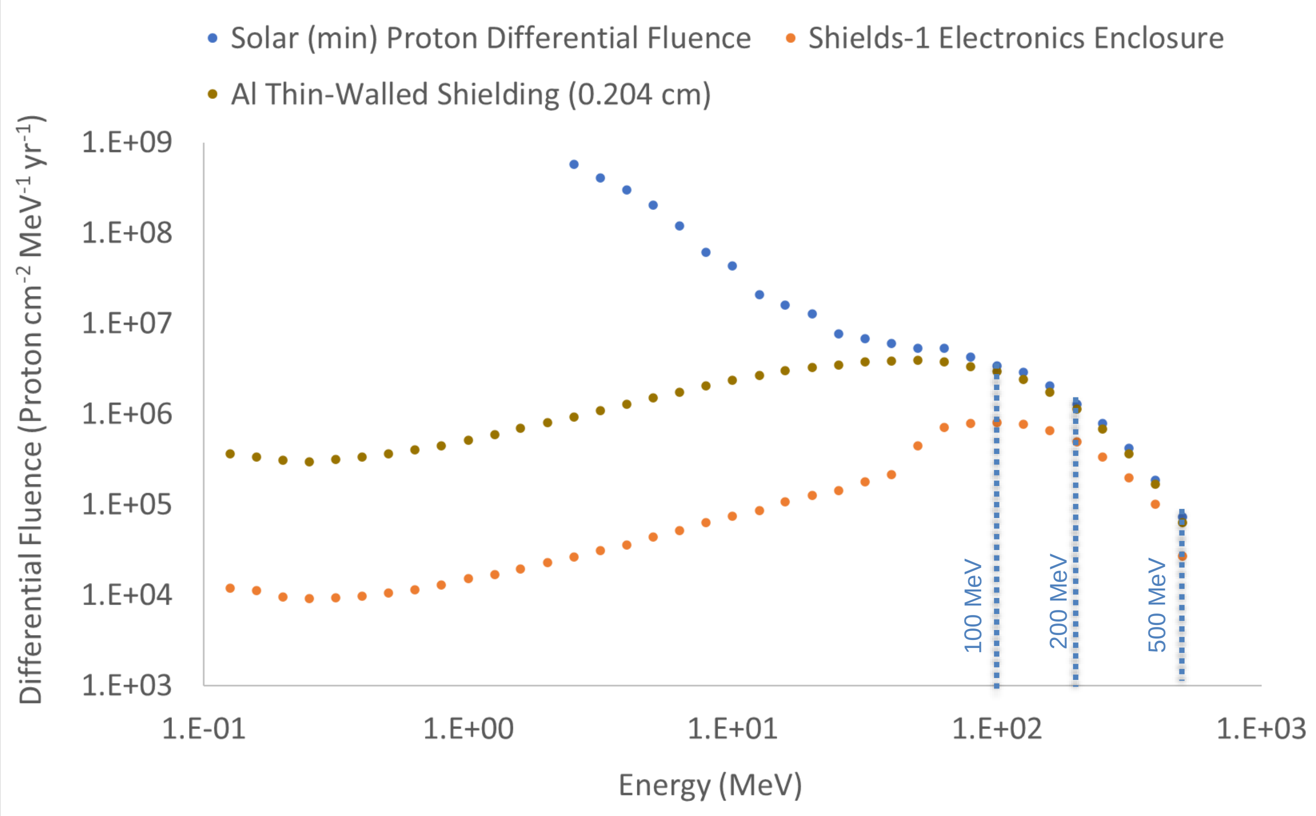
South Atlantic Anomaly (SAA) dominates the polar low-Earth orbit proton flux/fluence

Minimum Proton Energy Thresholds, Influence Proton SEE



Name	Material	Wall Areal Density (g/cm^2)	Total Proton Integral Fluence ($protons/cm^2$)	Proton Minimum Threshold Energy (MeV)	Effective Shielding (g/cm^2)	% Particles Remaining
Shields-1 Electronic Enclosure	AlTiTa	3.02	1.52E+08	151	21.3	6.90
Generic CubeSat (3U)	Al	0.550	5.68E+08	36.2	0.907	25.8
Solar Minimum Total Proton fluence = 2.20E+09 ($protons/cm^2$). *Extrapolated Proton Minimum Threshold Energy, assumes spherical shielding from Adjoint Model.*						

Shielding Contributes to Attenuation of Energetic Protons



Name	Proton Attenuation (%)		
	100 MeV	200 MeV	500 MeV
Shields-1 Electronic Enclosure	76.5	61.7	63.0
Generic CubeSat (3U)	13.7	12.4	12.6

Spacecraft of All Shielding Levels Influenced by Proton SEE

- **NOAA Space Weather Prediction Center (SWPC) Solar Radiation Storm Severity Scales**
  - **magnitude flux levels above 10-MeV proton energies from 1-5, and correspond to historical occurrence rates for a 11-year solar cycle.**
  - **Typically 50 minor, 25 moderate, 10 strong, 3 severe, and less than 1 extreme solar particle event (SPE). SEE events have increased probability of occurrence from moderate to extreme severity.**
  - **Many SPEs last several days and longer with increased flux over a short amount of time.**
- **In terms of reliability: Increased shielding reduces the effects of proton SEE by increasing minimum proton energy thresholds.**

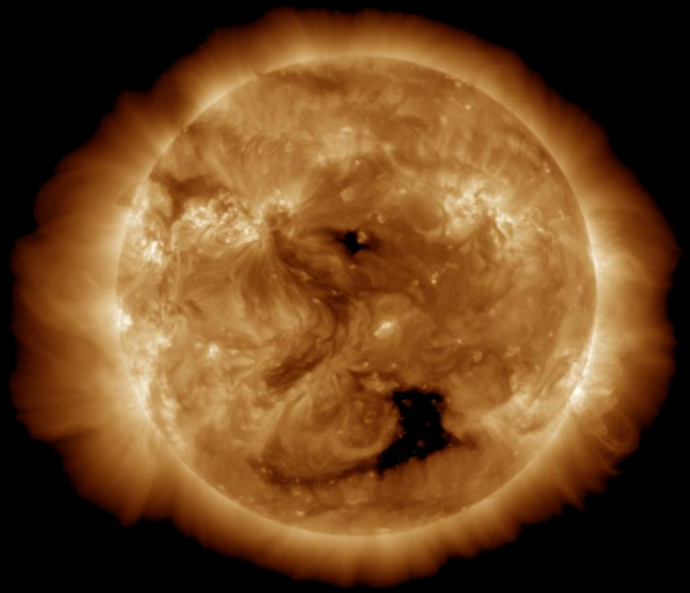


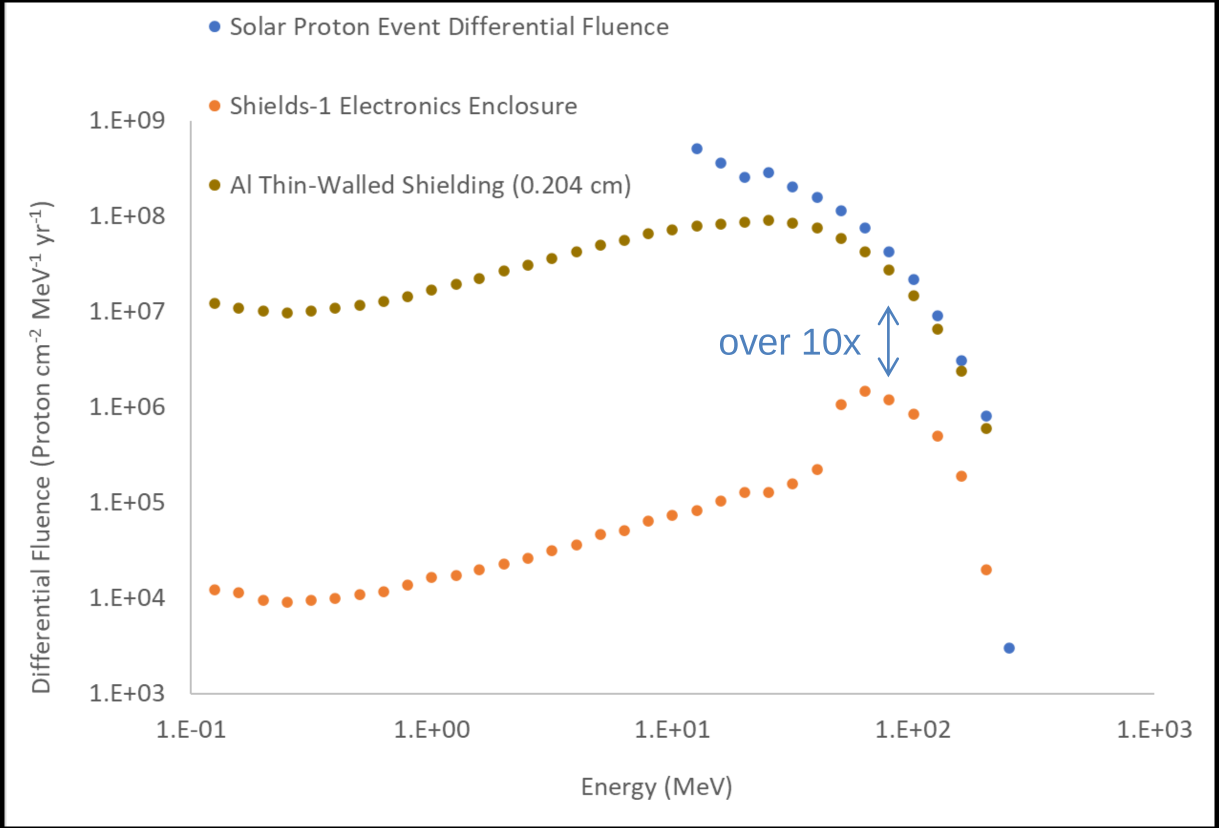
Image credit: NOAA

GOES-18 SUVI Composite 195 Angstroms 2023-05-04 13:20:07

https://www.swpc.noaa.gov/noaa-scales-explanation

National Oceanic and Atmospheric Administration = NOAA

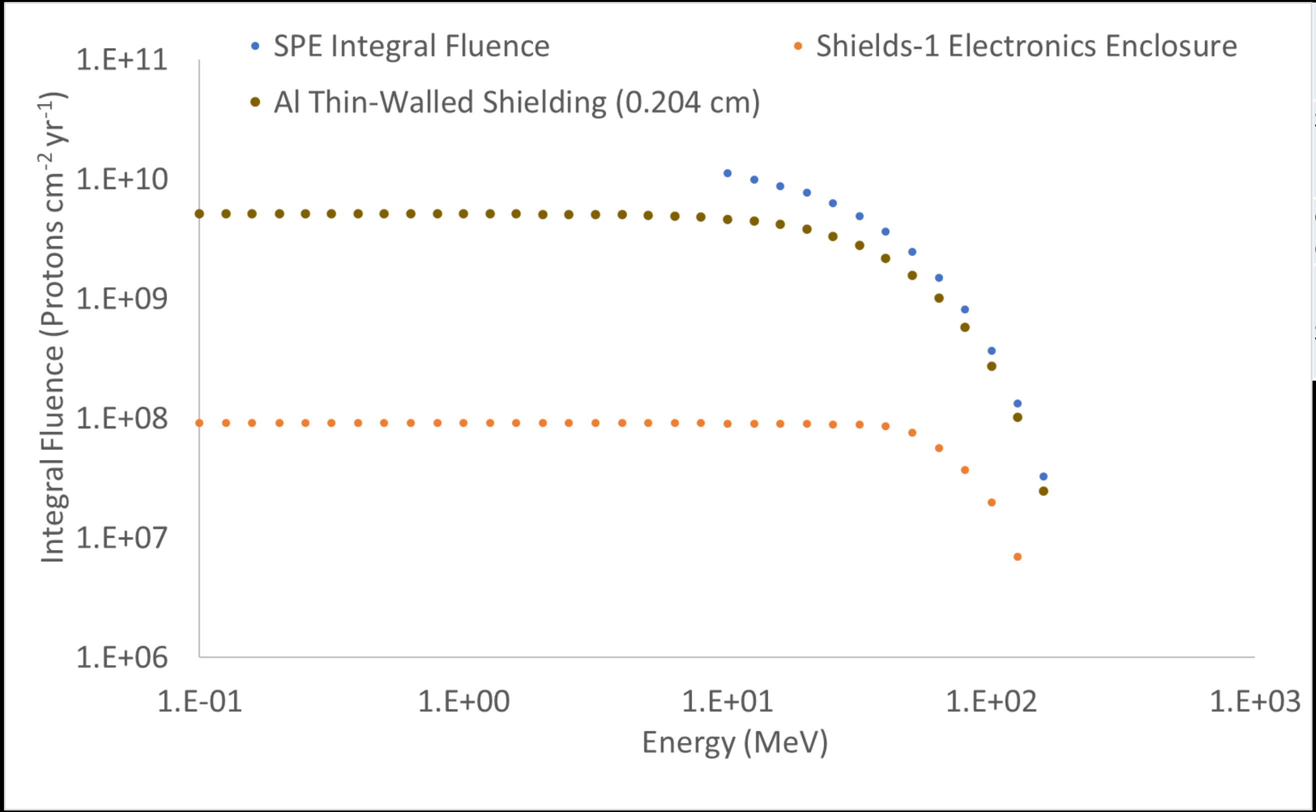
Attenuation of SPE Protons a Magnitude Lower with Z-Shielding



SPE worst-case over 1-yr mission, 95% Confidence Level without geomagnetic shielding, SOLPRO (1972 King) Model

CubeSats in polar low-Earth orbit exposed to solar activity over the poles

Worst-Case SPE Protons Penetrate Al Thin-Walled Structure



Name	Total Proton Integral Fluence (protons/cm^2)	% Particles Remaining
Shields-1 Electronic Enclosure	9.14E+07	0.809
Generic CubeSat (3U)	5.15E+09	45.6
SPE Proton Integral Fluence 1.13E+10		

Conclusions

- Shielding provides a system level mitigation for proton SEE and total ionizing dose.
- CubeSats have limited volume and wall thickness constraints using aluminum.
- TID increases behind Al Thin-Walled Shielding during solar maximum.
- Thin Z-Shields offer increased mass and therefore shielding for thin-walled structures (i.e., CubeSats).
- Minimum proton thresholds increase with shielding areal density, which reduces the number of energetic protons available for TID and SEE in SAA and during SPEs.
- Increased minimum proton thresholds with shielding reduces proton radiation effects from increased SPE severities.
- Energetic proton attenuation reduces TID and SEE for commercial, radiation-tolerant, and radiation-hardened parts.

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