Shields-1 Dosimetry Measurements in Polar Low Earth Orbit

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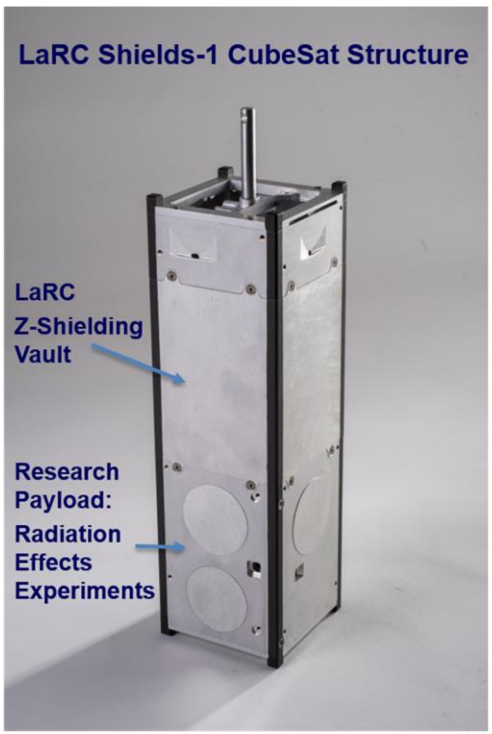
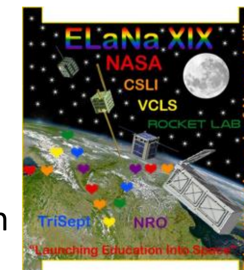
Shields-1, Space Radiation Effects Experiments
NORAD ID 43850

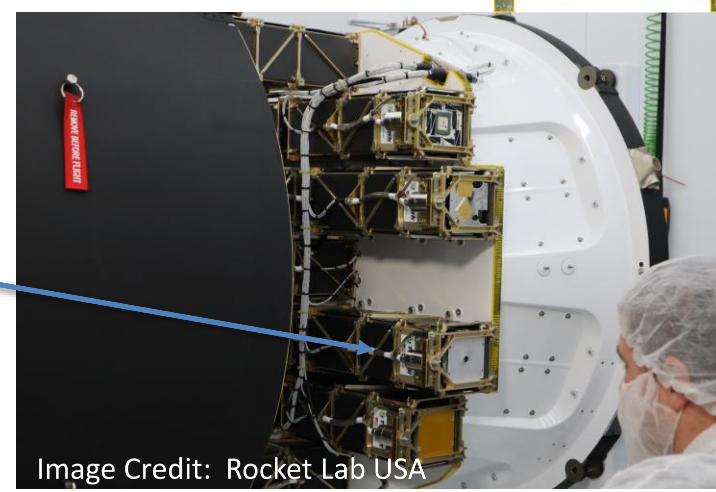
Presently, Shields-1 operates with Langley Research Center (LaRC) Z-Shielding providing radiation protection for the electronics over 10 months in polar low earth orbit.



Shields-1 structure and Final Preship Picture with LaRC Z-Shielding Vault and Experiment, Solar Panels and Thermal Radiator

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





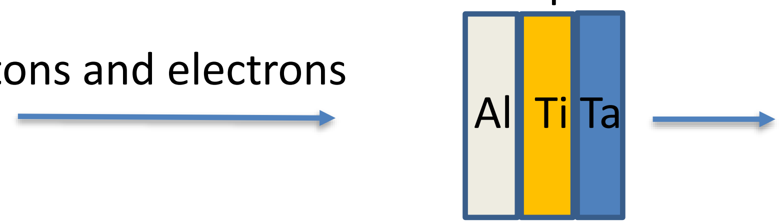
Shields-1 in Poly Picosatellite Orbital Deployer (P-POD), 2nd from bottom, inside Electron Rocket Fairing before encapsulation

Z-Shielding Characteristics

- **Low atomic number materials graded or layered to higher atomic number materials**

Z-Shielding layered example

Space Radiation
High Energy protons and electrons

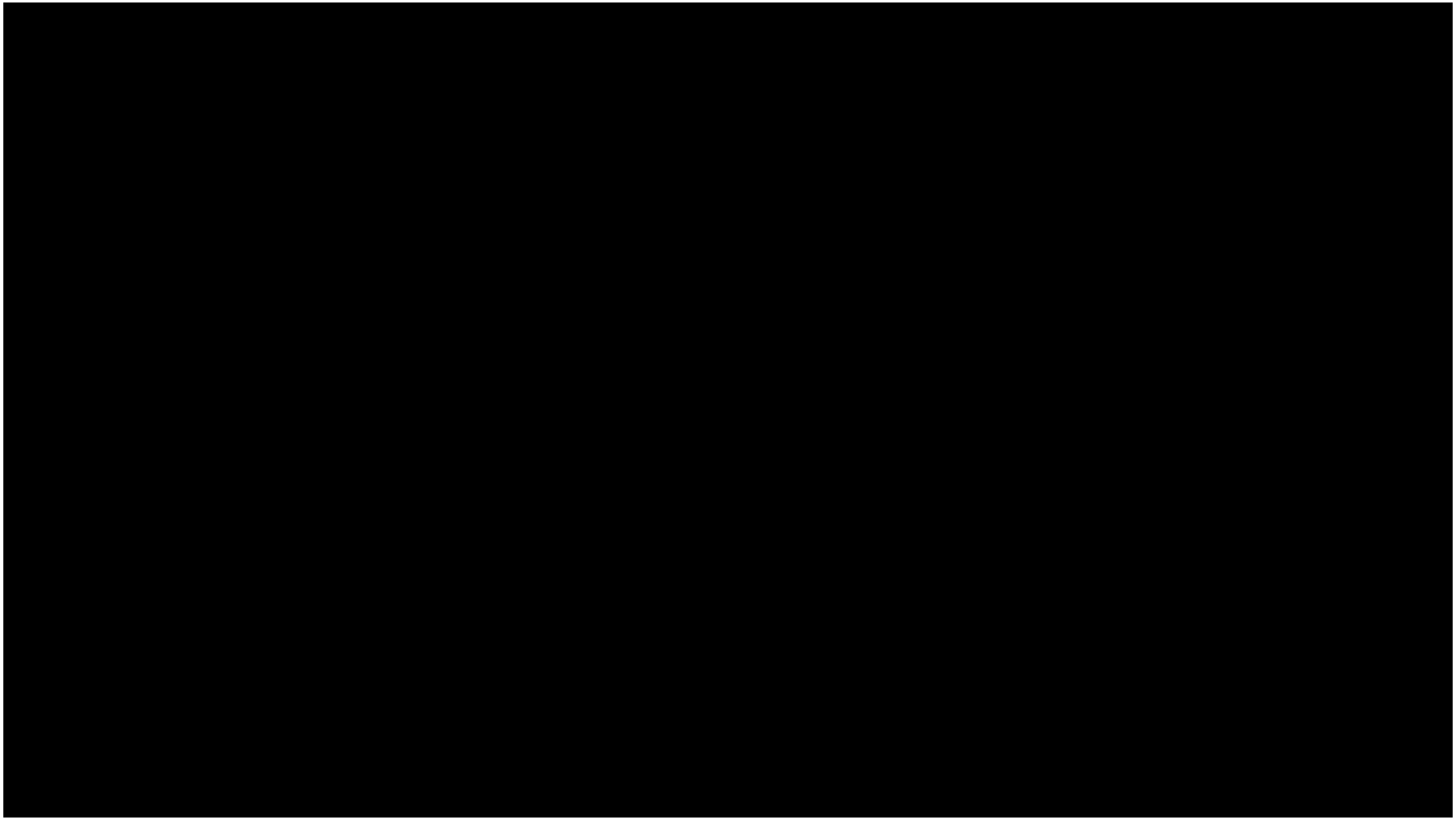


Attenuated protons and electrons

For many low earth orbits: electron radiation can be effectively shielded and the risks for internal charging substantially reduced with Z-Shielding

- **One piece structure**
  - **Continuous metallic properties: thermal and electrical continuity**
  - **Manufacturing methods: diffusion bonding, welding, plasma spray**
  - **Machining examples: milling, hot wire, and water jet**
  - **Thickness reduced by over half compared to Aluminum baselines**

Z-Shielding Overview



CubeSat Market: $0.5B-1B over 3yrs

- Over 1700 small satellites forecasted for 2017-2023 (www.spaceworksforecast.com)
- Over 500 over next 3 yrs into polar low earth orbit (PLEO) (www.spaceworksforecast.com)
- Typical CubeSats costs $1-2M* (https://esto.nasa.gov/techval_space.html)

  **NASA ESTO Office reported it is $1-$1.5M per U at the 2017 SmallSat Conference and is updating its figure.*
- CubeSat value at risk: <u>$0.5-1B in the next three years alone</u>

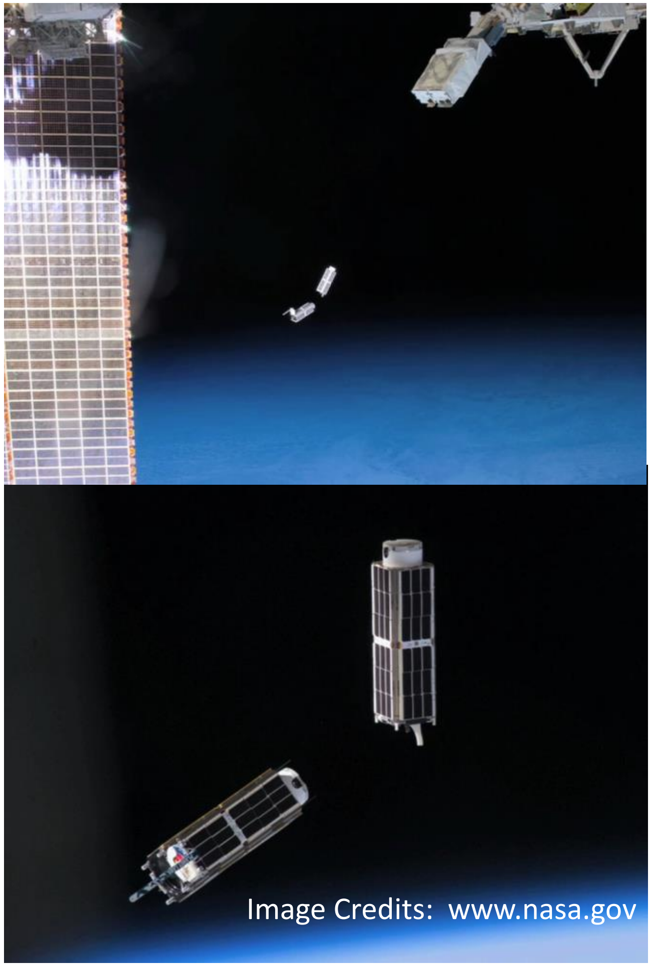
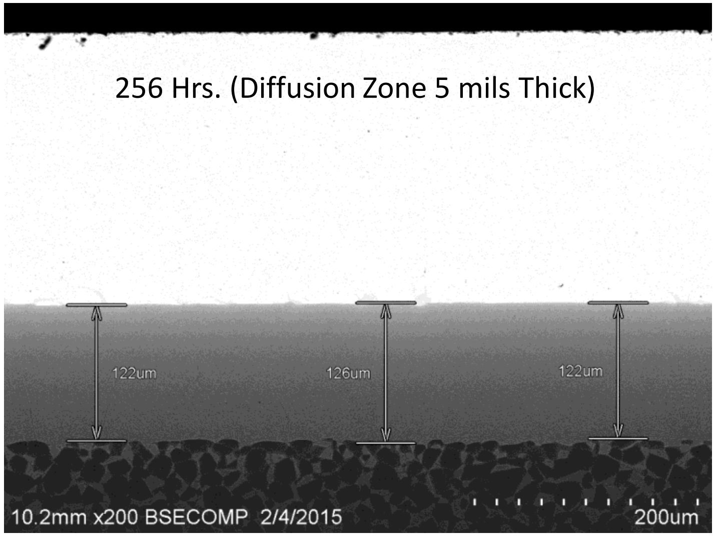


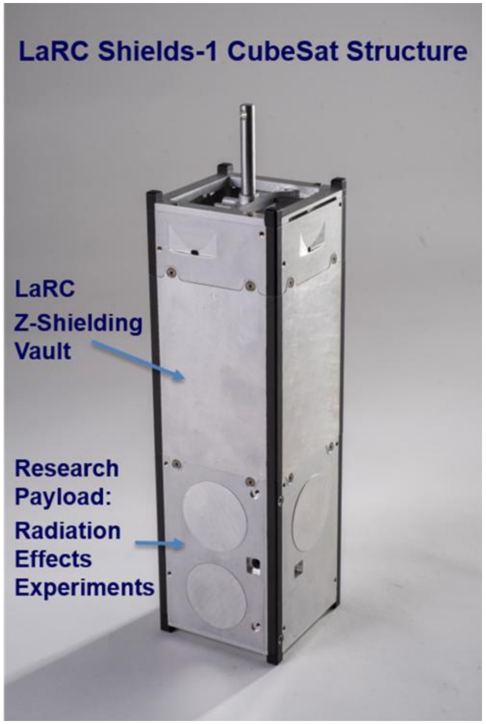
Image Credits: www.nasa.gov

Z-Grade Shielding Materials and Technology Development

Z-Grade Shielding from Titanium and Tantalum Diffusion Bonding



Product



Relevant Publications:

U.S. Patent No. 10,039,217, 31 July 2018, "Methods of Making Z-Shielding," D.L. Thomsen III, R.J. Cano, B.J. Jensen, S.J. Hales, and J.A. Alexa.
U.S. Patent Application No 15/949,644, LAR-19109, 12 April 2018, "Method of Making Thin Atomic (Z) Grade Shields," D.L. Thomsen III.
U.S. Patent Application No. 20170032857, 2 February 2017, "Atomic Number (Z) Grade Shielding Materials and Methods of Making Atomic Number (Z) Grade Shielding," D.L. Thomsen III, S.N. Sankaran, and J.A. Alexa.
D.L. Thomsen III, W. Kim, and J.W. Cutler, "Shields-1, A SmallSat Radiation Shielding Technology Demonstration," 29th AIAA/USU Conf. on Small Sat., SSC15-XII-9, August 2015.
U.S. Patent No. 8,661,653, 4 March 2014, "Methods of Making Z-Shielding," D.L. Thomsen III, R.J. Cano, B.J. Jensen, S.J. Hales, and J.A. Alexa.

Shields-1: Radiation Shielding Experiments

- **Vault Electronics**
  - To measure total ionizing dose (TID) over time and monitor system electronics performance.

- **Atomic Number (Z)-Grade Radiation Shielding**
  - To measure total ionizing dose of Z-grade radiation shielding and compare to baseline aluminum for at least 3 samples each.

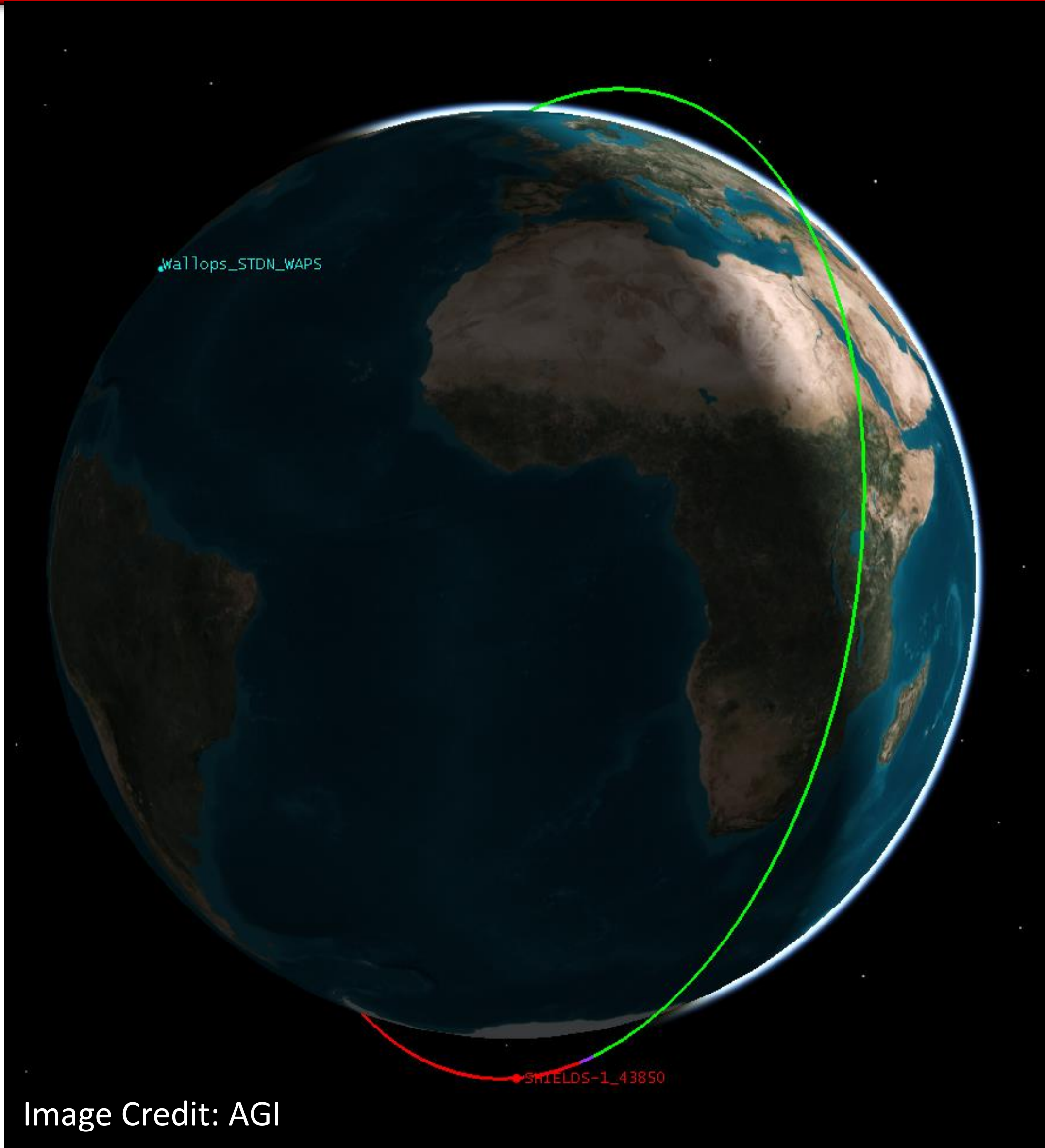
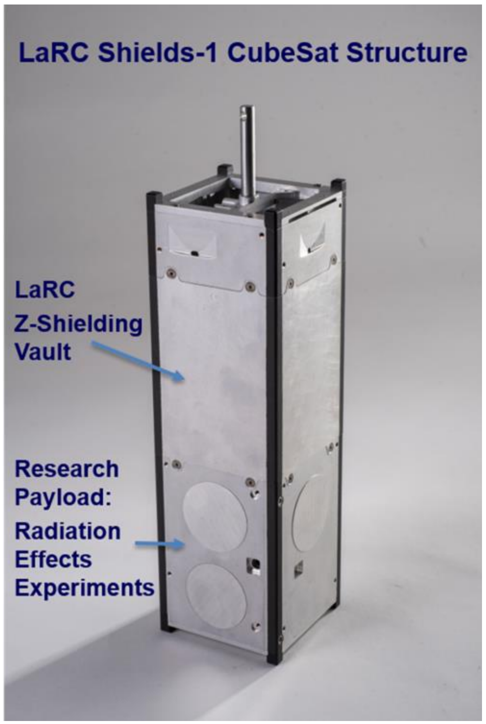
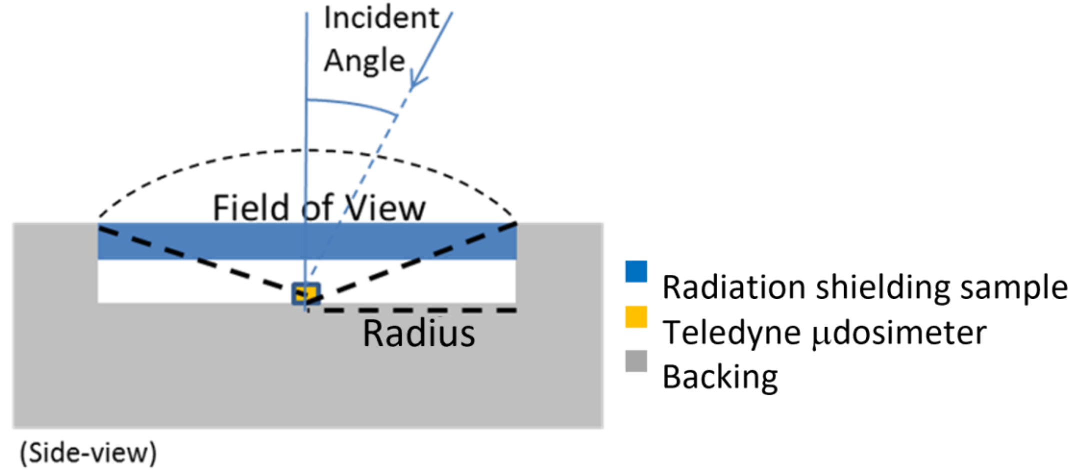


Image Credit: AGI

Z-Grade Radiation Shielding Experiment





Shielding Samples Behind μDosimeters (UDOS)s

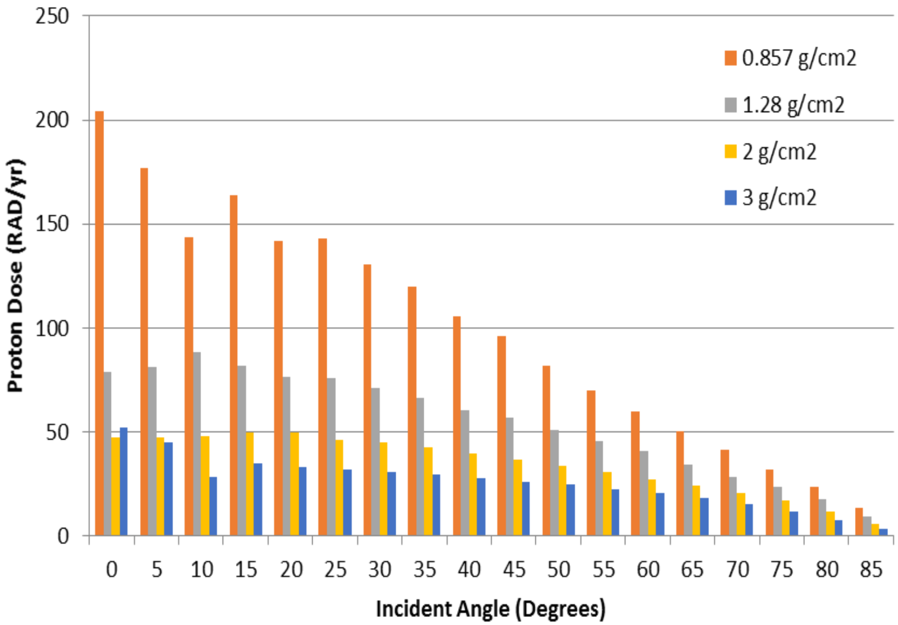
UDOS	Shielding	Areal Density (g/cm2)
1	Al	6.00
2	Al	3.00
3	AlTiTa	3.02
4	AlTiTa	2.08
5	AlTi	1.33
6	Al	1.29
7	Al	1.69

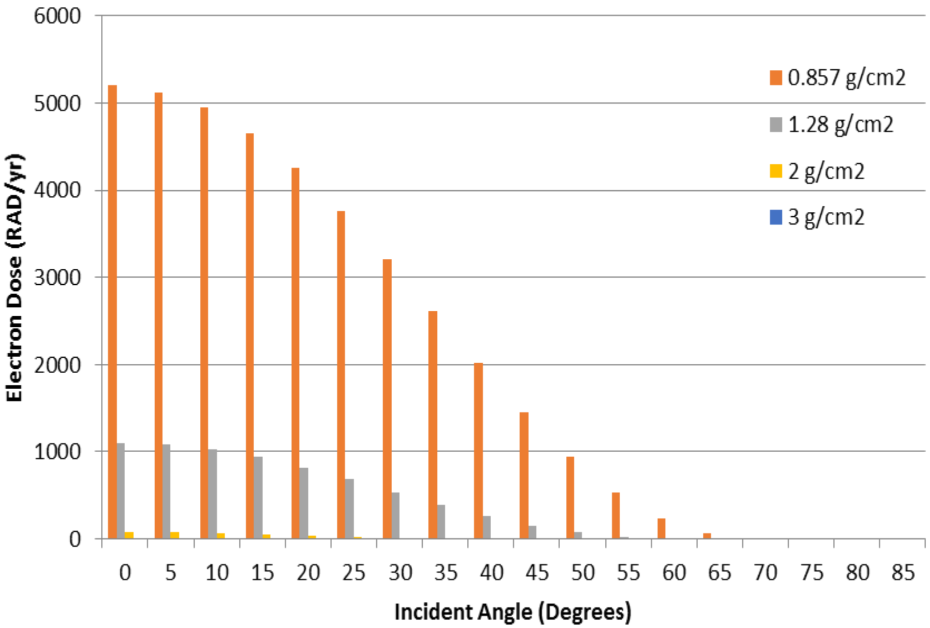
- **Infinite slab, geometry approximation**
- **>95% incident radiation through shielding sample**
- **Large sample field of views, thick backing**

Z-Grades:
Aluminum Titanium Tanalum (AlTiTa)
Aluminum Titanium (AlTi)

Aluminum (Al) Incidence Angle Dependence on Total Ionizing Dose (TID)

SPENVIS: Shieldose-2 from AP8min-AE8max Model Al half-sphere results with trigonometric determined incident angle dependencies of areal density in a slab geometry for geosynchronous transfer orbit.

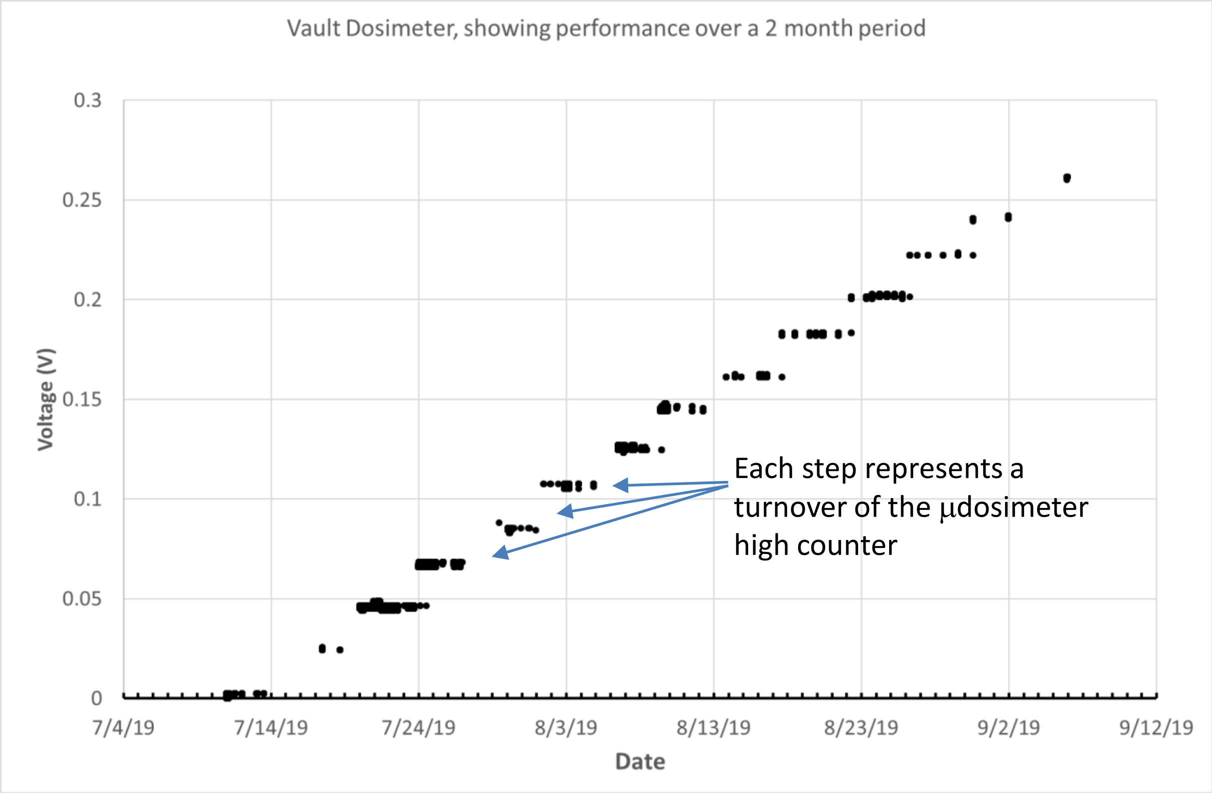




- Incident angle dependence used to determine shielding, field of view slab diameters.
- In order to receive greater than 95% of the proton radiation through a shielding slab the incident angles need to be at least 75 degrees.
- No electrons contribute to dose from incident angles greater than 70 degrees.

Reference: D.L. Thomsen III, W. Kim, and J.W. Cutler, "Shields-1, A SmallSat Radiation Shielding Technology Demonstration," 29th AIAA/USU Conf. on Small Sat., SSC15-XII-9, August 2015.

Shields-1 Vault Experimental Results

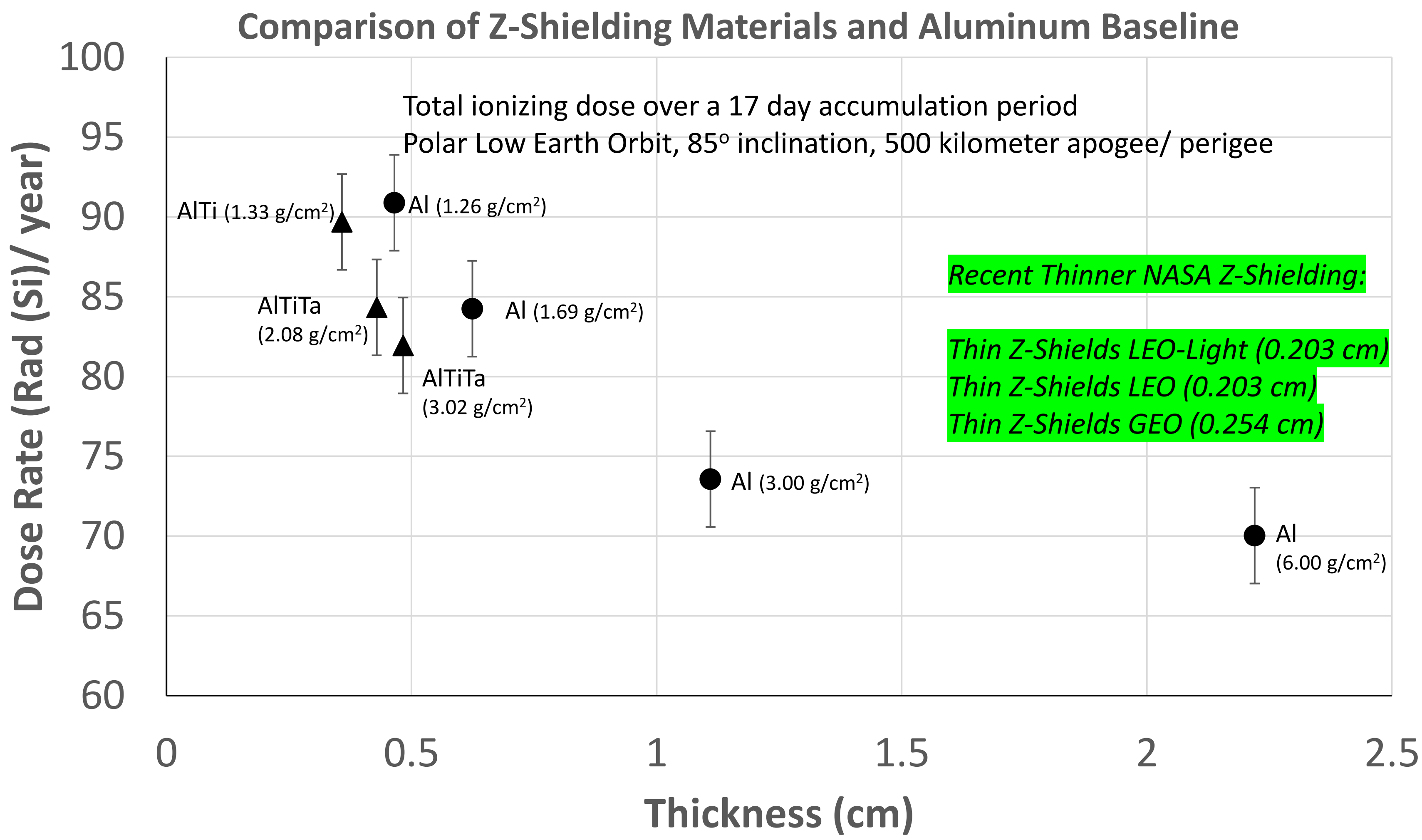


- Preliminary results: estimated dose rate per year: 75.6 +/- 3.2 Rad/Yr
- Suggests Z-Shielding Vault behaves similarly to a spherical shielding model
- Reduces total ionizing dose on sensitive electronic parts

High count = 256 counts (steps) of Medium
Med count = 256 counts (steps) of Low
High count step = 256 x 256 x 14.3 +/- 0.6 μRad/step = 0.94+/-0.04 Rad/step

Reference: Donald Thomsen, Kevin Somervill, Mark Jones, Raymond T. Lueg, William G. Girard, Alexander D. Scammell, Jing Pei, James W. Cutler, Robert G. Bryant, "Shields-1 Initial Space Operations, a NASA CubeSat Launch Initiative ELaNaXIX Mission," SmallSat Conference, 2019, Logan, Utah, 7 August 2019.
Teledyne μdosimeter: http://www.teledynemicro.com/product/radiation-dosimeter

Z-Grade Radiation Shielding Thickness Comparisons

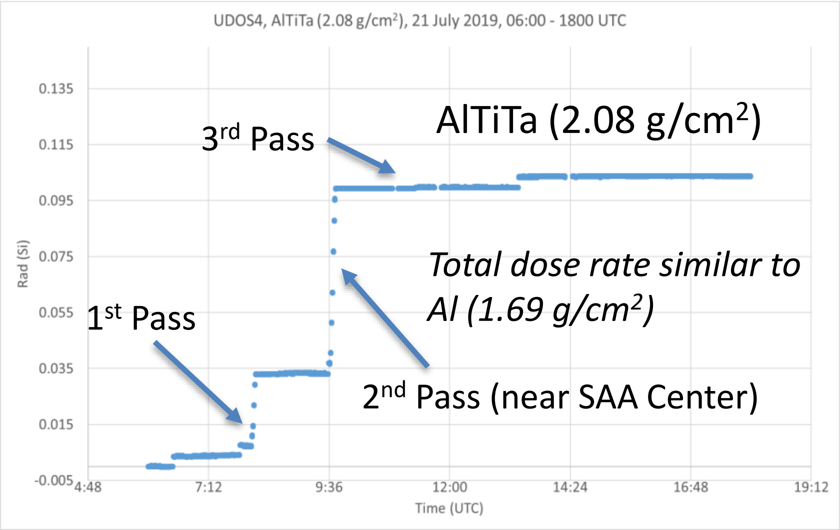


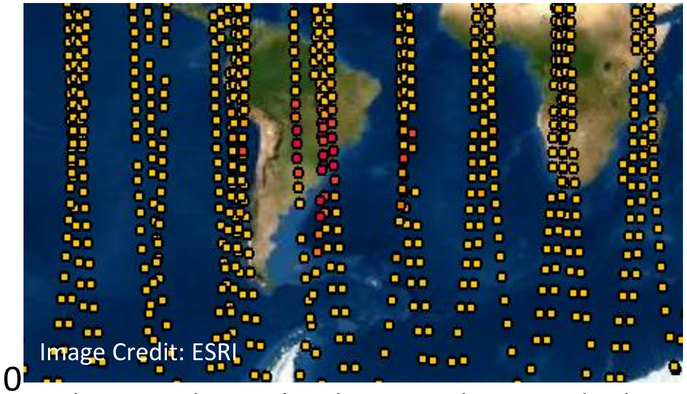
Shields-1: Shielding Dose Rate Comparisons

TID ELaNaXIX Mission Environment: 1 year duration at 500 km altitude and 85° inclination (UDOS 1-7 collected TID over a 17 day period for total dose rate, UDOS 0 over 2 months)

UDOS	Slab Shielding	Areal Density (g/cm2)	Thickness (cm)	Experimental TID (Rad (Si))/ Year	Modeled TID (Proton (p) & Electron (e)) (Rad (Si)) 2pistr omnidirectional	Modeled TID Total (Rad (Si)	Modeled TID with 6 g/cm 2 Backslab Rad (Si) Added
1	Al	6.00	2.22	**70.0 +/-3.0**	13.48+/-0.06 p, 0.21 +/- 0.03 e	13.69 +/- 0.07	27.38 +/- 0.11
2	Al	3.00	1.11	**73.6 +/-3.2**	21.77+/-0.09 p, 0.36 +/-0.03 e	22.13 +/- 0.09	35.82 +/-0.11
3	AlTiTa	3.02	0.483	**81.9 +/-3.4**	25.68+/- 0.10 p, 0.18 +/- 0.04 e	25.86 +/-0.10	39.55 +/-0.13
4	AlTiTa	2.08	0.429	**84.3 +/-2.5**	28.79 +/- 0.10 p, 0.15 +/- 0.03 e	28.94 +/- 0.10	42.63 +/-0.13
5	AlTi	1.33	0.378	**89.7 +/-2.7**	32.77+/-0.11 p, 6.36+/-0.25 e	39.03 +/- 0.27	52.72 +/-0.28
6	Al	1.26	0.465	**90.9 +/-2.7**	32.24 +/- 0.11p, 8.79+/- 0.29e	41.03 +/- 0.31	54.72 +/-0.32
7	Al	1.69	0.624	**84.3 +/-2.5**	28.67 +/- 0.10 p, 2.00 +/- 0.14 e	30.67 +/-0.14	44.36 +/- 0.16
	Sphere	Shielding	Relevant	Shielding	for Comparison		
	Al#	0.535	0.198	n/a	117 +/- 4 p, 1266+/-47 e	1383+/-47	n/a
	Z-Shield LEO Light*	1.05	0.203	n/a	104.2 +/-3.1 p, 45.5+/-8.7 e	149.7+/-9.2	n/a
	Z-Shield LEO	2.15	0.203	n/a	95.1+/- 2.7 p, 10.7 +/- 4.0 e	105.8+/-4.8	n/a
	Z-Shield GEO^	3.00	0.254	n/a	81.7 +/-2.9 p, 0 e	81.7+/-2.9	n/a
0	Z-Shield Vault	3.02	0.483	**75.6 +/- 3.2**	75.6+/- 6.1 p, 0 e	75.6+/-6.1	n/a
	Al	3.00	1.11	n/a	64.7 +/- 8.4 p, 1.5 +/- 1.5 e	66.2 +/-8.5	n/a

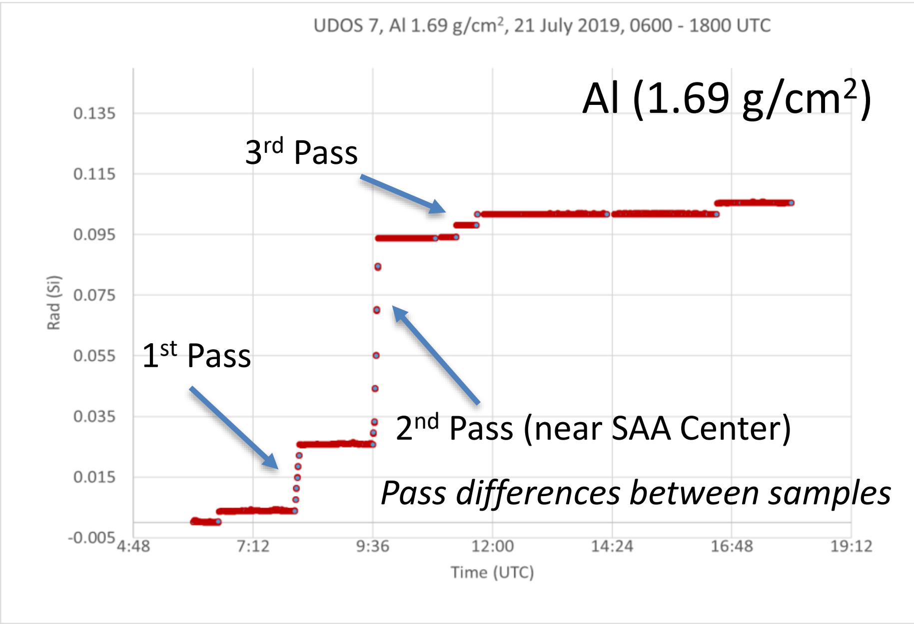
Dosimetry with the South Atlantic Anomaly (SAA)

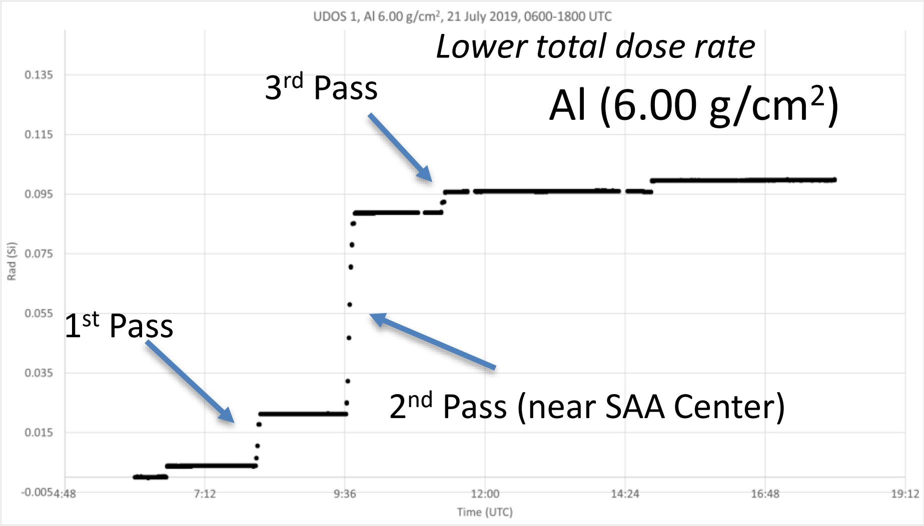




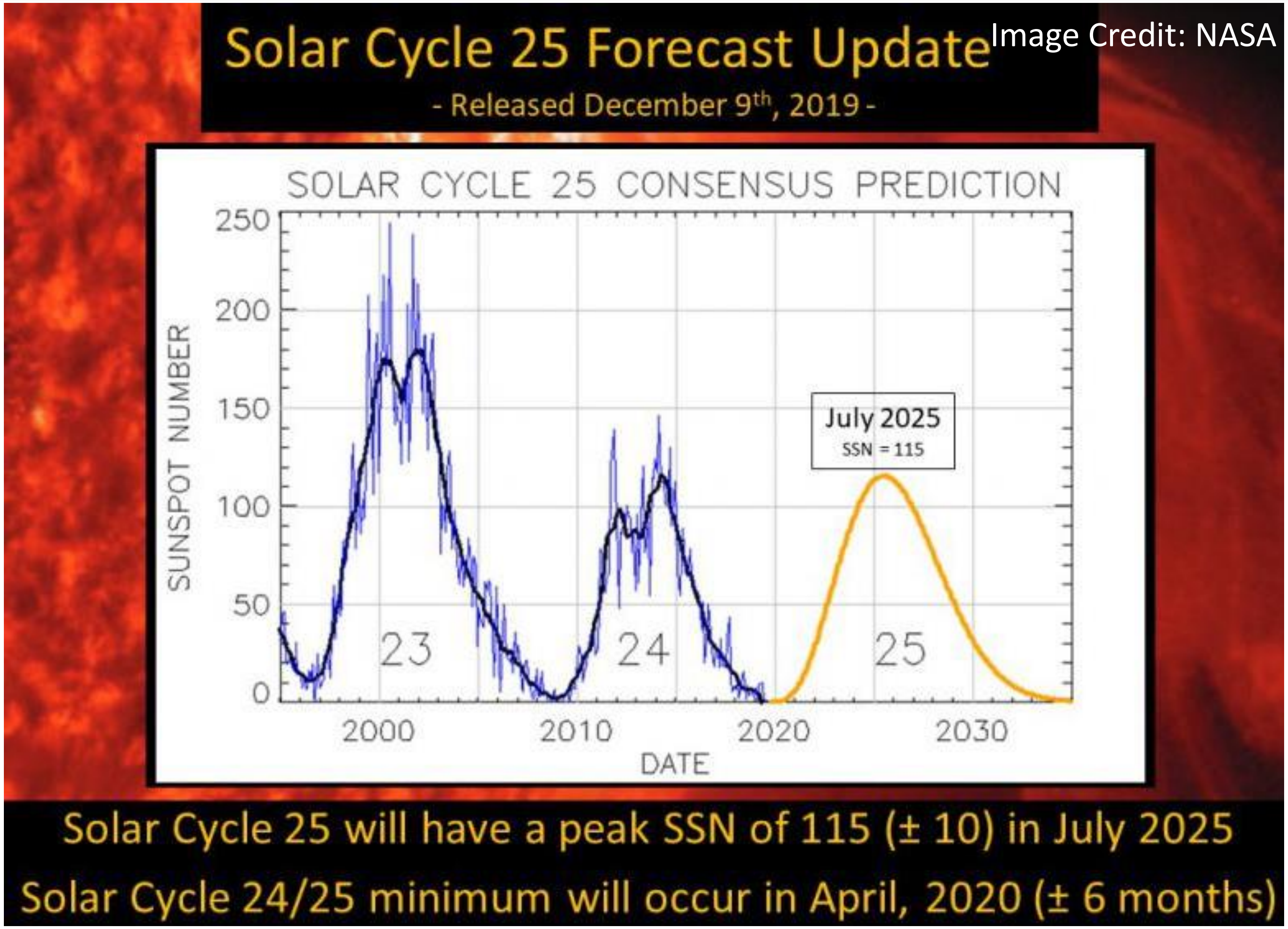
Relative Radiation levels over 2 day Period July 2019

Shielding samples behind μDosimeters (μDOS)s





Solar Activity Forecast: Solar Minimum Today and Maximum estimated for 2025



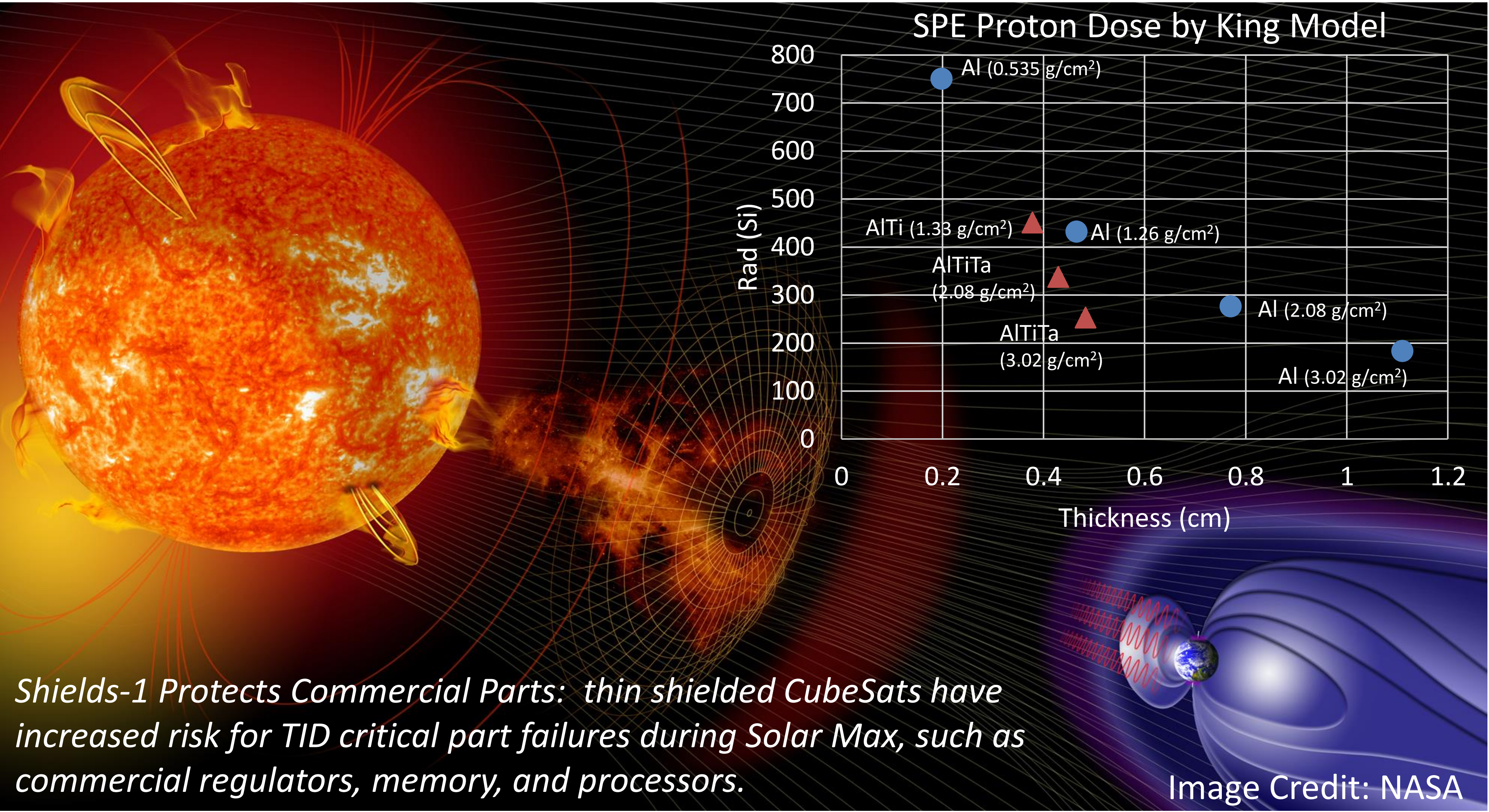
https://www.swpc.noaa.gov/news/solar-cycle-25-forecast-update

Solar Particle Event Animation

https://spaceplace.nasa.gov/solar-activity/en/

Solar Particle Event (SPE) Radiation Estimate: Polar Low Earth Orbit

Low volume Z-Shielding reduces potentially SPE catastrophic impacts on commercial parts



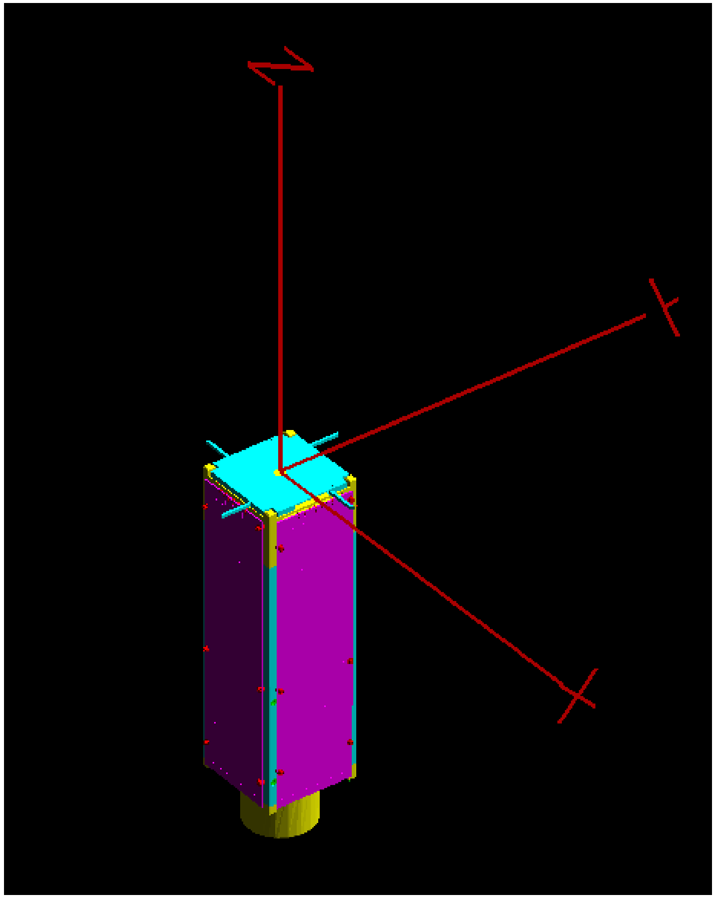
Shields-1 Protects Commercial Parts: thin shielded CubeSats have increased risk for TID critical part failures during Solar Max, such as commercial regulators, memory, and processors.

Image Credit: NASA

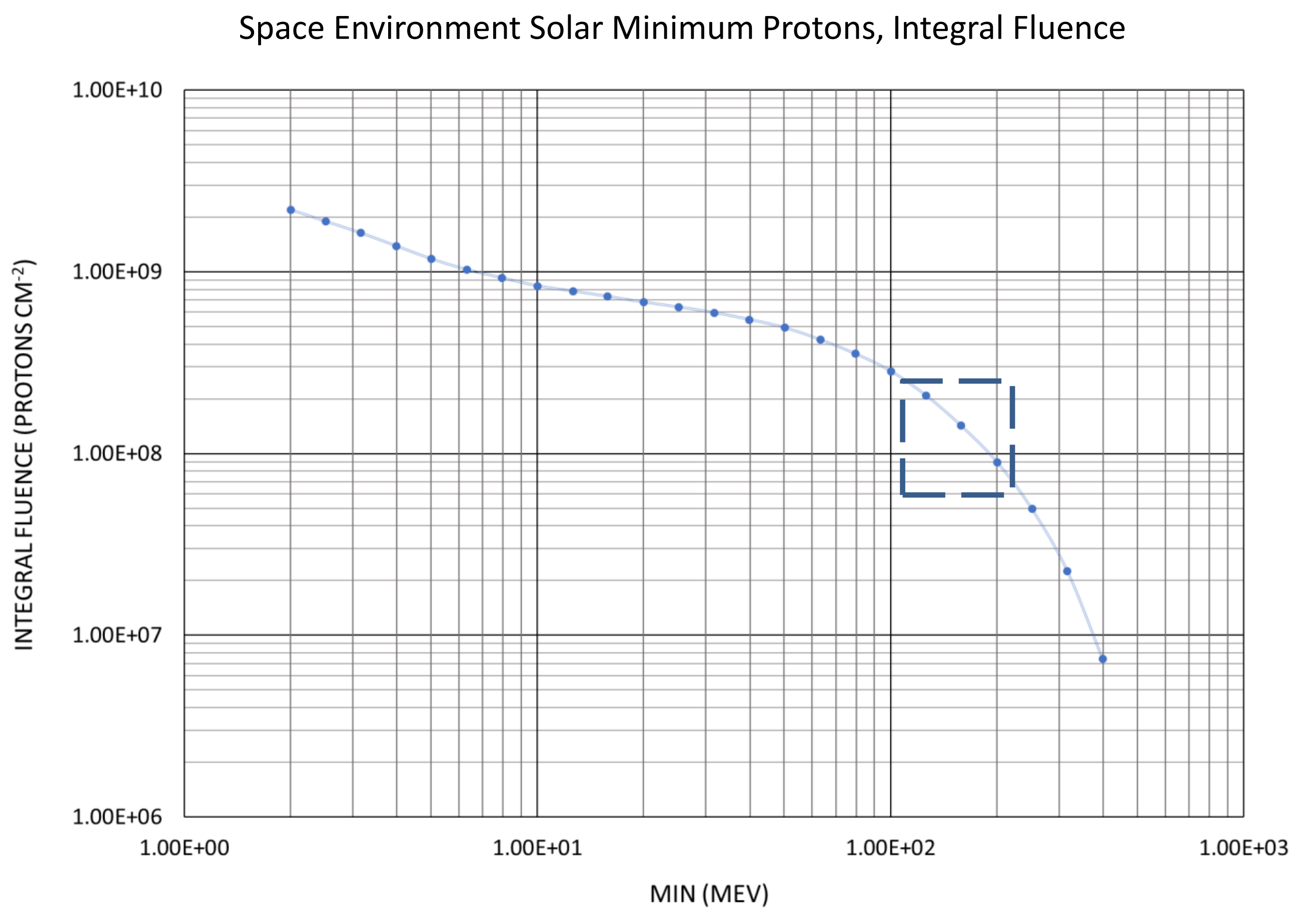
Effective Shielding Approximations by NOVICE

- **Polar Low Earth Orbit (LEO):**
  - **85º Inclination**
  - **500 km apogee/ perigee**
- **1 year mission, AP8 AE8 Radiation Belt Model, Solar Protons, SOLPRO (King) Model**
- **Adjoint Fluence measurements at 8 μDosimeter locations, behind shielding**
- ***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.***

Shields-1 CAD Model



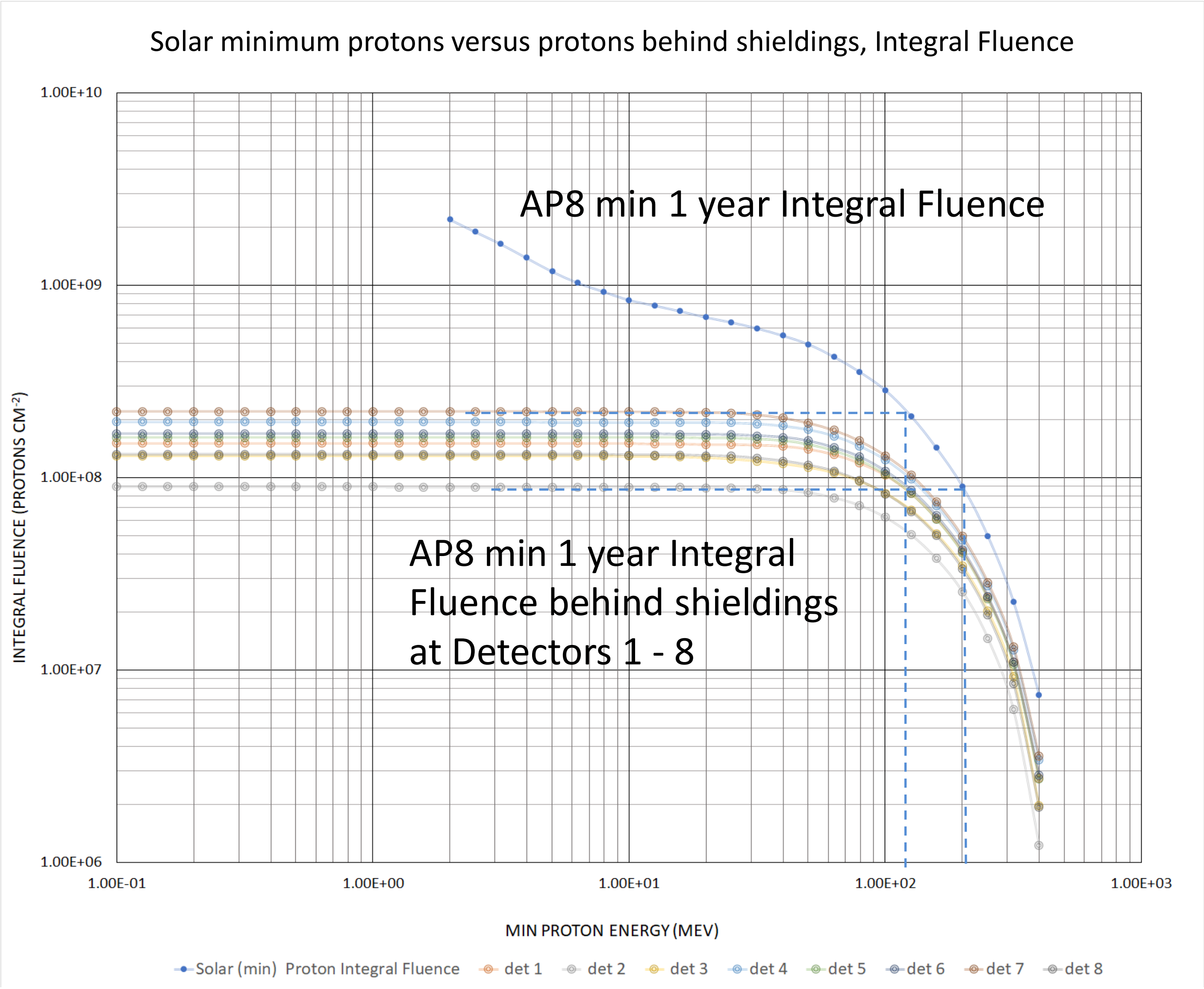
Shields-1 NOVICE Model Fluence (Solar min)



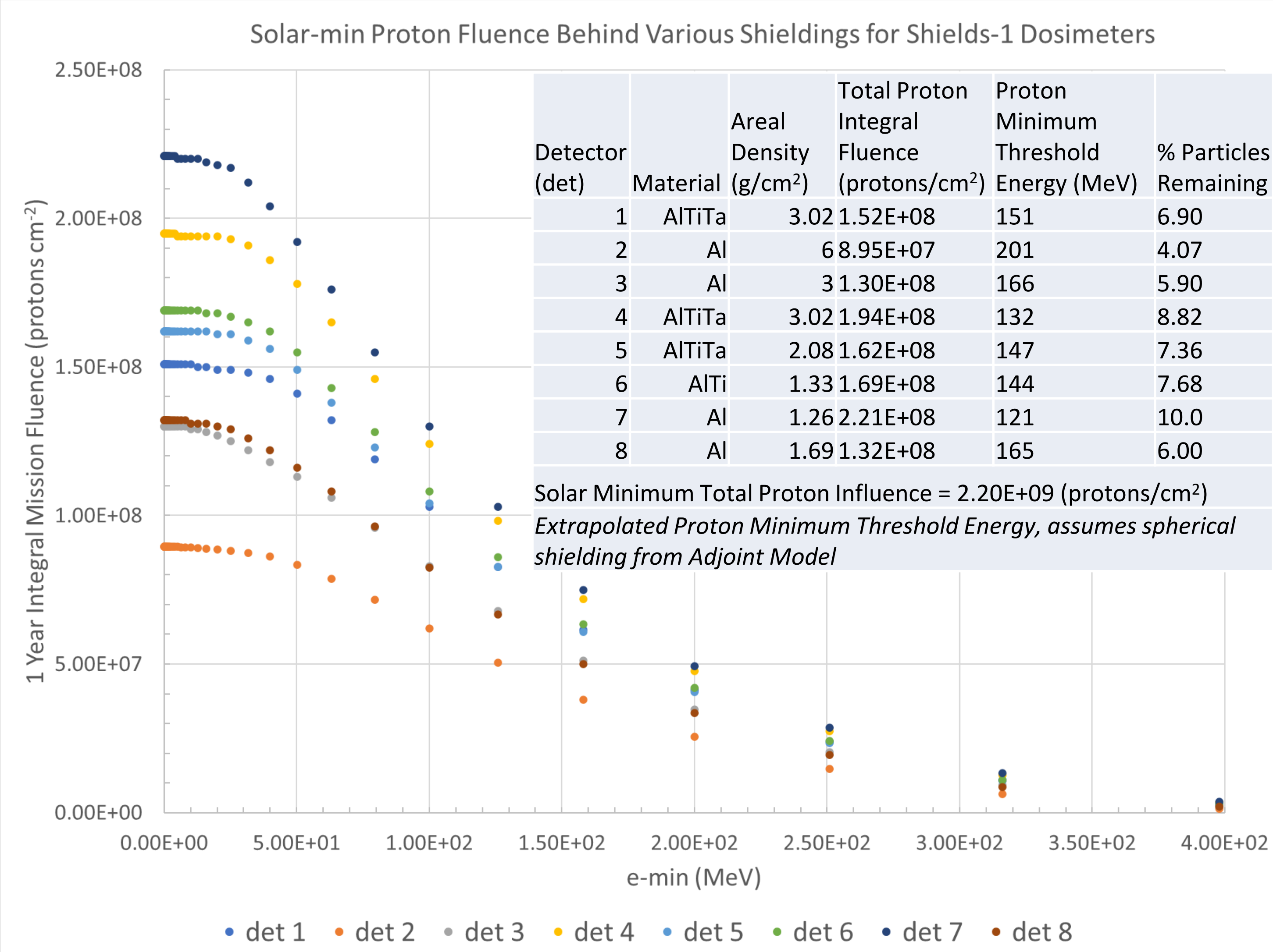
Boxed Area: 120 MeV to 220 MeV, *minimum proton energy thresholds for Shields-1 dosimeters behind shielding*

The exact minimum proton energy thresholds are determined from extrapolating each detector integral fluences from the space environment proton integral fluence versus minimum proton energy.

Visual Comparison of Remaining Protons Behind Shielding



Minimum Proton Energy Thresholds for Shields-1

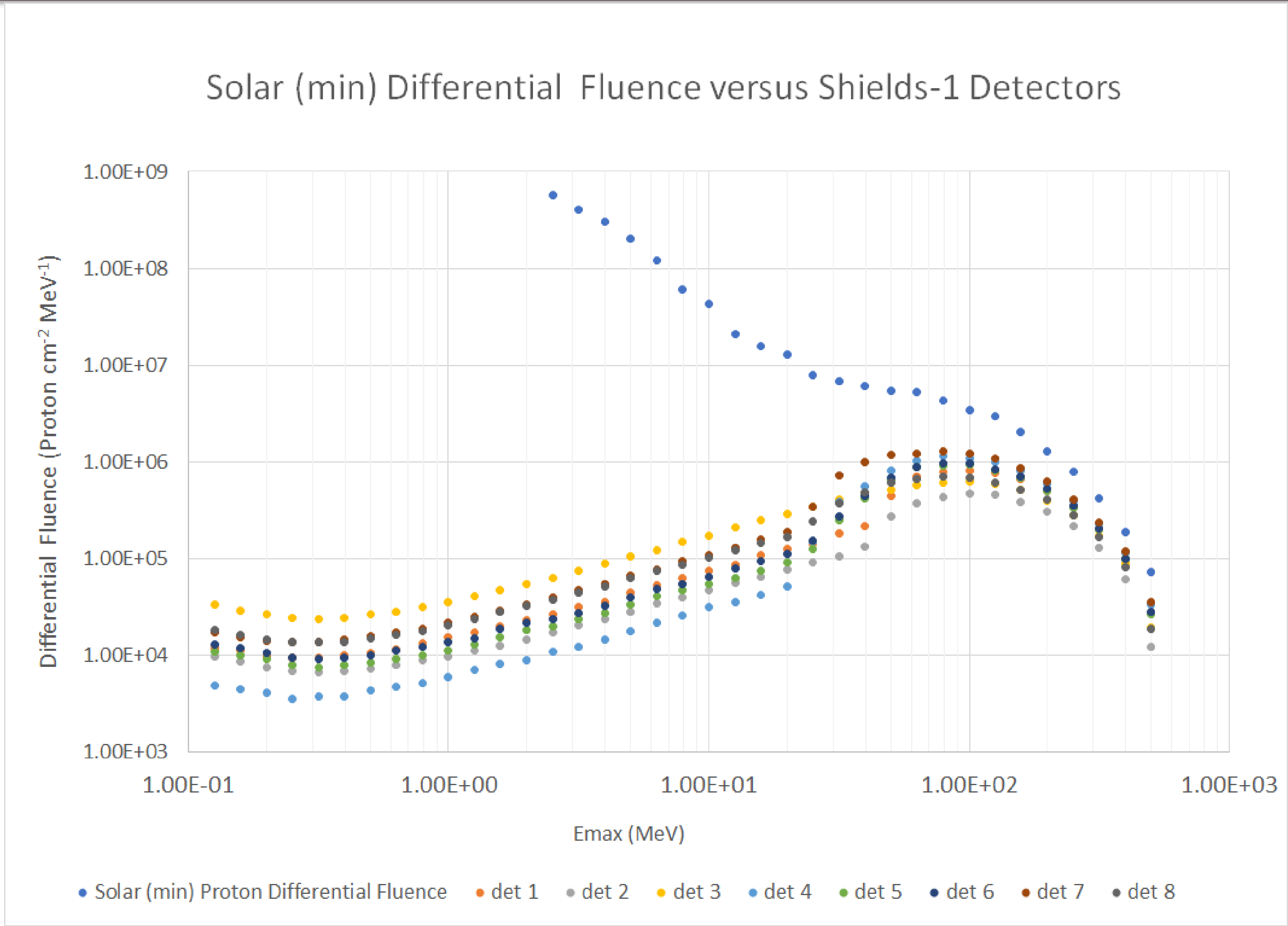


Detector (det)	Material	Areal Density (g/cm^2)	Total Proton Integral Fluence ($protons/cm^2$)	Proton Minimum Threshold Energy (MeV)	% Particles Remaining
1	AlTiTa	3.02	1.52E+08	151	6.90
2	Al	6	8.95E+07	201	4.07
3	Al	3	1.30E+08	166	5.90
4	AlTiTa	3.02	1.94E+08	132	8.82
5	AlTiTa	2.08	1.62E+08	147	7.36
6	AlTi	1.33	1.69E+08	144	7.68
7	Al	1.26	2.21E+08	121	10.0
8	Al	1.69	1.32E+08	165	6.00

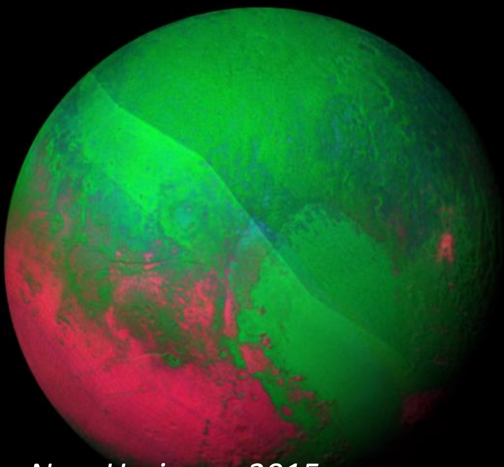
Solar Minimum Total Proton Influence = 2.20E+09 ($protons/cm^2$)

Extrapolated Proton Minimum Threshold Energy, assumes spherical shielding from Adjoint Model

Remaining Proton Energies and Numbers Behind Shieldings

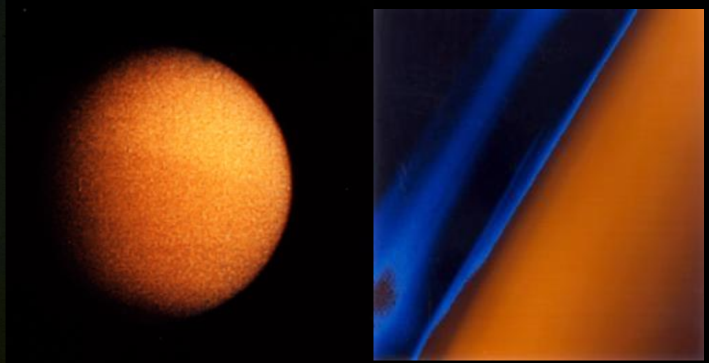


Outer Planets' and Moons' Flybys

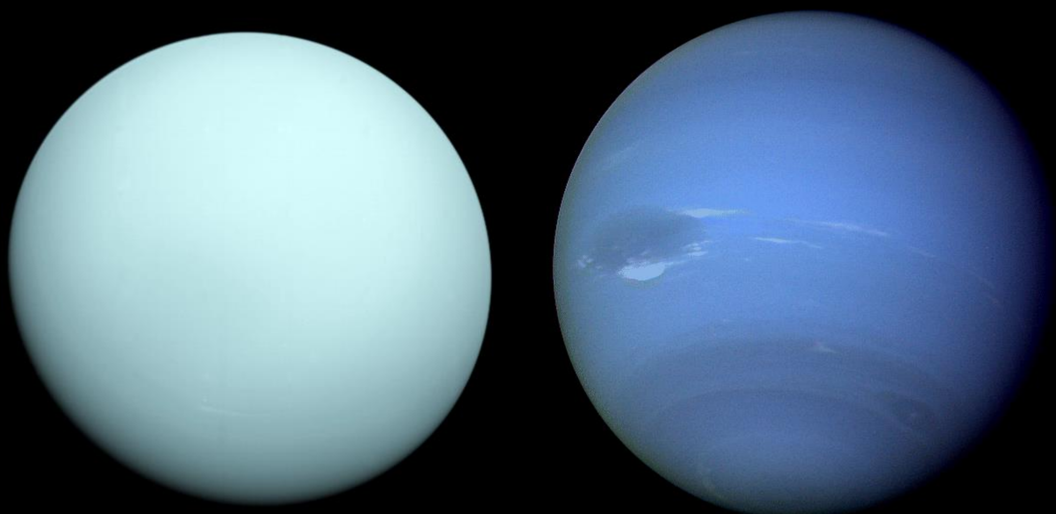


New Horizons, 2015

Pioneer 11, 1979



Voyager 1 1980



Voyager 2, 1986 and 1989

Pioneer 10 1973,

Image Credits: NASA

Previous Outer Planet FlyBys and Beyond

Image Credit: NASA

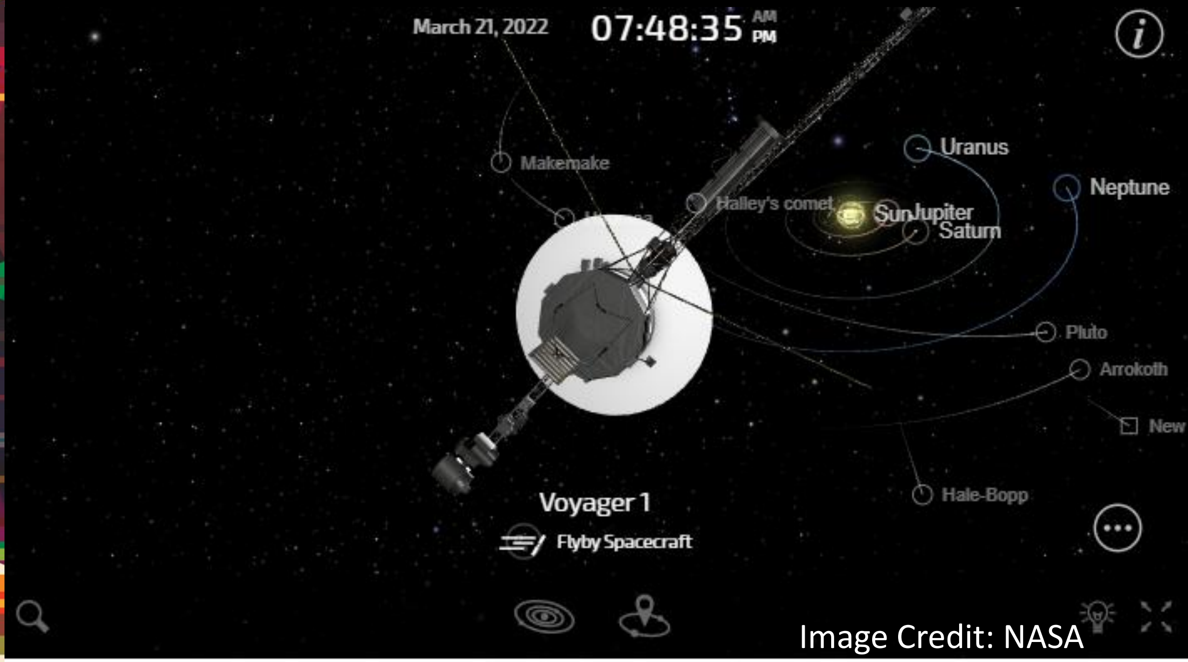


Image Credit: NASA

Slowing Down Radiation Effects like a Time Machine, Intergenerational: Missions Extending Beyond our Lifetimes

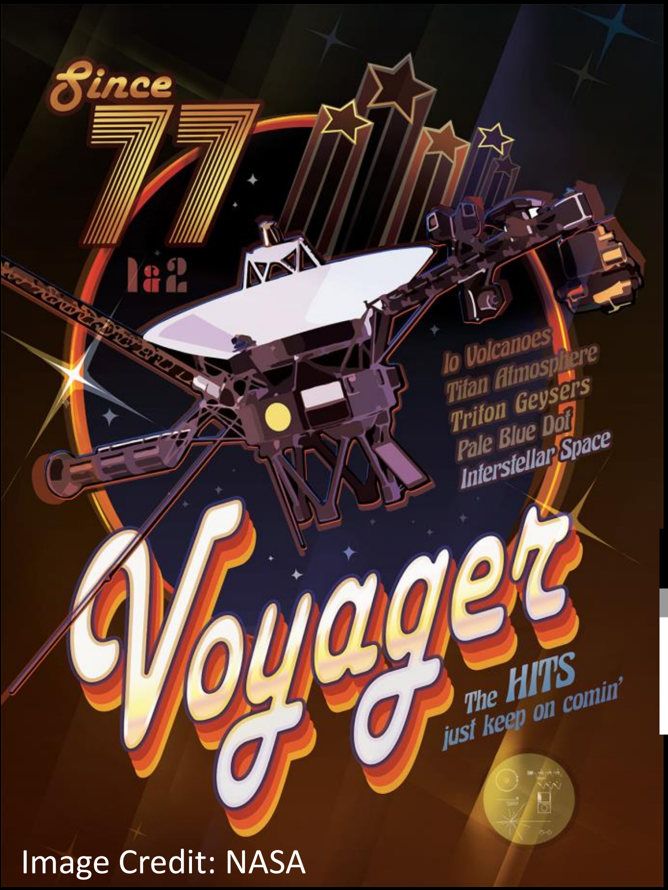


Image Credit: NASA

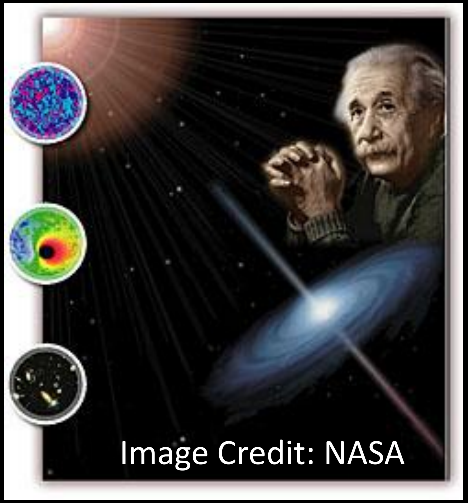
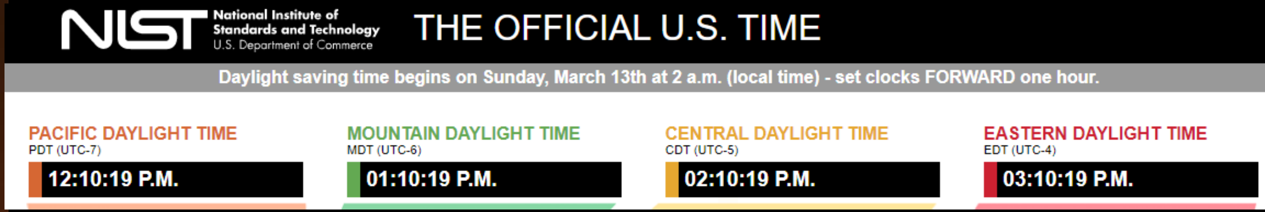


Image Credit: NASA


Image Credit: Microsoft



Disco to Hip Hop Generations

Planting the Seeds of Multigenerational Exploration

- Develop and prepare small spacecrafts that can withstand solar radiation environment, galactic cosmic radiation, and long duration missions
- Nurture academic, government, citizen interest
- Engaging our Scientific Curiosity
- Gifting Forward:
  - The story of our existence in the Solar System, Milky Way, and Universe
  - Training our next Science, Technology, Engineering, and Mathematics Explorers
- Coordinate multigenerational effort and data availability
- Adding to Peaceful Cooperation amongst Multiple Cultures and Countries


Image Credit: NASA


Image Credit: NASA

Image Credit: NASA

Conclusion

- Z-Grade Shielding offers reduction of total ionizing dose on sensitive electronics
- Almost all the radiation in Polar Low Earth Orbit is attributed to the South Atlantic Anomaly (SAA), when using shielding that stops electrons.
- Slab Radiation Shielding arrangement enables additional radiation dosimetry science, such as monitoring SAA behind different shielding thicknesses, as estimated using slowing down approximations for minimum proton threshold energies.
- Shields-1 dosimeters discern energetic proton contributions with energies higher than 201 MeV, which are ~4% of remaining particles contributing to total dose in polar low earth orbit.

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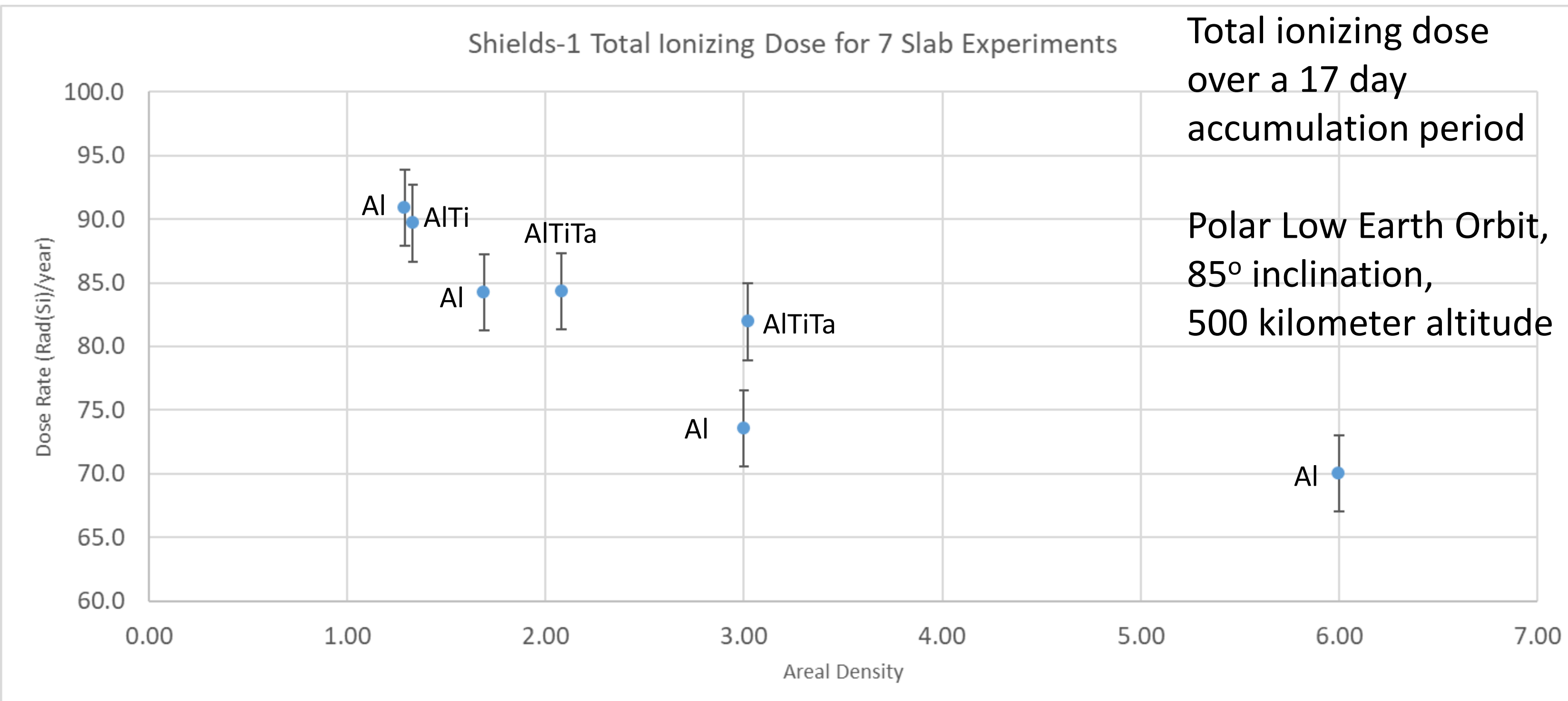
- ELaNaXIX Mission NASA CubeSat Launch Initiative
- NASA Wallops Flight Facility CubeSat Ground Operations

Back-ups

Z-Grade Radiation Shielding Compared to Baseline Aluminum



Total ionizing dose over a 17 day accumulation period

Polar Low Earth Orbit,
85° inclination,
500 kilometer altitude