SSC15-XII-9

Shields-1, A SmallSat Radiation Shielding Technology Demonstration

D. Laurence Thomsen III
NASA Langley Research Center, Advanced Materials and Processing Branch, 6A West Taylor Street, Hampton, VA 23681; 757-864-4211
d.l.thomsen@nasa.gov

Wousik Kim
Jet Propulsion Laboratory, Mission Environments Group, 4800 Oak Grove Drive, MS 122-107, Pasadena, CA 91109-8099; 818-354-7884
wousik.kim@jpl.nasa.gov

James W. Cutler
University of Michigan, Department of Aerospace Engineering 1320 Beal Avenue, 3013 FXB Building, Ann Arbor, MI 48109-2140, 734-615-7238.
jwcutler@umich.edu

ABSTRACT

The NASA Langley Research Center Shields CubeSat initiative is to develop a configurable platform that would allow lower cost access to Space for materials durability experiments, and to foster a pathway for both emerging and commercial-off-the-shelf (COTS) radiation shielding technologies to gain spaceflight heritage in a relevant environment. The Shields-1 will be Langley's first CubeSat platform to carry out this mission. Radiation shielding tests on Shields-1 are planned for the expected severe radiation environment in a geotransfer orbit (GTO), where advertised commercial rideshare opportunities and CubeSat missions exist, such as Exploration Mission 1 (EM-1). To meet this objective, atomic number (Z) graded radiation shields (Z-shields) have been developed. The Z-shield properties have been estimated, using The Space Environment Information System (SPENVIS) radiation shielding computational modeling, to have ~30% increased shielding effectiveness for electrons, at half the thickness of a corresponding single layer of aluminum. The Shields-1 research payload will be made with Z-graded radiation shields of varying thicknesses to create dose-depth curves to be compared with baseline materials. Additionally, Shields-1 demonstrates an engineered Z-grade radiation shielding vault protecting the system's electronic boards. The radiation shielding materials' performances will be characterized using total ionizing dose sensors. Completion of these experiments is expected to raise the technology readiness levels (TRLs) of the tested Z-graded materials. The most significant contribution of the Z-shields for the SmallSat community is that it enables cost effective shielding for small satellite systems, with significant volume constraints, while increasing the operational lifetime of ionizing radiation sensitive components. These results are anticipated to increase the development of CubeSat hardware design for increased mission lifetimes, and enable out of low earth orbit (LEO) missions by using these tested material concepts as shielding for sensitive components and new spaceflight hardware.

MISSION

Background:

The geotransfer orbit (GTO) has been a proving ground for space technology developments due to accelerated lifetime testing conditions[1,2,3]. One year in GTO has approximately a radiation dose equivalent to 8-10 years in low earth orbit (LEO) and geostationary earth orbit (GEO), enabling new technologies space heritage through demonstration in the severe radiation environment. The radiation levels are 10 times the level of LEO.[4] Multiple satellite missions in the 1990s have taken advantage of the GTO for technology development and science, including Combined Release/Radiation Effects Satellite (CRRES), Clementine, and Space Technology Research Vehicle (STRV). The Shields CubeSat platform is designed to raise the development levels of new radiation shielding and charge dissipation technologies from proof of concept, technology readiness level[5] (TRL) 3, to demonstration in space, TRL 6, within a year.

GTO also provides a relevant electron-rich space environment for technology development of radiation protection and charge dissipation materials. Internal electrostatic discharge has historically been the most significant reason for lost spacecraft with numerous arc discharges associated with deep charging of dielectrics.[6,7] 30 MeV electrons were first detected in the Jovian environment in 1975 during the Pioneer 11 flyby[8], which is significantly higher energy than Earth orbit electrons and is the basis of Jovian spacecraft mission planning.[9] For Outer Planet technology development, electrons in the Jovian environment associated with the Europa Mission have the largest contributions to the estimated 2.1 MRad behind 100 mil Al expected dose.[10] This is over 7 times the dose in GEO behind 100 mil Al[11]. Shielding is a critical design element of long duration spacecraft with defined weight budgets. Galileo Spacecraft mass, which includes shielding, was 2380 Kg.[12] Z-Grade shielding has been a method of reducing radiation with layered atomic number materials.

Science missions associated with the technology developments in GTO have consisted of space environment characterization with dosimetry. CRRES used dosimeters behind various shielding thicknesses to characterize low, high, and very-high linear energy transfer particles. The low-energy transfer particles contained electrons, protons, and plasma. The very-high linear energy transfer proton particles were energies from 100 to 200 MeVs.[1] Previous space environment materials technology development studies have been conducted through passive experiments where samples are returned, such as Long Duration Exposure Facility (LDEF)[13], Mir Environmental Effects Platform (MEEP)[14], and early Materials on International Space Station Experiment (MISSE)[15] in LEO. Shields-1 offers technology developments through rideshare within the CubeSat infrastructure. Radio Aurora Explorer-2 (RAX-2)[16] and MCubed-2[17] are two recent technology development successes. Shields-1 leverages the space heritage of these two systems' electronics to power and operate the research payload. Table 1 highlights anticipated Shields-1 contributions to technology development.

Concept:

Shields-1 will operate in GTO providing radiation and operational data from the inner proton and outer electron belt regions. If the preferred GTO rideshare is not available, Shields-1 can operate in the polar LEO environment. Table 2 describes desired orbit options for the technology development mission. The orbits can be GTO or highly elliptical orbit (HEO). The technology development can also be achieved with polar LEO, although it will not receive the same radiation dose. Dosimeters are behind a range of shielding areal densities and provide data about particle energies associated with linear energy transfer. Figure 1 depicts Shields-1 orbital trajectory traveling through both the outer electron (blue-green) and inner proton belts (magenta).

Table 1. Shields-1 Mission Highlights.

- Extends typical CubeSat missions from 3 months to years with an atomic number Z-grade vault and expected electron shielding effectiveness of ~30% or more compared to Al and with half the volume.
- Demonstrates a Charge Dissipation Film designed for extreme charging environments, such as Europa, medium Earth orbit (MEO), geosynchronous Earth orbit (GEO), and polar low Earth orbit (LEO).
- Develops and demonstrates a one-piece atomic number (Z)-grade radiation protection for electron radiation environments to TRL 6, applications for polar LEO, MEO, GEO, and Europa. (i.e., Earth orbits where over 99+% Earth-orbiting satellites operate).
- Matures innovative μdosimeters.
- Reduces technology development schedule and associated costs by collective testing in a relevant space environment.

Table 2. Shields-1 Mission Parameters.

Desired Orbits		Acceptable Orbit Ranges
Altitude (GTO/HEO)	350-37,500 km	240-200,000 km
Inclination	0-23	0-90
Altitude (Polar LEO)	450-800	400-1000
Inclination	80-110	70-120

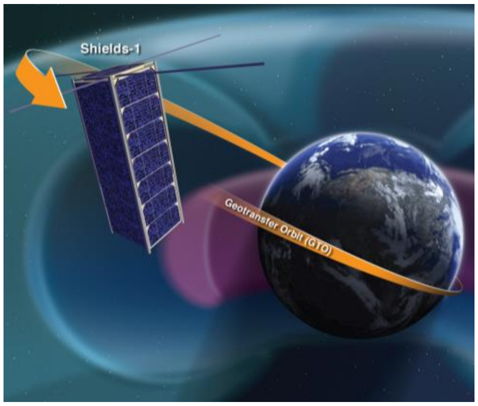

Figure 1. SHIELDS demonstrates CubeSat Vault Electronics and a charge dissipation film, enabling future long duration missions.

Experiments:

The Shields-1 CubeSat experiment design incorporates three experiments:

1. **Vault Electronics**: The atomic number (Z)-grade vault demonstrates shielding performance by measuring total ionizing dose and system health data. The incorporation of the system health information with total ionizing dose (TID) information benchmarks the system's performance in GTO. The vault electronics carries a Teledyne µdosimeter with sensitivities of 14 µRads.[18] The TID data, with health monitoring of memory errors and power on resets and the ephemeral location data, will support the characterization of the vault electronics and shielding. It is expected to have a yearly total dose of 2.9 kRad[19] for the trapped belt environments. This is almost a factor of 2 below the NASA design guideline for commercial off-the-shelf (COTS) devices for use in LEO.[20]

2. **Charge Dissipation Film Resistance**: A charge dissipation film technology demonstration using resistivity measurements as a function of temperature. LUNA XP-CD-B is a charge dissipation film designed for the extreme Outer Planet environments, developed through the NASA STTR Phase I proposal award NNX11CI29P. It is referred to often as a "leaky" dielectric with a volume resistivity range of 10^8 to 10^{10} ohm-cm. The experiment for Shields-1 is to measure the resistance of the charge dissipation film in its typical coating thickness electroded in a guarded parallel plate configuration[21] over time and compared to a baseline resistor of a known value. Table 3 shows the expected resistance values. The experiment is set-up for a 2-wire resistance measurement using a fixed-current source and sensing the voltage (Figure 2). The expected resistance is 2 MOhm at 25°C. The measured voltage is within the typical analog to digital converter (ADC) of the flight computer or an additional research ADC board. This experiment tests the stability of the measured resistance over time with respect to a known resistor as a baseline. This measurement is not a measurement for the charge dissipation application. A well-known example of charge dissipation was done on CRRES[22] showing clearly the contribution of a charge dissipation film and the corresponding reduction of arc discharges. An excellent ground-testing example has recently been done.[23] The ground testing charge dissipation experiments are beyond the current scope of this test, but are worthwhile to pursue in the future because those tests document the dissipation application directly to the operational use. The proposed material test herein regularly checks the performance of the resistance physical property over time in the relevant space environment, which is the critical charge dissipation physical attribute used for the technology development. The vault electronic boards will be coated with LUNA XP-CD-B to further reduce the risk of internal charging as a demonstration, in addition to the resistance experiment.

Table 3. Expected Resistance Results for Charge Dissipation Film

LUNA XP-CD-B Volume Resistivity	Specimen Dimensions	Expected Resistance
4.7 x 10e^9 ohm cm at 25°C	Area 5 cm^2 Thickness 0.0025 cm	2.3 MOhm

(I * Thickness*volume resistivity) / area = V V/I=R, I=Current, R=Resistance, excitation source 1µA

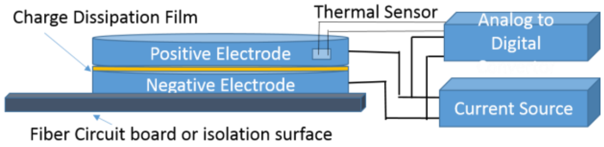

Figure 2, Charge Dissipation Film Experiment: expected resistance to support a 2-wire resistance measurement to measure resistance over time at a known temperature and compare to a baseline resistor of known value at a known temperature.

3. **Vault Shielding Development**: A Z-grade Al/Ta dose-depth curve experiment, with Al baselines, provides needed shielding data to support the vault electronics demonstration. The Z-grade shielding performance is benchmarked with Al baselines as a function of total radiation, proton belt radiation, and electron belt radiation environments. These experiments with baselines fully support the vault electronics demonstration.

Space Environment:

Neither the space environment nor the radiation transport models can be used to extrapolate and predict the durability of materials and devices in space where the radiation is mixed, the particle fluence and energy changes due to space weather[24], the temperature varies[3], and electromagnetic spectrum fluctuates[25]. The only way to assess the performance and advance the TRL is to fly in the relevant environment of space.

GTO has a significant radiation environment compared to polar LEO. GTO supports technology development experiments with the increased electron fluence. Using The Space Environment Information System (SPENVIS) radiation shielding computational modeling, figure 3A shows that protons less than 30 MeV have a larger fluence in GTO than polar LEO, and under a magnitude difference at higher energies. The GTO electrons, Figure 3B, have a significant fluence with magnitudes greater than 1e^{12} cm^{-2} up to 4 MeV, whereas, the same magnitude range is up to 4 MeV protons. In Figure 3B, polar LEO's electron fluence shows that there are 4-6.5 MeV electrons, which support shielding characterization, although significantly less fluence than in GTO. The electron particle fluence is 1 to 100 times greater for GTO for all energies less than 6 MeV.

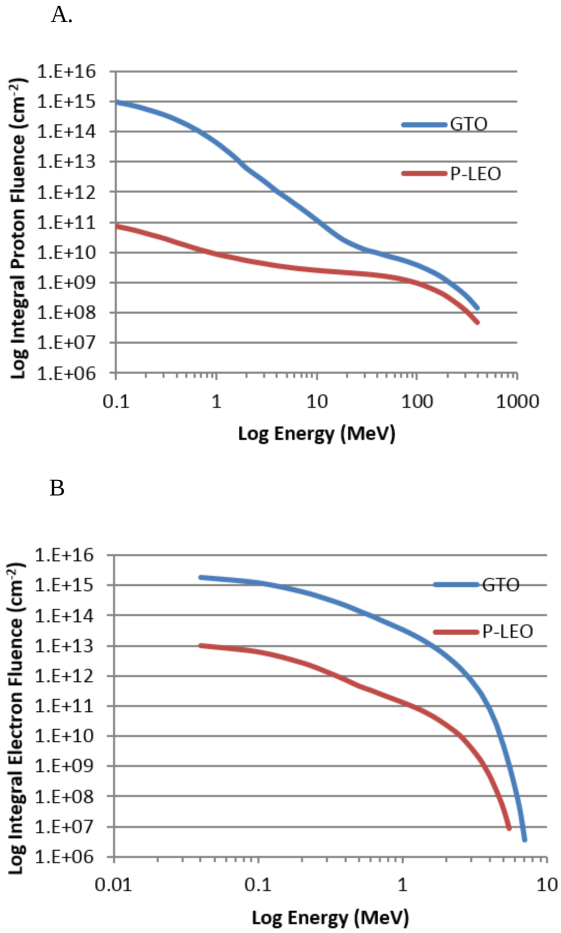

Figure 3 A and B. SPENVIS: AP8min-AE8 Max Model for GTO and Polar LEO, ELaNa III satellite environment particle fluence. A. Proton fluence. B. Electron Fluence.

It is well known that the range of an energetic electron penetrates through a material further[4], and the GTO environment supports electron shielding development. Although the electron energies are not as high as the 30-MeV Jovian environment[8], GTO is the closest relevant space environment available for rideshare.

Experiment Design:

In Figure 4A, the energetic protons penetrate the sample at all incident angles. Summation of angles less than 75-80 degrees have 95% or greater incident protons passing through the slabs. In Figure 4B, at angles greater than 75 degrees, there are no observable penetrations of electrons through the samples.

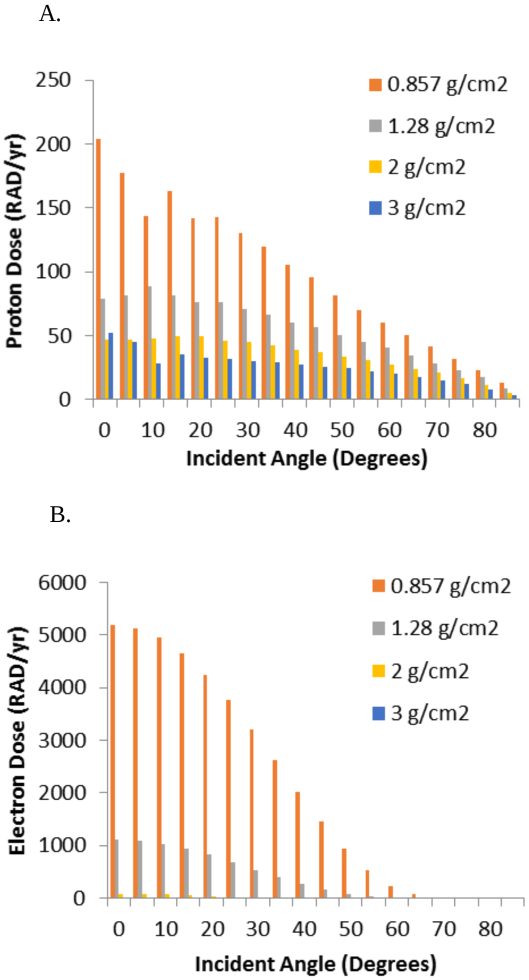

Figure 4 A and B. Dose determinations using SPENVIS Shieldose-2 Al model half sphere results with trigonometric determined incident angle dependencies of areal density in a slab geometry. A. Proton dose incident angle dependence. B. Electron dose incident angle dependence.

The CubeSat architecture permits shielding sample characterizations with an infinite slab shielding approximation approach, Figure 5. The calculations to determine approximate energies versus incident angles were critical in defining a working research payload architecture within the constraints of the CubeSat research payload surface area. A large shielding test sample area, supporting the required large field of views, enable wide angle incidence of space radiation onto planned test samples of varying areal densities, enabling the infinite slab shielding approximation.

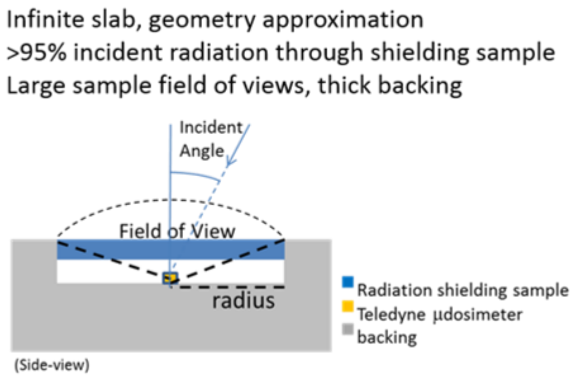

Figure 5: Setup as an infinite slab approximation with 6 g/cm^2 Al backing, promoting a repeatable experimental design with samples of varying thicknesses.

Expected Results and Discussion:

These shielding experiments are designed for GTO, where radiation levels are sufficient to build dose depth curves up to 3 g/cm^2, which is a typical vault areal density. The GTO used for radiation modeling in Shieldose-2 and SPENVIS MULASSIS (Figure 6A and 6B.) was 23° inclination, 37,500-km apogee, and 240-km perigee using the AP8min-AE8 Max Model Environment over a year period. In figure 6A, the expected ionizing dose of 10-400 MeV protons shows Al/TA has similar shielding performance to Al at approximately half the thickness. In figure 6B, the expected ionizing dose of 4-6.5 MeV electrons shows greater than 30% improvement in shielding effectiveness for Al/Ta over Al.

The predominant radiation dose received behind the shielding samples originated from the proton ionizing dose. In figure 6A, the dose levels appear below 1 kRad for Al and Al/Ta at areal densities above 1.7 g/cm^2, whereas Ta appears higher. In figure 6B, the electron radiation dose at areal densities above 1.7 g/cm^2 appear below 200 Rad for Al/Ta and Ta. At areal densities greater than 2 g/cm^2, the electron ionizing dose for the Al/Ta appears to be reduced almost completely. Overall, the expected accumulated total ionizing dose behind 3 g/cm^2 shielding will originate from proton radiation.

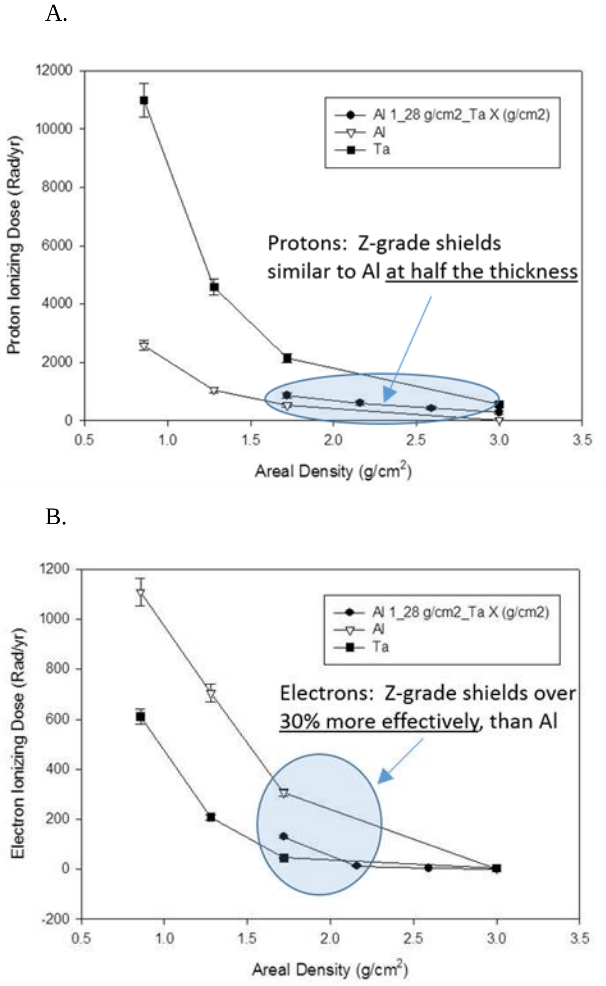

Figure 6 A. and B SPENVIS: Ionizing dose from AP8min-AE8 Max Model for GTO using MULASSIS with propagated integration error from the µdosimeter as a function of areal density for planned Al, Ta, and Al/Ta samples. A. Proton Ionizing Dose. B. Electron Ionizing Dose.

The Al/Ta Z-grade offers a thickness reduction approaching half of a typical 3 g/cm^2 (1.1 cm) Al shield. With CubeSat dimensions for a 1U at approximately 10 cm x 10 cm x 10 cm (1000 cm^3), the loss of electronics card volume area and cable volume would be 295 cm^3 or ~30% of the 1U volume. A shielding thickness of a 0.5 cm Z-grade would only have a volume reduction of ~14%. Overall, the Z-grade is anticipated to perform similar to Al for the proton environment and over 30% more effective at areal densities of 1.7 to 2.2 g/cm^2 for an electron environment.

The expected results demonstrate the shielding performance in the relevant modeled space environment. The actual Z-shielding testing during the mission is anticipated to raise the TRL to 5 by showing the durability of the shielding with long term dose measurements occurring over multiple orbits. In comparison, ground experimental testing Z-grade shielding samples over a period of minutes by exposing the shielding to mono-energetic radiation sources and measuring stopping power or dose behind shielding limits the TRL to 4. Successful system operation of the Z-grade vault electronics can raise the TRL higher than 5 with the Z-grade shielding being used as intended, protecting the system electronics and establishing space heritage.

Conclusion

The addition of Z-grade shielding into CubeSat missions offer the reduction of TID on sensitive electronic components, such as memory cards and complementary metal-oxide semiconductor (CMOS) devices. The near complete elimination of electron radiation at areal densities greater than 2 g/cm^3 reduces the chance of internal charging effects on electronic boards inside the CubeSat that causes anomalies. The use of the Z-grade radiation shielding enables shielding applications in volume constrained small satellites and instrument enclosures, where typical aluminum shielding is volume prohibitive. The technology development of the Z-grade radiation shielding and charge dissipation film through the planned Shields-1 spaceflight offer opportunities for incorporation into future missions with the acquired space heritage.

Acknowledgments

The authors wish to thank J.M. Lauenstein, A. Simon, C. Marshall, N Green, H. Garrett, I. Jun, K. Somervill, M. Cooney, R. Bryant, and S. Thibeault for helpful suggestions. DLT wishes to thank A. Goff, B. Seufzer, V. Stewart, M. Jones, N. Miller, and H. Soto for technical discussions.

References

---

1. Ray, K.P., Mullen, E.G., Stapor, W.J., Circle R.R., and P.T. McDonald, “CRRES Dosimetry Results and Comparisons Using the Space Radiation Dosimeter and P-Channel MOS Dosimeters”, CRRES Transactions on Nuclear Science, , Vol. 39, No 6, 1992, p. 1846.
2. Soli, G., Blaes, B., Buehler, M., Jones, P., Ratliff, J.M., and H. Garrett. “Clementine Dosimetry”, Journal of Spacecraft and Rockets, , Vol. 32, No. 6, 1995, p.1065.
3. Wells, N.R. and J. Eves, “The STRV 1 Microsatellite Series: Exploiting the Geosynchronous Transfer Orbit,” Acta Astronautica, Vol. 41, Nos 4-10, 1997, p.481.
4. Tribble, A.C., The Space Environment: Implications for Spacecraft Design. Princeton, NJ: Princeton University Press, 2003, p. 232.
5. https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html. http://esto.nasa.gov/files/trl_definitions.pdf.
6. Hastings, D. and H. Garrett, Spacecraft Environment Interactions. 1996. New York: Cambridge University Press, p.292.
7. Vampola, A.L., “Thick Dielectric Charging on High-Altitude Spacecraft”, Vol. 20, No. 1, 1987, p.21.
8. Van Allen, J.A., Randal, B.A., Baker, D.N., Goertz, C.K., Sentman, D.D., Thomsen, M.F., and H.R. Flindt, “Pioneer 11 Observations of Energetic Particles in the Jovian Magnetosphere”, Science, Vol. 188, 1975, p.459.
9. Divine, N., and H.B. Garrett, “Charged Particle Distributions in Jupiter’s Magnetosphere”, Journal of Geophysical Research, 1983, Vol. 88, A9, p. 6889.
10. Pappalardo, R. and B. Goldstein, “The Europa Clipper, Update to CAPS”, 11/4/2014, http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_084815.pdf
11. Barter, J. editor, “Space Data”, Northrop Grumman Space Technology, 2003, p.223.
12. http://nssdc.gsfc.nasa.gov/planetary/galileo.html.
13. Kinard, W., O’Neal, R., Wilson, B., Jones, J., Levine, A., and R. Calloway, “Overview of the Space Environmental Effects Observed on the Retrieved Long Duration Exposure Facility (LDEF)”, Advances in Space Research, Vol. 14, No. 10, 1994, p. 7.

14. Visentine, J., Kinard, W., Brinker, D., Banks, B., and K. Albyn, "Mir Solar-Array Return Experiment: Power Performance Measurements and Molecular Contamination Analysis Results", Journal of Spacecraft and Rockets, Vol. 39, No. 2, 2002, p. 187

15. http://www.nasa.gov/centers/langley/news/factsheets/misse_2005_prt.htm.

16. Springmann, J.C., Kempke, B.P., Cutler, J.W., and H. Bahcivan, "Initial Flight Results of the RAX-2 Satellite", 26th Annual AIAA/USU Conference on Small Satellites, 2012, SSC12-XI-5.

17. Pingree, P.J., "Looking Up: The MCUBED/COVE Mission", CubeSat Developer's Workshop, 23-24 Apr 2014, Cal Poly, San Luis Obispo, CA.

18. http://www.teledynemicro.com/product/radiation-dosimeter.

19. Spenvis Mulassis Spherical Shell Calculation for GTO 23^0 inclination, 37,500-km apogee, and 240-km perigee using the AP8min-AE8 Max Model Environment, trapped protons 10-400 MeV and electrons 4-6.5 MeV.

20. NASA Preferred Reliability Practices, PD-ED-1258. "Space Radiation Effects on Electronic Components in Low-Earth Orbit", April 1996. p. 7.

21. ASTM D257-14 "Standard Test Methods for DC Resistance or Conductance of Insulating Materials", 2014.

22. Frederickson, A.R., E.G. Holeman, and E.G. Mullen. "Characteristics of spontaneous electrical discharging of various insulators in space radiations", IEEE Transactions on Nuclear Science, Vol. 39, No. 6, 1992, p. 1773.

23. Kim, W., Katz, I., Green, N.W., and I. Jun, "An Internal Electrostatic Charging Test of Circuit Boards under Electron Beam", RADECS, 2001, p.1.

24. Lauenstein, J.-M., Barth, J.L., and D. G. Sibeck, "Toward the Development of New Standard Radiation Belt and Space Plasma Models for Spacecraft Engineering", Space Weather, Vol.3, 2005, S08B03, doi:10.1029/2005SW000160.

25. Mann, I.R., Lee, E.A., Claudepierre, S.G., Fennel, J.F., Degeling, A., Rae, I.J., Baker, D.N., Reeves, G.D., Spence, H.E., Ozeke, L.G., Rankin, R., Milling, D.K., Kale, A., Friedel, R.H.W., and F. Honary, "Discovery of the Action of a Geophysical Synchrotron in the Earth's Van Allen Radiation Belts", Nature Communications, Vol. 4, 2013, Article No. 2795, doi:10.1038/ncomms3795.