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Radiation Environment Description Document

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Goddard Space Flight Center
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Questions or comments concerning this document should be addressed to:

ICESat-2 Configuration Management Office

Mail Stop 425

Goddard Space Flight Center

Greenbelt, Maryland 20771

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Introduction

The purpose of this document is to define the radiation environment for the evaluation of degradation due to total ionizing and non-ionizing dose and of single event effects for the Ice, Cloud, and Land Elevation Satellite II (ICESat-2). The analysis takes into account the radiation exposure for 5.00 years and assumes a launch date in November 2014.

Based on additional input from the ICESat-2 project team, a later launch date of February 2016 was considered. The mission total ionizing dose for this later launch date increases by approximately 2 krad(Si) from the original launch date in November 2014. The original mission included 4 years in solar minimum and 1 year in solar maximum. With the push back to February 2016, the mission now spends 1.25 years in solar maximum and 3.75 years in solar minimum. The dose will increase rapidly at the 95% confidence level for solar protons as the spacecraft spends more time in solar maximum.

I. Radiation Environment

The natural space radiation environment of concern is classified into two populations: 1) the transient particles which include protons and heavier ions of all of the naturally occurring elements of the periodic table, and 2) the particles trapped in the Earth's magnetic field, which most importantly includes protons and electrons. The trapped protons have energies up to 100s of MeV and the trapped electrons have energies up to about 10 MeV. The transient radiation consists of galactic cosmic ray particles and particles from solar events (coronal mass ejections and flares). The galactic cosmic rays have low-level fluxes that peak as a function of energy around 1 GeV per nucleon. The solar eruptions periodically produce energetic protons, alpha particles, heavy ions, and electrons. These particle fluxes decrease monotonically with energy beyond about 1 MeV per nucleon and can reach energies as high as the GeV per nucleon range. All particle fluxes are isotropic and omnidirectional to the first order.

Space also contains low energy plasma of electrons and protons with fluxes up to 10^{12} $cm^{-2}\cdot sec^{-1}$. The plasmasphere environment and the low energy (< 0.1 MeV) component of the charged particles are a concern in the near-earth environment. In the outer regions of the magnetosphere and in interplanetary space, the plasma is associated with the solar wind. Because of its low energy, thin layers of material easily stop the plasma so it is not a hazard to most spacecraft electronics. However, it is damaging to surface materials and differentials in the plasma environment can contribute to spacecraft surface charging and discharging problems [1,2].

II. Description of Radiation Effects

Radiation effects that are important to consider for instrument and spacecraft design fall roughly into three categories: degradation from total ionizing dose (TID), degradation from non-ionizing energy loss (NIEL), and single event effects (SEE). Total ionizing dose in electronics is a cumulative, long-term degradation mechanism due to ionizing radiation—mainly primary protons and electrons and secondary particles arising from interactions between these primary particles and spacecraft materials. It causes threshold shifts, leakage current and timing skews. The effect first appears as parametric degradation of the device and ultimately results in functional failure. It is possible to reduce TID with shielding material that absorbs most electrons and lower energy protons. As shielding is increased, shielding effectiveness decreases because of the difficulty in stopping the higher energy protons. When

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manufacturers advertise a part as "rad-hard," they are almost always referring to its total ionizing dose characteristics. Rad-hard does not usually imply that the part is hard to non-ionizing dose or single event effects. In some cases, a "rad-hard" part may perform significantly worse in the space radiation environment than in the test environment (e.g. Enhanced Low Dose Rate Sensitivity (ELDRS) in linear bipolar devices.)

Displacement damage is cumulative, long-term, non-ionizing damage due to protons, electrons, and neutrons. These particles produce defects in semiconductor and optical materials that result in material property changes such as carrier lifetime shortening, mobility degradation and optical transmission. Displacement damage affects the performance of optocouplers (often a component in power devices), solar cells, charge-coupled devices, and linear bipolar devices. The effectiveness of shielding depends on the location of the device. For example, coverglasses over solar cells reduce electron damage and proton damage by absorbing the low energy particles. Increasing shielding beyond a certain point, however, is not usually effective for optoelectronic components because the high-energy protons penetrate most feasible spacecraft electronic enclosures. For detectors in instruments it is necessary to understand the instrument technology and geometry to determine the vulnerability to the environment.

Single-event effects (SEEs) result from ionization by a single charged particle as it passes through a sensitive region of an electronic or photonic device. SEE can be caused by heavier ions, but for some devices, protons and neutrons* can also contribute. SEE are caused either by direct ionization or by secondary particles produced by the interaction of the incident particle with a nucleus in the device material. Incident heavy ions produce SEE most often by direct ionization. However, in some cases secondary products can cause SEE. Conversely, incident protons most often produce SEE via secondary products, but in some cases they can be caused by direct ionization. In all instances for incident neutrons, SEE result from secondary particles produced when the neutron interacts with a nucleus in the device material. Some single-event effects are non-destructive, as in the case of single-event upsets (SEUs), single-event transients (SETs), multiple-bit upsets (MBUs), single-event hard errors (SHEs), etc. Single-event effects can also be destructive as in the case of single-event latchup (SEL), single-event gate rupture (SEGR), and single-event burnouts (SEB). The severity of the effect can range from noisy data to system shutdown, depending on the type of effect and the criticality of the system in which it occurs. Shielding is generally not an effective mitigation strategy for single-event effects, which can be induced by very penetrating high-energy particles. The preferred method for dealing with destructive failures is to use SEE-hard parts. When SEE-hard parts are not available, latchup protection circuitry is sometimes used in conjunction with failure mode analysis. (Note: Care is necessary when using SEL protection circuitry, because SEL may damage a microcircuit and reduce its reliability even when it does not cause outright failure.) For non-destructive effects, mitigation takes the form of error-detection and correction codes (EDACs), filtering circuitry, etc.

Total ionizing dose is primarily caused by protons and electrons trapped in the Van Allen belts and solar event protons. As electrons are slowed down, their interactions with orbital electrons of the shielding material produce a secondary photon radiation known as bremsstrahlung. Generally, the dose due to galactic cosmic ray ions and proton secondaries and bremsstrahlung is small compared to other sources in modern spacecraft having typical shielding. For surface degradation, it is also important to include the effects of very low energy particles.

SEEs can be induced by heavy ions (solar events and galactic cosmic rays) and, in some devices, protons (trapped and solar events) and neutrons*. Displacement damage is primarily due to trapped and solar protons and also neutrons*. High-energy electrons can also contribute to displacement damage, especially for lightly shielded

* Neutrons in space are produced by interactions of primary particles with spacecraft materials and planet soils. In avionics applications it is also necessary to consider neutrons that are produced by interactions of primary particles with the atmosphere.

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applications. Spacecraft charging can occur on the surface of the spacecraft due to low energy electrons. Deep dielectric charging occurs when high-energy electrons penetrate the spacecraft and collect in dielectric materials.

III. The Ice, Cloud, and Land Elevation Satellite 2

ICESat-2 is an Earth Observing System mission for measuring ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics. The ICESat-2 mission will provide multi-year elevation data needed to determine ice sheet mass balance as well as cloud property information, especially for stratospheric clouds common over polar areas. It will also provide topography and vegetation data around the globe, in addition to the polar-specific coverage over the Greenland and Antarctic ice sheets [3]. It is scheduled for a November 2014 launch and has a 5.00-year requirement. It has a circular orbit at an altitude of 600 km with a 92° inclination[*].

The ICESat-2 orbit radiation environment will consist of protons and electrons trapped in the Van Allen belts, protons and heavier ions from solar events, galactic cosmic ray ions, and solar wind plasma consisting of low energy electrons, protons and heavier ions.

IV. Total Dose and Degradation

The total ionizing dose accumulation causes performance degradation and failure of electronic and photonic components. Non-ionizing energy loss in materials (atomic displacement damage) causes degradation of systems consisting of components such as solar cells, optoelectronics, and detectors. The low energy particles also contribute to the erosion of surfaces.

A. Degradation Environment

1. The Plasma Environment

At the ICESat-2 orbits, low energy particles from the solar wind plasma inside and outside the magnetotail contribute to the degradation of surface materials and also cause charging effects. These charging effects should be considered in the spacecraft design [4]. Daily values of trapped electrons can fluctuate by two to three orders of magnitude depending on the level of activity on the sun and within the magnetosphere.

2. High Energy Particles – Spacecraft Incident Fluences

The spacecraft incident particle fluence levels given in this document can be used for standard solar cell analyses that take into account the coverglass thickness of the cell. There are three types of high energy particles that contribute significantly to solar cell degradation: trapped protons and trapped electrons encountered in the Van Allen

[*] Note that the Introduction discusses the later launch date of October 2015. This later launch date was deemed to not affect the spacecraft radiation environment substantially based on the original calculations for a November 2014 launch. The October 2015 launch (5.00 yr mission, 600 km circular orbit, and 94° inclination) modified the top-level mission total ionizing dose less than 100 rad(Si), so the tables and figures herein are still valid.

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belts and protons from solar events that are most likely to occur during solar maximum years. These fluence levels can also be used for other analyses. Most analysis methods require that the surface incident particles be transported through the materials surrounding the sensitive components.

The trapped particle fluxes were estimated with NASA's AP-8 model for protons [6] and AE-8 model for electrons [7]. It was calculated that the 5.00-year mission consists of 1.00 years during solar maximum followed by 4.00 years during solar minimum. The uncertainty factors given for the models are a factor of 2 for the AP-8 and 2 to 5 for the AE-8. These uncertainty factors apply to long-term missions.

Table A1 gives the incident trapped proton fluence. **Figure 1** is a plot of the fluence-energy trapped proton spectrum. The ordinate shows the proton fluence for the 5.00-year mission having energy, E, greater than the corresponding value shown on the abscissa. All results for the radiation environment in this document do not include design margin.

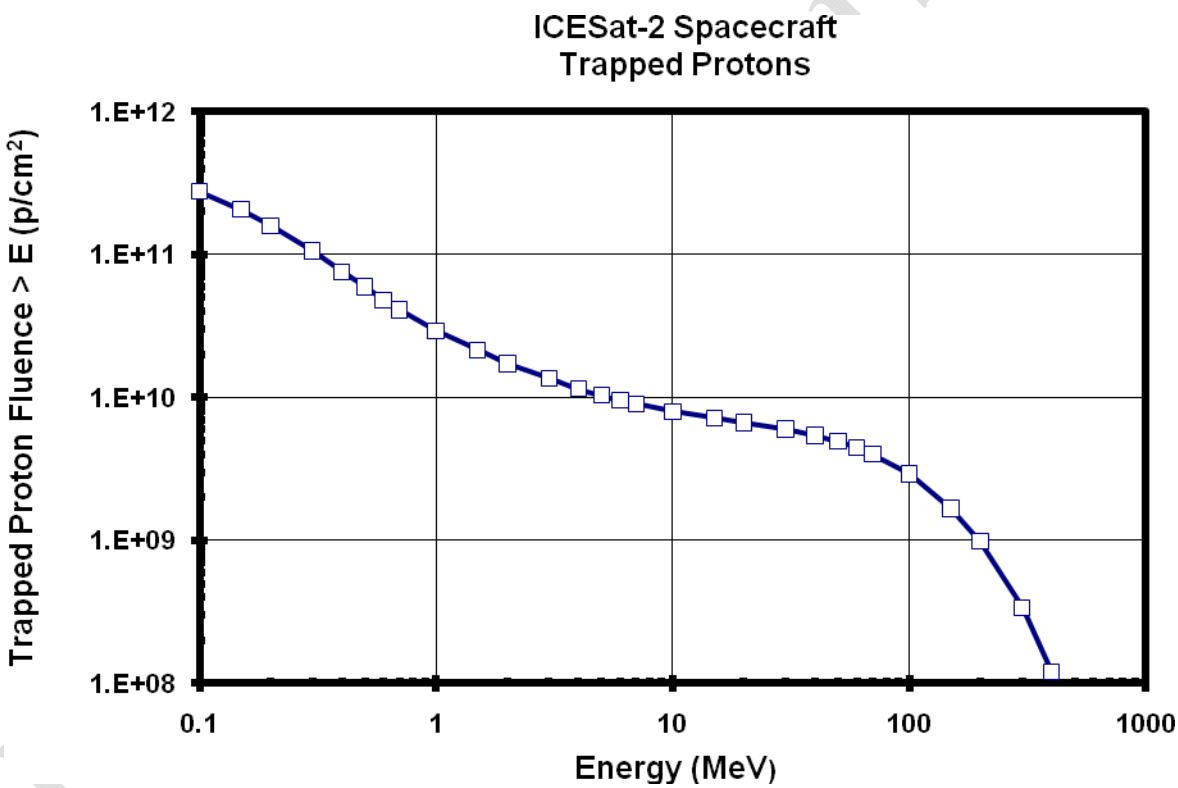

Figure IV-A: Surface incident integral trapped proton fluence for the 5.00-year ICESat-2 spacecraft

Table A2 gives the incident trapped electron fluence. **Figure 2** is a plot of the fluence-energy trapped electron spectrum.

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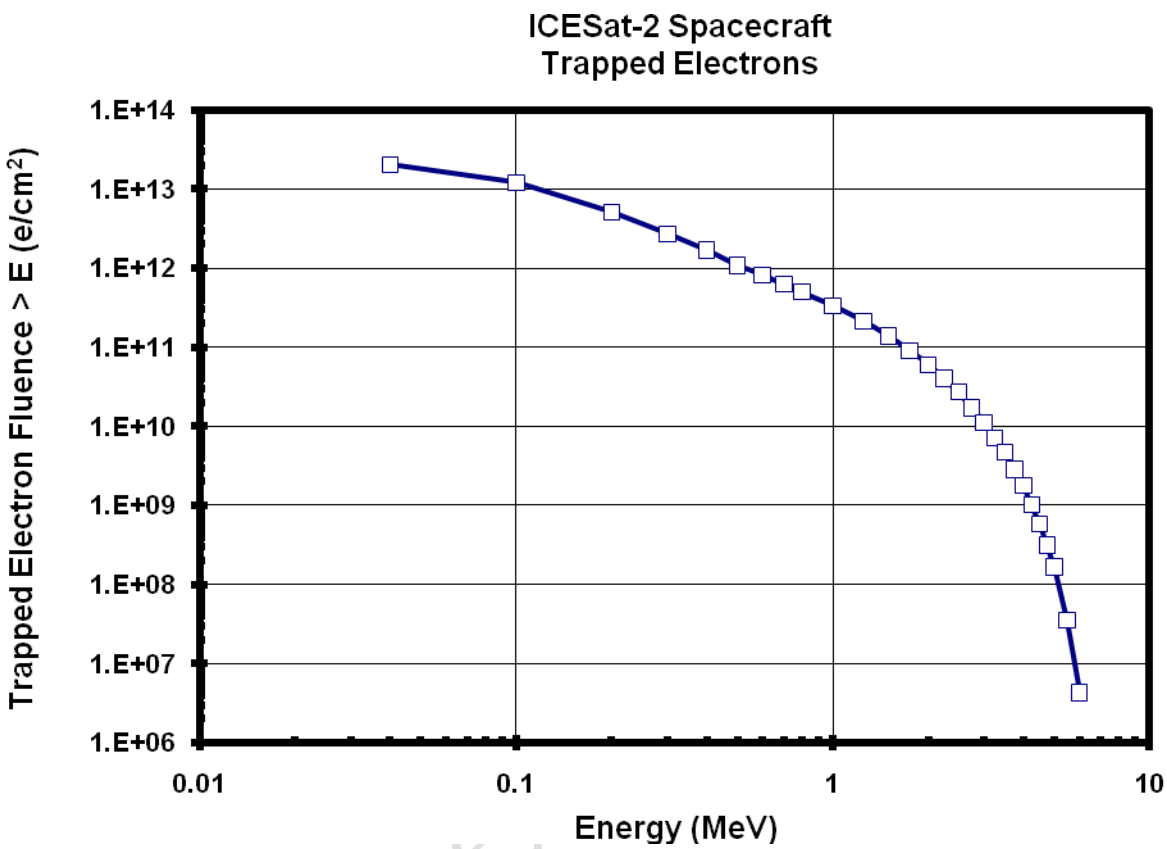

Figure 2: Surface incident integral trapped electron fluence for the 5.00-year ICESat-2 spacecraft

The solar proton levels were estimated using the Emission of Solar Protons (ESP) model [8]. The ESP model is based on satellite data from solar cycles 20 - 23. The distribution of the fluences for the events is obtained from maximum entropy theory, and design limits in the worst case models are obtained from extreme value theory.

Solar particle events are often described with probability distributions because of the statistical nature of the event magnitudes and times of occurrence. **Table A3** and **Figure 3** give the incident solar proton fluence-energy spectrum for the 95% confidence level. Since the solar proton predictions are based on probability distributions, they do not increase linearly with time. Only the mean value of the distribution increases linearly. Therefore, these estimates at high confidence levels lose accuracy if extrapolated to longer or shorter mission durations.

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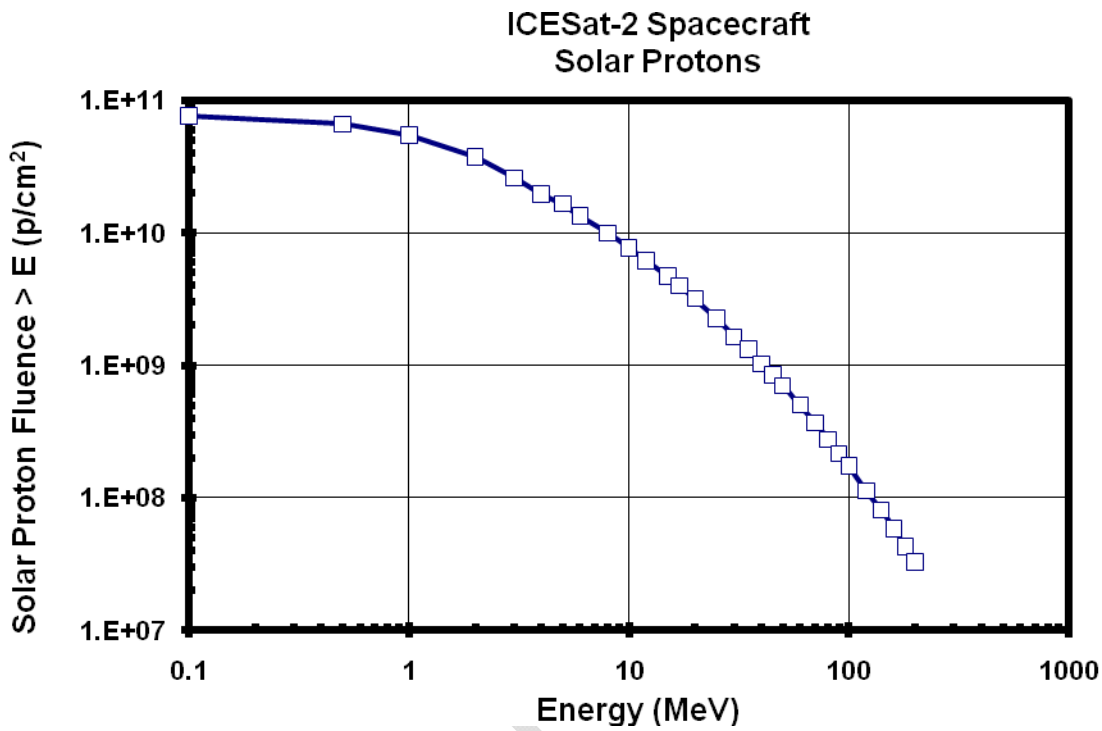

Figure 3: Surface incident integral solar proton fluences for the 5.00-year ICESat-2 spacecraft

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B. Total Dose Estimates

1. Top Level Ionizing Dose Requirement

Absorbed radiation doses are calculated from the surface incident integral fluences as a function of aluminum shield thickness for a simple geometry. The geometry model used for spacecraft applications is often the solid sphere. The solid sphere doses represent an upper boundary for the dose inside an actual spacecraft and are used as a top-level requirement. In cases where the amount of shielding surrounding a sensitive location is difficult to estimate, a more detailed analysis of the geometry of the spacecraft structure may be necessary to evaluate the expected dose levels. This is done by modeling the electronic boxes or instruments and the spacecraft structure. The amount of shielding surrounding selected sensitive locations is estimated using solid angle sectoring and 3-dimensional ray tracing. This is then combined with full Monte Carlo transport simulations of particle trajectories through the structure to evaluate the dose; it is described in more detail in Section 2.

Table A4 and **Figure 4** give the top-level total ionizing dose requirement for ICESat-2. The doses are calculated here as a function of aluminum shield thickness in units of krad in silicon. For a nominal 100 mil (2.54 mm) of equivalent aluminum shielding and the 5.00-year mission, the expected dose is about 6.5 krad(Si), with no design margin. A minimum design margin of 2*x* is recommended.

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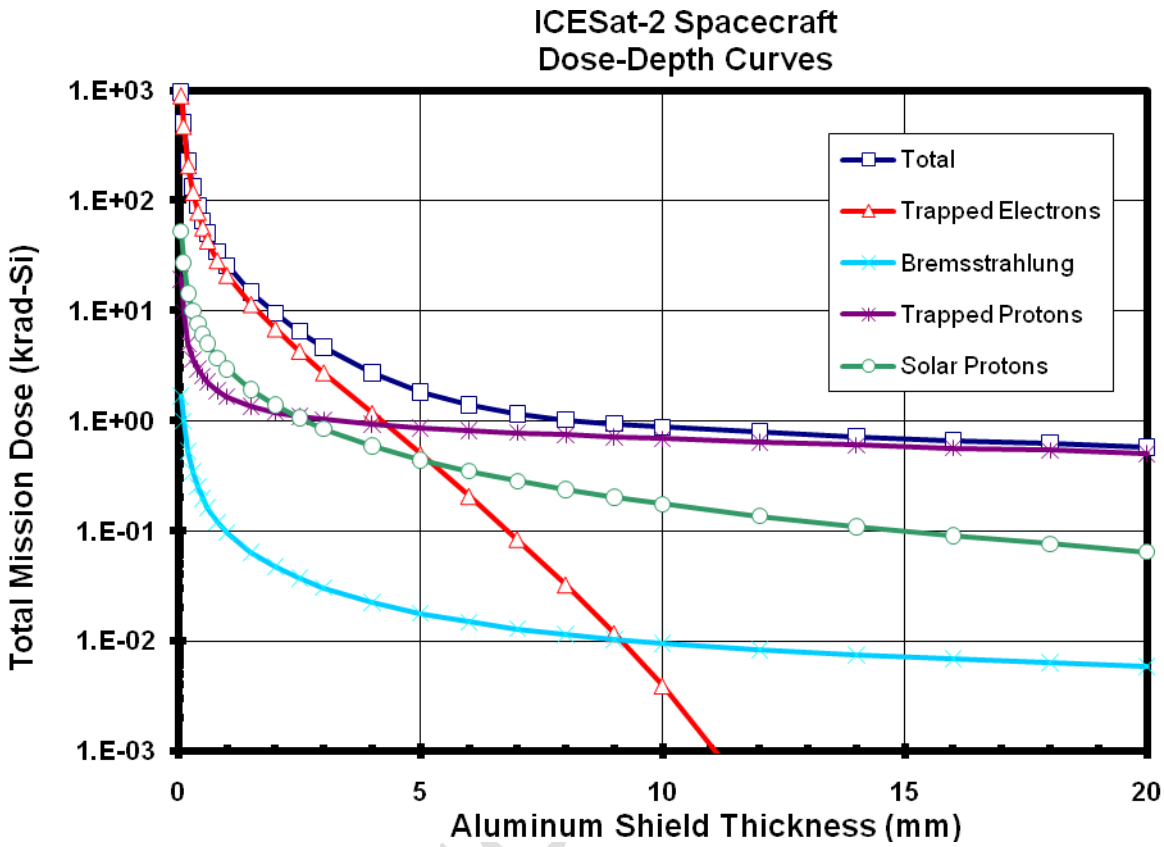

Figure 4: ICESat-2 spacecraft total ionizing dose curves for the absorbed radiation dose at the center of solid aluminum spheres. Values do not include design margins.

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2. Dose at Specific Spacecraft Locations

In cases where parts cannot meet the top-level design requirement and a "harder" part cannot be substituted, it is often beneficial to employ more accurate methods of determining the dose exposure for some spacecraft components to qualify the parts. One such method for calculating total dose, solid angle sectoring/3-dimensional ray tracing, and radiation transport simulation, is accomplished in three steps:

1) Model the spacecraft structure:
   -develop a 3-D model of the spacecraft structures and components
   -develop a material library
   -define sensitive locations
2) Model the radiation environment:
   -define the spacecraft incident radiation environment, as in this document
   -develop an attenuation model using the shielding configurations
   (similar to dose-depth curves).
3) Obtain results for each sensitive location:
   -divide the structural model into solid angle sectors
   -ray trace through the sectors to calculate the material mass distribution
   -use the ray trace results to simulate total doses from a Monte Carlo transport calculation.

Once the basic structural model has been defined, total doses can be obtained for any location in the spacecraft in a relatively short time. The value of dose mitigation measures can then be evaluated by adding the changes to the model and recalculating the total dose. This may help avoid unnecessary use of expensive or increasingly unavailable radiation hardened parts. Simplified models analogous to this may also be implemented, such as modeling only an electronic box or only an instrument.

C. Displacement Damage

The interaction of energetic charged particles with a solid results in both ionizing (SEE and TID) and non-ionizing effects; each can be transient or permanent. The majority of the incident particle's kinetic energy loss is ionizing. However, a fraction of that energy loss (increasing as the particle slows down) is channeled into non-ionizing events. This remaining energy loss causes atoms to be displaced from their normal lattice sites, which can degrade the electrical characteristics of semiconducting materials and devices. Regarding displacement damage, the challenge is to use a series of monoenergetic accelerated ground tests to infer the end-of-life performance of a device taking into account lattice damage from the accumulated particle fluence of a particular environment. This can be achieved by using a concept called non-ionizing energy loss.

To quantify microelectronics damage due to atomic displacement, the quantity often used is non-ionizing energy loss (NIEL). NIEL is a measure of the rate of energy loss due to atomic displacements (damage) as a particle traverses a material. It has units of linear energy transfer, $(\mathrm{MeV \cdot cm^2})/\mathrm{mg}$. While NIEL results from both protons and electrons, protons are much more difficult to shield and at a few MeV have a NIEL about 10^3 greater than electrons of the same energy – thus they are a more critical concern. For protons, NIEL contributions come from both elastic and inelastic collisions with the target material's atoms. Protons with kinetic energies below approximately 7 MeV

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do not have an inelastic NIEL component since they cannot disrupt the target nucleus. NIEL calculations are complex functions of elastic and inelastic interaction cross sections, recoil energy, and various angular dependencies. **Table A5a and Figure 5a** show NIEL equivalent fluences in silicon for several proton energies and

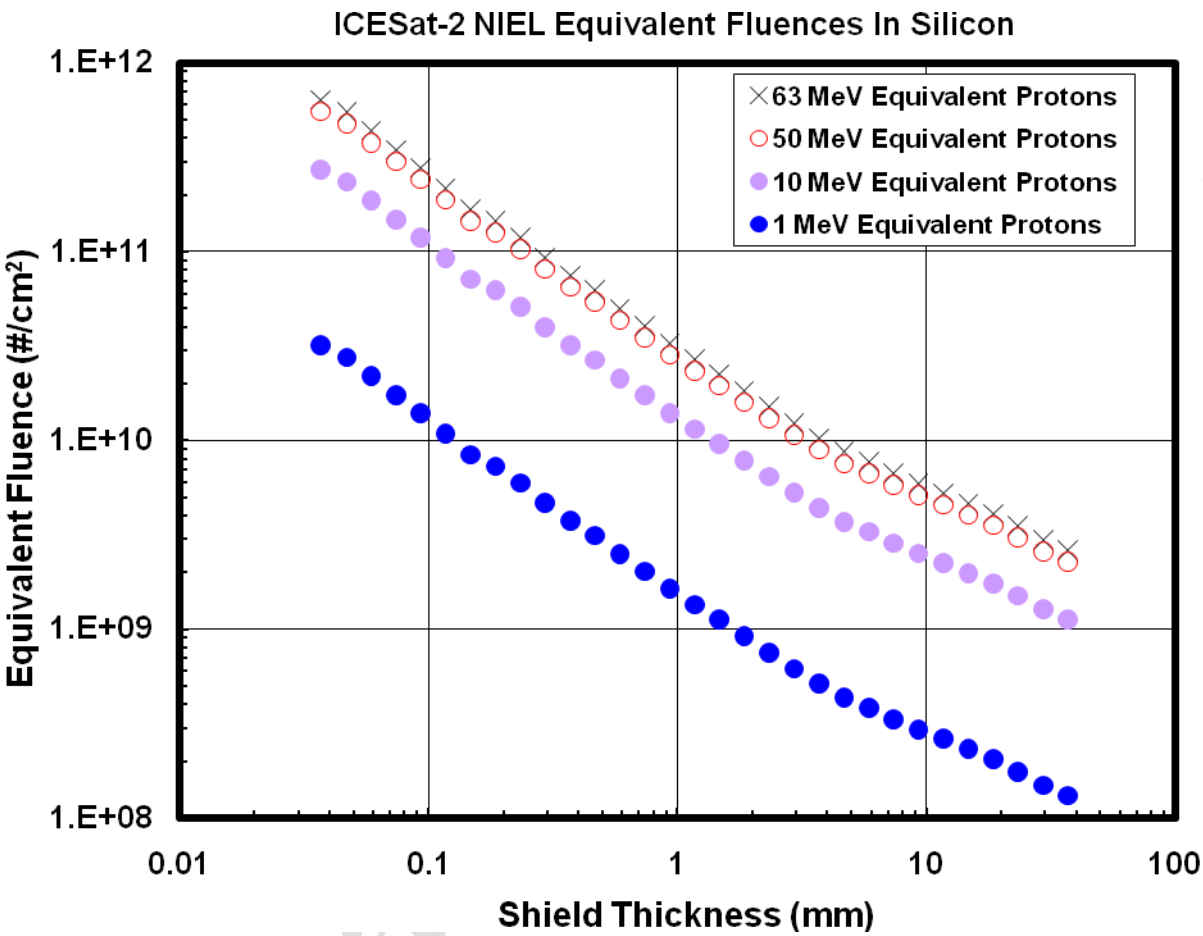

Figure 5a: ICESat-2 spacecraft NIEL equivalent proton fluence in silicon at the center of solid aluminum spheres. Values do not include design margins.

various aluminum shield thicknesses for the ICESat-2 mission. **Table A5b and Figure 5b** show NIEL equivalent fluences in gallium arsenide (GaAs) for several proton energies and various aluminum shield thicknesses for the ICESat-2 mission. **Tables A5a** and **A5b** can be used according to the following prescription: if 100 mil of aluminum shielding is assumed, the top level displacement damage requirement for a silicon device in terms of a 10 MeV equivalent proton fluence is approximately 6×10^{9} cm^{-2}, excluding a 2*x* design margin.

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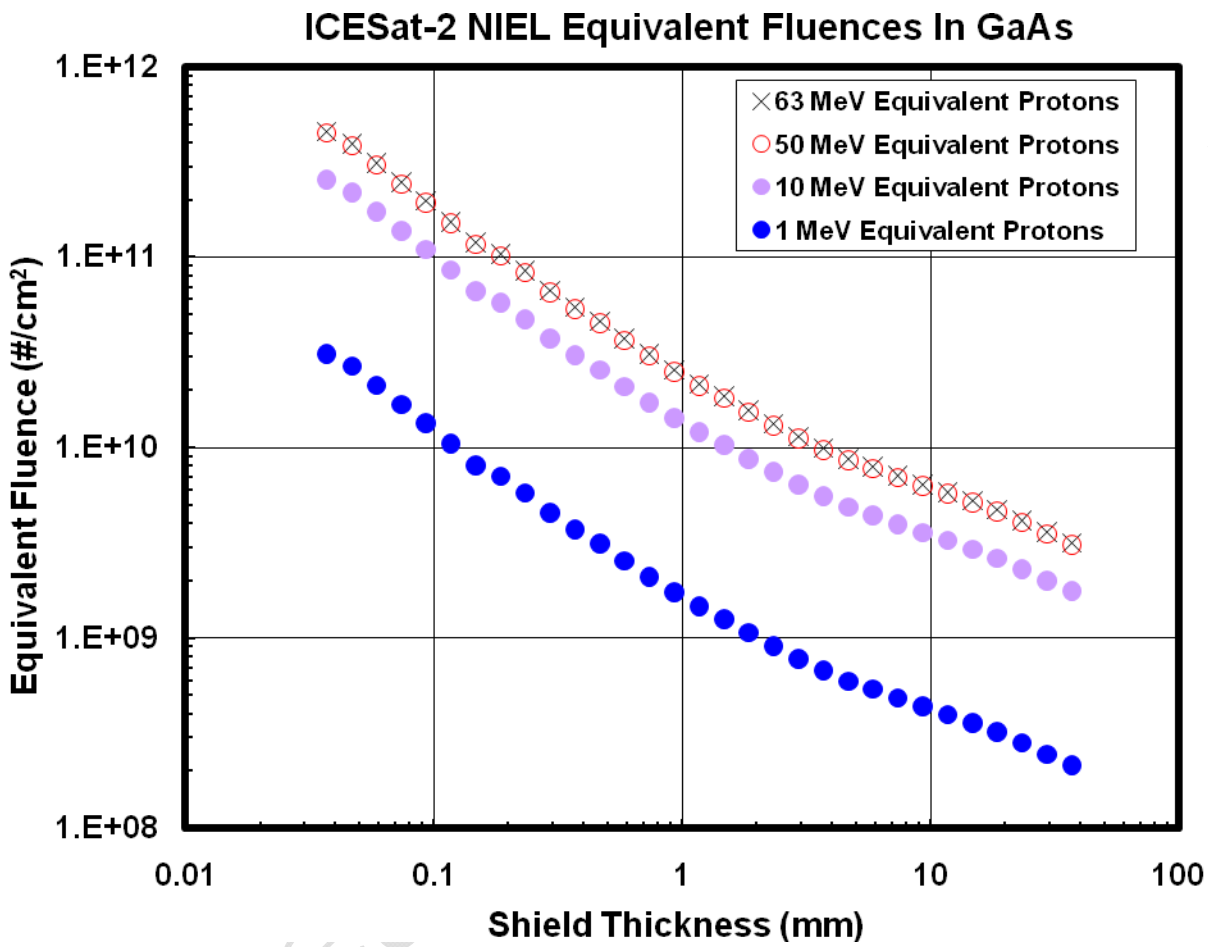

Figure 5b: ICESat-2 spacecraft NIEL equivalent proton fluence in GaAs at the center of solid aluminum spheres. Values do not include design margins.

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V. Single Event Effects Analysis

A. Heavy Ion Induced Single Event Effects

Some electronic devices are susceptible to SEEs, e.g., single-event upsets, single-event latchup, single-event burn-out. Heavy ions, such as galactic cosmic rays (GCR) and solar heavy ions, most often cause SEEs by the direct deposition of energy. The metric traditionally used to describe this is the ion's linear energy transfer (LET). The LET is the average energy lost by the ion per unit path length in the material of interest. In order to parameterize SEEs in terms of LET, the heavy ion abundances and energy distributions in the environment are converted to LET spectra. Once specific parts are selected for the mission and, if necessary, characterized by laboratory testing, LET spectra for the heavy ions in the space radiation environment are integrated with the device characterization to estimate SEE rates.

It should be noted that the LET metric may not be valid for some modern devices. This can be because of their highly scaled nature, the complexity of the geometry, the increased use of metal over-layers or other reasons not yet understood. Such instances underscore the importance of SEE testing and may require a more sophisticated SEE rate calculation than described above. Unless otherwise noted, geomagnetic attenuation, i.e., attenuation by the Earth's magnetic field of galactic cosmic rays and solar particles, for the ICESat-2 orbit is accounted for in this document.

1. Galactic Cosmic Rays

The GCR fluxes for elements hydrogen through uranium were used to calculate daily LET spectra for a nominal shielding thickness of 100 mil aluminum. Results are given in **Table A6** and **Figure 6**. The range of the cosmic ray abundances is bounded by the extrema of the solar maximum and minimum phases of the solar cycle with the highest values occurring during the solar minimum phase. The LET spectra values are given for the highest and lowest point of the solar cycle. The CREME96 [9] model was used to obtain the GCR abundances. This model has an accuracy of 25-40%.

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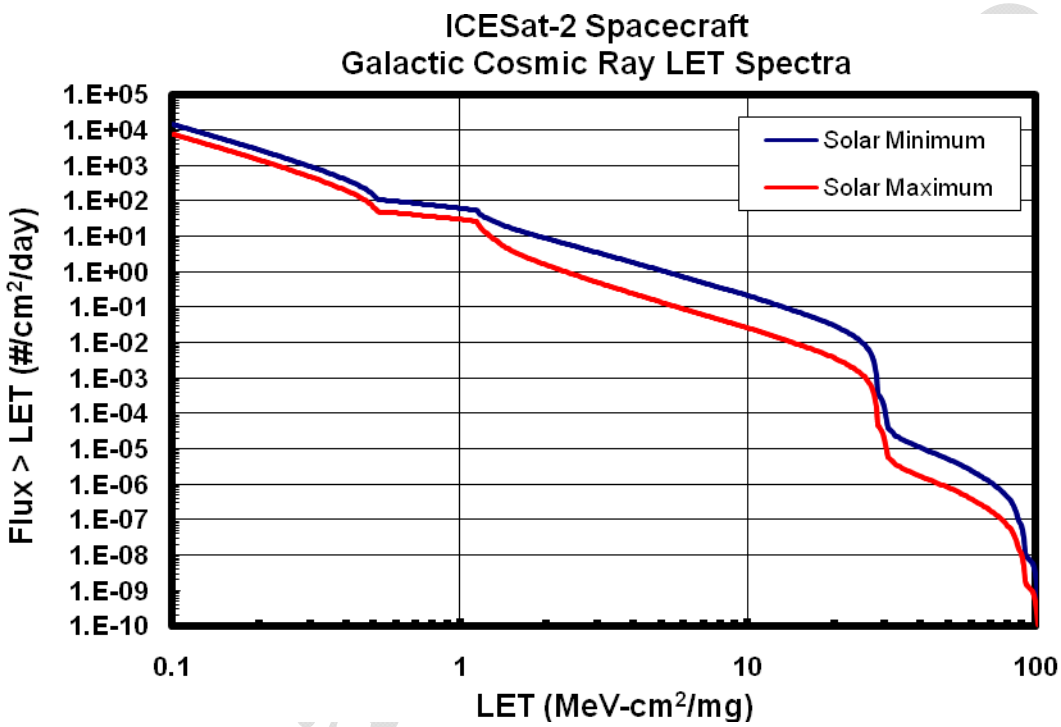

Figure 6: Integral LET spectra for galactic cosmic ray ions hydrogen through uranium assuming 100 mil of aluminum shielding

2. Solar Heavy Ions

The heavy ions from coronal mass ejections and solar flares can also produce SEEs. As discussed previously, these events are statistical in nature. The solar event fluxes for the elements hydrogen through uranium were used to calculate worst-case LET spectra for 100 mil of aluminum shielding. This is shown in **Tables A7a**, **A7b** and **Figure 7**. The intensity during an event is shown for two worst case situations – the flux averaged over the peak 5 minutes and the flux averaged over the peak 24 hours. The CREME96 model has been used for these situations, which assumes that the well-known October 1989 event is the worst case. In addition, a long-term solar particle LET spectrum during the solar maximum time period is given at the 90% level of confidence. This is interpreted to mean that 9 out of 10 identical missions will not observe a long-term LET spectrum that exceeds this. This is calculated with the PSYCHIC model [10], an update of the ESP model that includes heavy ions. The latter calculation does not

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include geomagnetic attenuation and is therefore conservative for this particular orbit. Note that the LET fluxes for these three calculations are per second, not per day as in the GCR calculations shown in **Figure 6**.

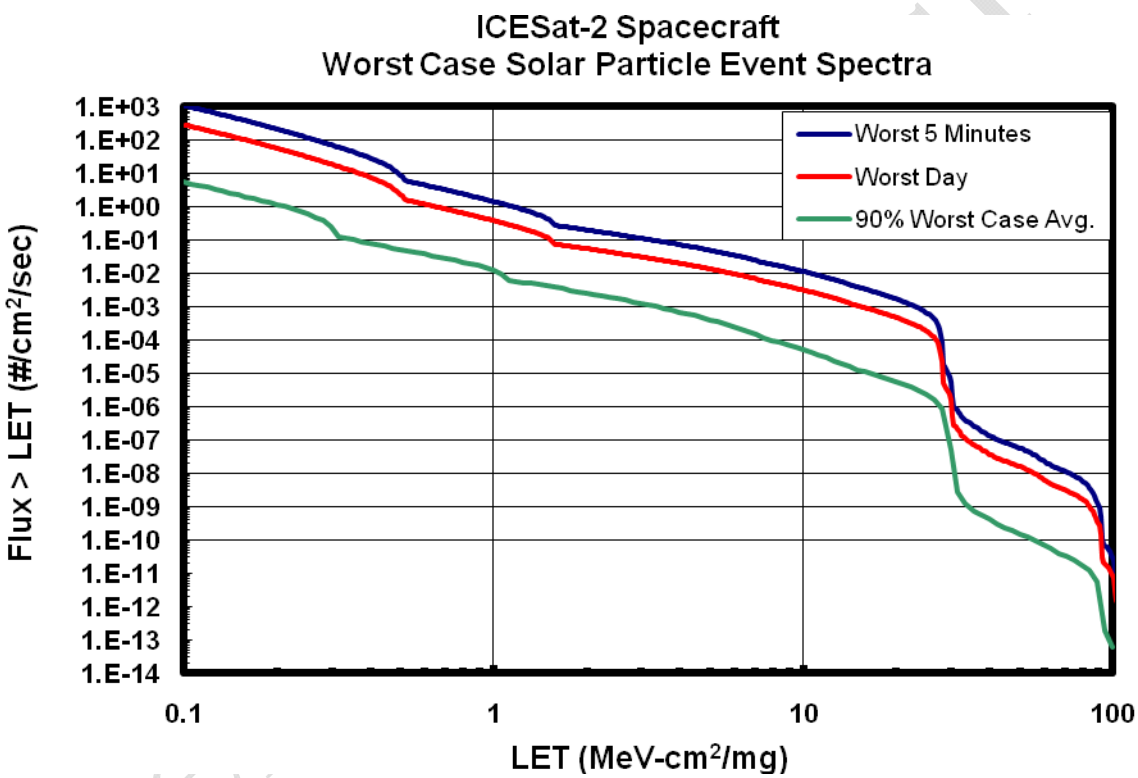

Figure 7: Integral LET spectra for hydrogen through uranium for 3 worst case situations: (1) average over the peak 5 minutes of the October 1989 event, (2) average over the worst day during the October 1989 event, (3) 90% worst case average over the solar maximum period. Note that this ordinate has units of 1/sec, whereas the GCR spectrum was 1/day.

B. Proton Induced Single-Event Effects

In some devices, SEEs are also induced by protons. In most cases, protons do not generate sufficient ionization to produce the charge necessary for SEEs to occur. More typically, protons cause SEEs through secondary particles via nuclear interactions, that is, spallation and fragmentation products. The proton energy (more than the LET) is

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important in the production of the secondary particles that cause the SEEs, so device sensitivity to these particles is typically expressed as a function of proton energy.

1. Long-Term Average Proton Fluxes

The proton fluxes in the Van Allen belts and from solar particle events can reach levels that are high enough to pose a significant risk for SEEs during the mission. **Table A8** and **Figure 8** show results for the long-term average proton fluxes during the solar maximum and solar minimum time periods for a nominal 100 mil of aluminum shielding. Protons from both sources are included in these average fluxes. They can be used to calculate long-term, average SEE rates induced by protons.

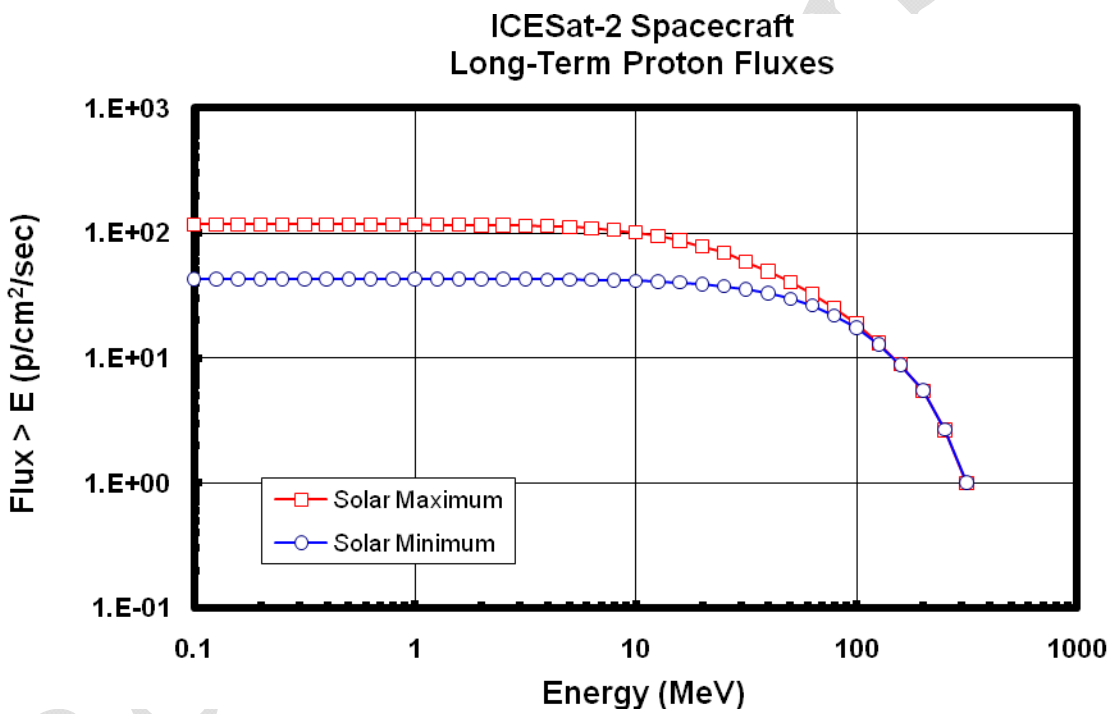

Figure 8: Long-term integral proton fluxes for single event effects evaluation. Included are the trapped proton and solar proton fluxes behind 100 mil of aluminum shielding.

2. Worst-Case Proton Fluxes

Both trapped proton and solar proton fluxes can reach levels that are a concern for short-term SEE rates. Worst-case proton fluxes for a nominal 100 mil of aluminum shielding are given in **Table A9** and shown in **Figure 9**. The worst-case trapped fluxes averaged over a 1-minute time interval are shown for the solar maximum and solar minimum time periods as calculated with the AP-8 model. Also shown is the worst case solar proton flux averaged

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over the peak 5 minutes during the event. This was calculated at the 90% confidence level using the ESP model. These results can be used to calculate worst-case SEE rates induced by protons.

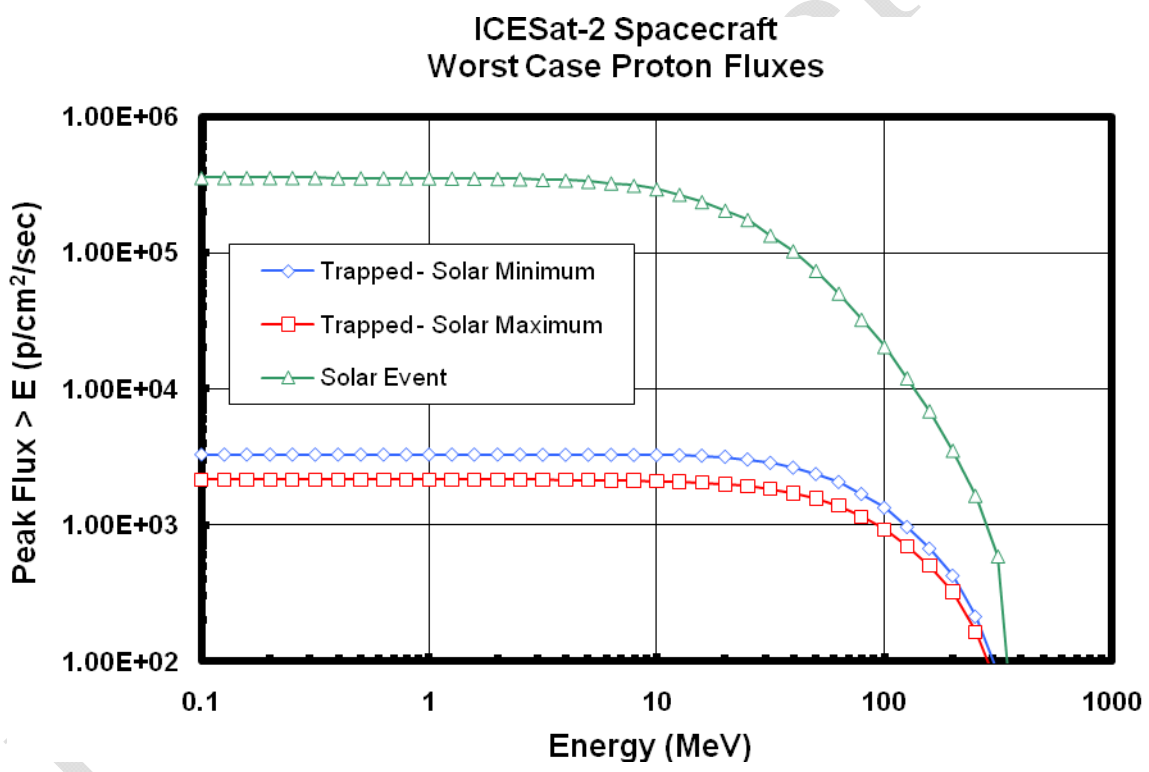

Figure 9: Worst case integral proton fluxes for single event effects evaluation. Included are the peak trapped proton fluxes averaged over a 1-minute interval during solar maximum and solar minimum. Also shown is the worst-case solar proton flux averaged over a 5-minute interval at the 90% confidence level. Calculations are done for 100 mil of aluminum shielding.

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VI. Spacecraft Charging and Discharging

Surface charging and deep dielectric charging must also be evaluated for ICESat-2 [5,11]. Both are potential problems during passes through the Van Allen belts. During a pass through the belts, high levels of charge can build-up on spacecraft surfaces (mainly due to low energy electrons) and in dielectrics in the interior (mainly due to high energy electrons).

VII. Summary

A top-level radiation environment specification was presented for ICESat-2. The total dose environment is somewhat moderate. However, some of the newer technologies and commercial-off-the-shelf (COTS) devices are very soft to total ionizing dose and displacement damage effects. The single event effects environment is more severe. Both total dose and single-event effects require careful radiation testing, part selection, and mitigation schemes.

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IX. Appendix – Table Values for 11/2014 Launch

Note: Values Do Not Include Design Margins

Table A1
Surface Incident Integral Trapped Proton Fluence for the 5.00-year ICESat-2 mission

Energy (> MeV)	Fluence (p/cm^2)
0.1	2.76E+11
0.15	2.07E+11
0.2	1.58E+11
0.3	1.06E+11
0.4	7.56E+10
0.5	5.93E+10
0.6	4.81E+10
0.7	4.11E+10
1	2.92E+10
1.5	2.15E+10
2	1.73E+10
3	1.36E+10
4	1.15E+10
5	1.04E+10
6	9.54E+09
7	9.00E+09
10	7.98E+09
15	7.19E+09
20	6.66E+09
30	6.01E+09
40	5.44E+09
50	4.93E+09
60	4.46E+09
70	4.02E+09
100	2.92E+09
150	1.68E+09
200	9.85E+08
300	3.39E+08
400	1.20E+08

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Table A2
Surface Incident Integral Trapped Electron Fluence for the 5.00-year ICESat-2 mission

Energy (> MeV)	Fluence (e/cm^2)
0.04	2.03E+13
0.1	1.20E+13
0.2	5.12E+12
0.3	2.70E+12
0.4	1.67E+12
0.5	1.09E+12
0.6	8.21E+11
0.7	6.28E+11
0.8	4.98E+11
1	3.36E+11
1.25	2.14E+11
1.5	1.38E+11
1.75	9.08E+10
2	6.01E+10
2.25	4.02E+10
2.5	2.71E+10
2.75	1.72E+10
3	1.12E+10
3.25	7.17E+09
3.5	4.68E+09
3.75	2.87E+09
4	1.78E+09
4.25	1.01E+09
4.5	5.80E+08
4.75	3.12E+08
5	1.68E+08
5.5	3.51E+07
6	4.26E+06
6.5	0.00E+00
7	0.00E+00

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Table A3
Surface Incident Integral Solar Proton Fluences for the 5.00-year ICESat-2 mission
95% Confidence Level

Energy (> MeV)	Fluence > (p/cm^2):
0.1	7.61E+10
0.5	6.63E+10
1	5.46E+10
2	3.75E+10
3	2.59E+10
4	1.96E+10
5	1.65E+10
6	1.34E+10
8	9.97E+09
10	7.70E+09
12	6.15E+09
15	4.71E+09
17	3.99E+09
20	3.17E+09
25	2.25E+09
30	1.64E+09
35	1.33E+09
40	1.02E+09
45	8.47E+08
50	7.04E+08
60	5.00E+08
70	3.67E+08
80	2.76E+08
90	2.14E+08
100	1.73E+08
120	1.12E+08
140	8.05E+07
160	5.81E+07
180	4.28E+07
200	3.26E+07

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Table A4
ICESat-2 Total Ionizing Dose at the Center of Solid Aluminum Spheres

Aluminum Shield Thickness			Dose [krad(Si)] - Total Mission				
(mm)	(mils)	(g/cm^2)	Total	Trapped Electrons	Bremsstrahlung	Trapped Protons	Solar Protons
0.05	1.97E+00	1.40E-02	9.69E+02	8.96E+02	1.69E+00	1.94E+01	5.24E+01
0.1	3.94E+00	2.70E-02	5.09E+02	4.71E+02	9.96E-01	9.75E+00	2.72E+01
0.2	7.87E+00	5.40E-02	2.28E+02	2.08E+02	5.31E-01	5.06E+00	1.43E+01
0.3	1.18E+01	8.10E-02	1.33E+02	1.19E+02	3.47E-01	3.62E+00	1.00E+01
0.4	1.57E+01	1.08E-01	8.96E+01	7.88E+01	2.52E-01	2.93E+00	7.62E+00
0.5	1.97E+01	1.35E-01	6.54E+01	5.66E+01	1.97E-01	2.54E+00	6.08E+00
0.6	2.36E+01	1.62E-01	5.05E+01	4.31E+01	1.62E-01	2.26E+00	5.01E+00
0.8	3.15E+01	2.16E-01	3.43E+01	2.86E+01	1.20E-01	1.88E+00	3.70E+00
1	3.94E+01	2.70E-01	2.56E+01	2.10E+01	9.63E-02	1.65E+00	2.94E+00
1.5	5.91E+01	4.05E-01	1.48E+01	1.14E+01	6.41E-02	1.36E+00	1.91E+00
2	7.87E+01	5.40E-01	9.50E+00	6.87E+00	4.73E-02	1.20E+00	1.38E+00
2.5	9.84E+01	6.75E-01	6.49E+00	4.29E+00	3.70E-02	1.10E+00	1.06E+00
3	1.18E+02	8.10E-01	4.64E+00	2.74E+00	3.04E-02	1.03E+00	8.44E-01
4	1.57E+02	1.08E+00	2.71E+00	1.17E+00	2.24E-02	9.28E-01	5.87E-01
5	1.97E+02	1.35E+00	1.81E+00	4.98E-01	1.78E-02	8.62E-01	4.37E-01
6	2.36E+02	1.62E+00	1.39E+00	2.07E-01	1.49E-02	8.17E-01	3.48E-01
7	2.76E+02	1.89E+00	1.16E+00	8.44E-02	1.29E-02	7.76E-01	2.83E-01
8	3.15E+02	2.16E+00	1.02E+00	3.26E-02	1.14E-02	7.41E-01	2.36E-01
9	3.54E+02	2.43E+00	9.39E-01	1.18E-02	1.04E-02	7.14E-01	2.03E-01
10	3.94E+02	2.70E+00	8.73E-01	3.94E-03	9.54E-03	6.85E-01	1.75E-01
12	4.72E+02	3.24E+00	7.87E-01	3.18E-04	8.32E-03	6.41E-01	1.37E-01
14	5.51E+02	3.78E+00	7.17E-01	8.09E-06	7.49E-03	6.00E-01	1.09E-01
16	6.30E+02	4.32E+00	6.62E-01	6.22E-08	6.85E-03	5.66E-01	8.99E-02
18	7.09E+02	4.86E+00	6.20E-01	6.70E-10	6.33E-03	5.38E-01	7.61E-02
20	7.87E+02	5.40E+00	5.75E-01	0.00E+00	5.84E-03	5.05E-01	6.43E-02

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Table A5a
ICESat-2 NIEL Equivalent Proton Fluences in Silicon

Aluminum Solid-Sphere Shield Thickness			1 MeV Equivalent Proton Fluence #/cm^2	10 MeV Equivalent Proton Fluence #/cm^2	50 MeV Equivalent Proton Fluence #/cm^2	63 MeV Equivalent Proton Fluence #/cm^2
mm	g/cm^2	mils				
0.037	0.01	1.46	3.18E+10	2.71E+11	5.52E+11	6.35E+11
0.047	0.013	1.85	2.75E+10	2.35E+11	4.77E+11	5.49E+11
0.059	0.016	2.32	2.18E+10	1.86E+11	3.79E+11	4.36E+11
0.074	0.02	2.91	1.74E+10	1.48E+11	3.01E+11	3.47E+11
0.093	0.025	3.66	1.39E+10	1.18E+11	2.41E+11	2.77E+11
0.117	0.032	4.61	1.08E+10	9.24E+10	1.88E+11	2.16E+11
0.148	0.04	5.83	8.38E+09	7.15E+10	1.45E+11	1.67E+11
0.186	0.05	7.32	7.31E+09	6.23E+10	1.27E+11	1.46E+11
0.234	0.063	9.21	5.95E+09	5.08E+10	1.03E+11	1.19E+11
0.294	0.079	11.57	4.66E+09	3.98E+10	8.09E+10	9.31E+10
0.371	0.1	14.61	3.75E+09	3.20E+10	6.50E+10	7.49E+10
0.466	0.126	18.35	3.12E+09	2.67E+10	5.42E+10	6.24E+10
0.587	0.158	23.11	2.50E+09	2.13E+10	4.34E+10	4.99E+10
0.739	0.2	29.09	2.03E+09	1.73E+10	3.51E+10	4.04E+10
0.931	0.251	36.65	1.64E+09	1.40E+10	2.84E+10	3.27E+10
1.172	0.316	46.14	1.35E+09	1.15E+10	2.34E+10	2.69E+10
1.475	0.398	58.07	1.12E+09	9.59E+09	1.95E+10	2.25E+10
1.857	0.501	73.11	9.17E+08	7.82E+09	1.59E+10	1.83E+10
2.338	0.631	92.05	7.53E+08	6.42E+09	1.31E+10	1.50E+10
2.943	0.794	115.87	6.17E+08	5.27E+09	1.07E+10	1.23E+10
3.705	1	145.87	5.13E+08	4.38E+09	8.91E+09	1.03E+10
4.665	1.259	183.66	4.35E+08	3.71E+09	7.54E+09	8.68E+09
5.872	1.585	231.18	3.84E+08	3.28E+09	6.67E+09	7.67E+09
7.393	1.995	291.06	3.34E+08	2.85E+09	5.79E+09	6.67E+09
9.307	2.512	366.42	2.94E+08	2.51E+09	5.10E+09	5.88E+09
11.717	3.162	461.30	2.62E+08	2.24E+09	4.55E+09	5.23E+09
14.751	3.981	580.75	2.32E+08	1.98E+09	4.03E+09	4.64E+09
18.57	5.012	731.10	2.04E+08	1.74E+09	3.55E+09	4.08E+09
23.378	6.31	920.39	1.76E+08	1.50E+09	3.05E+09	3.51E+09
29.432	7.943	1158.74	1.49E+08	1.27E+09	2.58E+09	2.98E+09
37.052	10	1458.74	1.31E+08	1.12E+09	2.28E+09	2.62E+09

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Table A5b
ICESat-2 NIEL Equivalent Proton Fluences in Gallium Arsenide

Aluminum Solid-Sphere Shield Thickness			1 MeV Equivalent Proton Fluence #/cm^2	10 MeV Equivalent Proton Fluence #/cm^2	50 MeV Equivalent Proton Fluence #/cm^2	63 MeV Equivalent Proton Fluence #/cm^2
mm	g/cm^2	mils				
0.037	0.01	1.46	3.11E+10	2.55E+11	4.48E+11	4.58E+11
0.047	0.013	1.85	2.68E+10	2.19E+11	3.86E+11	3.94E+11
0.059	0.016	2.32	2.12E+10	1.74E+11	3.05E+11	3.12E+11
0.074	0.02	2.91	1.68E+10	1.38E+11	2.42E+11	2.47E+11
0.093	0.025	3.66	1.34E+10	1.10E+11	1.93E+11	1.98E+11
0.117	0.032	4.61	1.04E+10	8.56E+10	1.50E+11	1.54E+11
0.148	0.04	5.83	8.09E+09	6.63E+10	1.16E+11	1.19E+11
0.186	0.05	7.32	7.07E+09	5.79E+10	1.02E+11	1.04E+11
0.234	0.063	9.21	5.77E+09	4.73E+10	8.31E+10	8.49E+10
0.294	0.079	11.57	4.55E+09	3.73E+10	6.56E+10	6.70E+10
0.371	0.1	14.61	3.71E+09	3.04E+10	5.35E+10	5.46E+10
0.466	0.126	18.35	3.13E+09	2.56E+10	4.50E+10	4.60E+10
0.587	0.158	23.11	2.54E+09	2.08E+10	3.66E+10	3.74E+10
0.739	0.2	29.09	2.10E+09	1.72E+10	3.02E+10	3.09E+10
0.931	0.251	36.65	1.74E+09	1.43E+10	2.50E+10	2.56E+10
1.172	0.316	46.14	1.47E+09	1.20E+10	2.11E+10	2.16E+10
1.475	0.398	58.07	1.26E+09	1.03E+10	1.81E+10	1.85E+10
1.857	0.501	73.11	1.06E+09	8.72E+09	1.53E+10	1.57E+10
2.338	0.631	92.05	9.07E+08	7.43E+09	1.31E+10	1.33E+10
2.943	0.794	115.87	7.77E+08	6.37E+09	1.12E+10	1.14E+10
3.705	1	145.87	6.75E+08	5.53E+09	9.72E+09	9.94E+09
4.665	1.259	183.66	5.93E+08	4.86E+09	8.54E+09	8.72E+09
5.872	1.585	231.18	5.38E+08	4.41E+09	7.75E+09	7.91E+09
7.393	1.995	291.06	4.83E+08	3.96E+09	6.95E+09	7.11E+09
9.307	2.512	366.42	4.36E+08	3.57E+09	6.28E+09	6.41E+09
11.717	3.162	461.30	3.97E+08	3.25E+09	5.71E+09	5.83E+09
14.751	3.981	580.75	3.57E+08	2.93E+09	5.14E+09	5.26E+09
18.57	5.012	731.10	3.20E+08	2.62E+09	4.61E+09	4.71E+09
23.378	6.31	920.39	2.81E+08	2.31E+09	4.05E+09	4.14E+09
29.432	7.943	1158.74	2.44E+08	2.00E+09	3.52E+09	3.59E+09
37.052	10	1458.74	2.15E+08	1.76E+09	3.09E+09	3.16E+09

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Table A6
Integral LET Spectra for Galactic Cosmic Ray Ions (Z=1-92)
100 mils Aluminum Shielding

LET ((MeV·cm^2)/mg)	Flux > LET (#/cm^2/day)	
	Solar Maximum	Solar Minimum
1.01E-01	7.49E+03	1.42E+04
1.27E-01	4.30E+03	8.20E+03
1.43E-01	3.27E+03	6.25E+03
1.61E-01	2.49E+03	4.75E+03
1.80E-01	1.86E+03	3.56E+03
2.03E-01	1.39E+03	2.68E+03
2.28E-01	1.04E+03	2.00E+03
2.55E-01	7.56E+02	1.46E+03
2.87E-01	5.51E+02	1.07E+03
3.22E-01	4.01E+02	7.85E+02
3.62E-01	2.75E+02	5.49E+02
4.06E-01	1.89E+02	3.81E+02
4.56E-01	1.19E+02	2.46E+02
5.12E-01	5.33E+01	1.18E+02
5.75E-01	4.60E+01	1.00E+02
6.46E-01	4.31E+01	9.20E+01
7.26E-01	3.87E+01	8.20E+01
8.15E-01	3.62E+01	7.53E+01
9.15E-01	3.27E+01	6.75E+01
1.03E+00	2.95E+01	6.06E+01
1.15E+00	2.28E+01	4.90E+01
1.30E+00	9.06E+00	2.76E+01
1.45E+00	4.65E+00	1.87E+01
1.63E+00	2.95E+00	1.39E+01
1.83E+00	2.02E+00	1.06E+01
2.06E+00	1.42E+00	8.12E+00
2.31E+00	1.02E+00	6.24E+00
2.60E+00	7.40E-01	4.82E+00
2.92E+00	5.42E-01	3.71E+00
3.28E+00	4.02E-01	2.87E+00
3.68E+00	2.99E-01	2.20E+00
4.13E+00	2.24E-01	1.69E+00
4.64E+00	1.67E-01	1.30E+00
5.21E+00	1.25E-01	9.89E-01
5.85E+00	9.42E-02	7.55E-01
6.57E+00	7.10E-02	5.74E-01

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7.38E+00	5.33E-02	4.31E-01
8.28E+00	4.07E-02	3.31E-01
9.30E+00	3.10E-02	2.53E-01
1.04E+01	2.34E-02	1.91E-01
1.17E+01	1.74E-02	1.42E-01

Table A6 (Continued)
Integral LET Spectra for Galactic Cosmic Ray Ions (Z=1-92)
100 mils Aluminum Shielding

LET ((MeV·cm^2)/mg)	Flux > LET (#/cm^2/day)	
	Solar Maximum	Solar Minimum
1.32E+01	1.28E-02	1.04E-01
1.48E+01	9.28E-03	7.55E-02
1.66E+01	6.71E-03	5.46E-02
1.87E+01	4.72E-03	3.84E-02
2.10E+01	3.11E-03	2.53E-02
2.35E+01	1.82E-03	1.47E-02
2.64E+01	7.64E-04	6.18E-03
2.97E+01	2.61E-05	2.01E-04
3.33E+01	3.36E-06	2.17E-05
3.74E+01	2.10E-06	1.35E-05
4.20E+01	1.42E-06	9.13E-06
4.72E+01	9.81E-07	6.27E-06
5.30E+01	6.53E-07	4.16E-06
5.95E+01	4.06E-07	2.57E-06
6.68E+01	2.33E-07	1.46E-06
7.50E+01	1.18E-07	7.36E-07
8.42E+01	3.98E-08	2.49E-07
9.46E+01	1.35E-09	8.42E-09
1.03E+02	1.06E-10	6.67E-10

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Table A7a
Integral LET Spectra for the October 1989 Solar Particle Event (Z=1-92)
Note that fluxes are given per second, not per day
100 mils Aluminum Shielding

LET ((MeV·cm^2)/mg)	Flux > LET (#/cm^2/sec)	
	Worst Day	Worst 5 Minutes
1.01E-01	2.74E+02	1.04E+03
1.27E-01	1.63E+02	6.16E+02
1.43E-01	1.25E+02	4.72E+02
1.61E-01	9.48E+01	3.59E+02
1.80E-01	7.13E+01	2.70E+02
2.03E-01	5.33E+01	2.02E+02
2.28E-01	3.93E+01	1.49E+02
2.55E-01	2.88E+01	1.09E+02
2.87E-01	2.08E+01	7.89E+01
3.22E-01	1.49E+01	5.63E+01
3.62E-01	1.04E+01	3.95E+01
4.06E-01	7.02E+00	2.66E+01
4.56E-01	4.29E+00	1.62E+01
5.12E-01	1.74E+00	6.57E+00
5.75E-01	1.26E+00	4.76E+00
6.46E-01	9.90E-01	3.72E+00
7.26E-01	7.71E-01	2.90E+00
8.15E-01	6.00E-01	2.25E+00
9.15E-01	4.62E-01	1.73E+00
1.03E+00	3.52E-01	1.31E+00
1.15E+00	2.63E-01	9.80E-01
1.30E+00	1.91E-01	7.11E-01
1.45E+00	1.30E-01	4.82E-01
1.63E+00	7.06E-02	2.57E-01
1.83E+00	6.06E-02	2.20E-01
2.06E+00	5.18E-02	1.88E-01
2.31E+00	4.41E-02	1.60E-01
2.60E+00	3.73E-02	1.36E-01
2.92E+00	3.16E-02	1.14E-01
3.28E+00	2.66E-02	9.63E-02
3.68E+00	2.22E-02	8.06E-02
4.13E+00	1.85E-02	6.71E-02
4.64E+00	1.53E-02	5.52E-02
5.21E+00	1.22E-02	4.42E-02
5.85E+00	9.93E-03	3.59E-02
6.57E+00	7.86E-03	2.84E-02
7.38E+00	5.82E-03	2.10E-02
8.28E+00	4.67E-03	1.68E-02
9.30E+00	3.66E-03	1.32E-02
1.04E+01	2.82E-03	1.02E-02

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1.17E+01	2.13E-03	7.67E-03

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Table A7a (Continued)
Integral LET Spectra for the October 1989 Solar Particle Event (Z=1-92)
Note that fluxes are given per second not per day
100 mils Aluminum Shielding

LET ((MeV·cm^2)/mg)	Flux > LET (#/cm^2/sec)	
	Worst Day	Worst 5 Minutes
1.32E+01	1.57E-03	5.64E-03
1.48E+01	1.10E-03	3.95E-03
1.66E+01	7.99E-04	2.87E-03
1.87E+01	5.81E-04	2.09E-03
2.10E+01	3.99E-04	1.43E-03
2.35E+01	2.52E-04	9.08E-04
2.64E+01	1.21E-04	4.35E-04
2.97E+01	2.18E-06	7.83E-06
3.33E+01	1.11E-07	3.98E-07
3.74E+01	5.30E-08	1.90E-07
4.20E+01	2.92E-08	1.05E-07
4.72E+01	1.95E-08	7.02E-08
5.30E+01	1.28E-08	4.61E-08
5.95E+01	6.74E-09	2.42E-08
6.68E+01	3.84E-09	1.38E-08
7.50E+01	2.32E-09	8.36E-09
8.42E+01	1.03E-09	3.70E-09
9.46E+01	1.84E-11	6.63E-11
1.03E+02	1.50E-12	5.37E-12

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Table A7b
Integral LET Spectra for Solar Particle Events During Solar Maximum (Z=1-92)
90% Worst Case Average
100 mils Aluminum Shielding

LET ((MeV·cm^2)/mg)	Flux > LET (#/cm^2/sec)
1.00E-01	5.31E+00
1.12E-01	4.17E+00
1.26E-01	3.28E+00
1.41E-01	2.55E+00
1.58E-01	1.98E+00
1.78E-01	1.51E+00
2.00E-01	1.14E+00
2.24E-01	8.40E-01
2.51E-01	5.91E-01
2.82E-01	3.72E-01
3.16E-01	1.21E-01
3.55E-01	9.78E-02
3.98E-01	7.86E-02
4.47E-01	6.39E-02
5.01E-01	5.15E-02
5.62E-01	4.20E-02
6.31E-01	3.36E-02
7.08E-01	2.73E-02
7.94E-01	2.15E-02
8.91E-01	1.66E-02
1.00E+00	1.20E-02
1.12E+00	6.15E-03
1.26E+00	5.23E-03
1.41E+00	4.42E-03
1.58E+00	3.72E-03
1.78E+00	3.09E-03
2.00E+00	2.55E-03
2.24E+00	2.08E-03
2.51E+00	1.70E-03
2.82E+00	1.37E-03
3.16E+00	1.10E-03
3.55E+00	8.73E-04
3.98E+00	6.84E-04
4.47E+00	5.29E-04
5.01E+00	3.88E-04
5.62E+00	2.95E-04
6.31E+00	2.09E-04
7.08E+00	1.45E-04
7.94E+00	9.46E-05
8.91E+00	7.13E-05

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Released Version

1.00E+01	5.05E-05

Table A7b (Continued)
Integral LET Spectra for Solar Particle Events During Solar Maximum (Z=1-92)
90% Worst Case Average
100 mils Aluminum Shielding

LET ((MeV·cm^2)/mg)	Flux > LET (#/cm^2/sec)
1.12E+01	3.61E-05
1.26E+01	2.33E-05
1.41E+01	1.63E-05
1.58E+01	1.10E-05
1.78E+01	7.87E-06
2.00E+01	5.61E-06
2.24E+01	3.80E-06
2.51E+01	2.31E-06
2.82E+01	8.67E-07
3.16E+01	2.65E-09
3.55E+01	7.46E-10
3.98E+01	4.07E-10
4.47E+01	2.25E-10
5.01E+01	1.51E-10
5.62E+01	9.63E-11
6.31E+01	5.45E-11
7.08E+01	3.18E-11
7.94E+01	1.79E-11
8.91E+01	5.59E-12
1.00E+02	5.91E-14

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Table A8
Long-Term Integral Proton Fluxes for SEE Evaluation
100 mils Aluminum Shielding

Energy (> MeV)	Average Flux > E ($p/cm^2/s$)	
	Solar Minimum	Solar Maximum
0.1	4.29E+01	1.17E+02
0.126	4.29E+01	1.17E+02
0.158	4.29E+01	1.17E+02
0.2	4.29E+01	1.17E+02
0.251	4.29E+01	1.17E+02
0.316	4.29E+01	1.17E+02
0.398	4.29E+01	1.17E+02
0.501	4.29E+01	1.17E+02
0.631	4.29E+01	1.17E+02
0.794	4.29E+01	1.17E+02
1	4.29E+01	1.17E+02
1.26	4.29E+01	1.17E+02
1.58	4.29E+01	1.16E+02
2	4.28E+01	1.16E+02
2.51	4.28E+01	1.15E+02
3.16	4.27E+01	1.15E+02
3.98	4.25E+01	1.13E+02
5.01	4.24E+01	1.12E+02
6.31	4.22E+01	1.09E+02
7.94	4.19E+01	1.06E+02
10	4.15E+01	1.01E+02
12.6	4.09E+01	9.47E+01
15.8	4.01E+01	8.66E+01
20	3.90E+01	7.81E+01
25.1	3.74E+01	6.98E+01
31.6	3.55E+01	5.87E+01
39.8	3.29E+01	4.95E+01
50.1	2.99E+01	4.05E+01
63.1	2.63E+01	3.23E+01
79.4	2.18E+01	2.49E+01
100	1.75E+01	1.89E+01
126	1.28E+01	1.32E+01
158	8.85E+00	8.92E+00
200	5.50E+00	5.46E+00
251	2.68E+00	2.65E+00
316	1.01E+00	9.96E-01
398	1.12E-02	1.13E-02

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Table A9
Worst-Case Integral Proton Fluxes for SEE Evaluation
100 mils Aluminum Shielding

Energy (> MeV)	Flux > E (p/cm^2/s)		
	Trapped Solar Maximum	Trapped Solar Minimum	Solar Particle Event
0.1	2.16E+03	3.29E+03	3.56E+05
0.126	2.16E+03	3.29E+03	3.56E+05
0.158	2.16E+03	3.29E+03	3.56E+05
0.2	2.16E+03	3.29E+03	3.56E+05
0.251	2.15E+03	3.29E+03	3.56E+05
0.316	2.15E+03	3.29E+03	3.56E+05
0.398	2.15E+03	3.29E+03	3.55E+05
0.501	2.15E+03	3.29E+03	3.55E+05
0.631	2.15E+03	3.29E+03	3.55E+05
0.794	2.15E+03	3.29E+03	3.55E+05
1	2.15E+03	3.29E+03	3.54E+05
1.26	2.15E+03	3.29E+03	3.53E+05
1.58	2.15E+03	3.29E+03	3.52E+05
2	2.15E+03	3.29E+03	3.51E+05
2.51	2.15E+03	3.29E+03	3.49E+05
3.16	2.15E+03	3.28E+03	3.45E+05
3.98	2.14E+03	3.28E+03	3.41E+05
5.01	2.14E+03	3.28E+03	3.34E+05
6.31	2.13E+03	3.28E+03	3.25E+05
7.94	2.12E+03	3.27E+03	3.12E+05
10	2.10E+03	3.26E+03	2.94E+05
12.6	2.08E+03	3.25E+03	2.68E+05
15.8	2.05E+03	3.23E+03	2.37E+05
20	2.00E+03	3.17E+03	2.05E+05
25.1	1.93E+03	3.03E+03	1.75E+05
31.6	1.84E+03	2.86E+03	1.34E+05
39.8	1.71E+03	2.64E+03	1.03E+05
50.1	1.57E+03	2.37E+03	7.38E+04
63.1	1.39E+03	2.07E+03	5.03E+04
79.4	1.15E+03	1.69E+03	3.23E+04
100	9.26E+02	1.34E+03	2.04E+04
126	7.01E+02	9.68E+02	1.20E+04
158	5.03E+02	6.72E+02	6.86E+03
200	3.22E+02	4.25E+02	3.52E+03
251	1.64E+02	2.13E+02	1.64E+03
316	6.49E+01	8.27E+01	5.87E+02
398	7.87E-01	9.32E-01	7.41E+00

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X. Appendix – Total Ionizing Dose for 10/2015 Launch

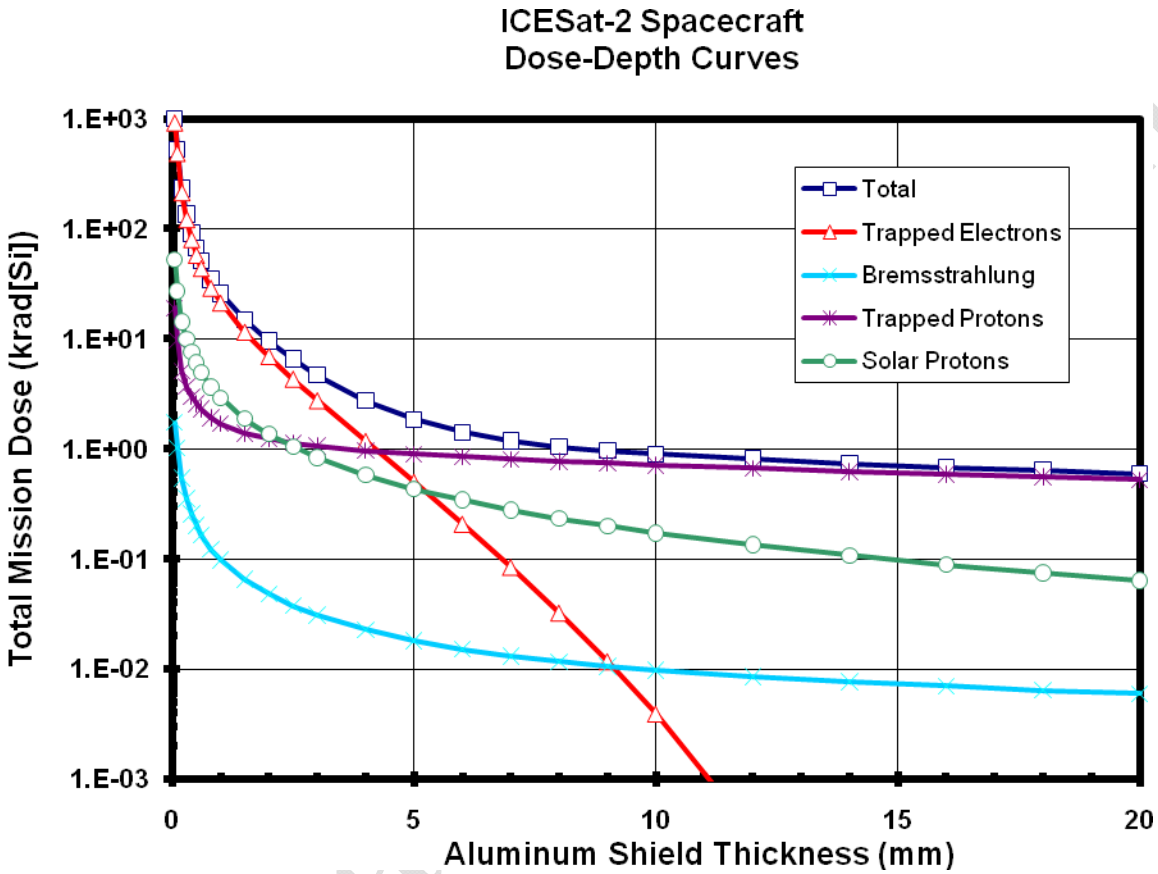

Figure X-A: ICESat-2 spacecraft total ionizing dose curves for the absorbed radiation dose at the center of solid aluminum spheres. Values do not include design margins. This dose-depth curve assumes a launch date of October 2015. The mission total ionizing dose behind 100 mil (2.54 mm) of aluminum is approximately 6.5 krad(Si) with no radiation design margin.

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Table X-A

ICESat-2 Total Ionizing Dose at the Center of Solid Aluminum Spheres for 10/2015 Launch Date

Aluminum Shield Thickness			Dose [krad(Si)] - Total Mission				
(mm)	(mils)	(g/cm2)	Total	Trap e	Brem	Trap p	Solar p
0.05	1.97E+00	1.40E-02	9.96E+02	9.23E+02	1.74E+00	1.91E+01	5.25E+01
0.1	3.94E+00	2.70E-02	5.24E+02	4.86E+02	1.03E+00	9.74E+00	2.72E+01
0.2	7.87E+00	5.40E-02	2.34E+02	2.14E+02	5.46E-01	5.11E+00	1.42E+01
0.3	1.18E+01	8.10E-02	1.36E+02	1.22E+02	3.56E-01	3.67E+00	9.95E+00
0.4	1.57E+01	1.08E-01	9.14E+01	8.06E+01	2.58E-01	2.98E+00	7.57E+00
0.5	1.97E+01	1.35E-01	6.65E+01	5.77E+01	2.01E-01	2.58E+00	6.03E+00
0.6	2.36E+01	1.62E-01	5.13E+01	4.38E+01	1.66E-01	2.30E+00	4.97E+00
0.8	3.15E+01	2.16E-01	3.48E+01	2.90E+01	1.23E-01	1.92E+00	3.67E+00
1	3.94E+01	2.70E-01	2.60E+01	2.12E+01	9.82E-02	1.69E+00	2.91E+00
1.5	5.91E+01	4.05E-01	1.49E+01	1.16E+01	6.52E-02	1.40E+00	1.89E+00
2	7.87E+01	5.40E-01	9.61E+00	6.96E+00	4.82E-02	1.24E+00	1.37E+00
2.5	9.84E+01	6.75E-01	6.56E+00	4.34E+00	3.77E-02	1.13E+00	1.05E+00
3	1.18E+02	8.10E-01	4.70E+00	2.77E+00	3.09E-02	1.06E+00	8.34E-01
4	1.57E+02	1.08E+00	2.75E+00	1.18E+00	2.28E-02	9.61E-01	5.79E-01
5	1.97E+02	1.35E+00	1.85E+00	5.03E-01	1.81E-02	8.93E-01	4.31E-01
6	2.36E+02	1.62E+00	1.41E+00	2.09E-01	1.52E-02	8.47E-01	3.43E-01
7	2.76E+02	1.89E+00	1.18E+00	8.46E-02	1.31E-02	8.05E-01	2.79E-01
8	3.15E+02	2.16E+00	1.05E+00	3.26E-02	1.17E-02	7.69E-01	2.33E-01
9	3.54E+02	2.43E+00	9.63E-01	1.18E-02	1.06E-02	7.40E-01	2.00E-01
10	3.94E+02	2.70E+00	8.96E-01	3.93E-03	9.72E-03	7.10E-01	1.72E-01
12	4.72E+02	3.24E+00	8.09E-01	3.20E-04	8.48E-03	6.65E-01	1.35E-01
14	5.51E+02	3.78E+00	7.37E-01	7.94E-06	7.63E-03	6.22E-01	1.08E-01
16	6.30E+02	4.32E+00	6.82E-01	6.11E-08	6.98E-03	5.86E-01	8.86E-02
18	7.09E+02	4.86E+00	6.37E-01	6.47E-10	6.44E-03	5.56E-01	7.50E-02
20	7.87E+02	5.40E+00	5.94E-01	0.00E+00	5.98E-03	5.25E-01	6.34E-02

**Corresponds to Figure X-A

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