Integral
Radiation Environment

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1 Introduction

The highly eccentric orbit of INTEGRAL evolves considerably throughout the mission. This strongly affects the radiation environment encountered. Initially, the spacecraft's orbit traversed both the proton and the electron radiation belts, but gradually the perigee has been raised above the trapped proton belt to minimise the proton radiation. An initial analysis of the radiation doses likely to be experienced by the spacecraft in its 5 year lifetime was made before the launch [1]. The launch was in October 2002, so we are approaching the end of the predictions.

Furthermore, orbital analysis performed by OPS-O predicts that the perigee height will start to drop quite strongly from 2007 and onwards, reaching a minimum of about 3000km in 2012. This will drastically increase the proton radiation likely to be experienced. One option is to use some fuel to raise the perigee height, and thus reducing the proton radiation. An initial analysis performed by OPS-O indicates that this could raise the height of the perigee by about 2000km. Figure 1 shows the evolution of the perigee for the current orbit as well as the perigee raising option under investigation.

The rest of this note is an update of the radiation analysis in [1] for the current orbit as well as the perigee raising option. For completeness a short general description of the space environment is also included.

[1] INTEGRAL Radiation Environment, H. Evans 16 July 2002, esa/estec/wma/he/Integral/17.

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The radiation environment

The space radiation environment presents a major problem to space systems. The environment consists of geomagnetically trapped charged particles, solar protons, and galactic cosmic rays. It is the penetrating particles that provide the main problems, which include upsets to electronics, payload interference, damage to components and deep dielectric charging.

Trapped Particle Radiation

Energetic electrons and ions are magnetically trapped around the earth forming the radiation belts, also known as the Van Allen belts. The radiation belts consist principally of electrons of up to a few MeV energy and protons of up to several hundred MeV energy. An inner belt contains mainly energetic protons and is reasonably stable in time and extends to a geocentric distance of 4-R_{Earth}. The outer belt consists primarily of energetic electrons and is highly dynamic, being subject to storms and injection events that follow solar-terrestrial disturbances. The electron belt extends to near the magnetopause at about 10 R_{Earth} radii.

Solar particle Events

Solar protons are products of solar events. During energetic events on the sun, large fluxes of energetic protons are produced which can reach the Earth. Solar particle events, because of their unpredictability and large variability in magnitude, duration and spectral characteristics, have to be treated statistically. However, large events are confined to a 7-year period defined as solar maximum. Although large events are absent during the remaining 4 solar minimum years of the 11-year solar cycle the occasional small event can still occur. Solar protons have energies in excess of several hundred MeV and peak fluxes in excess of 10^6 protons/cm^2/sec for protons with energies greater than 10 MeV. The duration of individual events is usually on the order of days. The large fluxes of energetic protons and heavier ions can contribute a large dose, increase upset rates in electronics and increase radiation induced background noise in detectors.

The individual flare spectra are very variable, and what constitutes a worst-case event for a given energy is not necessarily worst-case at another. For the higher energies, which are the most important for nuclear interactions giving rise to certain types of background and single-event upsets, the October 1989 event is normally seen as a worst-case.

Concerning the directionality of the event flux, there is a streaming taking place, but it is usually of short duration (short compared with the duration of the individual event), with field disturbances quickly changing it into near isotropic distribution. Also it seems less pronounced in larger events. Therefore for engineering considerations the flux can be assumed to be isotropic.

Further information about the space environment and its effects on spacecraft systems can be found in the ECSS-E-10-04 space environment standard, available at:

http://space-env.esa.int/standards/ecss/ecss.html

3 Analysis

All the analysis has been performed with SPENVIS [1].

The information on the orbit has been received from OPS-O consisting of the ephemeris for each orbit from the launch in October 2002 and until April 2017 for the current orbit and until August 2019 for the perigee raising option under investigation [2]. This has been sampled with 3 months interval. Although not enough to reflect the seasonal variations is it seen as sufficient to give a good picture of the long-term evolution.

Trapped Particle Fluxes

For trapped radiation, the standard models of radiation belt energetic particle are the AE-8 and AP-8 models for electrons and protons respectively. They were developed at the NSSDC at NASA/GSFC based on data from satellites flown in the '60s and early '70s, and give omni-directional fluxes as functions of idealized geomagnetic dipole co-ordinates B/B_0 and L. Figure 2 to 6 show the predicted fluxes for the INTEGRAL mission according to these models. Figure 2 to 5 show the evolution over the mission of the integral proton and electron fluxes for selected energies. Figure 3 shows the evolution of the important >10MeV proton flux and it is seen that a drastic increase can be expected after 2010 towards the end of the mission. For the perigee raising option the increase is delayed by almost a year and the maximum reached is only about 2/3 of what is predicted for the current orbit. Figure 6 shows the predicted mission proton spectrum until 2011.

Solar proton Fluxes

For solar proton fluxes the reference model used for engineering consideration of time-integrated effects is the JPL-1991 model. This statistical model is based on data from 3 solar cycles. Figure 7 shows the predicted spectrum for the INTEGRAL mission of solar protons based on this model assuming 90% confidence level. For comparison the trapped fluences are shown in the same plot. It is seen that a major contribution to the >10MeV protons can be expected to come from solar protons. This is especially important since we are going towards solar maximum as we are approaching the end of the mission. It should be remarked that the data are predictions made for the full mission, including the part, which has already taken place. The high eccentricity and long period of the trajectory leave the spacecraft out of the effective region for geomagnetic shielding, therefore, no attenuation of the solar proton fluence spectrum was performed.

Ionizing dose

For ionising dose the SHIELDOSE-2 model is used. This uses a pre-computed data set of doses from electrons, electron-induced Bremsstrahlung and protons, as derived from Monte-Carlo analysis. The doses are provided as functions of spherical material shielding thickness about a point. Figure 8 shows the expected evolution of the ionising dose for the INTEGRAL mission for 4mm spherical aluminium shielding. Figure 9 shows the total ionising dose for the mission until 2011 as a function

of shielding thickness. It is seen that there is little difference between the current orbit and the perigee raising option. Figure 10 shows the contribution to the total ionising dose from protons, electrons, bremsstrahlung and solar protons respectively (the plot is for the current orbit, but there is little difference between the current orbit and the perigee raising option).

Solar cell degradation

For silicon solar cell degradation the EQFRUX-Si model is used. In the analysis it is assumed that 10MeV protons cause equivalent damage to 3000 1 MeV electrons in silicon cells. Furthermore infinite rear-side shielding of cells are assumed. Figure 11 shows the predicted evolution of the equivalent 1MeV electron fluence for the INTEGRAL mission. The data is for Si solar cells for 152micron coverglass and for the maximum power and open-circuit voltage degradation.

Non-ionizing dose

For damage to CCDs and other electro-optical components susceptible to displacement damage the NIEL function (non-ionising energy loss) is employed to derive a 10MeV equivalent proton damage fluence. For more information see [3]. Figure 12 shows the NIEL function for protons and Silicon as target material. Figure 13 shows the evolution of the equivalent 10MeV proton fluence for the INTEGRAL mission. To turn this into a relative degradation (e.g. Charge Transfer Efficiency loss in a CCD) it is necessary to test the specific detector in question to find its response to such an environment.

[1] Space Environment Information System, http://www.spenvis.oma.be/spenvis/

[2] Email from M. Rosengren OPS-O 6/12-2006, 14/12-2006 and 31/1-2007, files future.txt, past.txt and futurem.txt

[3] ECSS-E-10-04 space environment standard, http://space-env.esa.int/standards/ecss/ecss.html

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Figures

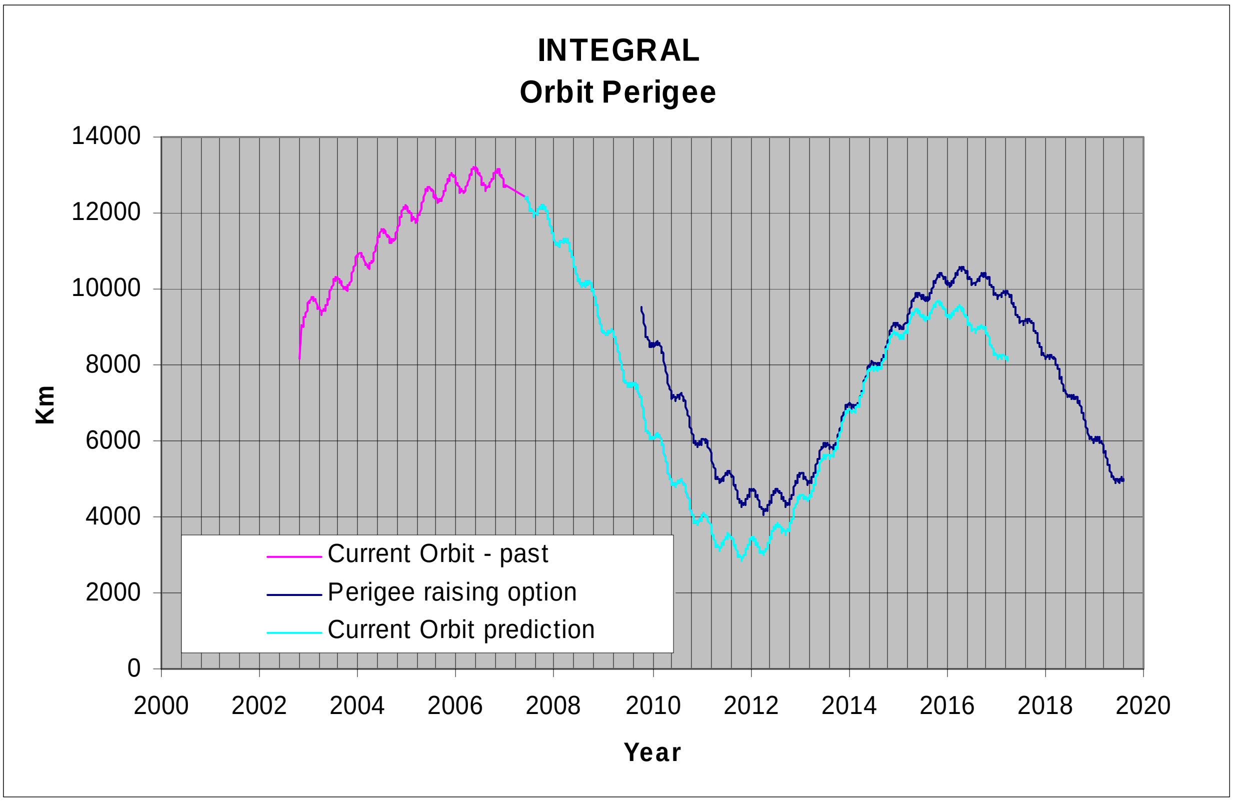

Figure 1: Orbit Perigee

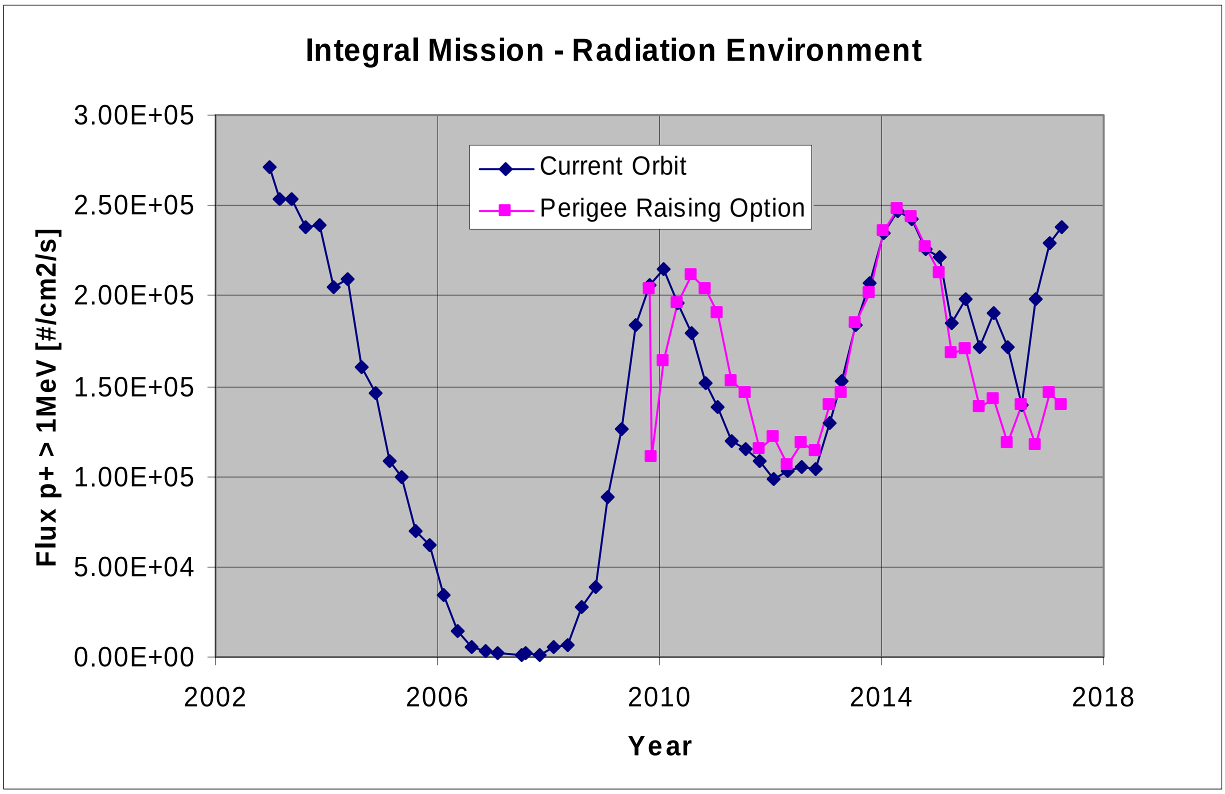

Figure 2: Evolution of the >1MeV proton flux

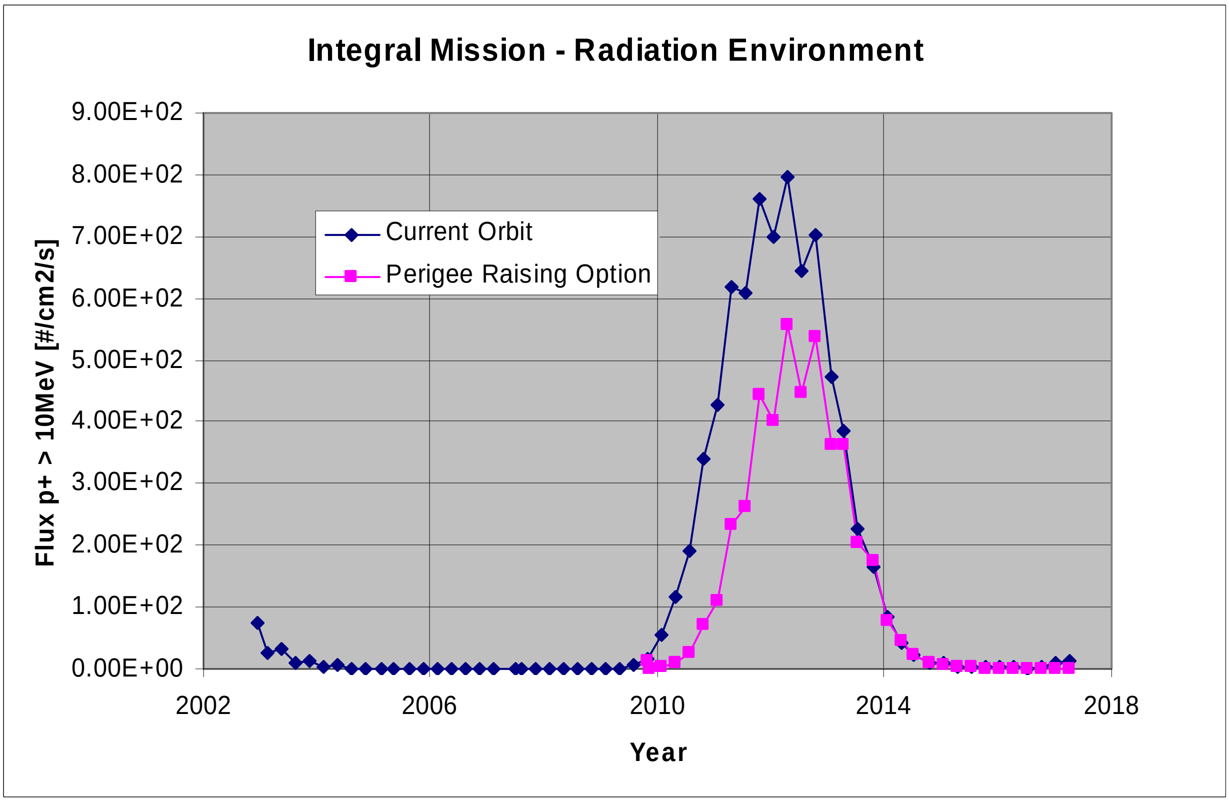

Figure 3: Evolution of the >10MeV proton flux

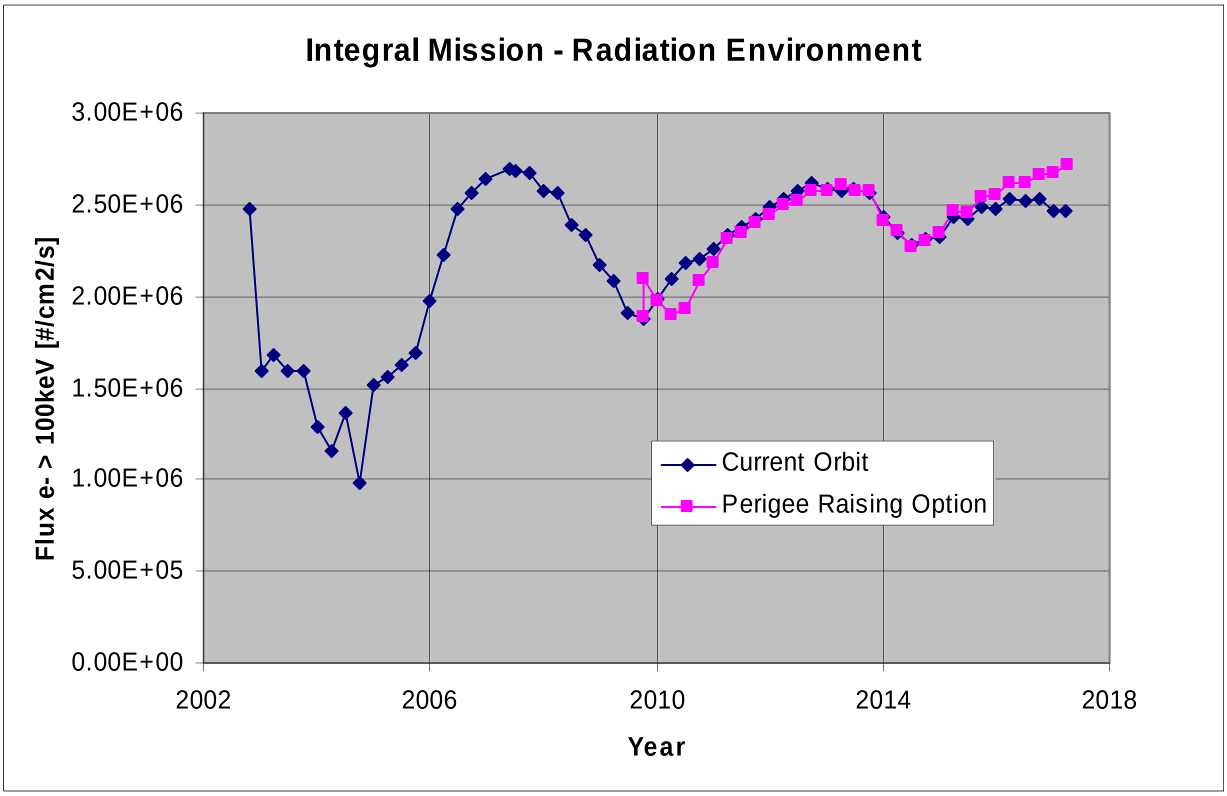

Figure 4: Evolution of the >100keV electron flux

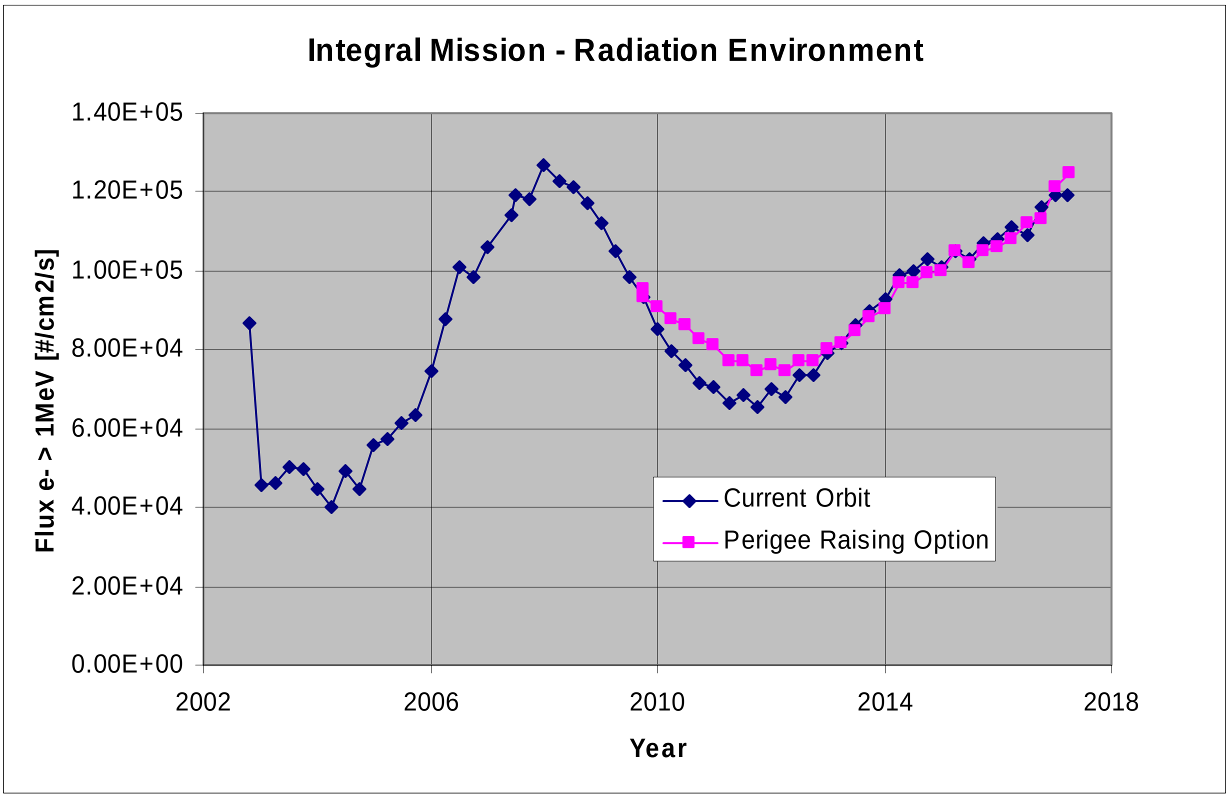

Figure 5: Evolution of the >1MeV electron flux

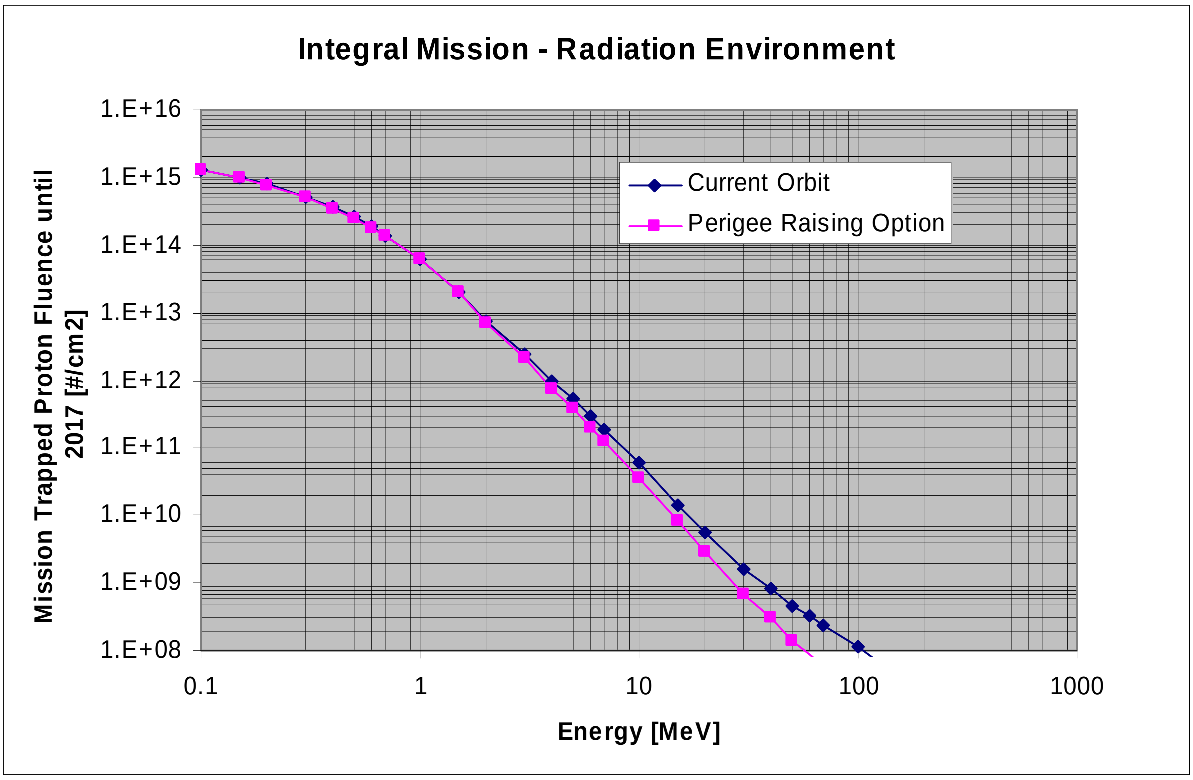

Figure 6: Mission proton fluence spectrum until 2017

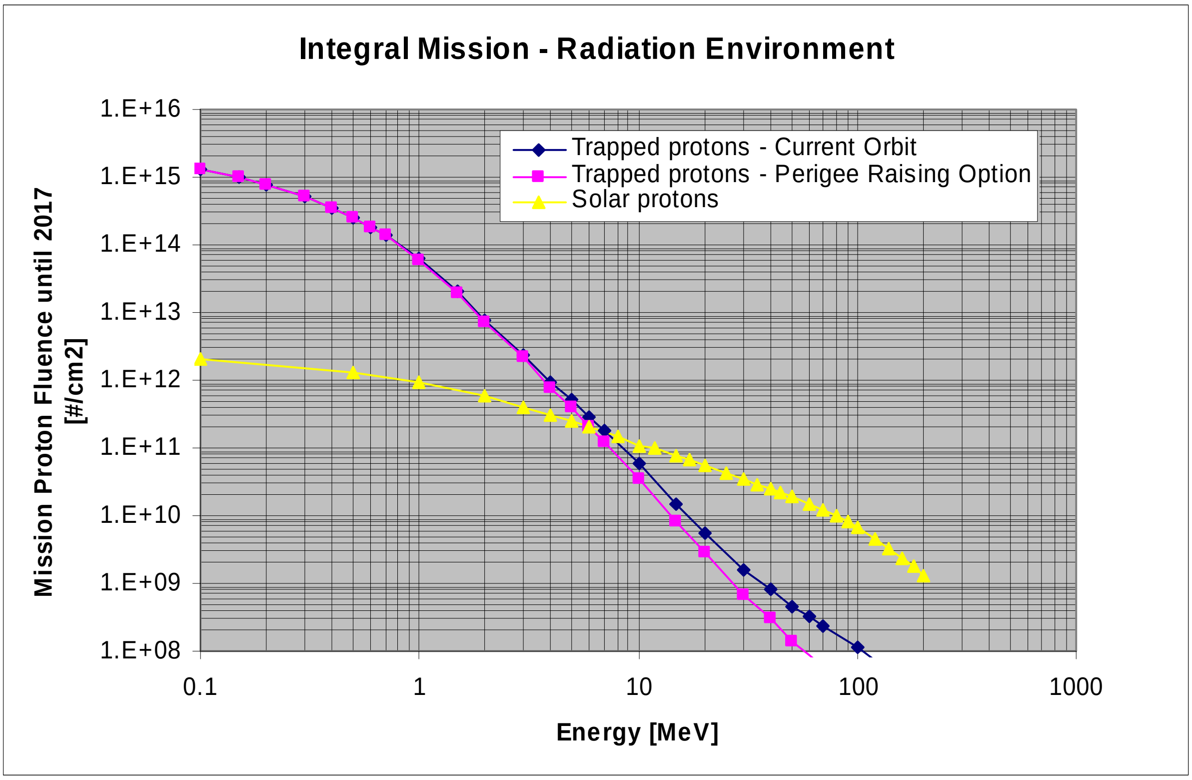

Figure 7: Mission proton fluence spectrum including solar protons until 2017

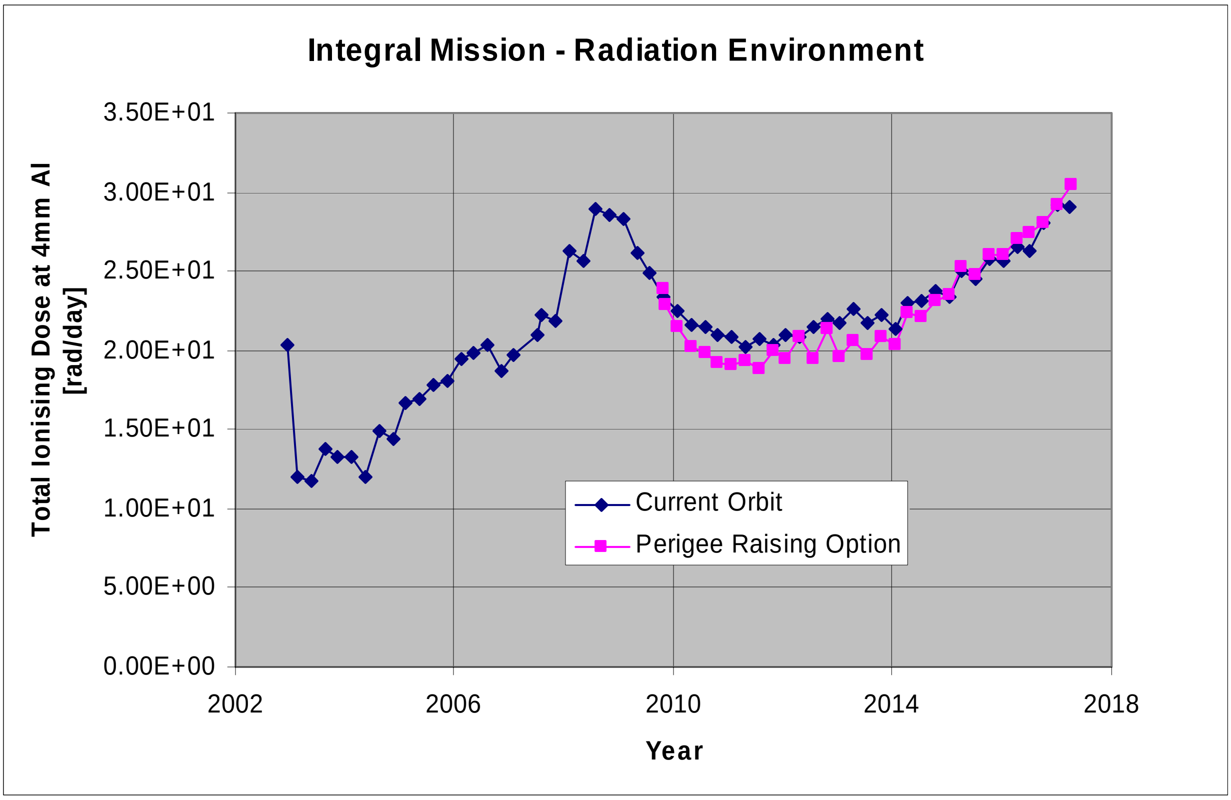

Figure 8: Evolution of the ionising dose

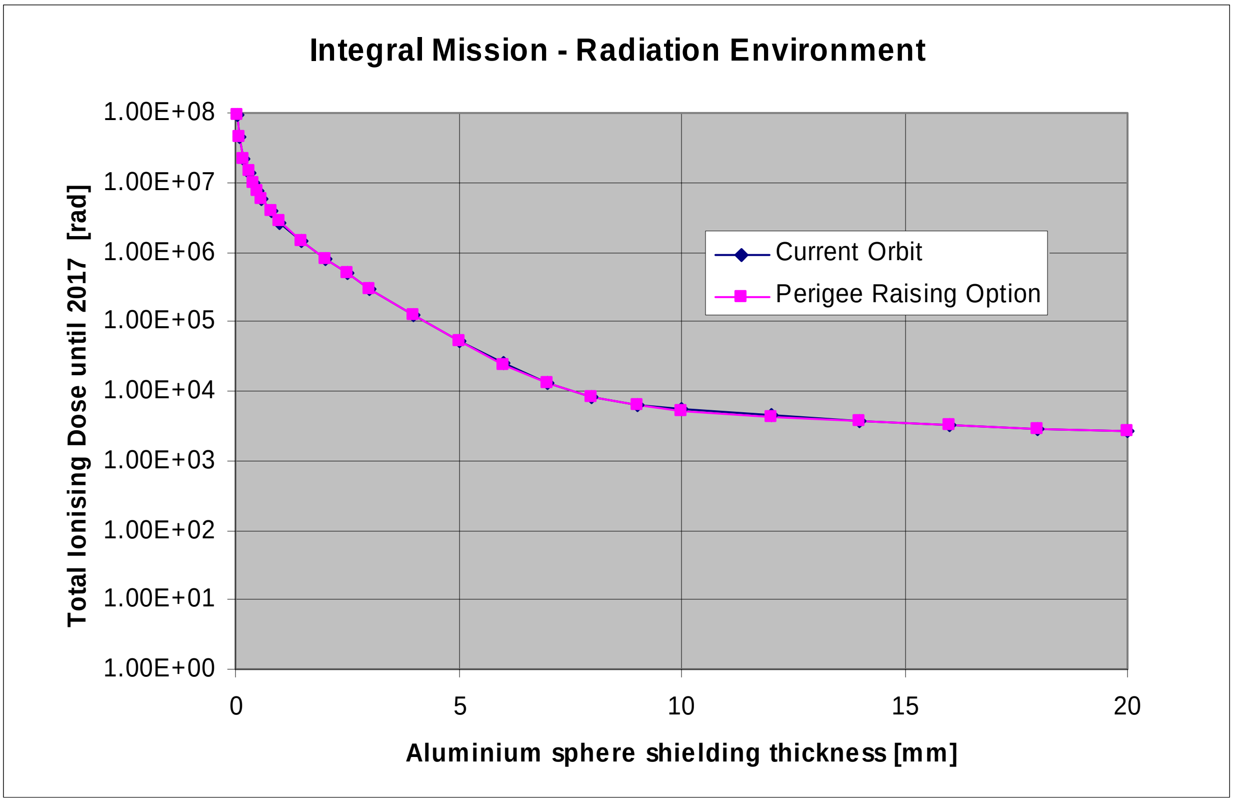

Figure 9: Total ionising dose for the Mission until 2017

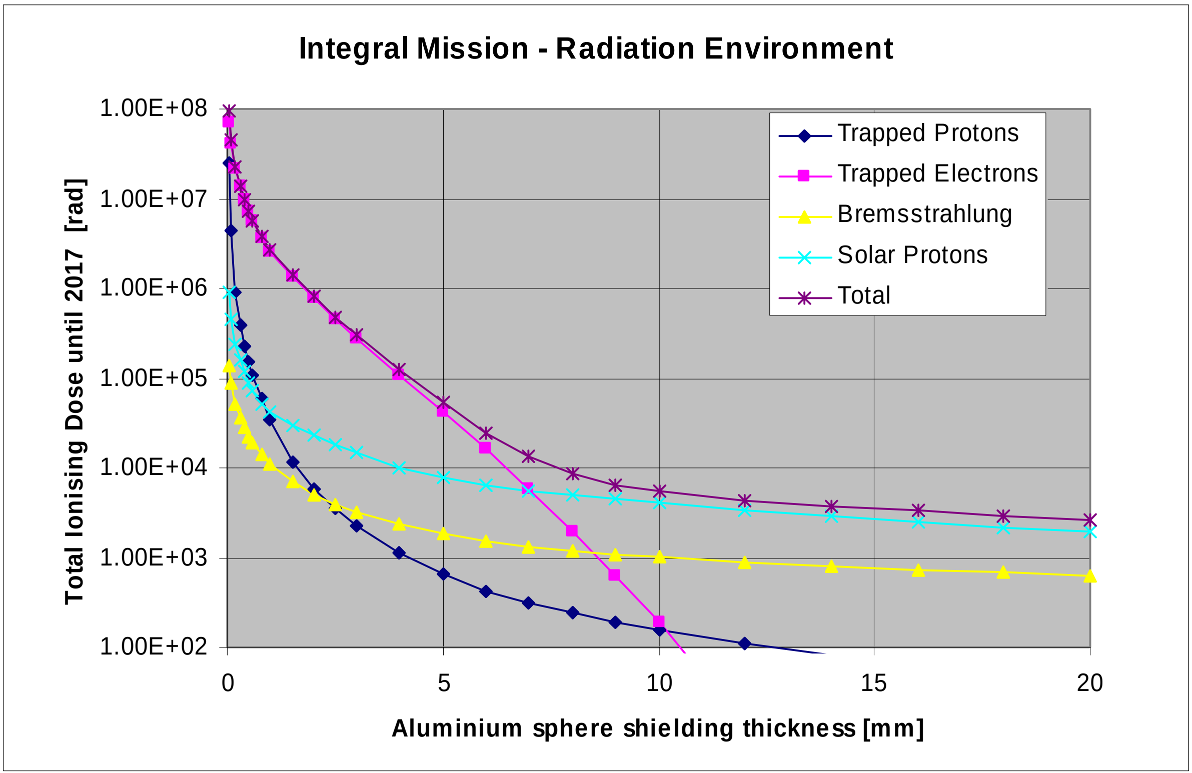

Figure 10: Total ionising dose for the Mission until 2017 split in the various contributions (current orbit)

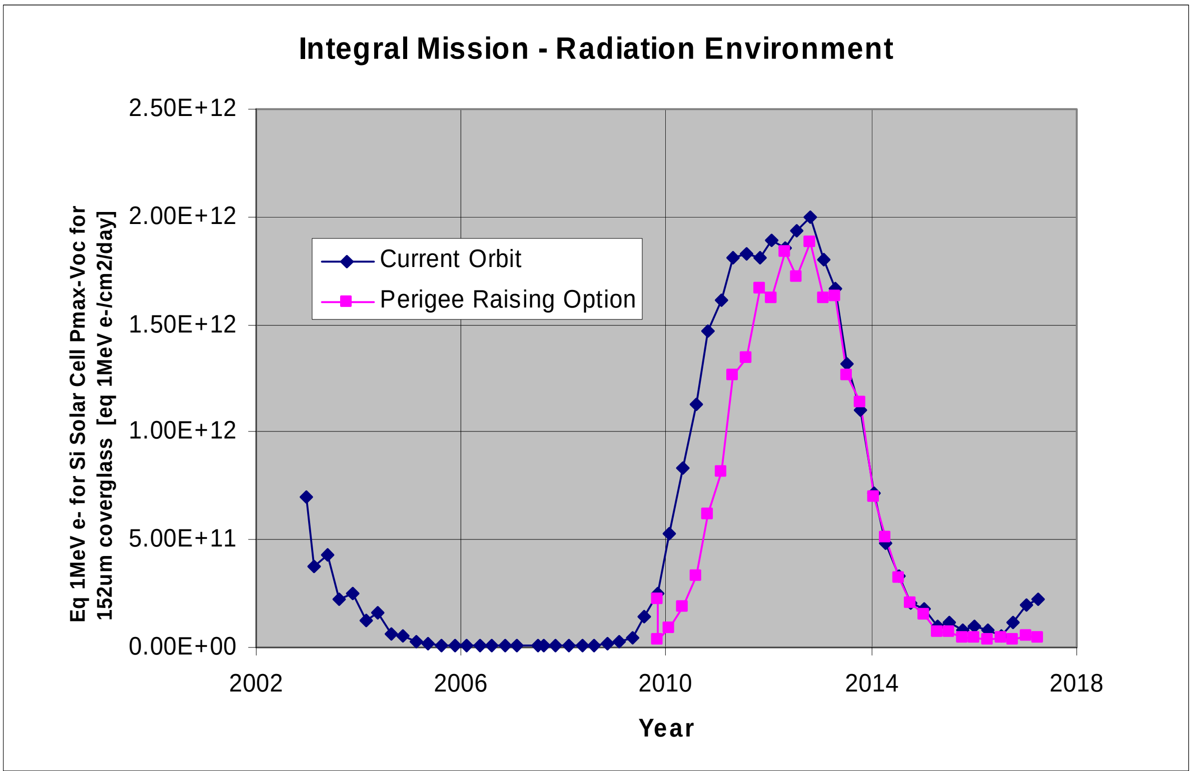

Figure 11: Evolution of the equivalent 1MeV electron fluences for Si solar cells with 152micron coverglass for Pmax-Voc

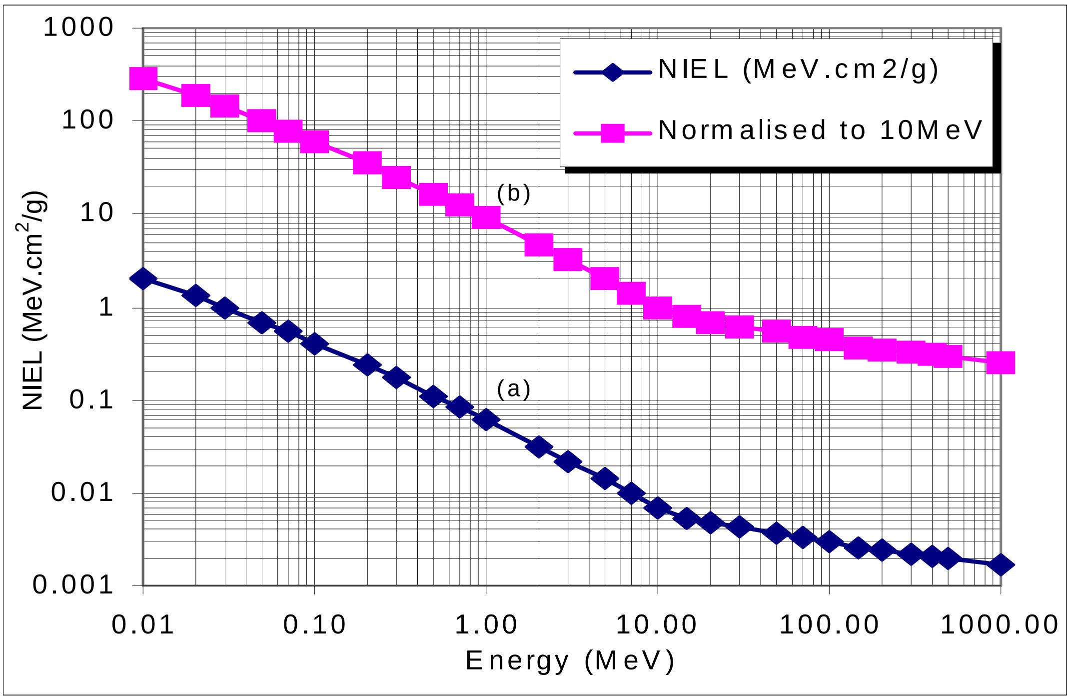

Figure 12: NIEL curve: (a) energy lost by protons in non-ionizing interactions (bulk, displacement damage); (b) NIEL relative to 10MeV giving damage-equivalence of other energies.

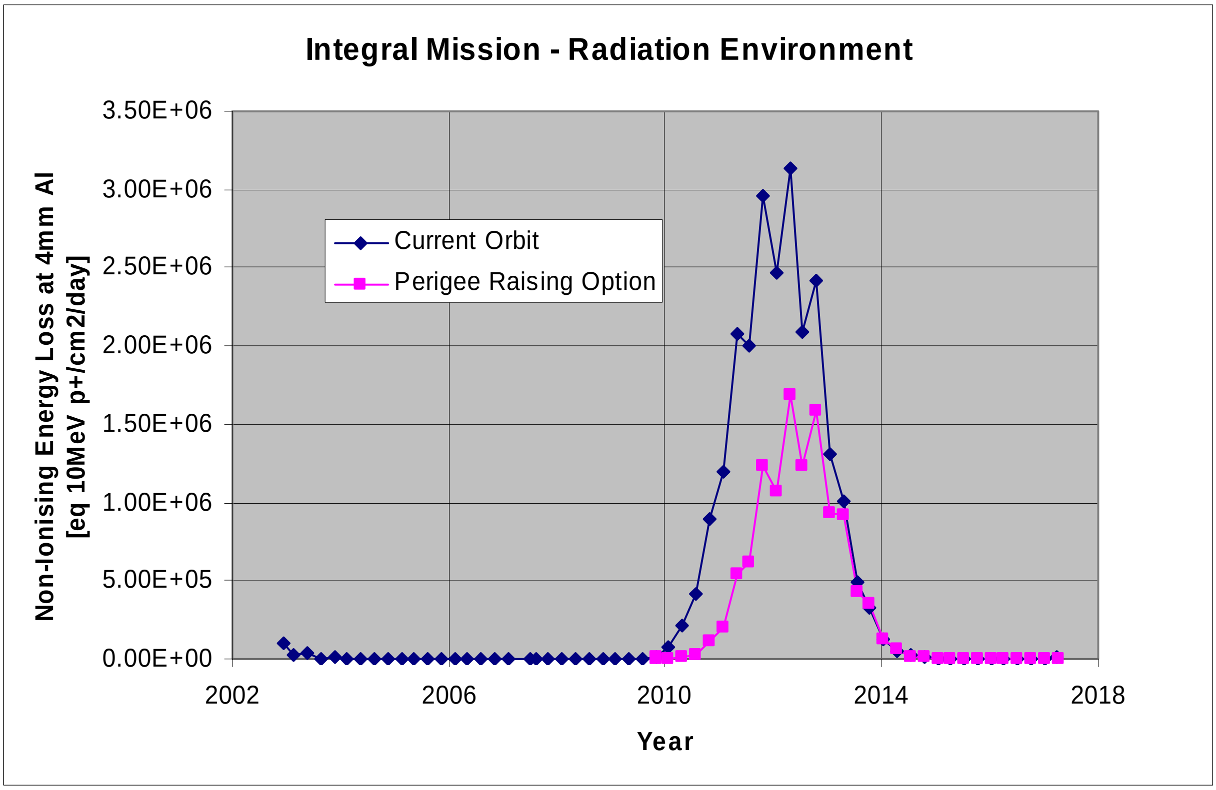

Figure 13: Evolution of Non-ionising energy loss at 4mm Aluminium shielding expressed in equivalent 10MeV protons

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Tables

Time [Year]	Fluence [#/cm2/day] Current Orbit			
	Proton >1MeV	Proton >10MeV	Electron >100keV	Electron >1MeV
2002.83	2.71E+05	7.40E+01	2.48E+06	8.69E+04
2003.01	2.54E+05	2.65E+01	1.59E+06	4.56E+04
2003.25	2.54E+05	3.28E+01	1.68E+06	4.62E+04
2003.50	2.38E+05	1.09E+01	1.59E+06	5.03E+04
2003.75	2.39E+05	1.29E+01	1.59E+06	4.96E+04
2004.01	2.05E+05	4.58E+00	1.29E+06	4.44E+04
2004.25	2.09E+05	6.56E+00	1.16E+06	4.01E+04
2004.50	1.60E+05	1.29E+00	1.36E+06	4.91E+04
2004.75	1.46E+05	9.93E-01	9.77E+05	4.44E+04
2005.00	1.08E+05	2.43E-01	1.52E+06	5.60E+04
2005.25	9.93E+04	1.82E-01	1.56E+06	5.73E+04
2005.50	7.01E+04	3.84E-02	1.63E+06	6.12E+04
2005.75	6.17E+04	2.21E-02	1.69E+06	6.33E+04
2006.00	3.43E+04	0.00E+00	1.97E+06	7.47E+04
2006.25	1.45E+04	0.00E+00	2.23E+06	8.77E+04
2006.50	5.37E+03	0.00E+00	2.48E+06	1.01E+05
2006.75	2.77E+03	0.00E+00	2.56E+06	9.86E+04
2006.99	2.07E+03	0.00E+00	2.64E+06	1.06E+05
2007.42	1.45E+03	0.00E+00	2.69E+06	1.14E+05
2007.50	2.04E+03	0.00E+00	2.68E+06	1.19E+05
2007.75	1.62E+03	0.00E+00	2.67E+06	1.18E+05
2008.00	5.81E+03	0.00E+00	2.58E+06	1.27E+05
2008.26	7.04E+03	0.00E+00	2.56E+06	1.23E+05
2008.50	2.81E+04	0.00E+00	2.39E+06	1.21E+05
2008.76	3.90E+04	9.83E-05	2.33E+06	1.17E+05
2009.00	8.82E+04	1.73E-01	2.17E+06	1.12E+05
2009.25	1.26E+05	8.28E-01	2.08E+06	1.05E+05
2009.50	1.84E+05	5.98E+00	1.91E+06	9.84E+04
2009.75	2.06E+05	1.55E+01	1.88E+06	9.33E+04
2010.00	2.15E+05	5.63E+01	1.99E+06	8.51E+04

Table 1: Fluence evolution current orbit

Time [Year]	Fluence [#/cm2/day] Current Orbit			
	Proton >1MeV	Proton >10MeV	Electron >100keV	Electron >1MeV
2010.25	1.96E+05	1.16E+02	2.10E+06	7.98E+04
2010.50	1.79E+05	1.90E+02	2.18E+06	7.63E+04
2010.75	1.52E+05	3.40E+02	2.20E+06	7.15E+04
2011.00	1.38E+05	4.26E+02	2.26E+06	7.07E+04
2011.25	1.20E+05	6.18E+02	2.33E+06	6.64E+04
2011.50	1.15E+05	6.09E+02	2.38E+06	6.85E+04
2011.75	1.09E+05	7.60E+02	2.42E+06	6.56E+04
2012.01	9.83E+04	6.98E+02	2.49E+06	7.00E+04
2012.25	1.03E+05	7.97E+02	2.53E+06	6.80E+04
2012.50	1.05E+05	6.45E+02	2.57E+06	7.37E+04
2012.75	1.04E+05	7.01E+02	2.62E+06	7.35E+04
2013.00	1.30E+05	4.73E+02	2.59E+06	7.93E+04
2013.25	1.53E+05	3.86E+02	2.58E+06	8.19E+04
2013.50	1.84E+05	2.26E+02	2.59E+06	8.63E+04
2013.75	2.07E+05	1.65E+02	2.56E+06	8.99E+04
2014.00	2.35E+05	8.34E+01	2.43E+06	9.26E+04
2014.25	2.47E+05	4.31E+01	2.35E+06	9.88E+04
2014.50	2.42E+05	2.19E+01	2.28E+06	9.98E+04
2014.75	2.26E+05	1.01E+01	2.31E+06	1.03E+05
2015.00	2.21E+05	8.27E+00	2.32E+06	1.01E+05
2015.25	1.85E+05	2.74E+00	2.43E+06	1.05E+05
2015.50	1.98E+05	3.72E+00	2.42E+06	1.03E+05
2015.75	1.72E+05	1.84E+00	2.49E+06	1.07E+05
2016.00	1.90E+05	2.96E+00	2.48E+06	1.08E+05
2016.25	1.72E+05	1.83E+00	2.53E+06	1.11E+05
2016.51	1.40E+05	9.26E-01	2.52E+06	1.09E+05
2016.76	1.98E+05	3.78E+00	2.53E+06	1.16E+05
2017.00	2.29E+05	9.46E+00	2.47E+06	1.19E+05
2017.24	2.38E+05	1.15E+01	2.47E+06	1.19E+05

Table 1(continued): Fluence evolution current orbit

Time [Year]	Fluence [#/cm2/day] Perigee Raising Option			
	Proton >1MeV	Proton >10MeV	Electron >100keV	Electron >1MeV
2009.75	2.04E+05	1.24E+01	1.89E+06	9.52E+04
2009.77	1.11E+05	4.51E-01	2.09E+06	9.35E+04
2010.00	1.64E+05	2.84E+00	1.98E+06	9.08E+04
2010.25	1.96E+05	9.74E+00	1.90E+06	8.78E+04
2010.50	2.11E+05	2.51E+01	1.93E+06	8.63E+04
2010.75	2.04E+05	7.07E+01	2.08E+06	8.28E+04
2011.00	1.90E+05	1.10E+02	2.18E+06	8.11E+04
2011.25	1.53E+05	2.34E+02	2.31E+06	7.73E+04
2011.50	1.46E+05	2.62E+02	2.35E+06	7.71E+04
2011.75	1.15E+05	4.45E+02	2.40E+06	7.44E+04
2012.01	1.22E+05	4.00E+02	2.44E+06	7.61E+04
2012.25	1.06E+05	5.57E+02	2.50E+06	7.44E+04
2012.50	1.18E+05	4.46E+02	2.52E+06	7.70E+04
2012.75	1.14E+05	5.38E+02	2.57E+06	7.69E+04
2013.01	1.40E+05	3.62E+02	2.58E+06	8.01E+04
2013.25	1.46E+05	3.62E+02	2.61E+06	8.16E+04
2013.50	1.85E+05	2.05E+02	2.58E+06	8.49E+04
2013.75	2.01E+05	1.74E+02	2.58E+06	8.81E+04
2014.00	2.36E+05	7.93E+01	2.41E+06	9.02E+04
2014.25	2.48E+05	4.69E+01	2.36E+06	9.69E+04
2014.50	2.43E+05	2.16E+01	2.27E+06	9.71E+04
2014.75	2.27E+05	1.03E+01	2.30E+06	9.96E+04
2015.00	2.12E+05	5.93E+00	2.35E+06	1.00E+05
2015.25	1.68E+05	1.68E+00	2.47E+06	1.05E+05
2015.50	1.70E+05	1.67E+00	2.46E+06	1.02E+05
2015.75	1.38E+05	6.44E-01	2.54E+06	1.05E+05
2016.00	1.43E+05	7.37E-01	2.55E+06	1.06E+05
2016.25	1.18E+05	3.29E-01	2.62E+06	1.08E+05
2016.50	1.39E+05	6.56E-01	2.62E+06	1.12E+05
2016.75	1.17E+05	3.24E-01	2.66E+06	1.13E+05
2017.00	1.46E+05	8.52E-01	2.67E+06	1.21E+05
2017.25	1.40E+05	6.87E-01	2.72E+06	1.25E+05

Table 2: Fluence evolution perigee raising option

Proton Energy [MeV]	Proton Fluence [#/cm2]	
	Trapped Current Orbit	Trapped Perigee Raising option
0.1	1.31E+15	1.28E+15
0.15	1.31E+15	1.28E+15
0.2	1.31E+15	1.28E+15
0.3	1.31E+15	1.28E+15
0.4	1.31E+15	1.28E+15
0.5	1.31E+15	1.28E+15
0.6	1.31E+15	1.28E+15
0.7	1.31E+15	1.28E+15
1	1.31E+15	1.28E+15
1.5	1.31E+15	1.28E+15
2	1.31E+15	1.28E+15
3	1.31E+15	1.28E+15
4	1.31E+15	1.28E+15
5	1.31E+15	1.28E+15
6	1.31E+15	1.28E+15
7	1.31E+15	1.28E+15
10	1.31E+15	1.28E+15
15	1.31E+15	1.28E+15
20	1.31E+15	1.28E+15
30	1.31E+15	1.28E+15
40	1.31E+15	1.28E+15
50	1.31E+15	1.28E+15
60	1.31E+15	1.28E+15
70	1.31E+15	1.28E+15
100	1.31E+15	1.28E+15
150	1.31E+15	1.28E+15
200	1.31E+15	1.28E+15
300	1.31E+15	1.28E+15
400	1.31E+15	1.28E+15

Table 3: Trapped proton fluence spectrum for the mission until 2017.

Proton Energy [MeV]	Solar Proton Fluence [#/cm2]
0.1	2.10E+12
0.5	1.30E+12
1	9.50E+11
2	5.90E+11
3	4.10E+11
4	3.00E+11
5	2.50E+11
6	2.10E+11
8	1.50E+11
10	1.10E+11
12	9.70E+10
15	7.80E+10
17	6.90E+10
20	5.70E+10
25	4.30E+10
30	3.40E+10
35	2.90E+10
40	2.50E+10
45	2.20E+10
50	1.90E+10
60	1.50E+10
70	1.20E+10
80	9.70E+09
90	8.00E+09
100	6.60E+09
120	4.60E+09
140	3.30E+09
160	2.40E+09
180	1.80E+09
200	1.30E+09

Table 4: Solar proton fluence spectrum for the mission until 2017.

Time [Year]	Total Ionising Dose at 4mm Al [rad/day]	Total Non-ionising dose at 4mm Al [eq 10MeV p+/cm2/day]	Eq 1MeV e- for Solar Cell Pmax-Voc for 152um coverglass [eq 1MeV e-/cm2/day]
2002.83	2.03E+01	1.04E+05	6.98E+11
2003.01	1.20E+01	2.31E+04	3.81E+11
2003.25	1.18E+01	3.15E+04	4.29E+11
2003.50	1.37E+01	6.29E+03	2.21E+11
2003.75	1.33E+01	8.17E+03	2.47E+11
2004.01	1.33E+01	1.70E+03	1.29E+11
2004.25	1.20E+01	2.92E+03	1.57E+11
2004.50	1.49E+01	7.30E+02	5.98E+10
2004.75	1.44E+01	5.16E+02	5.00E+10
2005.00	1.67E+01	0.00E+00	2.37E+10
2005.25	1.69E+01	0.00E+00	2.08E+10
2005.50	1.79E+01	0.00E+00	1.24E+10
2005.75	1.81E+01	0.00E+00	1.11E+10
2006.00	1.94E+01	0.00E+00	9.18E+09
2006.25	1.99E+01	0.00E+00	9.84E+09
2006.50	2.03E+01	0.00E+00	1.11E+10
2006.75	1.87E+01	0.00E+00	1.08E+10
2006.99	1.98E+01	0.00E+00	1.15E+10
2007.42	2.10E+01	0.00E+00	1.23E+10
2007.50	2.23E+01	0.00E+00	1.27E+10
2007.75	2.19E+01	0.00E+00	1.26E+10
2008.00	2.63E+01	0.00E+00	1.34E+10
2008.26	2.56E+01	0.00E+00	1.30E+10
2008.50	2.89E+01	0.00E+00	1.33E+10
2008.76	2.86E+01	0.00E+00	1.39E+10
2009.00	2.83E+01	0.00E+00	2.42E+10
2009.25	2.61E+01	4.63E+02	4.72E+10
2009.50	2.49E+01	3.12E+03	1.40E+11
2009.75	2.33E+01	1.27E+04	2.49E+11
2010.00	2.25E+01	8.10E+04	5.31E+11

Table 5: Dose evolution current orbit

Time [Year]	Total Ionising Dose at 4mm Al [rad/day]	Total Non-ionising dose at 4mm Al [eq 10MeV p+/cm2/day]	Eq 1MeV e- for Solar Cell Pmax-Voc for 152um coverglass [eq 1MeV e-/cm2/day]
2010.25	2.16E+01	2.16E+05	8.33E+11
2010.50	2.14E+01	4.17E+05	1.13E+12
2010.75	2.10E+01	8.96E+05	1.47E+12
2011.00	2.09E+01	1.20E+06	1.61E+12
2011.25	2.03E+01	2.08E+06	1.81E+12
2011.50	2.07E+01	2.00E+06	1.83E+12
2011.75	2.03E+01	2.96E+06	1.81E+12
2012.01	2.10E+01	2.47E+06	1.89E+12
2012.25	2.09E+01	3.14E+06	1.86E+12
2012.50	2.15E+01	2.09E+06	1.94E+12
2012.75	2.20E+01	2.42E+06	2.00E+12
2013.00	2.17E+01	1.31E+06	1.80E+12
2013.25	2.26E+01	1.01E+06	1.67E+12
2013.50	2.17E+01	4.93E+05	1.31E+12
2013.75	2.23E+01	3.25E+05	1.10E+12
2014.00	2.13E+01	1.29E+05	7.18E+11
2014.25	2.30E+01	5.13E+04	4.85E+11
2014.50	2.31E+01	1.93E+04	3.27E+11
2014.75	2.37E+01	6.32E+03	2.06E+11
2015.00	2.34E+01	4.47E+03	1.82E+11
2015.25	2.50E+01	9.32E+02	9.61E+10
2015.50	2.45E+01	1.42E+03	1.15E+11
2015.75	2.57E+01	2.81E+02	7.72E+10
2016.00	2.57E+01	1.05E+03	1.01E+11
2016.25	2.65E+01	2.32E+02	7.70E+10
2016.51	2.62E+01	5.21E+02	5.21E+10
2016.76	2.80E+01	1.49E+03	1.18E+11
2017.00	2.92E+01	5.97E+03	1.99E+11
2017.24	2.91E+01	7.79E+03	2.25E+11

Table 5 (continued): Dose evolution current orbit

Time [Year]	Total Ionising Dose at 4mm Al [rad/day]	Total Non-ionising dose at 4mm Al [eq 10MeV p+/cm2/day]	Eq 1MeV e- for Solar Cell Pmax-Voc for 152um coverglass [eq 1MeV e-/cm2/day]
2009.75	2.38E+01	9.31E+03	2.22E+11
2009.77	2.28E+01	1.59E+02	3.47E+10
2010.00	2.15E+01	1.06E+03	9.23E+10
2010.25	2.03E+01	6.40E+03	1.92E+11
2010.50	1.98E+01	2.49E+04	3.31E+11
2010.75	1.93E+01	1.09E+05	6.16E+11
2011.00	1.91E+01	1.97E+05	8.15E+11
2011.25	1.94E+01	5.37E+05	1.27E+12
2011.50	1.89E+01	6.23E+05	1.35E+12
2011.75	2.00E+01	1.24E+06	1.67E+12
2012.01	1.95E+01	1.07E+06	1.62E+12
2012.25	2.09E+01	1.68E+06	1.84E+12
2012.50	1.95E+01	1.23E+06	1.72E+12
2012.75	2.14E+01	1.59E+06	1.88E+12
2013.01	1.96E+01	9.27E+05	1.62E+12
2013.25	2.06E+01	9.23E+05	1.63E+12
2013.50	1.98E+01	4.32E+05	1.26E+12
2013.75	2.08E+01	3.47E+05	1.14E+12
2014.00	2.04E+01	1.20E+05	6.97E+11
2014.25	2.23E+01	5.75E+04	5.12E+11
2014.50	2.21E+01	1.86E+04	3.24E+11
2014.75	2.31E+01	6.53E+03	2.10E+11
2015.00	2.35E+01	2.71E+03	1.50E+11
2015.25	2.53E+01	1.43E+02	7.29E+10
2015.50	2.48E+01	5.18E+01	7.30E+10
2015.75	2.60E+01	2.81E+02	4.47E+10
2016.00	2.61E+01	3.60E+02	4.80E+10
2016.25	2.70E+01	0.00E+00	3.26E+10
2016.50	2.74E+01	3.02E+02	4.57E+10
2016.75	2.81E+01	0.00E+00	3.30E+10
2017.00	2.92E+01	4.41E+02	5.23E+10
2017.25	3.04E+01	3.43E+02	4.79E+10

Table 6: Dose evolution perigee raising option

Aluminium shielding thickness [mm]	Total ionising radiation dose in Si [rad]	
	Current Orbit	Perigee Raising option
0.05	9.59E+07	9.52E+07
0.1	4.54E+07	4.50E+07
0.2	2.23E+07	2.23E+07
0.3	1.41E+07	1.42E+07
0.4	9.94E+06	1.00E+07
0.5	7.41E+06	7.50E+06
0.6	5.74E+06	5.83E+06
0.8	3.78E+06	3.84E+06
1	2.70E+06	2.74E+06
1.5	1.40E+06	1.42E+06
2	8.10E+05	8.15E+05
2.5	4.88E+05	4.88E+05
3	3.01E+05	3.00E+05
4	1.23E+05	1.21E+05
5	5.28E+04	5.16E+04
6	2.46E+04	2.40E+04
7	1.32E+04	1.29E+04
8	8.42E+03	8.23E+03
9	6.41E+03	6.29E+03
10	5.39E+03	5.30E+03
12	4.40E+03	4.34E+03
14	3.75E+03	3.71E+03
16	3.28E+03	3.24E+03
18	2.93E+03	2.90E+03
20	2.60E+03	2.57E+03

Figure 7. Dose in Silicon as a function of spherical aluminium shielding for the mission until 2017.