



**HAL**  
open science

## How much solar cycle variations impact long term effect predictions at LEO?

Sébastien Bourdarie, Philippe Calvel, Catherine Barillot, Laurent Rey,  
Tommaso Parrinello, Berta Hoyos, R. Ecoffet

### ► To cite this version:

Sébastien Bourdarie, Philippe Calvel, Catherine Barillot, Laurent Rey, Tommaso Parrinello, et al.. How much solar cycle variations impact long term effect predictions at LEO?. European Conference on Radiation and its Effects on Components and Systems (RADECS) 2019, Sep 2019, Montpellier, France. hal-02797115

**HAL Id: hal-02797115**

**<https://hal.science/hal-02797115v1>**

Submitted on 5 Jun 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# How much solar cycle variations impact long term effect predictions at LEO?

S. Bourdarie, P. Calvel, C. Barillot, L. Rey, T. Parrinello, B. Hoyos, R. Ecoffet

**Abstract:** An 8 year long flight database from an EDAC counter implemented onboard an altimeter flying on CryoSat-2 spacecraft at 715 km altitude is analyzed to investigate on solar cycle variations impact on long term effect predictions. In-situ observations are then compared to various specification models including legacy models as well as models under developments.

## I. INTRODUCTION

To design space missions, the current standard models, AP8 [1] and AE8 [2], are widely used in space industries. These models were developed by NASA at the end of the 1970s and beginning of the 1980s. Two versions of each model were produced (AP8 max and AP8 min, AE8 max and AE8min) to reflect solar cycle variation only at  $L < 3$  and altitudes less than 1000 km. ECSS-E10-04 standard recommend the use of AP8 min plus AE8 max to design space vehicle. This is considered to be a conservative approach because AP8 min fluxes are higher than AP8 max ones and AE8 max flux are higher than AE8 min ones. Recently two initiatives to upgrade these models are ongoing: AE9/AP9 and GREEN [4] specification models. Currently, solar cycle variations are not accounted for in AE9/AP9 model while they are in GREEN.

According to the variety of space environment models now available with or without solar cycle variation it is important to address the following question to help space industries in their future development: how much solar cycle variation may impact long term effect (average SEE rate, ionizing dose, displacement damage) predictions? This paper addresses this issue for trapped protons at Low Earth Orbit (LEO). To do so, flight data from Error Detection And Correction (EDAC) counter collected over several years at LEO will be used. Then predictions obtained with AP8 min and max, AP9 mean and GREEN-p will be compared to flight data to deduce the most appropriate model to be used at LEO.

In Section II, flight data are presented as well as support data necessary to perform effect calculations, in Section III model predictions will be given and in Section IV results will be discussed.

## II. FLIGHT DATA

CryoSat-2 is a European Space Agency satellite flying on a Low Earth Orbit (near circular orbit: 715-735 km, inclination:  $92^\circ$ , 14.52 revolutions/day). It was launched on April 8<sup>th</sup> 2010. The evolution of perigee, apogee and inclination from launch date to April 4<sup>th</sup>, 2019 is given in Fig. 1. One can see that the orbit is almost the same over this time range, i.e. the spacecraft will encounter the same environment along the mission life time.

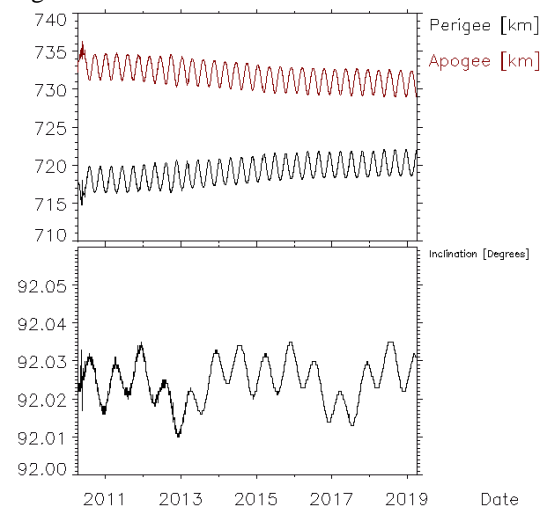


Fig. 1. CryoSat-2 orbital parameters out of Two Lines Elements versus time.

In [5] Single Event Phenomena (bit flips) recorded by an EDAC onboard the SAR Interferometer Radar Altimeter (SIRAL) being built by Thales Alenia Space (TAS) were analyzed. These errors are automatically corrected, listed by the EDAC counter and downloaded on ground station every month. The memory map of this payload is made of 10 SRAM (1MB SRAM M65608,  $0.5\mu\text{m}$  CMOS process, developed by ATMEL in cooperation with the European Space Agency).

The total number of Single Event Upset (SEU) recorded by the EDAC from November 1<sup>st</sup>, 2010 to March 31<sup>st</sup>, 2019 is 6927. The longitude-latitude event distribution is given in Fig. 2. The number of events is sufficient to nicely image the South Atlantic Anomaly. Following [5] SEU events can be sorted out to identify those induced by trapped protons in the radiation belts (McIlwain  $L < 1.9$ ) to those induced by Galactic Cosmic Rays (GCRs) or Solar Energetic Particles (SEP) (McIlwain  $L > 1.9$ ). As already reported in [5], most SEUs are recorded in the South Atlantic Anomaly (87.3%) while the SEUs at high and low latitudes can be attributed to GCRs and SEPs (12.7%). Note that since the time coverage is

This work was supported by grant n° 4500055131/DIA094 which is part of CNES R&T program (R-S17 / MT-0003-180).

S. Bourdarie is with ONERA The French aerospace lab/Département Environnement Spatial, 31400 Toulouse France (telephone; +33-562-2756, e-mail: [Sebastien.Bourdarie@onera.fr](mailto:Sebastien.Bourdarie@onera.fr)).

P. Calvel, C. Barillot, L. Rey are with Thales Alenia Space, 26 Avenue Champollion, 31027 Toulouse, France

T. Parrinello, B. Hoyos are with ESA/ESRIN, Largo Galileo Galilei, 1 00044 Frascati, Italy

R. Ecoffet is with CNES, 18 av. E. Belin 31401 Toulouse, France

longer here than in [5] the percentages obtained here are slightly different (~1%). The mean SEU rates then obtained are 1.88 SEU/day and 0.28 SEU/day attributed to trapped protons and GCRs plus SEPs respectively over the full time period.

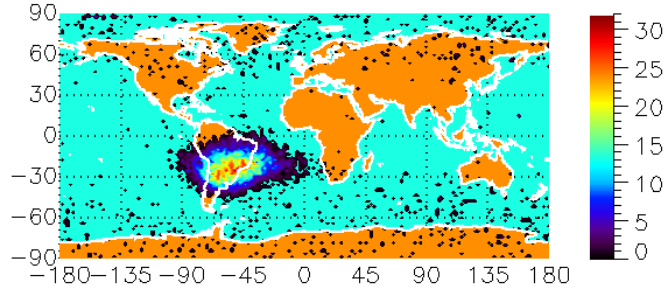


Fig. 2. SEU recorded by the EDAC implemented on the CryoSat-2/SIRAL payload from November 1<sup>st</sup>, 2010 to March 31<sup>st</sup>, 2019.

The time evolution of cumulated SEUs as well as the year average daily SEU rates attributed to trapped protons and GCRs plus SEP are plotted versus time in Fig. 3. The cumulated SEU values (top two panels) confirm that events are dominated by the trapped proton contribution. From the cumulative SEU values, it then possible to compute year average daily SEU rates attributed to trapped protons (third panel from top) and GCR plus SEP (fourth panel from top). In both cases, the solar cycle modulation in SEU rates can be clearly seen. Note that such variations cannot be attributed to an orbit change as apogee and perigee only evolve by 5 km from 2011 to 2019 and the inclination remains unchanged. As expected, the SEU rate attributed to GCR plus SEP is the lowest at solar cycle maximum phase (April 2014) and is increasing by a factor two from solar maximum (0.22 SEU/day in 2014) to almost solar minimum (0.48 SEU per day in 2019). The SEU rate attributed to trapped protons is decreasing slowly in time from year 2011 (2.1 SEU per day) to year 2015 (1.65 SEU per day), i.e. all along solar maximum phase a 30% decrease is found. Then from year 2015 (1.65 SEU per day) to year 2019 (2.22 SEU per day) a slow increase in SEU daily rates is observed, i.e. all along declining phase a 30% increase is found.

During solar energetic particle events, January 27-29, 2012 and March 7-11, 2012, a net increase is found in cumulated SEU values attributed to GCR plus SEP while no significant changes are visible in cumulated SEU values attributed to trapped protons (Fig. 4).

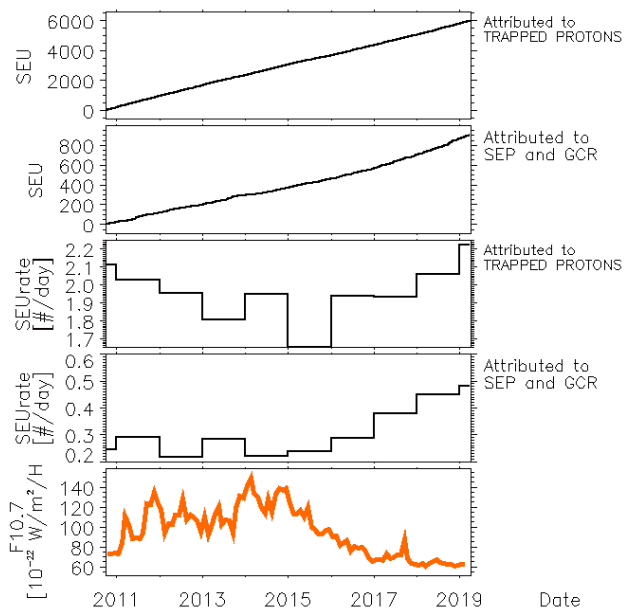


Fig. 3. Cumulated SEUs (top two panels) as well as the SEU rates (second and third panels from bottom) attributed to trapped protons and GCRs plus SEP versus time. The F10.7 solar radio flux is given to illustrate the solar cycle evolution.

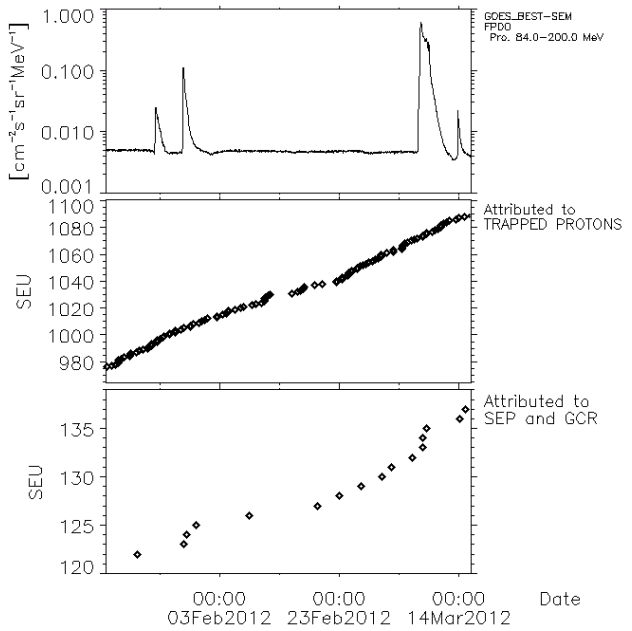


Fig. 4. Cumulated SEUs (bottom two panels) attributed to trapped protons and GCRs plus SEP from January 15, 2012 to March 15, 2012 and Solar Energetic Particles measured by GOES spacecraft.

To find out how accurate trapped proton specification models are, cumulated as well as SEU daily rates will be evaluated in the following section. To calculate an accurate SEU rate of mass memory of the SIRAL payload, the 3D shielding around the SRAM device and the device cross section versus proton energy must be well known. A full description of these inputs can be found in [5], and the same strategy will be applied in this paper to compute SEU cumulated values out of environment specification models.

### III. SPECIFICATION MODEL PREDICTIONS

To compute the trapped proton environment encountered by CryoSat-2 spacecraft, its orbit parameters (altitude, latitude and longitude) are computed with a 20 second time resolution from Two Lines Elements [6] using SGP4 orbit propagator [7] from launch date to April 1<sup>st</sup>, 2019. Then the proton fluxes are estimated at all orbital locations from AP8min with ESA interpolations, AP8max with ESA interpolations, AP9 V1.30.001 Mean, AP9 V1.50.001 Mean and GREEN-p. All calculations are performed using the Benchmark of Ionizing Space Environment tool [5].

A comparison of the mission average transmitted differential trapped proton spectrum (at the chip level) deduced from AP8 min with ESA interpolation, AP8 max with ESA interpolation, AP9 Mean V1.30.001, AP9 Mean V1.50.001 and GREEN-p models is given in Fig. 5. Note that, the transmitted proton fluxes at the chip level are calculated from a MCNPx V2.7.0 Monte-Carlo run accounting for the 3D shielding surrounding the chip. For energy greater than 40 MeV (proton energies reaching the chip) AP9 Mean V1.30.001 fluxes are the highest ones while AP8 max fluxes are the lowest ones, the differences being close to a factor 2.

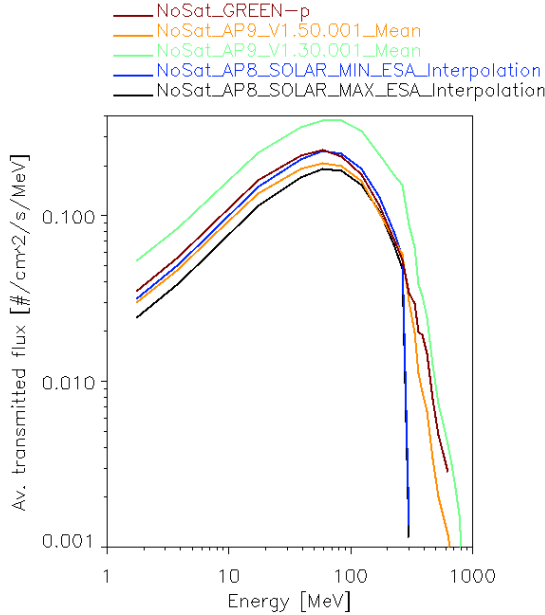


Fig. 5. Transmitted differential proton flux at the CryoSat-2/SIRAL/ chip level deduced from AP8 min, AP9 Mean V1.30.001, AP9 Perturbed Mean V1.30.001 median out of 40 scenarios and OPAL models.

A comparison of cumulated SEUs predicted from AP8 min with ESA interpolation, AP8 max with ESA interpolation, AP9 Mean, V1.30.001, AP9 Mean V1.50.001 and GREEN-p is shown in Fig. 6. At the end of the time period under study it is found that:

- AP8min with ESA interpolation underestimates the cumulated SEUs by 13.6%;
- AP8max with ESA interpolation underestimates the cumulated SEUs by 30.7%;
- AP9 mean V1.50.001 underestimates the cumulated SEUs by 17.2%;
- GREEN-p underestimates the cumulated SEUs by 4.1%;

- AP9 mean V1.30.001 overestimates the cumulated SEUs by 78.3%.

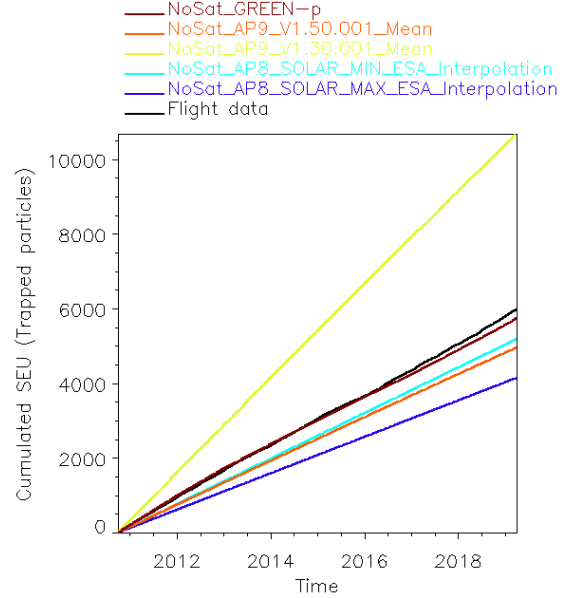


Fig. 6. Comparison of the cumulated SEUs measured by the EDAC on board CryoSat-2/SIRAL and predicted from AP8 min with ESA interpolation, AP8 max with ESA interpolation, AP9 Mean V1.30.001, AP9 Mean V1.50.001 and GREEN-p models.

To investigate which model reflects best the solar cycle modulation, daily SEU rates (averaged over each calendar year) can be deduced from those predictions. Results are given in Fig. 7. By definition, AP8 min and max do not vary along the solar cycle. Although there is an offset down in AP8 predictions the amplitude between AP8 min and AP8 max is quite representative of what to expect between solar max and solar minimum phase. While AP9 V1.30.001 Mean and AP9 V1.50.001 do not include solar cycle variations, results exhibit a general trend: predictions are decreasing along years. This feature cannot be attributed to an orbital effect as CryoSat-2 orbit remains unchanged throughout the time period under study. Predictions from the GREEN-p model track quite nicely in-flight data from 2011 to 2019. Nevertheless, a more or less similar trend as in AP9 predictions is suspected. In 2011 GREEN-p overestimates a little bit the SEU daily rates while it underestimates them in 2019. Note that IGRF being used in AE9/AP9 and in GREEN-p is extrapolated after 2015 to 2020 and may not represent accurately the real Earth internal magnetic field. Definitive IGRF coefficients to be used between 2015 and 2020 will be made available only during year 2021.

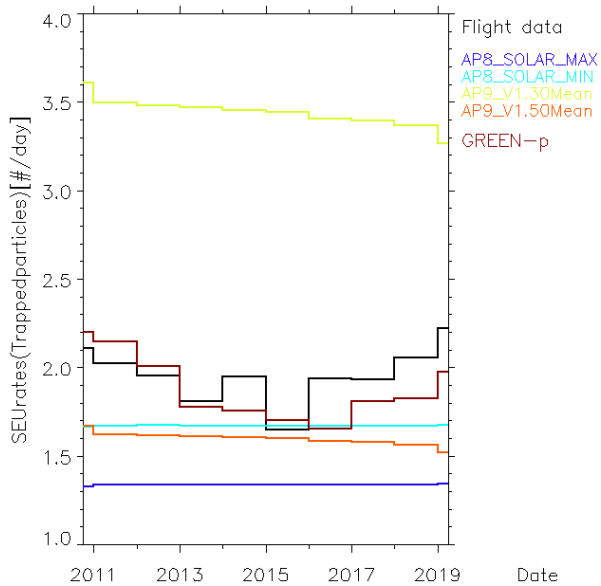


Fig. 7. Daily SEU rates from in flight data and predicted with AP8 min with ESA interpolation, AP8 max with ESA interpolation, AP9 Mean V1.30.001, AP9 Mean V1.50.001 and GREEN-p.

#### IV. DISCUSSION

The study concentrates on trapped proton environment with energies greater than 40 MeV at 715 km altitude along an 8 years sun synchronous orbit. The solar cycle impact on daily SEU rates was investigated thanks to a long duration flight database from an EDAC implemented on a TAS's payload flying onboard CryoSat-2 spacecraft. A 30% modulation along solar cycle 24 is found from in-situ data. So far only GREEN-p model appears to be the most suitable proton specification model to reproduce solar cycle modulation seen in flight observations. Such a detailed knowledge of the space environment allows revisiting the margin policy that must be applied to design space missions. In particular, it allows considering margins well below the de-facto factor 2 being often suggested at least at LEO. This point will be discussed in more detailed in the final paper.

#### V. ACKNOWLEDGMENTS

The authors wish to thanks the CNES R&T program for their full support to this activity.

#### VII. REFERENCES

- [1] D.M. Sawyer and J.I. Vette, "AP8 trapped proton model environment for solar maximum and minimum," *NSSDC/WDC-A-R&S 76-06*, Natl. Space Sci. Data Cent., Greenbelt, MD, Dec. 1976.
- [2] J. I. Vette, "The AE-8 Trapped Electron Model Environment," *NSSDC/WDC-A-R&S 91-24*, Natl. Space Sci. Data Cent., Greenbelt, MD, USA, 1991.
- [3] G. P. Ginet, T. P. O'Brien, S. L. Huston, W. R. Johnston, T. B. Guild, R. Friedel and D. Madden, "AE9, AP9 and SPM: New models for specifying the trapped energetic particle and space plasma environment," *The Van Allen Probes Mission*, Ed. N; Fox and J.L. Burch, *Springer Boston, MA.*, pp. 579-615, March 2013, doi: 10.1007/978-1-4899-7433-4\_18.

- [4] A. Sicard, D. Boscher, S. Bourdarie, D. Lazaro, D. Standarovski and R. Ecoffet, "GREEN: the new Global Radiation Earth ENvironment model (beta version)," *Ann. Geophys.*, vol. 36, no. 4, pp. 953-967, Jul. 2018, doi: 10.5194/angeo-36-953-2018.
- [5] S. Bourdarie, C. Inguibert, D. Standarovski, J. R. Vaillé, A. Sicard-Piet, D. Falguere and E. Lorfèvre, "Benchmarking ionizing space environment models," *IEEE Trans. Nuc. Sci.*, vol. 64, no. 8, pp. 023-2030, Aug. 2017, doi: 10.1109/TNS.2017.2654687.
- [6] Celestrak, accessed on April 10<sup>th</sup>, 2019. [Online]. Available: <http://www.celestrak.com/NORAD/elements/>
- [7] Celestrak, accessed on April 10<sup>th</sup>, 2019. [Online]. Available: <http://celestrak.com/NORAD/documentation/spacetrk.pdf>