Radiation Effects on Satellites during Extreme Space Weather Events

Alex Hands[1], Keith Ryden[1], Nigel Meredith[2], Sarah Glauert[2], Richard B Horne[2]
[1]Surrey Space Centre, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom
[2]British Antarctic Survey, High Cross, Madingley Rd, Cambridge CB3 0ET, United Kingdom
a.hands@surrey.ac.uk www.surrey.ac.uk/SSC www.spacestorm.eu

Abstract

We use the environment models and extreme environments generated by the EU-FP7 SPACESTORM project to estimate the consequences for satellites in terms of the radiation effects. A worst case event could lead to significant losses in terms of degraded capability and complete satellite failure. The potential consequences for such losses are hugely significant given our increasing reliance on satellites for a vast array of services, including communication, navigation, defence and critical infrastructure.

Introduction

The threat to satellites from high energy radiation in the space environment is well known. The EU FP7 SPACESTORM project has used statistical analysis of electron flux and charging current data sets to characterise worst case events over long time periods in geostationary and medium Earth orbits. In addition, a radiation belt model has been used to produce a reconstructed 30 year data set of the trapped electron environment, from which further deductions of extreme environments can be made. We use these outputs and those from environment models to quantify the degrading effects on satellites in extreme radiation environments.

In this analysis we focus on three key areas of radiation damage:

- Total Ionising Dose (TID): ionisation in insulating regions leads to charge trapping and device performance degradation.
- Displacement Damage Dose (DDD): atoms in a lattice structure are displaced by incident radiation, leading to 'dark' currents, loss of gain in bipolar transistors and damage to solar cells.
- Internal Charging: penetrating energetic electrons cause a direct build-up of charge in dielectric materials or isolated conductors that can lead to unsustainably high electric fields and electrostatic discharges (ESDs).

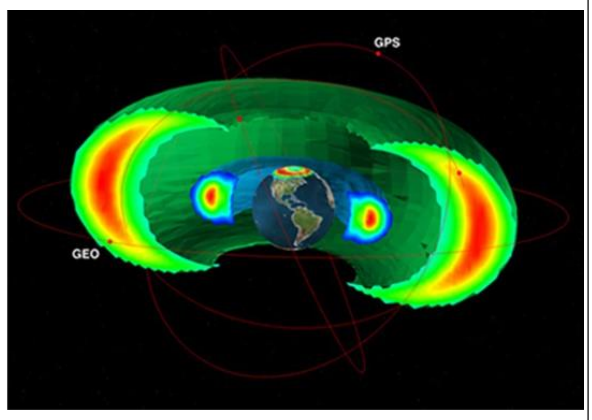

Figure 1: Van Allen belts diagram with representative orbits.

Although protons and heavy ions can also cause radiation damage, the focus of this work is on medium Earth orbits (MEO) and geostationary Earth orbits (GEO) where the trapped electron environment is dominant. We focus on short term enhancements to the electron environment, which may be caused by coronal mass ejections (CMEs) or fast solar wind streams from coronal holes. The tools used to calculate the radiation effects described here are available via the SPENVIS online system [1]. The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement number 606716 (SPACESTORM).

Environments

A variety of different enhanced trapped electron environments are considered in this work. Below we describe the different categories and the models or techniques used to quantify enhancements to them.

Long-term models

These models are well-suited to describing the static environment, but each also has the option of extension to perturbed environments.

- AE8: Industry standard model for many years. Includes simplistic statistical perturbations to static mean (e.g. 3σ).
- AE9: Successor to AE8 encompassing data from Van Allen Probes mission and with sophisticated statistical capability.

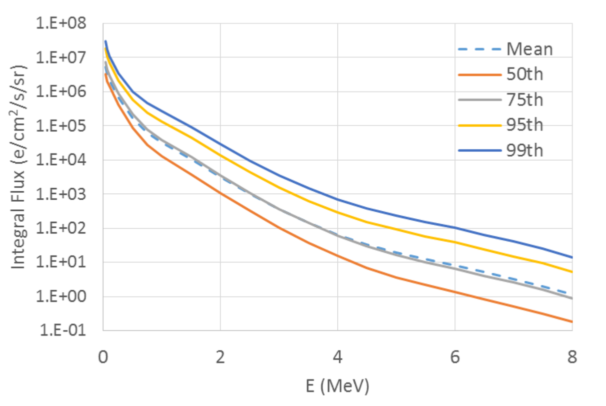

Figure 2: AE9 static mean percentiles for integral flux at GEO.

Short-term worst-case models

Models describing transient enhancements to trapped electron intensities, lasting from hours to days (well suited to internal charging).

- FLUMIC: Worst case model based on GEO data.
- MOBE-DIC: Outer belt model based on Giove-A data and defined by exceedance probabilities [2].

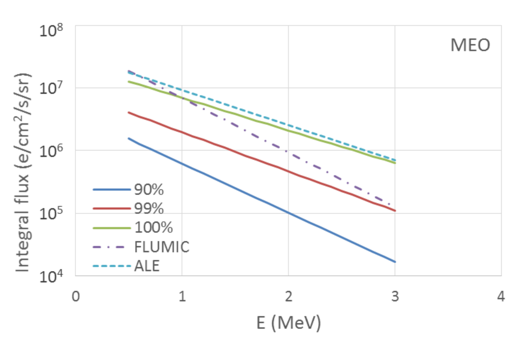

Figure 3: MOBE-DIC and FLUMIC electron spectra (including "Anomalously Large Event") at L=4.7.

Extreme Environments from Statistical Analysis

GOES geostationary data have been used to perform a statistical analysis of extreme events at GEO, leading to the estimates of 1 in N year worst case daily average fluxes (N from 10 to 150) [3]. We also include a theoretically-calculated extreme flux (from BAS) that is approximately 10x greater than the 1 in 150 year event.

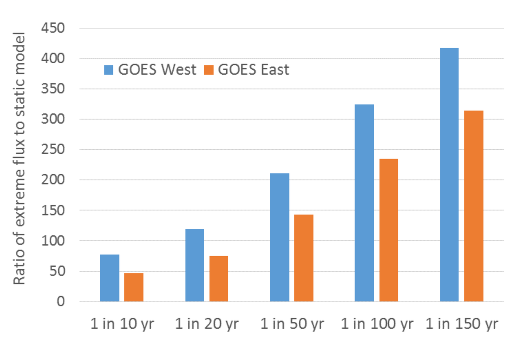

Figure 4: Enhancement factors of extreme events with respect to >2 MeV flux in AE8 static model.

Reconstructed 30 Year Data Set (Galileo MEO)

The NERC-BAS radiation belt model is used, along with input data to define boundary conditions, to recreate a 30 year data set from which environment extrema are extracted over different timescales.

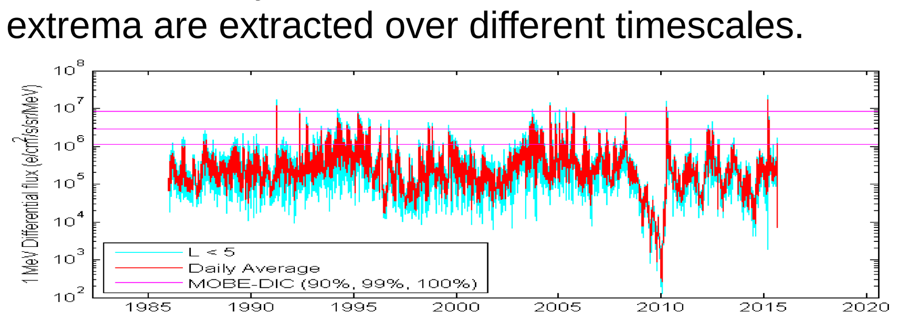

Figure 5: Reconstructed 30 year differential electron flux at 1 MeV. The daily average flux is overlaid, as are the three static percentiles of the MOBE-DIC model.

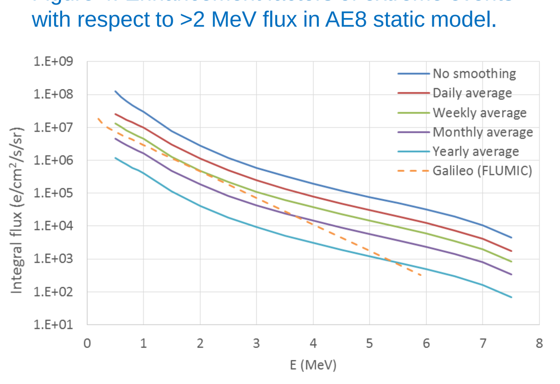

Figure 6: Composite worst-case spectra at MEO from NERC-BAS model, calculated over different timescales.

Total Ionising Dose

The permutations of orbit, environment model, effects and parameters are many. For TID we focus on the medium Earth orbit of the Galileo GNSS satellite constellation. We use Shieldose-2 to calculate long-term dose-depth curves for various trapped electron environments (Figures 8 and 10) and compare these to the expected dose enhancements from the worst case output from the NERC-BAS reconstructed data set over different timescales (Figure 7). We calculate the worst case dose enhancements (with 2 mm spherical shielding) to range from ~30% of mean annual dose in one day, to over 400% of mean annual dose in one year. The progression of cumulative dose over the 30 year period covered by the NERC-BAS data set is shown in Figure 10. A steady underlying increase, punctuated by small rapid enhancements, is clear.

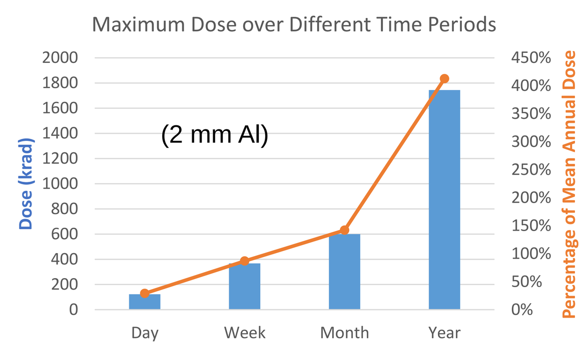

Figure 7: Worst Case doses over short timescales at 2 mm Al shield, compared to mean annual dose in MEO.

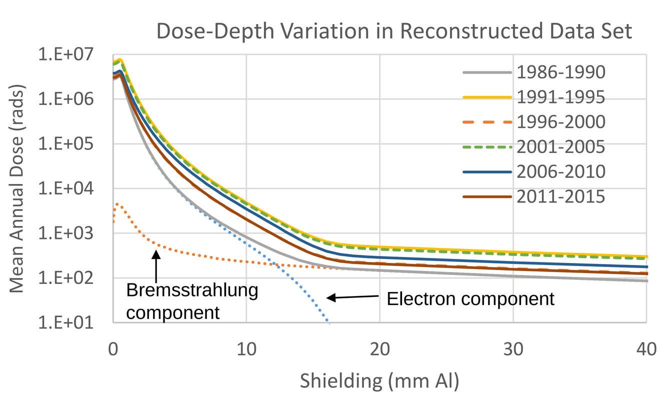

Figure 8: Dose-depth curves for six 5-year periods from the NERC-BAS reconstructed data set.

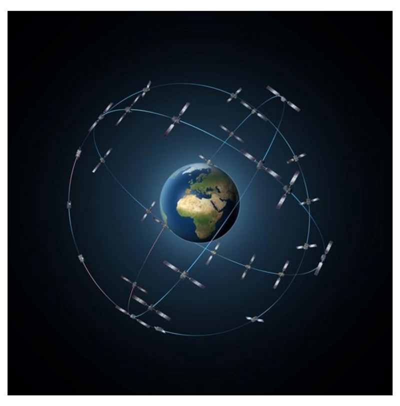
Figure 9: Schematic of Galileo Fleet.

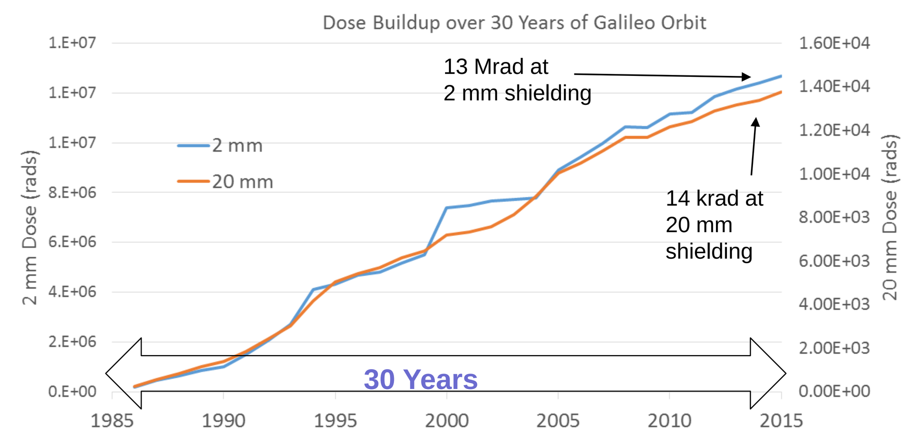

Figure 10: Cumulative Dose from reconstructed data set at two shielding depths.

Displacement Damage Dose

Displacement damage caused by non-ionising energy loss (NIEL) can affect various components and systems on a spacecraft. The most conspicuous is a loss of solar cell maximum power output (P_{max}). We use MC-SCREAM to compare the degradation from extreme transient events at geostationary orbits with the longer term degradation predicted using the AE8 mean model and its statistical extensions. Figures 11 and 12 show that if the theoretical maximum flux calculated by BAS were sustained for 1 week, the loss of power output in a single junction GaAs cell could approach 40% - equivalent to 80 years of AE8.

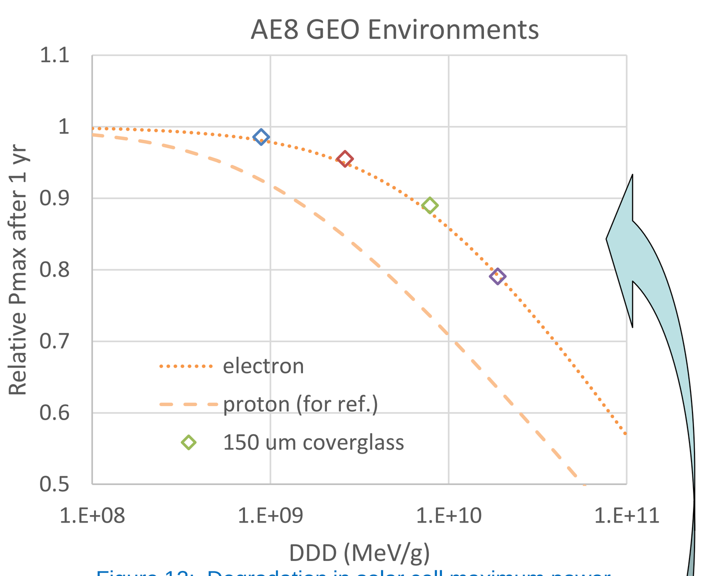

Figure 12:, Degradation in solar cell maximum power over one year of AE8 environments (see Fig. 13).

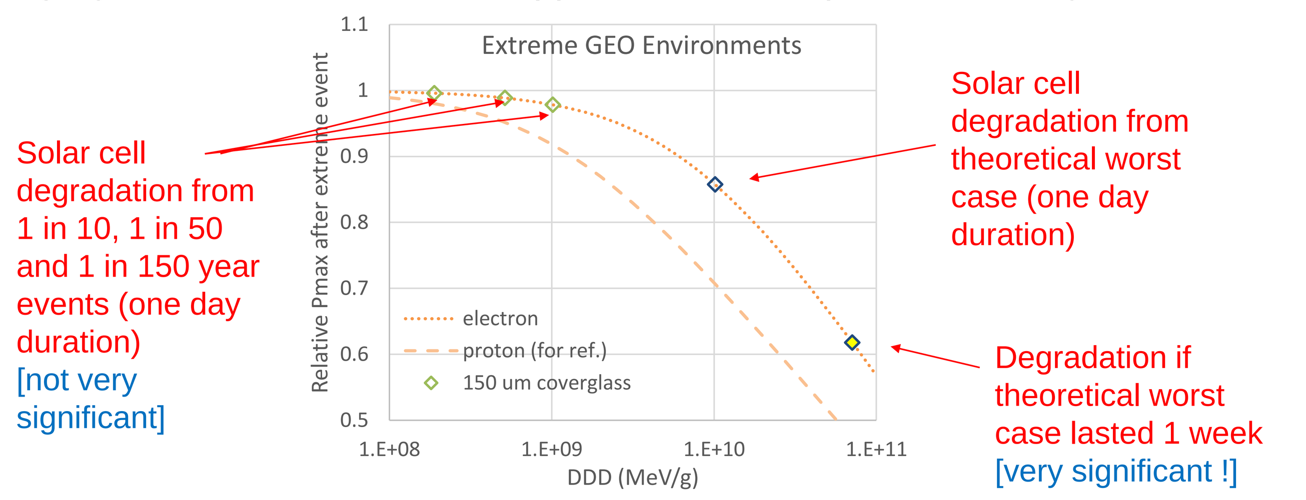

Figure 11: Degradation in solar cell maximum power from short-term extreme electron enhancements.

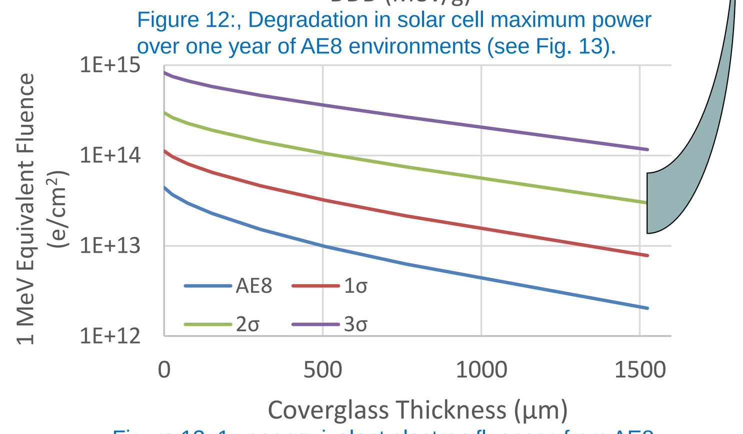

Figure 13: 1 year equivalent electron fluences from AE8.

Internal Charging

Key conductivity equations:

$$\sigma_{total} = \sigma_T + \sigma_{RIC} \qquad \sigma_{RIC} = k_p . \dot{D}^{\Delta}$$

High energy electrons that penetrate spacecraft shielding can result in the build-up of trapped charge and dangerously high electric fields. This is mitigated by radiation induced conductivity (RIC) from ionising dose caused by the same electron environment. We have used the DICTAT tool to quantify this effect in the extreme transient environments calculated for MEO and GEO. We use PEEK material as an example, with parameters derived from experiments within the SPACESTORM programme. We find that, due to RIC and other factors, there is a diminishing return in the ability of increasing electron intensity to cause higher electric fields (see Figure 15). Nevertheless, these extreme transient environments are very capable of resulting in unsustainably electric fields in PEEK and other materials. All DICTAT calculations assume 1 mm Al shielding and 298K unless otherwise specified.

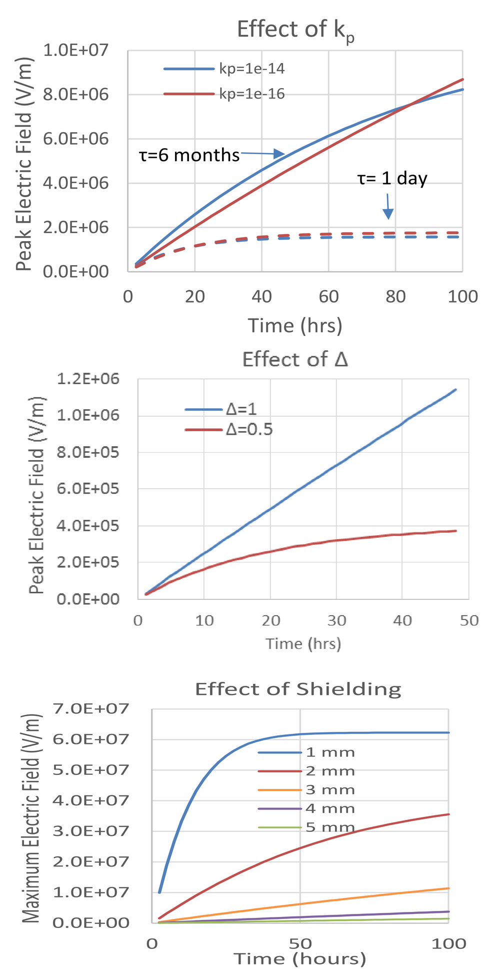

Figure 16: The effect on representative charging profiles of independently varying 3 key parameters: k_p (top), Δ (middle) and shielding (bottom).

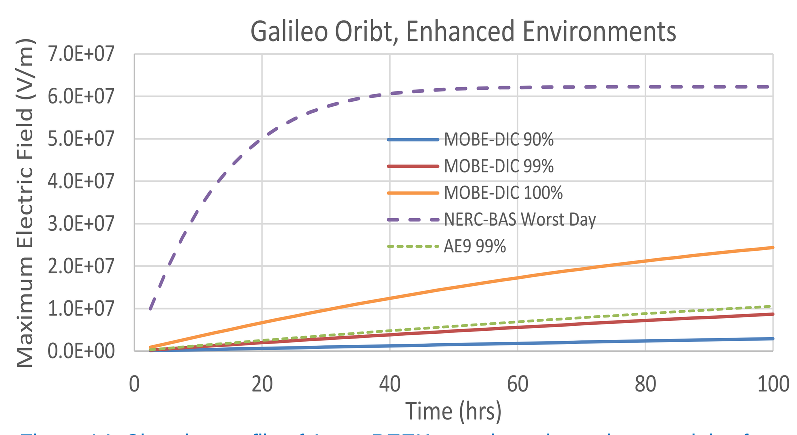

Figure 14: Charging profile of 1 mm PEEK sample under various models of electron enhancement at MEO. A typical breakdown threshold is 10^7 V/m.

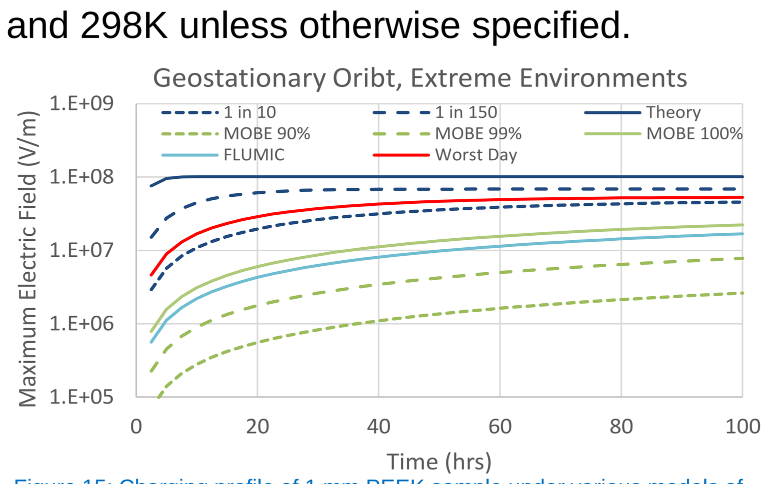

Figure 15: Charging profile of 1 mm PEEK sample under various models of electron enhancement at GEO. A typical breakdown threshold is 10^7 V/m.

Conclusions

Worst case MEO and GEO environments have been used to calculate radiation effects on satellites. Examples include:

- A "worst day" total ionising dose for the Galileo GNSS constellation could be equivalent to 30% of mean annual dose.
- If sustained for one week, the theoretical worst case GEO environment could result in a 40% loss in solar cell power.
- Radiation-induced conductivity limits the build-up of electric fields, however maximum fields of 10^7 - 10^8 V/m in PEEK have been calculated for a range of enhanced GEO and MEO environments from models, data and theory.

British Antarctic Survey
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References:

1. www.spenvis.oma.be
2. A. D. P. Hands, K. A. Ryden, D. Rodgers and H. Evans, "A New Model of Outer Belt Electrons for Dielectric Internal Charging (MOBE-DIC)," IEEE Transactions on Nuclear Science, pp. 2767-2775, 2015.
3. N. P. Meredith, R. B. Horne, J. D. Isles and J. V. Rodriguez, "Extreme relativistic electron fluxes at geosynchronous orbit: Analysis of GOES E > 2 MeV electrons," Space Weather , vol. 13, 2015.