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Space Weather Concerns for All-Electric Propulsion Satellites

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Abstract The introduction of all-electric propulsion satellites is a game changer in the quest for low-cost access to space. It also raises new questions for satellite manufacturers, operators, and the insurance industry regarding the general risks and specifically the threat of adverse space weather. The issues surrounding this new concept were discussed by research scientists and up to 30 representatives from the space industry at a special meeting at the European Space Weather Week held in November 2014. Here we report on the discussions at that meeting. We show that for a satellite undergoing electric orbit raising for 200 days the radiation dose due to electrons is equivalent to approximately 6.7 year operation at geostationary orbit or approximately half the typical design life. We also show that electrons can be injected into the slot region (8000 km) where they pose a risk of satellite internal charging. The results highlight the importance of additional radiation protection. We also discuss the benefits, the operational considerations, the other risks from the Van Allen radiation belts, the new business opportunities for space insurance, and the need for space situation awareness in medium Earth orbit where electric orbit raising takes place.

Introduction

Boeing was the first to introduce the concept of an electric orbit-raising mission for commercial satellites. In a conventional launch the satellite is placed into a geostationary transfer orbit by the launcher and then uses its own chemical propellants to raise the perigee to geosynchronous orbit. Typically, this takes a few days. However, for all-electric propulsion spacecraft there is no chemical propellant. After the initial launch electric propulsion is used to reach geosynchronous orbit which, due to its low but continuous thrust, may take 200 days but can be as long as 400 days. The main benefit of electric propulsion is that the mass of the spacecraft is significantly reduced. Thus, two spacecraft can be launched on the same launcher, almost halving the cost of launch, or alternatively, it enables a significantly larger payload resulting in increased revenue or greater technical capability. Alternatively the use of a lower cost launcher may allow the business case for a satellite to close, which may not have been possible with a heavier satellite and a more powerful expensive launch vehicle.

At first sight the reduction in launch costs suggests a very large saving but on closer inspection there are a number of factors that make the business case more complicated. The satellite takes much longer to pass through the heart of the Van Allen radiation belts where the radiation dose is most severe. During electric orbit raising the additional radiation dose due to electrons may be equivalent to up to 6.7 years of operation at geosynchronous orbit for a spacecraft designed with nominal shielding of 4 mm of Al suitable for geosynchronous orbit (see Figure 1). Depending on the launch strategy it can be higher. Radiation dose is one of the most important factors limiting the operational life of a satellite, and so for a satellite that has a design life of 15 years, 6.7 years is very significant. From a satellite operator's point of view it is potential lost revenue. For example, for a satellite carrying say 40 transponders with 80% utilization generating a revenue stream of say \$2m per year per transponder 1 year alone equates to \$64m. There is also the additional cost of financing the initial 200 day electric orbit-raising operations period until a new revenue stream is established. Thus, it is essential that additional shielding or radiation hardening is included not only to protect the spacecraft during electric orbit raising but also to extend the design life and hence compensate for the initial delay in revenue generation.

Radiation protection for all-electric satellites appears to be straightforward, but in fact raises new uncertainties. The usual procedure is to design for a reasonable worst case. For satellites at geosynchronous orbit designers use models to calculate the radiation dose over a projected 15 year lifetime. This includes the trapped radiation in the Van Allen belts, galactic cosmic rays, and bursts of solar energetic particles. They then select the amount

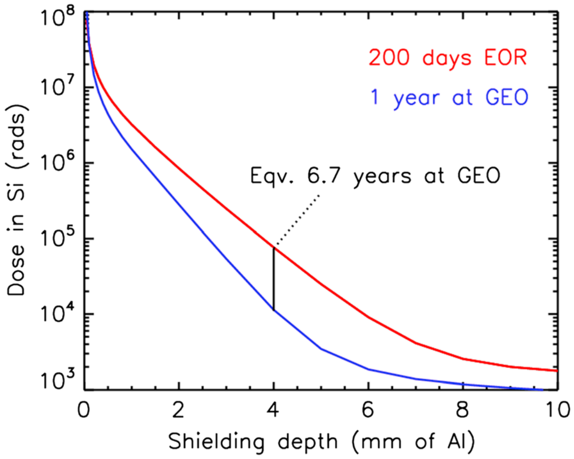

Figure 1. Comparison between (in red) the radiation dose accumulated over 200 days by a satellite undergoing electric orbit raising compared to (in blue) that accumulated over 1 year at Geostationary orbit at 115° W. Assuming a shielding of 4 mm of Al the dose for 200 days of electric orbit raising is equivalent to 6.7 years of operation at geostationary orbit. The dose is dominated by radiation belt electrons and the flattening of the curves beyond 6 mm of Al is due to Bremsstrahlung radiation. The calculations assume that the satellite was launched on 12 March 2015 during solar maximum using the electron and proton spectra from the AE8 and AP8 radiation models at the 97.73% confidence level. The initial perigee and apogee were 400 and 3600 km altitude, respectively, with an inclination of 25°. The perigee and inclination were changed in 10 equal steps to reach a final geostationary orbit at 115° W with zero inclination. The dose was calculated using the SHIELDOSE-2 model assuming a semi-infinite slab of Al shielding. The models were accessed via the space environment information system SPENVIS.

of shielding so that the dose reaching sensitive electronic components does not exceed an expected failure level or probability. Usually, a margin of error is included. However, at lower altitudes the electron flux in the heart of the Van Allen belts is much more intense than that at geosynchronous orbit (Figure 2) and so more protection is required. In addition, satellites undergoing electric orbit raising are likely to suffer increased radiation damage to solar cells as they traverse the proton radiation belt and may therefore need a thicker solar cell cover glass or an oversized solar array to ensure an adequate power supply at the end of mission life. One concern is that trapped radiation can vary widely at lower altitudes where electric orbit raising takes place. For example, in March 1991 the electron and proton flux increased by 4 orders of magnitude or more and persisted for much longer than at geosynchronous orbit (GEO) [*Blake et al.*, 1992] (see also Figure 2). New models such as AE9 and AP9 [*Ginet et al.*, 2013], also called IRENE, are now being introduced to help deal with this variability. Thus, by designing for a reasonable worst case the satellite is likely to require far more shielding than a conventional satellite simply to protect it for the first 200 days or so. As a result the mass saving in chemical fuel may be to some extent negated by extra mass for shielding. Of course once on station the spacecraft should be better able to withstand severe space weather radiation.

The risk of satellite anomalies associated with energetic protons in the inner belt and internal electrostatic discharge due to the main Van Allen belts and long-lived transient belts may also need to be reassessed. In particular, new research suggests that dielectric materials used as insulators can retain their charge for many months [*Bodeau*, 2010] and so the spacecraft may accumulate and retain a significant amount of charge during the long passage through the outer Van Allen belt. This suggests that the spacecraft may be at higher risk of electrostatic discharge and anomalies during electric orbit raising. Once the spacecraft has arrived at geosynchronous orbit the initial operating period is also likely to be at higher risk until the charge has decayed. Any anomalies that prolong orbit raising or affect subsequent operational activities are a particular concern.

During electric orbit raising the near continuous operation of an electric thruster for 200 days also raises concerns. The plume of ions emitted by the thruster tends to erode the thruster itself. Some of the eroded material is deposited on the satellite surfaces and can affect surface charging properties, thermal protection, and the transmission efficiency of solar array cover glasses. As these effects take place over the first 200 days their impact on the remaining 15 year mission needs careful analysis.

Electric orbit raising may enable new business opportunities for space insurance. Traditionally, space insurance policies cover launch, or launch plus 1 year on orbit, or on-orbit renewal. In the past launch to orbit took a few days, but it now seems likely that new policies are required for the 200 to 400 day electric orbit-raising period. One important consideration is loss of redundancy. To complete orbit raising as quickly as possible both primary and redundant sets of electric thrusters are used. However, if one thruster is lost, say due to a space weather anomaly, it would not be an insured loss as it is only a loss of

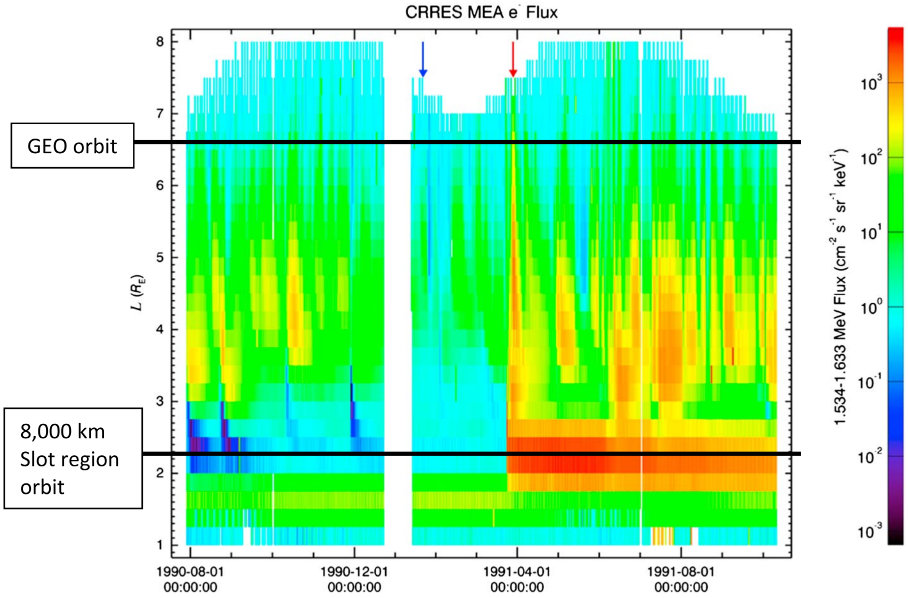

Figure 2. Differential electron flux for 1.53–1.63 MeV from the magnetic electron spectrometer on the CRRES spacecraft. The approximate location of GEO and the slot region obit at 8000 km altitude are also shown. Note the electron injection on 24 March 1991, first reported by *Blake et al.* [1992], and the persistence at low altitudes. Adapted from *Heynderickx* [2014].

redundancy. The operator would entail higher operational costs associated with the delay in reaching orbit, loss of customer revenue, and the potential loss of customers. Here insurers could offer additional coverage associated with loss of redundancy.

Previous experience with the European Space Agency SMART 1 spacecraft demonstrated the desirability of continuous spacecraft tracking. On several occasions satellite anomalies caused interruptions to the thruster system while out of ground contact and the satellite deviated from the planned orbit [*SMART-1*, 2007]. Continuous tracking, telemetry, and command during orbit raising require considerable ground resources with obvious cost implications. The alternative is to place greater reliance on onboard autonomy, which adds complexity and in turn highlights the need to protect against anomalies caused by space weather radiation.

Another important consideration is the maneuverability of the satellite once at geosynchronous orbit. In 2010 an anomaly on Galaxy 15, which was space weather related [*Space News*, 2010], resulted in the spacecraft drifting out of control around the geostationary orbit for almost 9 months. Operators had to be prepared to maneuver their spacecraft to avoid radio interference and reduce the risk of collision. Also, some operators require the ability to periodically move their satellites along the geostationary arc to other locations. The weak thrust afforded by electric propulsion does not enable these types of operations to be done quickly.

Electric orbit raising also demands a better space situation awareness and space weather forecasting capability. At present, real-time data are available for geosynchronous orbit but there is no real-time data provision at lower altitudes where electric orbit raising takes place. Variations at lower altitudes can be much higher and longer lasting that at GEO (see Figure 2). Here physical models of the radiation belts, which capture the variability, could be used to “fill-in” the low-altitude region and provide the real-time information required. Once such example was developed during the EU SPACECAST project [*Horne et al.*, 2013; *Glauert et al.*, 2014] (www.fp7-spacecast.eu) and now continued in the EU SPACESTORM project. Combining real-time information on the space radiation environment with radiation effects on materials could also provide valuable situation awareness for satellite operators.

Ultimately the market for satellites with all electric propulsion will depend on the business case. Already commercial operators such as Eutelsat of Paris and SES of Luxembourg are embracing this technological breakthrough by placing new orders for satellites with all electric propulsion. Worldwide, a total of 8 orders have been placed so far. This demand is providing new business opportunities for the space

Insurance industry. There are new challenges for radiation protection and the provision of real-time data and models for situation awareness. In future there could be many new satellites en-route to GEO when space weather events take place. It is important that we develop the tools and the services to support the emerging needs of the space industry and help protect our space assets.

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References

Blake, J. B., W. A. Kolasinski, R. W. Fillius, and E. G. Mullen (1992), Injection of electrons and protons with energies of tens of MeV into $L < 3$ on 24 March 1991, *Geophys. Res. Lett.*, *19*, 821–824, doi:10.1029/92GL00624.

Bodeau, M. (2010), High energy electron climatology that supports deep charging risk assessment in GEO, paper presented at 48th AIAA Aerospace Sciences Meeting, Orlando, Fla., 4–7 Jan.

Ginet, G. P., et al. (2013), AE9, AP9 and SPM: New models for specifying the trapped energetic particle and space plasma environment, *Space Sci. Rev.*, *179*, 579–615, doi:10.1007/s11214-013-9964-y.

Glauert, S. A., R. B. Horne, and N. P. Meredith (2014), Three-dimensional electron radiation belt simulations using the BAS Radiation Belt Model with new diffusion models for chorus, plasmaspheric hiss, and lightning-generated whistlers, *J. Geophys. Res. Space Physics*, *119*, 268–289, doi:10.1002/2013JA019281.

Heynderickx, D. (2014), NASA AE-9/AP-9 RadBelt Model Integration, NARMI Final Report, European Space Agency, 8 Dec.

Horne, R. B., S. A. Glauert, N. P. Meredith, D. Heynderickx, D. Boscher, V. Maget, and D. Pitchford (2013), Space weather impacts on satellites and forecasting the Earth's electron radiation belts with SPACECAST, *Space Weather*, *11*, 169–186, doi:10.1002/swe.20023.

SMART-1 (2007), End of mission operations, *Rep. ES1-ESC-RP-5716*, European Space Agency, 5th Nov.

Space News (2010), Orbital blames Galaxy 15 failure on solar storm, April 20. [Available at http://spacenews.com/orbital-blames-galaxy-15-failure-solar-storm/.]

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