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Name, title and organisation of the scientific representative of the project's coordinator:

Professor Richard Horne

British Antarctic Survey, Natural Environment Research Council

Tel: +44 1223 221542

Fax: + 44 1223 362616

E-mail: rh@bas.ac.uk

Project website address: http://www.spacestorm.eu/

Executive Summary

Europe has a major space industry. It is investing heavily in the Galileo radio navigation programme consisting of 30 satellites and the Copernicus Earth observation programme. It is at the forefront of new technological advances such as satellites with all electric propulsion. In total there are more than 1400 operational satellites on orbit, more than three times as many as there were in 2003.

All these satellites either orbit inside the Earth's magnetic field or pass through it. They are subject to radiation exposure from high energy electrons in the Earth's van Allen radiation belts. During space weather events the number of electrons in the radiation belts can increase rapidly causing disruption to satellite services, ageing and in some cases total satellite loss. For example, in 2003 during the so-called Halloween storm 10% of the entire satellite fleet reported malfunctions and one satellite costing $640m was a total loss.

The goals of the SPACESTORM project was to model space weather events and mitigate their effects on spacecraft. The project delivered several major new results. We have:

- Shown that the daily average electron flux for a 1 in 100 year event for geostationary orbit is 7 times higher than previous work, due to the inclusion of dead-time corrections and magnetic latitude effects
- Calculated for the first time the charging currents and the electron flux for a 1 in 100 year event for Medium and Low Earth orbit (MEO and LEO), respectively
- Modelled extreme space weather events and showed that the orbits most at risk are MEO and LEO for storms driven by a coronal mass ejection, and geostationary orbit (GEO) for fast solar wind stream events
- Provided the first 30 year re-construction of the outer radiation belt, enabling the better design of satellites for MEO
- Shown how electron radiation exposure can increase the conductivity of new insulating materials making them less susceptible to breakdown via an electrostatic discharge
- Shown that high intensity short duration laboratory experiments can be used to assess long term exposure in space for materials that are not significantly affected by radiation induced conductivity
- Shown that even for very low levels of radiation highly resistive materials can charge up to dangerously high levels and pose a risk of an electrostatic discharge, and therefore the time history of radiation exposure must be taken into account
- Shown that by including passive electron emitters on solar arrays surface charging can be reduced by as much as 4 kV and thus help prevent satellite anomalies
- Shown that an additional shielding of 1.5 to 2 mm of aluminium at GEO and 0.5 mm of Al at MEO would be sufficient for most satellites to survive an extreme space weather event
- Developed a new set of mitigation guidelines to reduce the impact of extreme space weather
- Introduced 4 risk indicators that integrate the radiation environment with radiation effects on satellites so as to better quantify the risk of damage due to space weather
- Provided a world leading situation awareness and forecast of risk indicators for GEO, Galileo and slot region orbits, updated every hour
- Developed a stakeholder community across Europe of satellite operators, designers, insurers, engineers, scientists and other Agency representatives
- Provided advice to Government on extreme space weather and contributed to the European Cooperation for Space Standardisation (ECSS)

A summary description of project context and objectives

The number of operational satellites has increased by 40% over the last 5 years and there are now over 1400 on orbit. This growth in the satellite industry is unprecedented and shows how much we rely on satellites for applications such as communications (including TV, internet, and mobile phones), navigation, positioning, timing, and Earth observation. In 2015 the revenue from satellite services was $127 Bn which illustrates how important satellites are to the global economy. In terms of application, about 37% of all satellites are used for commercial communications and the largest income stream is from satellite TV [SIA, 2016].

All satellites must be designed to withstand the harsh radiation in space for a design life that can be up to 15 years or more. All satellites in geostationary orbit (GEO) and Medium Earth orbit (MEO) either lie inside the Earth's Van Allen radiation belts or pass through them. Satellites in high inclination low Earth orbit (LEO) pass through the footprint of the radiation belts. The radiation belts consist of high energy charged particles that are trapped inside the Earth's magnetic field and which encircle the Earth like a ring doughnut. The radiation levels inside the radiation belts are not constant but vary with location and can change rapidly when the Earth's magnetic field is disrupted.

Space weather events can severely disrupt the Earth's magnetic field and significantly increase the radiation hazard to satellites. They cause electron acceleration inside the Earth's magnetic field which increases the number of charged particles in the radiation belts. These increases usually take place over a period of hours to days, but events as short as 2 minutes have been observed. Once the radiation belts are enhanced they can take months or even years to recover back to normal levels. On occasions they can also be rapidly depleted. Thus the period over which satellites are at risk is very difficult to predict and hard to assess. Increased electron radiation can cause a number of effects, most notably satellite charging and the risk of an electrostatic discharge. An electrostatic discharge can damage satellite components causing interruptions to service and in exceptional cases total satellite loss. For example, 10% of the entire satellite fleet reported anomalies (malfunctions) and one satellite was a total loss during the 2003 Halloween storm. All the satellites suffered ageing. Today the cost of a modern telecommunications satellite is about $250m and about $80m to launch into GEO. With more than 500 in GEO alone there is a tremendous financial investment that needs protection from space weather.

Despite all the advances in the design and operation of satellites disruption to satellite services still occurs. The last satellite failure occurred on 31 March 2017 and was a total satellite loss. Several more satellites reported anomalies during the lifetime of this project (2014-2017) which are believed to be associated with space weather events. To help mitigate the effects satellite operators need real-time information on the radiation environment so that that can take extra care during periods of high radiation to reduce the risk of damage. Examples of the action they can take include switching off non-essential systems, re-scheduling an orbit manoeuvre, delaying a major software upgrade, having more staff available to deal with problems and having extra transmission capacity immediately available in case of an interruption to service.

Space weather not only affects satellite operations, it also affects the design and construction of spacecraft and space insurance. Satellite designers need to know the reasonable worst case for the space radiation environment so that they can provide shielding around electronic components to help make the satellites more resilient. Space insurers also have an interest to ensure that designers and operators take all reasonable precautions, and need environmental observations to assess independently the cause of a satellite failure.

While design models and forecasting services have been provided for a number of years new advances in the satellite industry have created new drivers for space weather services, particularly for MEO. For example, eighteen of the European Galileo radio-navigation satellites have now been deployed into MEO and the system became operational in December 2016. While traditional space weather services have concentrated on geostationary orbit there is no dedicated information for MEO and satellite operators have to try to extrapolate information into a region that is not well known. A second example is the introduction of electric orbit raising. The first two satellites with electric instead of chemical propulsion were launched in 2015. The main advantage of electric propulsion is that the mass of the spacecraft is almost halved which means that a smaller launch vehicle can be used and hence launch costs can be reduced significantly. However, instead of taking 5 to 10 days to reach geostationary orbit it can now take 200 to 300 days. As a result satellites spend much longer in the heart of the outer Van Allen radiation belt where radiation levels are much more severe than geostationary orbit and also highly variable. Again there is no space weather service for this. A third example is the increasing use of lower altitude orbits such as the slot region at 8,000 km altitude, and the thousands of satellites that have been registered with the International Telecommunications Union to utilise Low and Medium Earth Orbit for internet services in the near future. There are little or no space weather services designed for these orbits.

Another key driver is the need to assess the impact of an extreme space weather event. Following the volcanic eruption in Iceland in 2010 that disrupted air travel, and the Tsunami that caused the nuclear disaster in Japan in 2011, Governments have recognised the importance of extreme events. These are events with a low occurrence rate but high impact. In the UK space weather has been put on the National Risk Register of Civil Emergencies. However, the impact of an extreme space weather event is still very uncertain.

Given this background, the goal of the SPACESTORM project was to model space weather events and mitigate their effects on satellites by developing better mitigation guidelines, forecasting, and by experimental testing of new materials and methodologies to reduce satellite vulnerability.

To achieve this goal the objectives of the SPACESTORM project were:

- To model space weather events using dynamic physical models in order to test and validate the models, and to increase our physical understanding
- To construct a 30 year dataset for MEO and GEO using data and physical models
- To determine the space radiation environment for extreme space weather events via data analysis and theoretical models
- To determine the impact of space weather events on satellites, especially satellite charging and single event upsets
- To develop better mitigation guidelines for MEO and GEO
- To provide mitigation via a monitoring, forecasting and warning system
- To test experimentally new methods of reducing satellite charging

A description of the main S&T results/foregrounds

The SPACESTORM project began on 1 April 2014 and ended on 31 March 2017. The project made several major advances during that period and all the objectives were met. Below is a summary of some of the main results.

Determining the 1 in 100 year event for GEO

One of the most important hazards for satellites on orbit is internal charging caused by high energy electrons at energies between a few hundred keV to a few MeV. These electrons are trapped inside the Earth's magnetic field in the van Allen radiation belts and encircle the Earth like a ring doughnut. During space weather events the flux of electrons can change by up to five orders of magnitude. When these levels are enhanced more electrons can penetrate the outer skin of a spacecraft and accumulate in dielectrics such as circuit boards and insulators. If the charge builds up faster than it can leak away for a substantial period of time then an electrostatic discharge can occur which breaks down the material and can cause serious problems. In the past such events have been known to cause interruptions to service, ageing and in some cases total satellite loss.

In order for designers to protect satellites they require information on the maximum electron flux which is likely to occur. This is so that they can select the most appropriate amount of shielding to put round sensitive electronic components so as to prevent radiation exposure from high energy electrons. One of the difficulties is calculating the maximum flux since the radiation belts are so variable. Satellite designers usually use static models such as the NASA AE-8 and the new AE-9 model, also known as IRENE. These models are based on data collected over a number of years during different parts of the solar cycle and can provide the electron flux for different orbits. However, there is still a large uncertainty as to the highest level the electron flux can reach, particularly for an extreme space weather event.

One of the major achievements of the SPACESTORM project was to determine the high energy electron flux for an extreme space weather event. This was done by performing a statistical analysis of electron data from the GOES satellites at geostationary orbit. Approximately 19.5 years of data for an energy greater than 2 MeV was analysed using the method of extreme value analysis. The analysis enabled a calculation of the daily average electron flux for a 1 in 10, a 1 in 50, 1 in 100 and 1 in 150 year event. The analysis revealed a surprising new result. It showed that the daily averaged electron flux greater than 2 MeV at GOES West for a 1 in 100 year event is 7.68 x 105 cm–2 s–1 sr–1, which is a factor of 7 higher than that found from previous work. One of the main reasons for the higher values was that we had included a "dead time correction" to the data which had been omitted in earlier work. Dead time corresponds to the short period of time when the detector cannot count electrons as it is processing the signal from a previous count.

The analysis also showed that the maximum electron flux varies according to the longitude of the spacecraft. The flux at GOES West is approximately 2.5 times higher than at GOES East. This is due to the offset between the geomagnetic and geographic poles at different longitudes so that for example GOES West is at a lower magnetic latitude than GOES East. The higher latitude of GOES East maps to an equatorial distance farther away from the Earth and hence, since the electron flux decreases with distance at this location, GOES East measures a lower flux. From the analysis satellites located near 20o E and 160o W will, on average, experience the largest fluxes due to this offset.

This information was used by one of our stakeholders to help in the purchase of new satellites and to assess whether the periods of high flux are related to satellite anomalies.

Determining the 1 in 100 year event for LEO and MEO

Low Earth Orbit (LEO) is an orbit close to the Earth, typically at altitudes below 1000 km. It is a particularly important for Earth observation and military surveillance since it is best placed for obtaining high-resolution images of the Earth. Satellites in LEO with inclinations greater than about 40o are exposed to electrons injected into the inner magnetosphere during storms and substorms and, at higher energies, to electrons from the radiation belts. Such exposure can damage or even prove fatal for a satellite.

Using 16 years of data from the low altitude National Oceanic and Atmospheric Administration (NOAA) Polar Operational Environmental Satellites (POES) we conducted an extreme value analysis for LEO and provided the first calculation of the satellite charging currents for a 1 in 10, 1 in 50 and 1 in 100 year event. The results showed that two of the top five injection events occurred in July 2004 and were associated with three magnetic storms in quick succession. They were also associated with the loss of the secondary ion propulsion system on Galaxy 10R. A similar extreme value analysis was also performed for MEO using data from the Galileo test satellite Giove A. The results showed that the NASA design guidelines on charging currents for the higher levels of shielding are exceeded some 6.8% of the time. The analysis provides a benchmark against which to compare other space weather events, and can be used to calculate the return period for a space weather event as a function of energy and location.

To our knowledge this is the first time this type of analysis had been done for LEO and MEO and will greatly aid satellite designers in assessing the worst case radiation exposure.

Modelling extreme space weather events for high energy electrons

The largest magnetic storm on record is widely acknowledged to be the so-called Carrington storm of 1859. There was widespread disruption to telegraph systems and low latitude aurora associated with this storm. However, technology at the time was rather primitive compared to today's technology. The big concern today is what the impact would be if an extreme space weather event such as the Carrington storm were to occur again.

Unfortunately there were no measurements of the space radiation environment during the Carrington event, but we do have information on several recent magnetic storms showing that the electron flux can vary by up to 5 orders of magnitude. We also know that during the so-called Halloween storm of 2003 approximately 10% of the entire satellite fleet reported anomalies (malfunctions) and one satellite was a total loss. However, the Halloween storm was by no means as big as the Carrington storm.

To assess the impact of an extreme space weather event we conducted a series of modelling studies. These studies were done using the BAS radiation belt model (BAS-RBM) to study high energy relativistic electrons greater than 150 keV that cause internal charging and the Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM) to study lower energy electrons less than 150 keV that cause surface charging.

In the first instance a series of studies on smaller weaker storms were performed so as to test the model against data and to improve the BAS-RBM model. The Halloween storm of 2003 was used as an important test case since it was a relatively large storm and since there are plenty of data available. This proved to be very valuable as several lessons were learnt in setting up the most appropriate boundary conditions. For example, the outer boundary of the magnetic field was pushed inside geostationary orbit during this storm.

This is very important as it leads to electron losses and a depletion of the radiation belts. New techniques were developed to take the motion of this boundary into account and to include losses associated with the boundary. A second example was to find a method to include changes in the low energy electrons that form the boundary of the simulation. Again a new technique was developed to extract electron data from low altitude POES satellites which provided much higher time resolution and spatial coverage than before.

Results from the initial simulations showed that they could reproduce the losses from the radiation belts during the initial part of the storm but they were not able to reproduce the recovery and enhancement of the belts during the latter part of the storm. However, a series of tests showed that the high density plasmasphere was being re-filled too quickly and that this was preventing significant electron acceleration and hence preventing the re-formation of the outer belt. New methods to include a more realistic timescale for the refilling of the plasmasphere were implemented which then gave a much better agreement between the model and the data.

Following these tests the model was adapted to simulate an extreme space weather event. In July 2012 a very fast coronal mass ejection (CME) was emitted by the sun with a speed of over 2500 km s-1. It was detected by the STEREO spacecraft but luckily the CME did not come in the direction of the Earth. If it had encountered the Earth it is widely recognised that this would have caused the modern day equivalent of the Carrington storm. This event was therefore chosen as an example of an extreme space weather event for modelling. The model showed that the outer magnetic field boundary was pushed inside geostationary orbit to as low as 4 Re (Earth radii). As a result of electron losses to the boundary and into the atmosphere the outer radiation belt was depleted of all high energy electrons down to 3 Re. At lower altitudes some of the electrons were transported inwards and formed a new radiation belt in the slot region which is usually devoid of particles. Following the main phase of the storm the magnetopause returned to its usual position and there was rapid electron acceleration which led to the reformation of the outer belt but at a location closer to the Earth than the pre-storm location, typically near 4 Re.

The main conclusion from these simulations is that satellites at MEO and in the slot region would be exposed to high levels of electron radiation and that this could last for days at MEO and even longer in the slot region. Satellites in high inclination LEO that pass through the footprint of the radiation belts would also have a higher exposure. At GEO satellites on the dayside of the Earth would be exposed to the solar wind during the main phase of the storm. As a result the electron flux would be lower. However, satellites that use magnetorquers for orientation would be affected since the direction of the magnetic field would change substantially and these satellites might attempt an orbit manoeuvre. During the recovery phase radiation exposure would depend on the amount of geomagnetic activity but without further information this was hard to assess.

A series of studies were also done on extreme events associated with fast solar wind stream events. These studies showed that the electron flux at GEO could reach very high values comparable to the 1 in 150 year event calculated from statistical methods. It is perhaps remarkable that models which are based on physical processes such as particle acceleration and loss should be able to produce results that agree with those based on statistical analysis of electron data alone.

In conclusion the model simulations have been able to shown that there are at least two types of extreme space weather events, one driven by a coronal mass ejection, and one driven by a fast solar wind stream. Satellites in MEO and LEO are more at risk from an extreme CME while satellites in GEO are more at risk from a very fast solar wind stream.

Modelling space weather events for low energy electrons

Increases in the flux of electrons at energies of a few hundred eV to a few hundred keV increase the risk of satellite surface charging. This is potentially dangerous as it can result in an electrostatic discharge and damage to components such as solar array panels. IMPTAM was used to model the transport and loss of these lower energy electrons. Again before attempting to model an extreme event a number of simulation studies were performed on smaller events to verify the model.

The IMPTAM model was used to model the transport electrons from a source region near 10 Re towards the Earth and around geostationary orbit. The transport is governed by electric fields that are set up across the geomagnetic field by the flow of the solar wind. By analysing scientific satellite data a model for the source electron population in the outer magnetosphere was developed. A key factor in this model was the shape of the energy spectrum. Simulations showed that by making the energy spectrum much harder than that used in previous work (i.e., using a kappa index of 1.8 or lower instead of 5) there was a much better agreement between the data and the model. Test runs comparing the outputs of the model against data at geostationary orbit for a range of local time showed a much better agreement at energies below 100 keV than previous simulations.

To gain confidence in the model several simulations were performed and compared against satellite data at GEO. The modelled events corresponded to some of the most important surface charging events detected by the LANL satellites. The model was able to demonstrate transport of electrons from the tail across GEO and into MEO, and showed an increase in the electron flux by 2 to 3 orders of magnitude. The model was able to show that satellite charging events were a result of substorm activity and newly injected electrons which had been transported towards the Earth from the tail.

After testing the IMPTAM model on these smaller events it was used to simulate an extreme space weather event based on the July 2012 CME. The TS05 magnetic field model was selected for these simulations since it was constructed from data taken from several geomagnetic storms. The electric field was based on data from solar wind derived from STEREO data and a model for the electric potential across the polar cap. A new electron loss model due to wave-particle interactions was also included into the simulations. As the CME hit the Earth the magnetic field model indicated that the magnetopause was pushed inside geostationary orbit and the magnetic field on the nightside was stretched. The model also showed that some electrons could be transported to lower altitudes and become trapped. However, at GEO there was a net loss of electrons to the magnetopause on the dayside and a drop in the flux on the nightside as a result of the stretched magnetic field.

A series of studies were also done on other severe storm events where satellite data are available. Again one of the key findings was that the low energy electron flux at GEO could be significantly reduced due to loss processes and the stretched magnetic field configuration. The simulations also showed that it was very difficult to capture rapid variations in the electron flux observed in the data. This was partly due the magnetic field model which was not able to capture rapid changes in the geomagnetic field. Thus the modelling of extreme space weather events remains a challenging problem.

30 year re-construction of the space radiation environment for MEO and GEO

For many years most satellites have been launched into two main orbits, GEO and LEO. However, MEO is becoming increasingly important. For example, the GPS constellation operates in MEO and the new EU Galileo radio-navigation system is being launched into MEO. The Galileo system went operational in 2016, but there are still 12 satellites to be launched. MEO is also being used for radio-navigation systems by other nations and for commercial operations.

One of the difficulties of designing satellites for MEO is that the data are very sparse compared to geostationary orbit. There are a few scientific satellites that have operated at various parts of the solar cycle such as the CRRES and Van Allen Probes missions, and the Giove A and B test satellites, but there are no continuous measurements.

To address this issue the BAS-RBM was adapted to re-construct the whole of the outer radiation belts for the past 30 years. Data from the NOAA GOES satellites at GEO was processed to provide an outer boundary condition for the model just beyond geostationary orbit. This included removing any proton contamination of the electron data, taking into account the diurnal variation, the location of the spacecraft and converting the integral electron flux to the differential electron flux using a novel technique. The low energy boundary was taken from an average over the CRRES electron observations. Using these boundary conditions the model was able to re-construct the entire outer radiation belt for 2 Re to 6 Re by including the physics of radial transport, particle acceleration, loss by wave-particle interactions, plasma density variations, and losses to the atmosphere via collisions with atmospheric gasses.

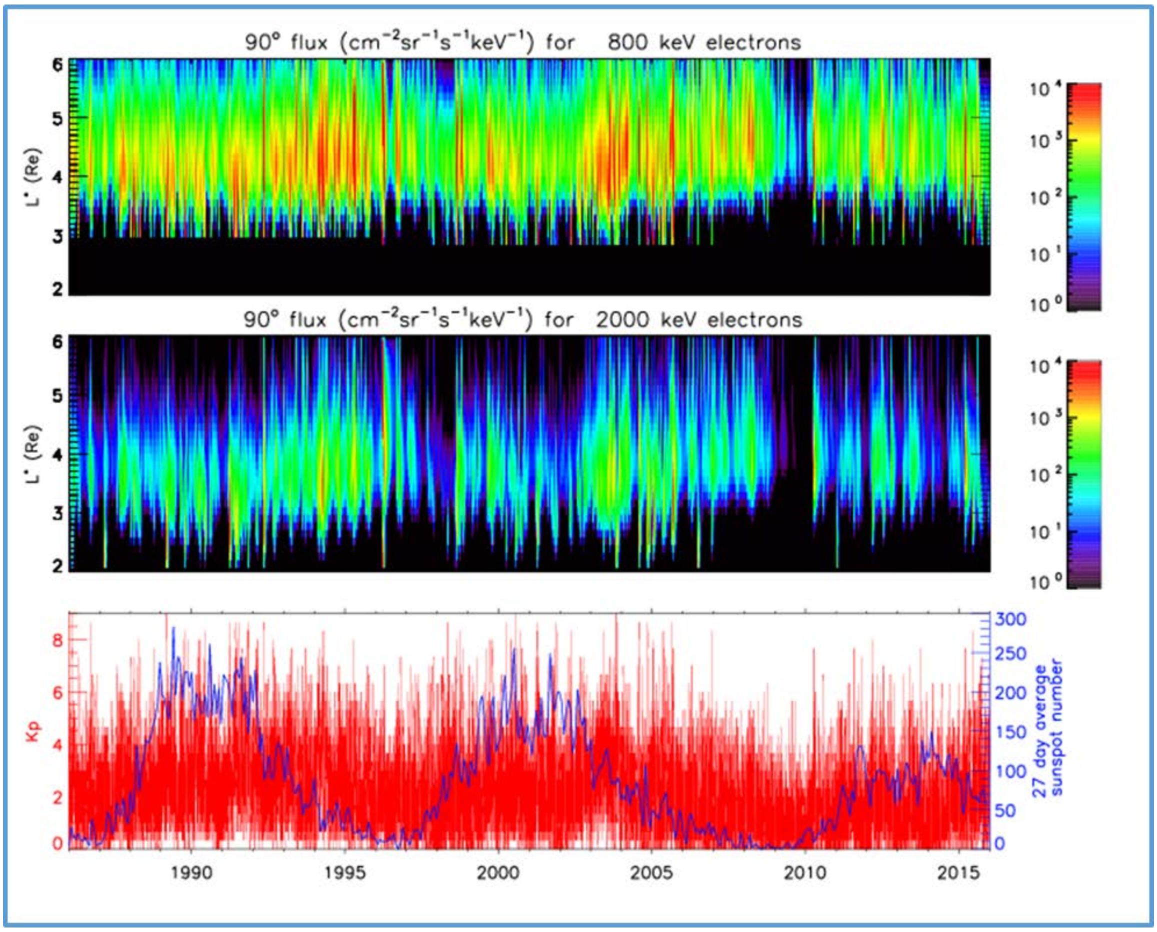


Figure 1. 30 year re-construction of the van Allen electron radiation belts. Shown are (top) the electron flux greater than 800 keV colour coded, (middle) flux greater than 2 MeV, and (bottom) the solar cycle and Kp index which is a measure of geomagnetic activity.

As far as we are aware this is the first re-construction of the entire outer radiation belt and slot region. The re-construction covers the period January 1986 to January 2015, or about two and half solar cycles. Solar cycle variations are clearly visible. Periods with more intense flux are present during the declining phase of two solar cycles which are associated with fast solar wind streams. They extend Earthwards from GEO through MEO to the slot region. Similarly, the so-called 'electron desert' which occurred in 2009 and early 2010 is also present and extended from GEO through MEO and into the slot region. The simulations also showed injections of high energy electrons into the slot region which took weeks or even months to decay indicating that radiation exposure in the slot region can be a hazardous to spacecraft.

To test the accuracy of the re-constructed dataset the simulations were compared to electron data from the SREM instrument on GIOVE-B. These data are from MEO between 2008 and 2012 and therefore provide an excellent test of the simulation. The calculated skill score fluctuated around the 0.7 level for each year of the comparison. While a perfect comparison would have a skill score of 1.0 and a skill score of 0 could be obtained by simply assuming average conditions, a skill score of 0.7 is regarded as very good and comparable to the best predictive models at present.

The re-constructed dataset now forms a resource that can be used to help calculate radiation exposure future missions for MEO. It was used later on in the project to help determine the engineering effects on satellites and develop better mitigation guidelines.

Determining the impact of space weather events on satellites

Laboratory experiments

Modern commercial satellites have a design life of up to 15 years or more. As new technology is developed it is important to conduct experimental tests to ensure that they can survive for such long periods in space. One of the difficulties is that the duration of a laboratory experiment is limited to much less than 15 years. A second problem is that it is very difficult to reproduce the space radiation environment in the laboratory. On the other hand laboratory experiments are very valuable since they allow the radiation intensity and energy spectrum to be varied in a controlled way and thus better understand the response of different materials.

With the growing importance of MEO, especially for the Galileo radio-navigation system, MEO was a particular orbit of interest. For example, the intensity of high energy electrons at MEO is much harsher than GEO and the spectrum of the radiation is very different which can lead to a strong charging hazard.

Experiments for MEO were carried out at the French Aerospace Laboratory in Toulouse, France using the SIRENE and GEODUR electron beam facilities. The worst case electron energy spectrum for MEO was obtained from previous work. Assuming 2.5 mm of Al shielding the electron spectrum emerging from the shielding was then calculated. The resulting current rapidly dropped to zero above 900 keV. The electron beam system in the laboratory chamber (GEODUR) was then adjusted to reproduce the energy spectrum extremely well for energies up to 750 keV and with a rapid reduction in current at about 1.1 MeV which was slightly higher than calculations. Several materials representative of PCBs, insulating materials used on PCBs and connectors, cable insulation and paint coatings were then evaluated.

One of the most important results was the measurement of radiation induced conductivity. As materials are irradiated some of the high energy electrons are absorbed by the material and change the electrical properties, for example, increasing the conductivity. This radiation induced conductivity can to some extent mitigate the charging hazard as some of the charge can leak away. For materials such as ETFE used for cable insulation there was very little radiation induced conductivity and therefore even thin samples of these materials can charge up to dangerously high levels after a few hundred hours and pose a risk of an electrostatic discharge (ESD). On the other hand materials such as PEEK and Kapton which are used for thermal and electrical insulation exhibited significant radiation induced conductivity and therefore were better able to reduce the risk of an ESD.

A second very important result was the determination of how well short duration laboratory experiments can be used to assess long term exposure in space. The idea is that by irradiating materials with a very high beam intensity in the laboratory, much higher than is observed in space, that this could accelerate the ageing and charging processes of materials in space. However, there has always been some uncertainty over the validity of this method. The results of the experiments showed that the acceleration method is valid for materials like ETFE that do not have any significant radiation induced conductivity. For materials such as PEEK where there is moderate radiation induced conductivity the acceleration method is also valid. However, for materials such as Kapton the results are more complicated. The irradiation changes the electrical properties significantly so that it may still be possible to use the acceleration method but only provided more experiments are done to better understand the changes in the electrical properties.

A very different class of experiments were also performed to examine the effects of low intensity long duration irradiation. In this case materials were irradiated for up to 1800 hours in the Realistic Electron Experiment Facility (REEF) at the University of Surrey. The REEF facility has a Strontium 90 source which produces an electron spectrum very similar to that observed in the radiation belts. The experiments were done for low charging currents of typically 0.01, 0.07 and 0.22 pA cm-2. Note that the NASA handbook recommends that sensitive electronic components should be shielding so that the current does not exceed 0.1 pA cm-2, so these experiments were designed to represent the radiation belts in a very realistic way.

These experiments showed that even with very low charging currents an order of magnitude below the NASA recommended safety threshold dielectric materials with very low bulk conductivities can charge up and develop high internal electric fields and therefore present a risk of ESD. Some materials such as PEEK which is used for thermal and electrical insulation exhibited a sensitivity to temperature variations of 5 degrees, such that as the temperature increased the charging rate decreased indicating an increase in the conductivity that enabled the charge to leak away. In general the electric field that builds up inside the material depends on the electron fluence and not the electron flux, i.e. a longer time history of the radiation exposure. The results have important implications for satellite internal charging and suggest that the risk of damage to spacecraft is higher when the radiation belts are enhanced for longer periods rather than a short duration high amplitude peak.

One particularly interesting result concerned experiments where the samples were irradiated with a very low current for 200 hours or more followed by a short period of high current irradiation. This represents the type of behaviour that occurs in the radiation belts during storms and fast solar wind stream. Materials such as PEEK and FR4 showed that the charging rate was higher during the high current irradiation than if the material had been irradiated from the beginning with high current. This suggests that the initial low current irradiation changed the electrical properties via radiation induced conductivity. This result suggests that the variability of the radiation belts can have a significant effect on the charging properties, and is actually more complicated than we thought.

Testing new methods of reducing satellite charging

Satellite anomalies related to surface charging have become one of the most important issues in the operation and efficiency of solar arrays. One of the ways of trying to mitigate surface charging is to include what is known as a passive emitter. The idea is that as the surface charges up to a negative potential, which is usually the case, an emitter on the surface would be able to reduce the charge and hence reduce the risk of an anomaly. In a passive emitter small microscopic irregularities create very large electric fields at the surface. When this field exceeds a threshold electrons are emitted from the irregularities by a field effect. The charge is emitted from the spacecraft at a point where a conductor, a dielectric and the plasma meet at what is known as a triple point.

Four new experimental samples were designed and tested in the PHEDRE facility at the French Aerospace Laboratory (ONERA) in Toulouse. The experiments showed that strong electron emission occurred at the triple point after they were exposed to UV light, thus proving the concept. The experiments also showed that electron emission is much more effective when using a highly resistive insulator for the dielectric.

In order to scale up the results and apply them at spacecraft level the SPIS simulation software package was used to define a realistic spacecraft configuration and size. The plasma was defined according to the European Cooperation for Space Standardisation (ECSS) worst case environment for surface charging based on observations by the SCATHA spacecraft on 24 April 1979. Simulations showed that without the passive emitter the satellite charged negative to between -6 and -7 kV. However, when 10 emitters were switched on this reduced the potential by about 4 kV after 15 minutes. Thus the main conclusion is that passive emitters could provide a very effective means of reducing surface charging on solar arrays.

Mitigation guidelines for MEO and GEO

Using the maximum electron flux calculated from the 1 in 100 year event, simulation studies, results from an alternative model based on physical principles and other radiation design models, the radiation effects on engineering systems were assessed. These calculations showed that satellites at GEO could be aged by as much as 8 years due to ionising dose during an extreme space weather event. Furthermore there is a high risk of an ESD and satellite outage.

One way to mitigate the effects of a 1 in 150 year event at GEO would be to include an additional 1.5 to 2 mm of Al around sensitive electronic components. This is assuming an existing shielding of 2 mm of Al due to the structure of the spacecraft and that around electronic components. The additional shielding would result in an increased mass of about 50 kg for a medium sized satellite depending on the configuration and the components. For MEO an additional 0.5 mm of Al would be required assuming a nominal shielding of 2.5 mm of Al. For a satellite the size of Galileo the additional mass would be 20 kg.

To protect solar arrays from an extreme event an over sizing of the arrays would be able to compensate for the degradation in performance. Alternatively an increase in the thickness of the cover glass could also be employed. This would lead to an extra mass of between 10 kg for a communications satellite at GEO and 5 kg for a Galileo type satellite at MEO.

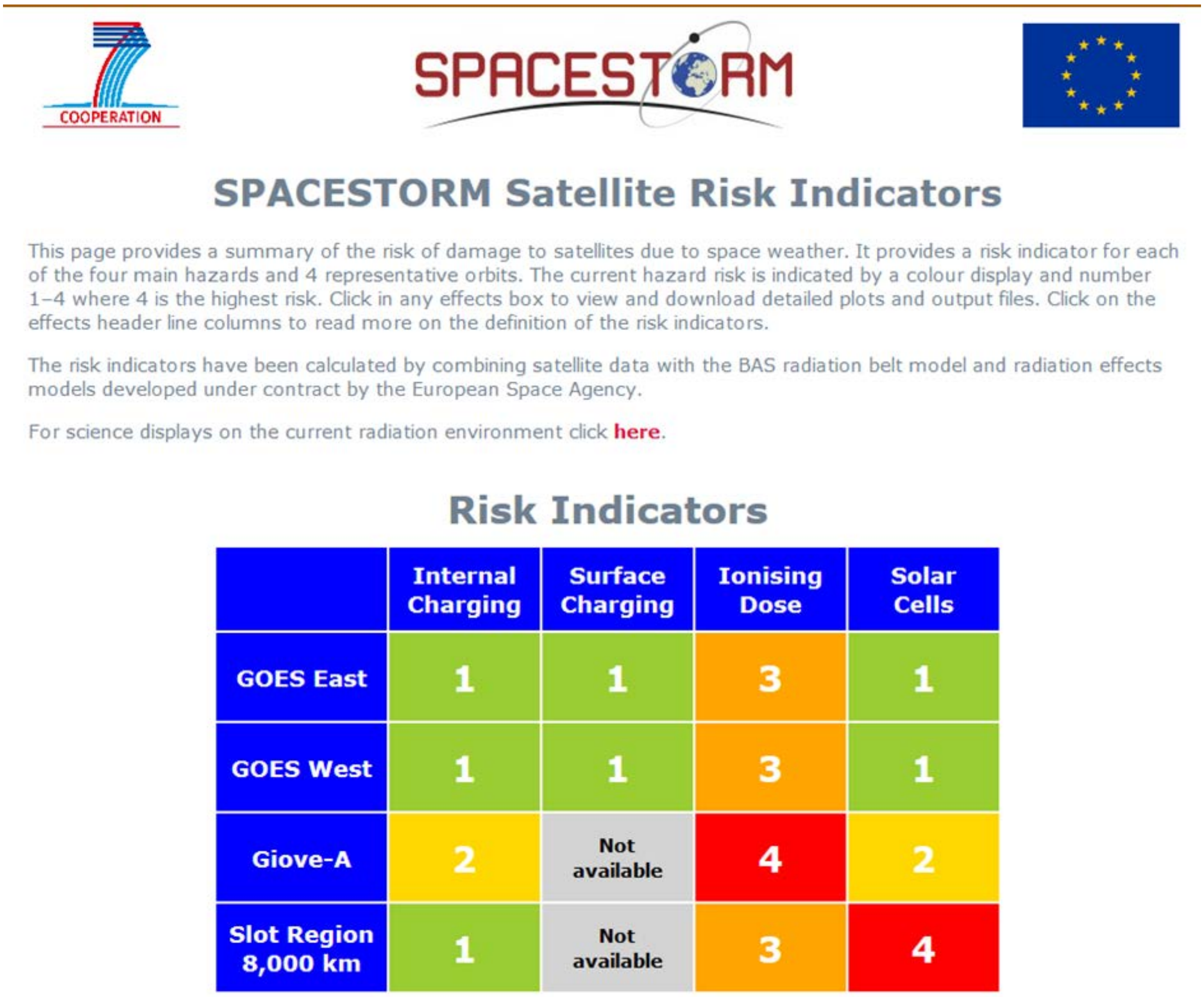
Analysis by the SPACESTORM team show that there is more than one approach to mitigation. For example, satellite operators of military and critical systems may want to protect their spacecraft from a 1 in150 year event and thus adopt additional shielding. This would increase launch costs. However, commercial operators may take a different approach and offload the risk by taking out insurance.

Another type of mitigation is situation awareness, forecasting and warning. Given a forecast or an alert, or a set of conditions where there has previously been an operational problem satellite operators can take action. This includes re-scheduling non-essential procedures until after the event, e.g. a manoeuvre, configuring equipment for best resilience, having more staff on standby to deal with any problems and ensuring that recover procedures are ready and rehearsed.

To our knowledge this is the first calculation made public of how much additional shielding is required for most satellites in MEO and GEO to survive an extreme space weather event.

Monitoring, Forecasting and Warning

Another major result has been the development of the real time forecasting system to better reflect the needs of the satellite industry. Space weather forecasts are freely available from the Space Weather Prediction Centre in the USA, but they are somewhat generic and the satellite forecasts are focussed on GEO. In the previous EU funded SPACECAST project a prototype forecasting system was developed for satellites in MEO and GEO. These forecasts were based on running physical models to forecast the high energy electron flux and a nowcast of the low energy flux. They also provided data on high energy protons. However, one limitation of these forecasts is that they do not take into account radiation effects on satellites. Our research has shown that the time history of the electron flux can be very important for assessing risk, and that the amount of shielding should be taken into account when assessing risk.



SPACESTORM Satellite Risk Indicators

This page provides a summary of the risk of damage to satellites due to space weather. It provides a risk indicator for each of the four main hazards and 4 representative orbits. The current hazard risk is indicated by a colour display and number 1–4 where 4 is the highest risk. Click in any effects box to view and download detailed plots and output files. Click on the effects header line columns to read more on the definition of the risk indicators.

The risk indicators have been calculated by combining satellite data with the BAS radiation belt model and radiation effects models developed under contract by the European Space Agency.

For science displays on the current radiation environment click **here**.

Risk Indicators

	Internal Charging	Surface Charging	Ionising Dose	Solar Cells
GOES East	1	1	3	1
GOES West	1	1	3	1
Giove-A	2	Not available	4	2
Slot Region 8,000 km	1	Not available	3	4

Figure 2. The SPACESTORM forecasting web page. Four risk indicators are provided along 4 different orbits representative of the Galileo orbit, MEO and GEO.

To take these factors into account we introduced the concept of risk indicators for the four most important risk factors affecting satellites. These include internal charging, surface charging, total ionising dose and solar cell degradation. The idea was to take data from satellites and models on the radiation environment and use it as input to calculate radiation effects on materials typically used in spacecraft. In this way the risk indicators would give a much more accurate representation of periods of high risk, and the risk affecting different parts of the spacecraft, for example, for solar arrays and electronic components. The risk indicators also take into account the time history of the radiation. As a guiding principle real time data was used wherever possible and missing data were 'filled-in' with results from the models. A second principle was to provide the risk indicators along four selected orbits representative of GEO and MEO, and in particular the Giove orbit representative of Galileo.

After several discussions with our Stakeholders the web page was re-designed to give a high level warning system of 1 to 4, colour coded, where red exceeds a well-defined threshold in a design standard such as the NASA handbook or the ECSS standard. An example is shown below. By clicking on the colour coded box the time history of the risk indicator is shown, together with the forecast if it is available. In this way an operator or designer can drill down for more information. Information on the electron and proton spectra are also provided.

To ensure the forecasts are as accurate as possible several improvements to the forecasting models were made. These included including the development of a better set of initial conditions to run the IMPTAM and BAS-RBM models, better models of losses due to wave-particle interactions, more realistic magnetic field models, using data from GEO as a boundary condition and including losses due to changes in the outer boundary of the geomagnetic field. The models went through a rigourous set of tests and comparisons against satellite data for specific events. As a result, the forecast of the greater than 800 keV and greater than 2 MeV electron flux at geostationary orbit has been improved considerably and we now have a skill score of approximately 0.7 as described earlier.

As far as we are aware this is the first time that forecasts have been provided along orbits representing Galileo, the slot region and GEO. It provides a world leading situation awareness and forecast of the different types of risk to satellites. The web site can be found at www.spacestorm.eu.

Stakeholders and advice to government

SPACESTORM has also helped significantly to develop a network of Stakeholders across Europe on space weather and satellites. Members of our Stakeholder team included representatives from satellite operations, design, Insurance, space data and space science. We also extended this network by working with the European Space Agency to organise a special lunch time discussion meeting each year at the European Space Weather Week in Belgium (in collaboration with the BIRA) consisting of up to 30 scientists and representatives from the space industry. Each year was focussed on a particular topic and included a dedicated discussion of user needs. One of the outcomes was to recognise the importance of linking together forecasting of the space environment with radiation effects on satellites to assess risk. Input from these meetings was used to revise the SPACESTORM web site and introduce the new risk indicatoors, discussed above.

Stakeholders also organised meetings for the team in Germany and in London showing commitment to and interest in the project. Finally the SPACESTORM project held a close-out meeting in March 2017 which was attended by more than 40 people from several space sector companies across Europe, 2 Space Agencies, forecasters, scientists and engineers and policy makers. The results of the SPACESTORM project have been made publicly available and have been subsequently used to help evaluate tenders on the procurement of new satellites.

A particularly important result from the project was the advice to the UK Government on extreme space weather provided by two members of the SPACESTORM team. The advice included a new assessment on the 1 in 100 year event and the impact this could have on the satellite fleet. The advice was provided via the Space Environment Impacts Expert Group (SEIEG) which included representatives from the UK Cabinet Office and was used as reference material to update the UK National Risk Register. Members of the SPACESTORM team also contributed to the European Cooperation for Space Standardisation (ECSS).

A final highlight has been two media broadcasts which both included interviews with the SPACESTORM Project Coordinator, Professor Richard Horne, on space weather. Both programmes described some of the SPACESTORM research from Antarctica. The first was broadcast on BBC Radio 4 on 6 March 2016 and the second was a TV documentary (Horizon) shown on BBC2 on 4th May 2016.

A list of all the reports and publications from the project, together with summary presentations given at the public close-out meeting in March 2017 are available via the project web site www.spacestorm.eu.

The potential impact

The SPACESTORM project came to an end on 31 March 2017. The project has had, and will continue to have a significant impact in five main areas:

1. **To significantly contribute to the European capacity to improve the accuracy and reliability of the Galileo system and to prevent damage / protect space assets from space environment events**

We have:

- Significantly improved the accuracy of the BAS Radiation belt model and the Finnish Inner Magnetosphere Particle Tracing model (IMPTAM) used in our forecasts which has increased European capacity to protect space assets.
- Re-constructed a 30 year dataset of the outer radiation belt which includes MEO and GEO. This provides a resource for post-event analysis to identify the cause of a satellite anomaly.
- Calculated the radiation levels for a 1 in 10, 1 in 50 and 1 in 100 year space weather event for LEO, MEO and GEO. These results can now be used to design new spacecraft (including Galileo) to survive an extreme space weather event. They have been used already in the procurement of new spacecraft.
- Enabled access to the REEF facility by the wider community to perform long term radiation experiments.

2. **To significantly contribute to both identify the impacts of space environment events in particular on space-based navigation systems including space- and ground-based infrastructure**

We have

- Modelled extreme space weather events and shown the MEO and LEO are most at risk from a major CME driven storm while MEO and GEO are more at risk from a fast solar wind stream event
- Shown that the time history of radiation exposure is very important for satellite anomalies
- Shown that satellites in GEO could be aged by up to 8 years as a result of an extreme space weather event.

3. **To develop concrete solutions to mitigate these risks**

We have

- Show that to protect most satellites from an extreme space weather event an additional 0.5 mm of Al shielding is required for MEO and an additional 1.5 – 2 mm for GEO
- Written new mitigation guidelines to cope with extreme space weather events
- Implemented a new real-time forecast of risk indicators for internal charging, surface charging, ionising dose and solar array degradation along the Galileo orbit and 3 other orbits for MEO and GEO (www.spacestorm.eu).
- Shown that passive electron emitters can significantly reduce surface charging on solar arrays

4. **Cooperation with international partners from third countries (ICPC) as well as other space faring nations (e.g. US and Japan)**

We have

- Including 3 stakeholders from the USA on our Stakeholder Advisory Committee
- Using data from US satellites including POES, GOES, THEMIS and Van Allen Probes
- Analysing GIOVE data with collaborators in Greece and the Netherlands
- Publishing several research papers that include authors from the USA, Japan and Europe

5. **Training of young scientists**

Four young scientists have been employed as vacation students to work on short research projects directly related to SPACESTORM. This provided an important training element and work experience in a research environment. One additional young scientist has submitted his work on SPACESTORM to the Open University as part of his PhD in 2016. The results from the SPACESTORM project have also been used to improve of the graduate course on “Observational Space Physics”, which Dr. Ganushkina has developed and taught at the University of Helsinki, and at the University of Michigan, USA. They have also been incorporated into the postgraduate (MSc) and Undergraduate (BEng/MEng) Space Technology courses taught at the University of Surrey, as well as Surrey’s Industrial Short Course portfolio, which includes a 2 day course on space radiation environments and effects. The University of Surrey also hosts the International Space Innovation Centre – Surrey (ISIC Surrey) which engages with SMEs to promote the adoption of space technologies and techniques into industry. The results from this research have been made available to the on-going programme of workshops held at ISIC-Surrey.

Contact

Professor Richard Horne (SPACESTORM Project Coordinator)
SPACESTORM Programme Office
British Antarctic Survey
High Cross, Madingley Road
Cambridge
CB3 OET
United Kingdom

Email: rh@bas.ac.uk

http://www.SPACESTORM.eu