Chapter 5

# Outlook on Space Weather Effects on Spacecraft

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**Abstract**: Spacecraft are becoming more susceptible to space weather hazards for a number of reasons. The types of missions being flown are increasingly demanding and payloads are becoming more sophisticated. In addition, commercial pressures can result in selection of more lightweight spacecraft and less radiation hardened components. Non-availability of radiation-hardened components in some areas can lead to the use of technologies that are sensitive to radiation effects. New types of space weather effects are also emerging. Traditionally the concerns have been with effects such as single event upsets and latch-up, internal and external electrostatic charging, drag effects and some communications effects. Modern systems have to contend with new kinds of problems, for example ion-induced circuit transients, and with increasing complexity associated with other problems such as interference with sensors. To these problems must be added the hazards to man in space, especially in the light of ambitions to progress beyond low Earth orbit. Serious problems persist with capabilities to evaluate space weather hazards to spacecraft. For example, single event upset and internal charging anomalies remain difficult to predict quantitatively. This contribution reviews the trends and problems arising, and proposes actions that are needed to address the problems.

**Key words**: ESA, space weather, space environments and effects

## 1. INTRODUCTION

Space missions are becoming more susceptible to space weather hazards for a number of reasons. Spacecraft themselves are becoming more complex, resulting in greater sensitivity to radiation and other environmental effects. The types of missions being flown are also increasingly demanding, both in terms of what they aim to do and where they try to do it. Commercial pressures can result in lighter spacecraft or parts of spacecraft, which implies



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less shielding against radiation. Such pressures can also result in selection of less radiation hardened components. Obtaining radiation-hardened components with the required performance is in any case proving more and more difficult. The nature of effects is also continually changing. For example, systems now have to contend with circuit signal transients induced by ion strikes on analog electronics, while problems related to radiation interference with sensors are increasing.

It is expected that human presence in space will expand. Space agencies around the world have bold ambitions, including putting humans on Mars. Such enterprises entail considerable risks, among which radiation from “space weather events” is a major one.

Serious problems are evident in the techniques used to evaluate quantitatively many of the space weather hazards to spacecraft. As a result, new types of evaluation techniques and supporting development programmes are needed.

Several reviews are available of space weather effects on spacecraft in general and on ESA’s spacecraft in particular (e.g. Daly, 2001), and it is not the purpose of this paper to repeat such reviews. It rather seeks to address the ways in which the evolution of mission types and space technologies will change the susceptibilities of space missions to space weather. After a brief overview of space weather effects, future mission trends are presented. The implications for space weather effects are detailed, and the means needed to deal with them discussed. It will be seen that radiation environments and effects receive the most attention. It is the opinion of the author that this is the most important and challenging area for the future and the reader should appreciate that this is a personal view.

## 2. SPACE WEATHER EFFECTS

Space Weather effects on space systems include:

– Radiation damage to spacecraft electronics, solar cells and materials from Earth’s radiation belt particles and solar energetic particles - The Earth’s inner (proton) radiation belt is relatively static, arising from cosmic ray atmospheric neutron decay but is affected indirectly via atmospheric changes and can be subject to changes during particularly severe events. The outer (electron) belt by contrast is highly dynamic over short times. Jupiter and Saturn also have intense radiation belts. Since radiation damage is a time-integrated phenomenon, the dynamic behaviour of the environment is not important. The exception is with solar cycle variations; inner belt proton fluxes are higher at solar minimum when the atmospheric densities are lower and the outer belt electron fluxes are higher on average during the declining phase of the solar activity due to recurrent geomagnetic storms induced by coronal holes;

– Single event effects in spacecraft electronics due to the ionization tracks from galactic cosmic ray or solar energetic particle ions, or due to the ionizing products of nuclear interactions between radiation belt or solar protons and component materials - Since the sources of these particles are strongly time varying, responding to solar and geomagnetic activity, the rates of single event effects such as memory errors can vary significantly. Sudden increases in error rates can cause serious problems for systems;

– Interference to spacecraft imaging and sensing systems - These effects are similar to single event effects. Particles passing through a detector can cause noise in the detector, obscuring the signal being sought. In this case, the particles can also include electrons and the many secondary products of particle interactions with surrounding material;

– Radiation hazards to astronauts - The international space station (ISS) is located close to the Earth, keeping it below the most dangerous parts of the radiation belts and shielded by the Earth's magnetic field from most solar energetic particles and, to some extent, from galactic cosmic rays. Nevertheless, the doses are important and so the environment must be continually monitored. The ISS inclination brings it into contact with the high latitude extensions of the outer radiation belt, where "space-walks" have to take account of enhancements due to geomagnetic storms, as well as exposure to solar energetic particles at these less well-shielded parts of the orbit. Future missions passing through the radiation belts and into interplanetary space, beyond the protection of geomagnetic shielding, will be subjected to more severe radiation hazards and so radiation protection and space weather warning are important elements for these ventures;

– Electrostatic charging from "hot" (~keV electron temperature) plasmas and energetic (~MeV) electrons - In a plasma, because of the higher mobility of electrons, surfaces usually charge negatively. Although in space this behaviour is modified by secondary emission and sunlight induced photoemission, close to the Earth (and close to Jupiter and Saturn) the currents of hot electrons can cause high levels of electrostatic charge to accumulate. Subsequent spontaneous discharging can disrupt electrical systems. The higher energy electrons can give rise to a similar phenomenon inside a spacecraft – charges can build up on internal cable insulation or other dielectric materials and lead to discharges. These phenomena are often closely associated with strong geomagnetic storms when hot plasma and energetic electrons are injected into near-Earth regions;

– Drag caused by the upper layers of the Earth's atmosphere - Since the upper atmosphere responds to changes in solar radiations and particle inputs, the drag effects observed on satellites are often strongly affected by space weather. Sudden increases in drag can cause premature orbital decay or attitude de-stabilization. Tracking of orbiting objects can also be disrupted during such episodes;

– Interference with electromagnetic signals - The ionosphere responds strongly to changes in solar inputs, geomagnetic storms, and charged particle precipitation. Ionospheric variations can include changes to electron density and therefore to the "total electron content" encountered by a signal, and sources of ionospheric "noise" such as scintillation. As a consequence, space weather seriously disrupts ground-to-ground communications channels that employ the ionosphere, degrades space-based communications, and can cause errors and outages in navigation systems.

During the development of spacecraft, the expected environmental effects are carefully considered. The development process includes definition of the environment, analyses of possible problems caused, and implementation of appropriate measures to avoid or cope with effects. Analyses make use of information on the environment in the form of models and tools that have developed over the years to cope with an evolving set of problems.

## 3. TRENDS AND FUTURE ISSUES

Future ESA and European space missions will continue across a broad range of domains:

– Science missions in space, using space as a vantage point for astrophysics missions, for solar-terrestrial investigations, for exploration of the solar system and as a place to perform fundamental physics experiments;

– Space applications development programmes such as Earth observation programmes, communications technology development, development of programmes for Global Monitoring for Environment and Security (GMES), and development of navigation systems;

– Commercial space activities, built on the technology and applications development programmes mentioned above, notably including communications, meteorology and navigation systems,

- Manned missions to ISS and beyond, particularly missions to the Moon and Mars;
- Launcher developments.

### 3.1 Science Programmes

While European science activities will continue in near-earth orbit, there is a trend towards putting astrophysics missions at the L2 Lagrange point for launch, thermal, space environment and communications reasons. Here, the plasma environment is relatively mild, characterised by the deep geomagnetic tail and there are no radiation belt populations. The radiation environment becomes dominated by sporadic solar energetic particle events, in addition to background cosmic rays.

Solar-terrestrial and solar-heliospheric missions are also planned away from the immediate vicinity of Earth, for example the Solar Orbiter mission will approach the Sun to within 21 solar radii. Planetary missions are a strong feature of the future programme, requiring consideration of non-terrestrial atmospheres, magnetospheres and other environments. The BepiColombo mission to Mercury, as with Solar Orbiter, will have to cope with an environment potentially quite different from the near-Earth interplanetary environment. Fundamental physics missions (tests of relativity and detection of gravitational waves for example) also favour locations in deep space although precursor missions could take place close to the Earth.

## 3.2 Navigation

The principal challenge for Europe in this area is the Galileo programme and the development and maintenance of its constellation of "Galileosat" satellites. Their radiation and plasma environments will be particularly severe, and service quality issues related to interference with propagation of signals through the ionosphere are also an important factor for the system. Clearly, in an eventual commercial environment, there will be a drive to minimise the procurement costs and spacecraft mass.

## 3.3 Commercial Satellites

The main market for commercial satellites at present is in communications and broadcasting. Here again, procurement costs and spacecraft mass issues are important, as are minimisation of operations effort and long-term reliability. The trends in this sector include more on-board processing and extensive use of commercial off-the-shelf components (COTS). These are usually considerably less radiation hardened or poorly characterised compared to “traditional” parts and have a greater degree of on-chip complexity.

## 3.4 Earth Observation Missions

The trend here is towards smaller, lower cost individual missions with a high level of on-board processing or storage. Stability requirements are increasing and the use of electric propulsion, advanced attitude sensing and sensitive payloads lead to increasing environmental susceptibility.

## 3.5 Manned Missions

Radiation effects are mission-limiting in view of their potentially lethal effects. In the near-term, the international space station will be the main concern. But in the more distant future, returns to the Moon and missions to Mars are expected. ESA’s Aurora programme is intended to prepare for such exploration missions, and the programme includes the necessary preliminary studies and technology activities. While radiation issues can be expected to have a high profile in this programme, other environmental components are also important. Meteoroids and space debris are potentially catastrophic for manned missions, and planetary missions also need good understanding of planetary atmospheres for aero-manoeuvring, entry, decent and landing.

## 3.6 Platform and Generic Trends

On-board complexity is increasing and advanced platform concepts are being pursued to reduce mass and power, and increase performance. Some technology trends lead to increasing environmental susceptibility, such as: platform wireless and fibre interconnectivity, widespread use of application specific integrated circuits (ASICs), increasing on-chip complexity of components, star-tracker based attitude control systems, electric propulsion, and solar cell technology advances. The rate of change of technology is a problem. Components are quickly introduced, replaced and retired. There is a general acceptance that space mission developments are hampered by the inability to reduce launch costs. As a consequence, there are trends towards smaller, lighter weight spacecraft to get more performance per kilogram.

# 4. IMPLICATIONS FOR SPACE WEATHER RESEARCH

A significant part of future scientific and technological research on space weather should aim to support the abilities of industries and agencies to execute ambitious programmes. There is a general need to improve “analysis tools” to allow quantitative evaluations of the effects in the various environmental domains. Models of the environment, based on in-flight measurements and on physical principles are needed, along with models of the effects of the environment based on ground-based testing. The links between environmental assessments and testing and ground-based assessments are important and need strengthening. Rigorous methodologies combining testing with application of quantitative assessment tools are needed. An example of what is meant here is the way in which ground-based accelerator testing of electronic components’ susceptibility to single event upset is combined with models of the environment and the single-event upset (SEU) process in sensitive chip geometries. It is also believed that the need for in-orbit experimentation is increasing. This allows testing in environments that cannot be simulated numerically or experimentally on the ground, the proper validation of methodologies and analysis tools, and the gathering of data on environments and effects. In this section the trends in effects of various parts of space weather are outlined taking into account the mission trends presented in Section 3. The research and development directions are indicated in each area. A summary of these space weather components is given in Table 1, along with the main effects of each of them.

## 4.1 Radiation Environments and Effects

For future space missions, improved models of the radiation environment are needed for each of the environmental sources. Because of the trends in the science programme in particular, better treatment of solar energetic particles is needed, including their time-behaviour and their variation with location in the heliosphere. Closer to Earth, this needs to be accompanied by improved treatment of the modification of solar event and cosmic ray fluxes by the Earth's magnetic field known as geomagnetic shielding. Given the growing importance of applications programmes that have spacecraft located in the radiation belts, better modelling of the energetic electron environment for medium-altitude orbits is needed.

*Table 1.* The various space weather environments and their effects

| Environment | Effects |
|---|---|
| High Energy Radiation: | |
| Cosmic Rays | Upsets in electronics;<br>Long-term hazards to crew;<br>Interference with sensors; |
| Solar Energetic Particle Events | Radiation damage of various kinds;<br>Upsets in electronics;<br>Serious prompt hazards to crew;<br>Massive interference with sensors; |
| Radiation Belts | Radiation damage of various kinds;<br>Upsets in space electronics;<br>Hazards to astronauts;<br>Considerable interference with sensors;<br>Electrostatic charging and discharges |
| Near-Earth Plasma Populations: | |
| Geomagnetic (sub-) storms | Electrostatic charging and discharges; |
| Ionospheric Effects | Communications disruption;<br>Navigation services disruption |
| Others: | |
| Atmosphere | Increased drag on spacecraft and debris;<br>Attitude perturbation |
| Meteoroids | Spacecraft damage |

Many of the future requirements for environmental data, and assessments of effects arising, are not met by traditional approaches of synthesising space environment data into models. This inevitably involves some averaging or establishment of worst-cases. Data-based analyses are preferable, holding data in a form including time and location information. Then, better statistical information concerning effects end-points such as background, single-event effects and charging effects, which are time-dependent effects, can be derived (Stamper and Hapgood, 2001). Physics-based models, for example of the radiation belts (Boscher et al., 2001), have the ability to provide more extensive information on the environment and in many ways are analogous to satellite data. They can therefore be used to augment such data-driven models.

The following sub-sections highlight some specific issues and requirements.

### 4.1.1 Solar Particle Environments and Effects Models

The future Science programmes outlined in section 3 require the use of models of the solar particle environment and appropriate models of consequent effects. In addition, the Aurora exploration programme has similar requirements. Current statistical models of solar particle radiation focus on provision of long-term radiation damage estimates. New requirements include the assessment of the temporal behaviours (durations, peaks, thresholded durations, spectral variations) and sounder treatment of heavy ions in solar particle events. The data-based analysis techniques mentioned in the previous section are applicable to such problems. In addition, the variations of the solar energetic particle environment with position in the heliosphere need to be known for unmanned missions to the inner (<1AU) heliosphere and for manned missions beyond the near-Earth environment. However, the most extensive data sets on solar energetic particles are from spacecraft close to the Earth. Helio-radial variations are therefore very difficult to derive without recourse to models of solar energetic particle acceleration and propagation (Aran et al., 2001), since a significant proportion of the energetic particles are produced in interplanetary shocks. As a result, their variations in space are far more complex than represented by simple engineering rules, such as the commonly used $1/r^2$ scaling (r being the helio-radial location). Finally, the high radiation levels possible necessitate better quality assessment of radiation shielding and radiation effects, whether for automated missions to the inner heliosphere or for manned missions to the Moon, Mars and Lagrange points.

### 4.1.2 Radiation Effects on Components, Detectors, Solar Arrays and Materials

Severe problems are being encountered in the development of radiation hardened technologies for space. With some export restrictions on US products and the reducing production facilities for rad-hard technologies due to lack of commercial viability, hardened components are becoming increasingly difficult to procure, particularly in the higher performance components needed by users. Together with the increasing radiation sensitivity of payloads on scientific spacecraft, this leads to a requirement to improve assessment methodologies to enable "softer" technologies to be employed. Improvements are needed in tools for predicting the environment, in testing methods and in the gathering of key space environmental and in-orbit technology performance data.

Single event effects in electronics appear to be a growing problem (Harboe-Sørensen, 2002). Modern components are increasingly complex. Memories for example now include control logic that can be susceptible to upsets, "locking" the component, or to destructive latch-up. Manufacturing processes vary considerably making it difficult to ensure that a flight component is from the same manufacturing batch as a tested component. The complexity of modern electronics makes quantitative assessment difficult. For example, in the past one was able to assume that all the sensitive parts of “bits” on a chip where well approximated by identical rectangular parallelepipeds. This considerably simplified the prediction of single event upset rate since a component could be characterised by a single “path-length distribution”. Modern electronics, including memory devices, have many different logical elements on the chip and these are often not parallelepipeds. In such a situation, many of the assumptions made in the prediction break down. Furthermore, many of the assumptions made in interpreting accelerator test data also break down. Tilting a component with respect to the accelerator ion beam is a common way of trying to mimic ions that produce greater ionisation, but this is only true for flat two-dimensional structures. There has recently been a growth in problems related to “analog SEU”, the single event transient (SET), which is also a complex problem to deal with. This is where an ion strike on linear circuits such as comparators, operational amplifiers or analog-digital converters can result in a transient pulse of variable magnitude on the output. Generally the seriousness of the SET depends on where in the linear circuit the ion strikes, on the settings of the circuit, on the filtering of the signal and on the way in which the signal is used. For example it may be “latched” to indicate a warning condition – with subsequent effects on the spacecraft.

As a result, assessments of single event effects require improved methods for predicting charge generation in complex modern component circuit geometries, and improved testing methods, which allow correlations to be made. In-space data on the behaviour of new component technologies is also very important.

Radiation background in detectors is a related phenomenon, but is often much more complex to analyse because the specific sensitivity of a payload system depends on its application, what background event rates can be coped with and whether there are specific energy (or energy-deposit) threshold in play. Often background can be rejected by software, but such solutions depend on a clear difference in nature of the background events, and good knowledge of them. Analysis depends increasingly on application of Monte-Carlo simulation of the passage of the radiation through the spacecraft and detector and of the interaction with detector elements. Such techniques may also be necessary for electronic effects. An important toolkit for these applications is Geant4, developed and supported by a world-wide collaboration including ESA (Agostinelli et al., 2003). In applying such tools, it is often important to have good environmental input, and methods that synthesize the required input spectra directly from databases of flight measurements are best.

Solar cell assessment methods have been based in the past on a “damage-equivalence” methodology where extensive testing of cell types was used to derive the behaviour in space. With more complex cell types, a more general approach, utilising direct calculation of the non-ionising dose in the cell materials, and an assessment of cell structure, is necessary. Materials, including optical components, are also become complex and in need of special attention.

### 4.1.3 Radiation Effects to Crew

For assessment of effects in the future ISS exploitation phase and for missions beyond low Earth orbit, the astronaut *dose equivalent* has to be evaluated. This evaluation relies on data on biological effects of radiation, and international standards defining the biological effectiveness continue to evolve as knowledge improves.

For the environmental part of the problem, particular importance is attached to solar energetic particle events, which are by their nature difficult to predict. Apart from statistical models of the near-Earth environment based on long-term records of solar particle event fluxes, the variability of event characteristics with location in interplanetary space mentioned above has to be dealt with. For real-time protection, means of predicting event occurrence and magnitude based on solar precursors have to be established. Also important is the prediction of shielding effects and consequent secondary radiation production. Finally, equipment for monitoring crew, habitat, and ambient environments are needed.

### 4.1.4 In-flight Measurements

Continued and improving monitoring of the environment is obviously important for improving knowledge of the environment, but also for providing the resources to respond to emerging requirements and for use in new analysis methods. ESA has successfully promoted the idea of having standard radiation environment monitors (SREMs) on as many missions as possible. These both contribute to the general body of data and provide mission-specific data, which can be used in real-time for protection, or later for evaluation of spacecraft or instrument behaviour. At the time of writing, SREMs are flying on PROBA and INTEGRAL, providing high-quality data (Mohammadzadeh et al., 2003), and the future missions carrying SREMs include Rosetta, Galileo-GSTB-V2, Herschel and Planck. A demonstration version of a scintillator-based miniature radiation monitor is also flying on PROBA. Manned missions have important requirements for monitoring and this may include a tissue equivalent proportional counter (TEPC).

There are a number of other European radiation instruments either ready or under development, and coordination of efforts both within Europe and beyond needs to be established. It is important that proper attention is given to data merging and quality issues. Experience has shown that different detectors can give very different results making them difficult to use. In addition, detectors often have data gaps or saturate during extreme environments. Such behaviour is often acceptable for science missions but for "applications", it is not. In addition, any detector for applications has to have open development information, with full simulation and calibration history. The International Standards Organization working group on space environment standards has recently highlighted such requirements (Heynderickx, 2003).

## 4.2 Plasma Environments and Effects

Plasma-induced hazards continue to be a concern (Harris, 2001). While the engineering of spacecraft needs to take account of surface charging and the related material properties and electrical bonding issues (Purvis et al., 1984), design of science missions often requires careful treatment of the electrostatic fields of a spacecraft. The effects of solar array voltages and electric propulsion can cause further complications. Ground testing of system-plasma interactions is virtually impossible so there is a heavy reliance on numerical plasma simulation. Tools exist, such as NASCAP (the NASA Charging Analysis Program, Katz et al., 1979), to predict the electrostatic surface charging of a satellite, but improved tools that can handle finer geometrical details and details of the time behaviour, such as those arising from space weather environmental changes, are needed. A collaboration has recently been established by ESA to go a large way to developing the tools necessary to perform such analyses (Roussel, 2003).

Improved understanding of the environment and its time and spatial variations – rather than crude worst-case specifications – is also needed. Related to this is the need for *operations* support. If satellite-specific forecasting of severe environmental conditions can be made available at a high level of reliability, safeing of system, avoidance of hazardous operations and general operator vigilance can improve the resistance of systems to charging-related anomalies.

As with radiation, there is a clear need to validate any methods or results obtained through numerical or ground experiment simulation in real space conditions. In addition, characterisation of the ambient environment around a spacecraft is required both for gathering data for future missions but also for aiding interpretation of spacecraft behaviour (e.g. anomalies, unexpected behaviour).

## 4.3 Atmosphere

Improvement of models of the Earth's upper atmosphere and its response to space weather drivers is a subject well covered and coordinated by international actions such as the COSPAR International Reference Atmosphere (Rees, 1986). The importance of drag effects has led to considerable effort being deployed in this area.

Because of the increasing number of planetary missions, models of planetary atmospheres also have to be developed to support design of aero-manoeuvring, entry, decent, landing and operations. Planetary global circulation models and climatic databases are being developed and will continue to be improved. In the case of Mars, dust storms are also an important part of that planet's "weather".

## 4.4 Ionosphere

Communications and navigation systems in orbit need to take account of ionospheric disruption to their signals. The developing European navigation programmes in particular – including the Galileosat constellation – are paying careful attention to the inclusion of ionospheric corrections in system designs and account is being taken of potential service degradation. As a result of the effects, considerable effort is being devoted to understanding and anticipating ionospheric effects, much of it sponsored by the military sector because of its strategic importance. Within Europe, the European Union sponsored "Cooperation on Science and Technology" (COST) action 271 on "Effects of the Upper Atmosphere on Terrestrial and Earth-Space Communications" (Zolesi and Cander, 2002) provides an important focus for research.

### 4.4.1 Microparticle Environments and Effects

While not normally considered part of space weather, microparticles (micrometeoroids and small-sized space debris) are nevertheless an important environmental hazard to spacecraft and crew, are variable and are affected by other space weather phenomena such as atmospheric density variations. However, apart from details of the populations and their fluxes, prediction of effects requires knowledge of the way penetration of spacecraft surfaces depends on particle properties – so-called damage equations. These are constantly in need of improvement. As far as knowledge of the environment is concerned, better in-orbit data, including analyses of retuned surfaces are needed (Drolshagen, 2001). Apart from the obvious hazard to manned missions through penetration of crew modules or space suits, many elements of spacecraft and payloads are sensitive, including pressurise fuel and other tanks, solar arrays, and instrument baffles. One interesting issue recently discovered relates to X-ray astrophysics experiments, where the open nature of grazing incidence X-ray optics can allow propagation of microparticle fragments to the focal plane (Struder, 2001). This issue will be important to consider for future X-ray mission such as XEUS. Impact penetration of light shades and other important enclosures of scientific payloads also have to be carefully assessed. For this good flux models and risk analysis tools are needed, sometimes augmented by dedicated impact testing.

Analyses of surfaces returned from space are very important, as exemplified by the analyses of Hubble solar arrays. Return of structural elements from space is likely to decrease in the future as Shuttle missions become space station oriented and the Shuttle is replaced by a vehicle without return capabilities. Therefore in the longer term, it will be necessary to ensure that surfaces can be returned from space for analysis or that analyses of space hardware impact effects are performed in-situ.

### 4.4.2 Microsatellites and Facilities for In-Orbit Experimentation

Lack of rapid, frequent and cheap access to space for technology experiments is a serious impediment to technology progress, both for assessing space environmental effects on systems, and in other areas. Microsatellites and nanosatellites offer relatively low-cost access to space for technology flight experiments and are often ideal for experiments related to environmental effects and as platforms for monitoring the environment in important regimes. This has been recognised by those establishing the Living with a Star programme in the US, and while the programme has been broadened to become the International Living with a Star programme, the testbed elements are still essentially a US initiative. Expansion of activities of this type is needed. Cheap and frequent access to space would allow in-flight testing of components, emerging technologies, materials, solar cells, etc. It would allow the environment mitigation methodologies employed on the ground – usually combinations of model application and testing to simulate the environment – to be validated and improved.

## 4.5 Space Weather

What has been described so far has been a perspective of requirements in each of the space weather sub-domains or relevant technology domains. The space weather paradigm stresses the treatment of the solar-terrestrial system in a unified fashion. From the point of view of space weather *applications*, a space weather service would ideally make use of a dedicated network of ground-based and space-based observations of solar-terrestrial conditions and, together with mature models, be able to make predictions or interpretations of the environmental conditions. Crucially, space weather applications services include the integration functions and major information technology elements such as data systems and communications. In this context, integrated space weather resources are highly valuable for application to space systems design and operation, as well as for other users.

### 4.5.1 Space Based Measurements

Studies performed in the past (Glover et al, 2003) have provided a detailed analysis of the parameters that need to be measured, the characteristics of these measurements (parameter ranges, accuracy, acceptable delay, etc.) and the locations where they should be made. Key requirements are:

- Monitoring of the solar surface to identify flares and mass ejection events and to establish inner boundary of interplanetary environment models;
- Monitor the solar wind plasma conditions as a warning for Earth-directed hazardous events;
- Monitor the environment close to the earth in various orbits to establish the plasma and energetic particle environments.

Further in the future, as the scientific understanding of processes close to the solar surface advances, it may be possible to identify important solar features before they give rise to flares or coronal mass ejections.

### 4.5.2 Ground Based Measurements

Ground based measurements are inexpensive compared to space and should be exploited wherever possible. Valuable ground-based measurements include:

- Geomagnetometry networks;
- Visible and Lyman-alpha solar imaging;
- Solar Magnetography;
- Cosmic Ray Neutron monitoring.

Emerging measurement techniques include:

- Muon telescope observations of cosmic ray modulation;

- Interplanetary scintillation observation of coronal mass ejections;
- High altitude and balloon-based solar observations.

These need to be exploited and monitoring facilities installed where gaps exist in global coverage, particularly in the European sector. For example, the extensive ground based monitoring network of the former Soviet Union is degrading and needs to be replaced in some way. Dedicated small-size solar telescopes (E.g. Lyman–alpha) are lacking in Europe.

### 4.5.3 Space Weather Economics

While the economic impact of "spectacular" space weather induced problems, such as the loss of a complete satellite or the collapse of a regional power grid, is easy to gauge, identifying the economic impact of non-spectacular space weather events is difficult. If a purely economic rationale is attempted, the costs of establishing a space weather service need to be weighed against the financial benefits that the products can bring. In particular one needs to address the question of whether having better data, predictions and tools for space weather can allow measures to be taken other that those taken at present which are generally characterised by "design for the worst case". In space systems this can, for example, translate into additional mass to protect systems and this has knock-on effects on cost. It is probably not possible to perform such cost-benefit analyses in all user domains while the user communities are still becoming educated to space weather hazards and what can be done about them. Another problem is that much of the data on the cost impacts of space weather effects are commercially confidential. It has also to be recognised that many of the benefits of an application-oriented space weather service are unquantifiable and relate to strategic advantages or the well being of citizens.

The strategy being perused by ESA is to initiate "pilot" service provision projects across the many user domains, and subsequently to investigate their values and costs (Glover et al, 2003). This type of activity, and benefits analyses in general, will continue to be necessary to justify any large-scale system developments. Nevertheless, in the space-effects field there is a clear appreciation of the need to continue to develop space weather resources for future missions.

## 5. CONCLUSIONS

Space missions are becoming more susceptible to space weather hazards and while on the one hand this necessitates work to understand more fully the phenomena, it is important that efforts are also made to establish the capability to link in a quantitative way the environment with the resulting effects. This more engineering-oriented aspect is somewhat underplayed in much discussion of space weather. Nevertheless, those aspects are becoming increasingly difficult as the technologies affected and the effects "pathways" become more complex.

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