ESA Space Weather Programme Study
Alcatel Consortium

Benefits of a Space Weather Programme

WP1100

Richard B. Horne

British Antarctic Survey
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ESA Officer: A. Hilgers ESTEC

R. B. Horne
British Antarctic Survey
Natural Environment Research Council
Madingley Road
Cambridge, CB3 0ET
U.K.
Email r.horne@bas.ac.uk

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Executive Summary

The purpose of this document is to identify the benefits of an ESA Space Weather (SW) Programme. Analysis of potential markets in terms of economic benefits and business development is covered in a separate workpackage and is not presented here.

In this workpackage we identified several market sectors that are directly affected by space weather, including satellite manufacture and design, satellite operators, space Agencies (man in space), launch operators, civil aviation, power generation and supply, prospecting for minerals oil and gas, oil and gas pipeline distribution, space insurance, railways, tourism, and defence. We identified more than 75 contacts, and obtained a response from more than 32 by personal interview, telephone and email. We obtained a response from more than 2 contacts in each market sector and covering Europe, Canada and the USA.

At present there are over 600 satellites in-orbit valued at between US$50-100B. Over the next ten years the Teal Group forecast more than 900 launches (400 commercial) carrying 1400 satellites (900 commercial) valued at over $220B. Every spacecraft is and will be subject to damage from space weather effects in a variety of different ways. Over the last four years SW has been suggested as a cause or contributor to more than $500M of satellite insurance claims. Since the total satellite communications market is expected to grow from $20B to $100B over the next 10 years, the true impact to society will grow considerably. Similarly, the UK National Grid calculate that the annualized cost of unsupplied energy due to space weather at $ 450 M/year. As we depend more and more on technological systems the major benefit of an ESA SW programme is to protect our investment in space and on the ground.

Although the Space Environment Centre (SEC) at NOAA provides space weather predictions now, free of charge, all the companies we spoke to would support a European SW programme since this would provide additional and alternative sources of data and interpretation, and lead to improved prediction reliability and improved models. The elements required for an ESA programme include data collection from critical regions, a warning, prediction, and nowcast capability, and the provision of data for post-event analysis.

The impact of space weather on commercial companies is not yet fully recognized. For example, the NOAA database contains more than 5000 satellite anomalies reported by 259 spacecraft, but the cause of more than half of these anomalies is stated as unknown. Commercial operators, designers and insurance companies would benefit from an ESA SW programme since it would help them identify whether SW is the cause. Commercial companies would benefit in other ways as well, through improved satellite design, preparedness and efficiency in satellite operations, reduced radiation exposure for astronauts and aviation aircrew, improved reliability for power generation and supply utilities, better risk evaluation and mitigation for insurance and the development of new business markets. More examples are summarised in Table 2.

An ESA SW programme would have strategic benefits for Europe. It would provide European infrastructure and opportunities for commercial spin-off companies. There are already examples where small companies and research Institutes have contracts for SW prediction and data analysis with large commercial companies. There are opportunities for European autonomy, through collection and provision of data, leadership, through new methods of reliable forecasting and analysis, collaboration within Europe, through dedicated teams to solve critical problems, and collaboration external to Europe (including ESA member states such as Canada), through satellite missions, exchange of data and research. More examples are summarised in Table 3.

European defence would benefit from a civilian programme through the collection of additional data, new models and interpretation, and through the free exchange of data from the scientific community around the world that may not be directly available for defence otherwise. Defence would also be able to draw on advances in civilian research. While commercial companies are driven by profit and loss, Defence is driven by different considerations, they must identify the cause of failure and whether or not it is a hostile act as quickly as possible.

An ESA SW programme would stimulate basic research in solar terrestrial physics, plasma physics, atmospheric physics, and solid earth geophysics. It would lead to greater focus on scientific problems that need to be understood in order to improve models and provide a more reliable SW capability. Basic research would feed back benefits into space weather. It would also stimulate more applied research to identify cause and effect, and to develop better empirical, physical and artificial intelligence models for prediction of events.

A space weather programme that includes data collection, event prediction, post-event analysis and scientific interpretation, together with a clear aim to protect our European space investment is more likely to gain public support than a pure science mission, and hence public support for ESA. The public could understand the need to carry out basic research into the sun, interplanetary medium, magnetosphere, ionosphere and atmosphere in order to protect technological systems such as telecommunications, and domestic power supplies that affect their daily lives. It also offers the opportunity for high profile publicity of European science and technology across the world through the issue of SW warnings and predictions, provided they are reliable. Finally, the glamour of space science is one of the reasons students are attracted to take up physics based subjects. An ESA programme with a strong publicity element would attract more students to space science and provide a pool of highly trained labour with benefits for the commercial space sector.

We are now close to maximum of the solar cycle (2000). Missions such as SOHO and CLUSTER have raised public awareness of SW. Recent events such as the 14th July 2000 solar proton event have raised the importance with commercial companies. The time is ripe to build on these achievements to develop an ESA SW capability.

1 Introduction

1.1 Purpose of this Document

The purpose of this document is to identify the benefits of an ESA Space Weather Programme, mainly from a scientific point of view. Analysis of potential markets in terms of economic benefits and business development is covered in a separate workpackage (WP1200) and will not be presented here.

Here we identify different market sectors and how they are adversely affected by space weather events. We provide information on the driving forces within each market sector and why space weather is becoming more important for their operations. We present some of the problems related to space weather that these market sectors encounter now, and how they might benefit from a space weather programme. We consider the case for warnings and predictions, and post event analysis according to the perceived needs of each market sector.

1.2 Definition of Space Weather

We define Space Weather as

"Conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life and health".

Within this definition we include the effects of galactic cosmic rays that originate from outside our solar system, space debris, and dust, since they also affect technological systems, and endanger human life and health, because their flux is modulated by solar processes.

1.3 Method of Approach

The method we have adopted in this work is a bottom-up user approach. By identifying user needs and assessing their requirements we will provide a more realistic view of the benefits of a space weather programme. A top down approach is also being conducted by other workpackages. Within the framework of the whole study, merging of the bottom up and top down requirements should capture the most important elements for a Space Weather Programme that has real benefits for the users.

The first step in the bottom up approach is to identify the users. In some cases this is fairly well defined since some companies are already using space weather prediction services, for example, power distribution networks, and oil and gas pipeline networks. In other cases, markets can be identified, such as Insurance, but may have very little appreciation of space weather and how it impacts their operations. These areas are discussed in more detail below.

The market sectors we identified for this study were split into two categories, space and non-space. They are given in Table 1. It should be noted that scientific research and education are treated differently to the other markets in this report since they are unlikely to form a commercial market that will pay for SW services. In addition, research is required in order to develop an effective space weather capability, and in return, would benefit from a space weather programme. Similarly, education is both a requirement for an effective space weather capability, and a benefit. These topics are included under strategic benefits later.

Space	**Non-space**
Commercial Satellite Design	Civil Aviation
Satellite Operators including: • Communications • Broadcasting • Navigation • Remote sensing • Science	Power Generation and Supply
Space Agencies including: • Man in space	Prospecting for Minerals, Oil and Gas
Launch Operators	Oil and Gas Pipeline Distribution
European Defence	Space Insurance
	Railways
	Tourism
	Scientific Research and Education

Table 1.

In order to obtain information for this study we decided to take a pro-active approach. Within the consortium we identified potential users of a space weather programme, experts in the field who already have contracts to provide space weather services, and expert scientists with detailed knowledge of the effects of space weather gained through years of professional research. These users and experts were drawn from across Europe, in particular the UK, France, Germany, and Sweden, but also included experts and companies from Canada and the USA. We took the view that space weather is a global issue and therefore valuable information could be obtained from the experience in other countries outside Europe. This proved to be particularly important in the case of the USA which has a far better developed Space Weather programme than Europe, but where important lessons can be learned. More than 75 contacts were identified in different areas, and we were able to obtain a response from 33, as listed in Appendix 1. This is a very good response compared with previous studies (e.g., 9 out of 32 response for the study by Koskinen and Pulkkinen, 1998). The response is representative of all the different areas, and covers all the above mentioned countries in Europe, and includes Canada and the USA.

Information for this study was obtained in four ways. First by a series of personal interviews with experts in the field, and users who have first hand knowledge and experience of problems associated with space weather. This yielded a very valuable source of in-depth information, but had the disadvantage of being very time consuming. Second, by a series of telephone interviews with users. In some cases users were very happy to answer questions over the telephone, but, in other cases, users would only reply in writing after having received a copy of our Aide Memoire. This often resulted in long delays but had the advantage of providing accurate information. Third, members of the team attended the NATO Advanced Study Institute on Space Storms and Space Weather Hazards in June 2000, which provided a valuable source of information from both experts and users alike. Fourth, this pro-active effort was complemented by reviews of existing literature and web information.

To carry out the interviews an Aide Memoire was developed by research scientists at BAS and market research professionals at the Company ESYS. A copy of the Aide Memoire is included as Appendix 2. It was designed to capture information on the Company, their existing knowledge about Space Weather, prediction requirements, post event analysis, existing uses of space weather services, the impact and risk on their business, the maturity of the industry and the drivers for a space weather programme. The Aide Memoire also includes a table of the different problems caused by space weather by market sector, and the possible benefits of a space weather programme as a prompt and guide for users to refer to. In some cases where users did not have much appreciation of the effects of space weather this table proved to be very helpful in both educating and making people more aware of potential problems.

The information presented here is based on the results of the interviews with consultants and companies across Europe and the USA. We acknowledge their help in contributing to this report, and list their names in Appendix 1. Furthermore, we respect some strongly held views in some areas and have refrained from quoting anybody verbatim. Any errors of fact in this report are not attributable to them.

2 Growth in the Number of in-orbit Satellites

There has been significant growth in the number of satellites in orbit over the last ten years. For example, between 1990 and 1999, there were 125 to 300 satellites launched per year, and between 25 to 45 satellites launched per year into geostationary orbit [source, J. Mc Dowell table of launches, 2000]. This growth has arisen from the growth of several markets. As an example, consider the growth in telecommunications. The growth is driven by several opportunities including

Growth in international trade
Opportunities for new services, such as internet, and mobile phones
Deregulation of overseas markets

There are other contributory factors which make satellite systems desirable, for example satellites require little infrastructure or public works, and can broadcast across national boundaries. However, there is increased competition. For example, now that defence orders have declined, there are several defence companies, such as Loral, Motorola, and Lockheed Martin, that are looking for opportunities in the civil sector. Limited resources such as the number of geostationary orbit slots and frequency allocations are driving competition and the need to use valuable resources more efficiently and hence the need to introduce new technology.

The present trend in telecommunications is to provide services to individual users, for example, mobile communications, broadcasting and interactive media. The total annual market is expected to grow from about $20B to about $100B over the next 10 years [UK House of Commons Select Committee Report, 2000]. This has been made possible by new technology including high power availability on satellites (> 10 kW) that enable more transponders, and digital signal compression techniques that allow 10 TV channels to be transmitted by 1 transponder. Other examples include cellular voice transmissions to mobile users. Proposed systems include Iridium, (66 satellites, but now subject to receivers), Globalstar (48 satellites), ICO-Global (10 satellites), Ellipso (17 satellites) and Aires (46 satellites) in mainly low Earth orbit.

There is now growth in multi-media satellite systems. Proposal that have been granted licenses to operate at Ka band (20-30 GHz) include Teledesic (288 satellites) mainly at low and medium Earth orbit, and Astrolink (9), Cyberstar (3), Galaxy (20), GEstar (9), and Morning Star (4) at geostationary orbit. Another multi-media system at Ku-band is proposed by Skybridge LP.

The cost of a new telecommunications satellite is about $150M to construct, plus $100M to launch, plus insurance (based on the contract between Alcatel and GE American Communications Inc. to construct 7 telecommunications satellites, Space News, 24 July, 2000). Therefore even one new telecommunications spacecraft represents an enormous level of investment for one company. However, world-wide it is estimated that there are more than 600 satellites in-orbit (250 operating at geostationary orbit) valued at between

US$50-100 Billion. Only 254 satellites are insured with a total insured value of approximately $21B. Over the next 10 years, the Teal Group forecast of space activity (as of January, 2000) forecast 900 launches (400 commercial) carrying 1400 satellites (900 commercial) valued at $220 billion ($80 billion commercial). Thus the existing and projected level of space investment world-wide is huge. For the year 2000, Europe won more orders (16) than the US (13) to construct communications satellites for geostationary orbit [Space News, January, 2001] indicating that Europe has a significant share of the market.

All these spacecraft are subject to anomalies and interruptions to service caused by space weather events, as discussed below.

Since our society is becoming more and more reliant on satellite systems, and interacts on a global scale, one of the primary benefits of a European space weather programme is to protect our space investment.

3 Effects of Charged Particles on Satellite Systems

Satellites in-orbit are affected in several ways by the radiation environment, resulting in anomalies. Here we identify the major effects and their consequences.

3.1 Surface Charging

Due to their material properties, surfaces that are electrically insulated from each other can charge to different potentials due to photoelectron emission and the energy spectrum of the surrounding plasma. Potential differences of up to 20 kV have been recorded. Large potential differences between different components on the surface of the satellite can result in an electrostatic discharge (ESD). An ESD may damage components directly, (e.g., solar cells) and send electrical pulses along cables causing phantom commands, and damaging other electronic circuits.

Electrons and ions from thermal energies up to 100 keV or so are particularly important for surface charging. So too are plasma boundary crossings and changes in solar illumination during the passage across eclipse.

ESD is a clear example where knowledge of the spacecraft environment, and analysis of satellite anomalies, has been fed back to improve the design of new spacecraft. For example, some designers now cover the spacecraft surface with conducting material and use conducting glass to protect solar cells to avoid large potential differences. However, in some cases the cost is too high and these measures are not included as a fundamental rule of design. Surface ESD still remains a problem, for example, ESDs are still recorded in the post midnight early morning local time sector at geostationary orbit [Gubby and Evans, 1999; Wrenn and Sims, 1996], and in the high latitude auroral zones during substorms and magnetic storms [Wahlund et al., 1999]. Furthermore, meteroid impacts puncture the conducting surface material and increase the risk of ESD.

3.2 Internal Charging (Deep Dielectric Charging)

Energetic electrons at energies of a few MeV (also known as ‘killer’ electrons) can penetrate through the outer conducting surface and thermal insulation of spacecraft and deposit charge in insulators (e.g., cables) and circuit boards. The important energy range is from 100 keV to several MeV. Typically a 2 MeV electron can penetrate 5 mm of Aluminium. If the flux of these particles is sufficiently high, as it is in the radiation belts and during magnetic storms, such that the charge accumulates faster than it can leak away then this can result in a break down in the insulation resulting in an electrostatic discharge. On 20 Jan, 1994, ANIK E1 and E2 (communications satellites) both suffered momentum wheel failures and loss of service due to internal (deep dielectric) charging [Wrenn, 1995]. Anik E1 was brought under control after 8 hours, Anik E2 was returned to useful service 7 months later after engineers devised a control system using multiple firings of the satellite thrusters. More than 20 satellites are known to have suffered ESD arising from internal charging [Wrenn, and Smith, 1996].

Deep dielectric charging is difficult to engineer a solution. One can bury the cables and sensitive electronic circuits inside the spacecraft, but to protect with extra shielding poses important weight restrictions and has cost implications.

During our study, four out of five satellite designers stated that internal charging is one of the most important design problems to overcome.

3.3 Degradation of Components

Radiation damage due to energetic electrons, protons, and heavy ions has cumulative effects that build up over the lifetime of the spacecraft and lead to gradual degradation of performance and eventually to systems failures. For example, radiation damage may result in lattice defects and displacement damage in materials that cause swelling of mirror surfaces, darkening of glassy surfaces, damage to thermal control coatings, reduced solar cell efficiency resulting in reduced power, and damage electronic components resulting in increased noise and eventual systems failure. Radiation damage depends on the orbit and lifetime of the spacecraft.

Cumulative effects are one of the most important factors limiting the lifetime of a spacecraft. Designers use models of the radiation environment to calculate the total radiation dose for the particular orbit of the spacecraft (i.e., the total electron flux integrated along the orbit for the lifetime of the satellite) so that they can then decide how much shielding to use and the radiation hardness of the components. Even so, it is not possible to shield components for all radiation effects since this would impose very severe weight restrictions. Secondly, radiation hardened components are very expensive.

During the course of this study two out of five satellite designers stated that accurate estimates of the total dose for the lifetime of the spacecraft are the second most important problem they have to overcome.

3.4 Single Event Effects (SEE)

Miniaturization and the introduction of very large-scale integrated (VLSI) circuits have now reduced the size of electronic components so much that they can be damaged by the passage of a single charged particle. As more and more systems are included on the spacecraft, and as the complexity and sophistication of the systems increases, this poses additional risk to the space environment. Single charged particles, such as protons and heavy ions, can damage components in several ways by the deposition of energy or charge in a sensitive region of an electronic device. Heavy ions are particularly effective in creating ionization since the amount of ionization is directly proportional to the square of the atomic mass.

3.4.1 Single Event Upsets (SEU)

The passage of a single energetic charged particle can create enough ionization to change the logic state of a device and introduce errors into memory chips and other electronic devices. This is known as a single event upset (SEU). SEUs can lead to corruption of data in memory chips and phantom commands. They are known as soft errors since the memory can be re-set by commands from the ground, or by fault detecting software.

3.4.2 Single Event Latch-up (SEL) and Burn-out (SEB)

In some cases a proton or heavy ion can create a conducting path in an electronic device such that it draws high current and will no longer operate until power to the device is switched off and on again. This is known as single event latch-up. If the latched state is not corrected then the high current can destroy the device resulting in a permanent hardware failure. This is known as single event burn-out (SEB).

3.5 Sensor Interference

Protons and heavy ions cause ionisation damage and displacement damage in sensors such as charged coupled devices and other sensors used to detect electromagnetic radiation. This increases the noise level in the detectors. One particular problem that has been encountered is the blinding of star trackers on spacecraft due to solar energetic particle events.

Since solar energetic particles, and in particular, galactic cosmic rays are so penetrating, it is impossible to shield components from the effects of single charged particles.

4 Benefits by Market Sector

In this section we consider the adverse effects of space weather on different market sectors. Analyzing space weather effects by market sectors helps to identify whether there is a potential commercial interest in space weather predictions, and post event analysis. In some cases the market is well defined (e.g., commercial satellite operators and service providers), in other areas the main users may be the public (e.g., HF communications, outside defence requirements) where a commercial market is more difficult to define. In both cases we have used the responses to our Aide Memoire to make an assessment of the benefits for each market sector.

Our analysis shows that space weather may affect many different market sectors. Within that, a particular type of space weather event, e.g., an anomaly on a spacecraft, can affect more than one market sector. Conversely, a market sector may be affected in several ways by a space weather event.

4.1 Commercial Satellite Design

4.1.1 Driving Forces

There are several forces driving the design of commercial satellites that mean that spacecraft are becoming more susceptible to space weather effects. First, the market is very competitive and there are large sums of money at stake in the construction of each spacecraft. For example, to construct a modern communications spacecraft for geostationary orbit costs more than US$150M. The need to keep costs down imposes new pressures not to over-engineer solutions to radiation problems. On the other hand, it is important to provide sufficient protection against the environment to guard against premature loss. For example, the now defunct IRIDIUM system did not protect component parts to the same level as other spacecraft and seems to be part of a trend to use more commercially available parts that are not radiation hardened to the same extent as before. This trend will increase the susceptibility of spacecraft to damage from space weather effects, particularly for orbits that traverse the radiation belts and orbits such as GEO that are subject to large variations in the energetic particle flux. Thus there is a requirement for better understanding and characterisation of the space radiation environment, and its extremes.

Second, as a result of commercial pressures, spacecraft are being designed for longer operational lifetimes of up to 15 to 20 years. The operational life of a satellite in geostationary orbit is limited by three main factors: fuel for in-orbit manoeuvres; battery power for operations during eclipse, (mainly at equinox); and power available from solar cells. Space weather affects the radiation environment, particularly energetic charged particles, and causes radiation damage to electronic components, including solar cells. The integrated effects of radiation damage over the lifetime of the spacecraft, measured as the total dose, results in the degradation of performance of electronic components and the reduction of power available from solar cells. For example, one solar energetic particle event may reduce the power from solar cells permanently by as much as 2%-5%. Communications satellites are designed to have a 5 - 10% margin of power available at the end of their working life, above that needed for operations. If the total dose is underestimated, or if number of significant solar energetic particle (SEP) events is underestimated by more than two events, then some systems may have to be switched off in order to continue operating towards the end of the working life. This results in a reduced level of operations, reduced profitability, and the possibility of insurance claims. The number of significant SEP events may vary between 0 and 6 over one solar cycle (11 years) and is unpredictable at present. Thus satellite designers need to have a better characterization of the radiation environment that the spacecraft will encounter.

A third factor driving satellite design is the need to fly more commercial systems on one spacecraft in order to maximize efficiency and generate more revenue. At one end of the scale, new communications satellites are planned with increased size, larger solar arrays, increased launch mass (7.5 tonnes), more transponders (up to 150) and increased solar array power (over 30 kW) [Space News, Jan, 2001]. At the other end of the scale, new concepts are being developed whereby constellations of small and micro satellites are being tested for different applications. In both cases there is pressure to reduce component mass, increase functionality and capacity. This has led to miniaturization, particularly of electronic components. Electronic components and integrated circuits are now so small that they are susceptible to damage caused by the passage of a single energetic charged particle through the component. This was not the case in the design of satellites 15 years ago or more. Satellites are therefore subject to damage caused by galactic cosmic rays and energetic charged particles trapped in the Earth's magnetic field, particularly in the radiation belts, and to SEP events associated with coronal mass ejections and solar flares on the sun.

A fourth factor is the design of new spacecraft is the introduction of new technology. Examples of the new technology being introduced on communications satellites include high power field effect devices, on-board microprocessor operations, large-scale integrated circuits with systems on a chip, autonomous systems management, plasma and ion propulsion systems, lithium batteries, and the use of commercial off-the-shelf parts. New technology requires extensive ground testing not just for average conditions, but also for extreme conditions caused by space weather events. New technology therefore requires data and the evaluation of worst case scenarios. Since ground testing can never reproduce the space environment exactly, the introduction of new technology is always likely to present new risks.

4.1.2 Current Practice and its Limitations

Satellite designers use space radiation models to calculate the total radiation dose received by the spacecraft during its operational life. Calculations of the total dose enable designers to calculate the amount of shielding required to protect electronic circuits, and the type of radiation hardened parts. The models used include CREME96 for galactic cosmic rays, SPENVIS, DICTAT, AE8 and AP8 for the radiation belts, the JPL code for solar proton events, and ESA micro-meteroid codes. However, there are several problems with these codes. They are based on old data that provides an incomplete description of the regions of interest. No models exist to describe energetic heavy ions that are particularly damaging to electronic components. Most importantly is that the radiation environment varies with different phases of the solar cycle, and is highly dynamic during space weather events. For example, the energetic electron flux may increase by more than two orders of magnitude after a magnetic storm. The view of the satellite designers we spoke to during this study was that there are no codes available that can adequately describe the radiation flux during disturbed times.

Space weather events that change the energetic particle flux are therefore very important for satellite design, and highlight the need to characterise and quantify their effects and to develop better radiation belt models.

4.1.3 Requirements

Satellite design would benefit directly from a space weather programme that included the following elements

1. Collection of new data from the magnetosphere and solar wind.
2. The characterization of space weather events, their magnitude, duration, and probability of occurrence as a function of solar conditions.
3. The impact of space weather events on different orbit types, including geostationary, sun synchronous, medium and low Earth orbit.
4. Better characterize the radiation environment, the time varying nature and average properties at different phases of the solar cycle, and extreme events.
5. The development of better radiation environment models for mission planning based on the maximum amount of data.
6. A database of satellite anomalies for analysis in relation to space weather events.
7. The establishment of a common set of design standards.

4.1.4 Benefits for Satellite Design

Satellite designers do not need predictions of space weather events. However, the collection of data for post event analysis is very important. The main benefits for satellite design include

Data to identify failures related to space weather
Development of more accurate radiation models for use in design
Prevention of over-design, and associated cost and weight
Establishment of a new set of design standards
Extended design life
More reliable operations
Cost savings associated with the above

4.2 Satellite Operators

4.2.1 Driving Forces

The growth in the number of satellites, and the use of satellites for a wider range of applications, for broadcasting, email, internet, navigation, banking, remote sensing, scientific and other applications, indicates that satellite control and operation is an increasingly important market. Operators are driven by a highly competitive market to provide the best service for their customers. This means managing the satellite systems efficiently to minimise interruptions to service and to carry out orbit control manoeuvers at the appropriate times in order to conserve fuel.

Operators of scientific satellites have been able to switch off experiments during periods when the risk of damage to instruments is very high. For example, particle detectors on AMPTE were switched off when the satellite traversed the radiation belts. However, operators of commercial spacecraft are generally forced to keep operating due to commercial pressures. For example, the consequences of switching off satellite broadcasting of World Cup football or the Olympics during a space weather event are unacceptable. Nevertheless, there are mitigation procedures that could be employed, as discussed below.

4.2.2 In-Orbit Anomalies

Satellite operators must deal with a variety of space weather effects. For example, phantom commands and mode switches are two examples of satellite anomalies that may result from electrostatic discharges and single event effects caused by changes in the radiation environment. In some cases these effects are small and the relevant systems can be re-set by commands from the ground, or be dealt with by fault tolerant software on board. In other cases, anomalies have been known to affect the stability of satellites in orbit, and have led to the total loss of satellites. There are several well known examples of satellites suffering anomalies during, or just following magnetic storms when the flux of energetic radiation belt particles was increased, such as Intelsat K, Anik E1 and E2 in January 1994, Telstar 401 in January 1997, and Galaxy IV in May 1998. The failure of Galaxy IV resulted in the loss of 80% of North American pagers [Baker, 1998]. However, there has been some controversy as to whether space weather events were directly responsible for the anomalies on some of these spacecraft. In many cases there is not enough data on the space environment to show conclusively that space weather is the cause. Unless the cause can be properly identified, it is difficult to learn lessons and improve future satellite design. Identifying the cause is also important since it may have a direct impact on the pay out of insurance premiums amounting to several hundred million US dollars, and future insurance policies.

More generally, NOAA keep a database of more than 5,000 satellite anomalies from 259 satellites. In the database the ‘anomaly diagnosis’, or cause, for more than 2,500 of these anomalies is stated as unknown. Given the importance of identifying the cause of anomalies for operators and designers, this indicates the scale of the problem.

A space weather programme that collects data on the space environment and makes it available for analysis of satellite anomalies in relation to space weather events is extremely important for satellite operators, owners, and insurance companies, as well as satellite designers discussed above. Continuous data collection is required from the critical regions of the magnetosphere, such as the radiation belts, geostationary orbit, where most commercial satellites operate.

4.2.3 Effects on Ground-Satellite Communications Links

Communication links between the ground and satellites are used in a variety of different applications. As the signals pass through the ionosphere they can be interrupted by ionospheric irregularities caused by space weather events. For example, ionospheric irregularities in the electron density can cause scintillations of up to 20 dB in the amplitude and phase of GPS signals leading to loss of signal and hence service interruption. Scintillations are particularly important in the equatorial region, and high-latitude regions in the auroral oval during magnetic storms and substorms. There are several areas where these disturbances can affect satellite operators, and the services that they provide.

4.2.3.1 Disruption to Satellite Command and Control

Operators require secure ground-satellite communications links for housekeeping activities to monitor the status of spacecraft systems, identify anomalies, check station keeping, and to send commands to control the spacecraft, including orbit manoeuvres. The ability to minimise disruption to these links is very important for the whole operation of the spacecraft. Commercial operators now operate at high frequencies (e.g. Ku band 10-14 GHz, and Ka band 20-30 GHz) where the effects of the ionosphere are not very important and where signal attenuation is mostly affected by rain. Some commercial operators also use more than one station for up- and down-links and can switch between different sites. They also try to build in enough safety margin to deal with signal absorption. Disruption to commercial satellite command and control by space weather effects is therefore not considered very high. However, this may not always be true for the reception of weak signals from deep space missions. Operators dealing with deep space missions would benefit from predictions of periods of ionospheric disruptions and scintillation, and identifying extreme events.

4.2.3.2 Disruption to Broadcasting and Satellite Services

Ionospheric irregularities, scintillations and solar radio emissions interrupt the provision of service from satellites, such as broadcasting, mobile phones, and wireless communications leading to loss of revenue. Furthermore, search and rescue operations at sea are occasionally put at risk. Enhanced solar radio emissions cause interruption to service when the sun is in the field of view of the ground antenna.

4.2.3.3 Disruption to Remote Sensing

Remote sensing is used for a variety of applications, for example, weather forecasting, estimating crop yields, sea surface temperature etc.. Ionospheric irregularities are particularly important at longer wavelengths used by synthetic aperture radar [Quegan, 1993]. For example, ionospheric irregularities affect the total electron content between the ground and the spacecraft and hence rotate the plane of polarisation of linearly polarised waves. This can be overcome with orthogonal antennas, but reduces the data rate by a factor of 2.

Some of the lost information can be regained by constructing maps of the total electron content, for example, by using GPS signals. Thus users of remote sensing satellites would benefit from predictions of ionospheric irregularities, and measurements of the total electron content from a network of receivers over the regions affected. The most important regions are near the magnetic equator, and at high latitudes around the auroral ovals, and over the polar caps in both hemispheres.

4.2.4 Unexpected Orbit Manoeuvres

Satellite operators occasionally experience unpredictable orbit manoeuvres in spacecraft that use the polarity of the magnetic field for orbit corrections. In order to keep antennas correctly pointing at the ground station, and solar arrays facing the sun, some spacecraft use magnetic torquers to provide a torque against the ambient background field and make the orbit correction. This is usually done automatically. However, during magnetospheric compressions the background magnetic field at the spacecraft can change polarity resulting in orbit manoeuvres in the wrong direction. As an example, during the storm of 13/14 March 1989, the magnetopause moved inside geostationary orbit and the magnetic field at geostationary orbit reversed sign for more than 3 hours due to the orientation of the interplanetary IMF [Allen et al., 1989].

As far as we are aware, this problem is very important for the operation of Anik E2 which has no on-board momentum stabilization. It is less important for normally operating satellites. Nervertheless, a space weather programme would be able to provide warnings of these events so that operators could take preventative action, for example, to disengage automatic torquing during the event.

4.2.5 Atmospheric Drag and Re-Entry

Atmospheric drag is very important for satellites in low Earth orbit, such as remote sensing and surveillance satellites. Drag increases orbit decay and operators must periodically boost the spacecraft into higher orbits. Atmospheric drag can increase for three main reasons associated with space weather, an increase in the flux of solar EUV and X ray radiation, Joule heating associated with large ionospheric currents, and collisional heating due to particle precipitation.

Increases in solar EUV and X ray radiation, associated with changes in solar activity, heat and expand the atmosphere resulting in increased atmospheric drag. Since solar EUV and X rays are largely absorbed in the upper atmosphere before reaching the ground, the radio flux at 10.7cm (F10.7) is use as a proxy for solar UV [Feynman and Gabriel, 2000]. F10.7 varies with solar cycle by a factor of 5 between solar min and max, and is also correlated with the 28 day solar rotation period. However, F10.7 can be a poor proxy for EUV and X ray flux and there is a basic need to improve techniques for predicting EUV and X ray flux [Barth et al., 1990].

Strong magnetic activity, including magnetic storms, result in large currents up to a few million Amperes flowing in the high latitude auroral regions at altitudes of about 100 km. These currents give rise to collisional dissipation that heats and expands the atmosphere. During large magnetic storms, these current systems expand towards the equator and have been detected as far south as Greece. Particle heating also contributes significantly during storms (about 15% of the energy of Joule heating).

Increased atmospheric drag due to magnetic storms has resulted in changes to the position of low Earth orbiting spacecraft such as SPOT by as much as 8 km in one day [Boscher et al., 1999]. Furthermore, changes in atmospheric drag can result in large errors in the prediction of atmospheric re-entry. For example, the predicted re-entry of MAGSAT from an apogee of 550 km was initially 4 months but turned out to be to 6 months due to uncertainties in atmospheric drag near solar maximum in 1980.

Large magnetic storms have caused uncontrolled re-entry of low Earth orbiting spacecraft such as Skylab in July, 1979, with potential risk to life. De-orbiting is very important consideration, and detailed planning is now under way for the de-orbiting of the MIR space station (January, 2001).

In order to compensate for periods of increased atmospheric drag, satellites must expend more fuel to maintain accurate station keeping, or suffer reduced mission lifetimes. Prediction of atmospheric drag is a very important requirement for a space weather programme.

4.2.6 Space Debris, Meteroids and Dust

Space debris poses an important risk to operational satellites, and to man in space. Space debris is comprised of several types, including spent rocket stages, defunct satellites, and fragments of rockets and hardware that will remain in orbit for hundreds of years. In addition, meteoroids and dust also pose a threat. Meteoroids and dust are mainly the result of comet ablation and form a trail of particles following the orbit of the comet. When the Earth interests a comet trail a meteor shower results. The US Air Force Space Command tracks over 7,000 objects with size > 10 cms, and have estimated that there are tens of thousands of smaller objects.

Space debris can damage spacecraft in different ways. Direct impact by a sufficiently large object can cause mechanical damage. Typically, a hyper velocity impact by a 90 gm particle is sufficient transfer over 1MJ of energy and cause catastrophic damage to any spacecraft. Smaller objects cause surface erosion and can puncture the conducting surface of a spacecraft and create a plasma cloud. If the spacecraft has undergone charging due to the natural plasma environment, then the puncture can initiate an electrostatic discharge and result in an anomaly. Debris also poses a serious risk to astronauts during EVA activity, particularly during the construction of the international space station when the amount of EVA activity will be at its peak.

Orbit predictions are made for space debris in order to calculate the risk of collision with spacecraft, and with the manned space station. They are also tracked by the military in order to identify a surprise missile attack. If the risk of collision is sufficiently high then operators can take mitigating action. For example, meteor showers are highly directional and one operator manoeuvered their spacecraft to minimize the surface area presented to the Persied meteor shower. No damage was reported, and no loss-claims were reported by insurance companies. Similarly, structures such as the international space station can be manoeuvered to a different location to avoid collision with relatively large pieces of space debris, and EVA activity can be curtailed.

Since the orbits of space debris are mainly influenced by atmospheric drag in low earth orbit, space weather effects that heat and expand the atmosphere (enhanced solar X ray and EUV flux, particle precipitation, and Joule heating) are very important. These effects can cause important orbit perturbations and create enough uncertainty to increase the risk of collision. Satellite Operators, and Space Agencies responsible for the safety of astronauts, would therefore benefit from the space weather programme that includes event prediction, calculation of atmospheric heating, and enhanced orbit drag. It would enable them to minimize the risk of collisions with spacecraft, and reduce a life-threatening risk to astronauts.

4.2.7 Mitigating Action for Satellite Operators

Satellite operators would derive several benefits from a space weather programme that included both prediction and post-event analysis.

The possible actions that could be taken for a prediction service include:

Enable staff to be on alert ready to deal with problems
Enable better planning of orbit manoeuvres to conserve fuel and extend mission lifetimes
Enable the suspension of certain activities such as testing and upgrading software
Re-route ground-satellite communications
Certain non-essential systems can be switched off to reduce the risk of anomalies
Automatic magnetic torque systems can be switched off to prevent unexpected orbit manoeuvres

4.2.8 Benefits for Satellite Operators

The four satellite operators we spoke to said they would derive a variety of benefits for a space weather programme including:

Preparedness to deal with potential problems
Reduced risk of satellite anomalies and failures
Prevent unexpected satellite manoeuvres
More reliable provision of service for broadcasters
Reduced down time and hence reduction in lost revenue
Extended operational life for satellites through conservation of fuel
Offer a more competitive service
Identify the cause of satellite anomalies
Feedback of information to improve future satellite design

One of the satellite operators stated that being informed of space weather events is also important for their customer relations. Space weather warnings provided by the NOAA SEC have prompted telephone calls from customers asking operators if they are aware of the warnings and what they intend to do about mitigating the effects. A SW warning service can provide operators with information to deal with these customer concerns in a diplomatic way.

4.3 Space Agencies: Man in Space

4.3.1 Driving Forces

Space Agencies have a duty to protect the Health and Safety of their employees, and people under their care. This includes astronauts. ESA is a partner in the International Space Station (ISS) and therefore shares some responsibility for the safety of its inhabitants. There is a requirement to ensure minimum radiation exposure to astronauts, and to comply with legislation on maximum radiation exposure limits (250 mSv/month, 500 mSv/year). If astronauts receive a high dose then the Agencies may encounter additional costs in reducing the number of astronaut flight opportunities, and training additional astronauts.

4.3.2 Risk to Astronauts

The ISS is being constructed over a four year period that spans the peak and declining phase of the solar cycle. Recent studies have shown that during construction at least 2 out of 43 construction flights will overlap with a significant solar energetic particle event [Siscoe and Kelley, 2000]. Furthermore, the high inclination orbit of the ISS takes it over regions where solar energetic particles and relativistic electrons in the outer radiation belts have access. This constitutes an important radiation hazard. The main threat is from energetic particles (protons and ions) at energies > 10MeV/nucleon that can penetrate space suits.

It is estimated that the received radiation dose will not be immediately life threatening, but will increase the chances of cancer in later life. For example, it is estimated that, for an astronaut outside the ISS in a high latitude region for 6 h during a solar energetic particle event, he or she would receive a radiation dose equivalent to the short term limit set for eyes and skin [Siscoe and Kelley, 2000].

Solar energetic particle events are associated with CMEs. The delay time in arrival may only be less than 1 hour, and therefore it is very important to have real time monitoring and forecast. Given a warning, astronauts can stop their extra vehicular activity (EVA) and return to the ISS. Inside, they can stay behind large amounts of shielding until the event is over.

NASA is one of the leading entities with long experience in the radiation effects on astronauts. ESA also funds research into the effects of space radiation on humans [e.g., Reitz, NATO ASI conference, 2000]. There is now a requirement to develop models using real time data to predict the intensity and location of solar energetic particle events, and to study the longer term effects of space radiation.

4.3.3 Benefits for Space Agencies

The benefits of a space weather programe is that it would enable

Warning of solar energetic particle events
Reduced radiation dose to astronauts
Financial savings through not having to reduce astronaut flight opportunities and training new astronauts
Carry out duty of care as required by Health and Safety legislation

Clearly, these activities should be carried out in collaboration with other Agencies.

4.4 Launch Operators

4.4.1 Projected Number of Launches

The first launches of constellations of communications satellites into non-geostationary orbit in 1997 stimulated new demand for launch services. However, since the failure of IRIDIUM, there is now some controversy over future demand. The projected number of launches has now been revised down taking this into account. It is now projected that between 2000 and 2010 the average number of medium-to-heavy commercial launches into geostationary orbit will be 23.5 per year, 7.5 per year into low earth orbit, and using small launch vehicles, 10.4 per year into low earth orbit [2000 Commercial Space Transportation Forecasts, 2000]. Each launch may include multiple spacecraft. The figures do not include defence or other requirements. The total number of launches is projected to increase by 15% from 1999 levels.

4.4.2 Risk from Space Weather Events

The probability of launch failure due to a space weather event such as a solar energetic particle event depends on the type of orbit. The risk of launch failure for ARIANE 5 has been published in a previous report [Boscher et al., 1999]. They calculate that the increased risk of failure for launch into geostationary orbit is insignificant, but is increased by a factor of 200 for launch into sun synchronous, and by a factor of 10 for launch into geostationary transfer orbit (GTO). However, the overall probability of failure still remains below the target values for launch (typically 2×10^{-2}) with the possible exception of launch during a solar energetic proton event.

The most important case for space weather predictions is for the launch of manned space missions. A solar energetic particle event may provide an unacceptably high radiation hazard for astronauts. In view of the high costs associated with delaying launch, and possibly missing launch windows, only a nowcast could provide a sufficiently reliable service.

Space weather predictions could be important in the optimisation of launch procedures. For example, predictions of the amount of atmospheric heating and resulting density profile may enable better timing of launch procedures (such as opening and discarding of launch fairings) that reduce the amount of unwanted mass into orbit [Boscher et al., 1999]. Timely and accurate predictions up to 24 and 12 hours ahead would be required.

Large magnetic storms and increased solar EUV and X ray emissions that heat and expand the atmosphere may also impact launchers into low earth orbit by causing orbit trajectory errors. These effects may be particularly important for smaller spacecraft, and therefore require timely and accurate predictions.

4.4.3 Benefits for Launch Operators

The most important benefits of a space weather programme for launch services can be summarized as

Reduced radiation dose to astronauts
Optimisation of launch procedures

More research is required into assessing optimisation procedures.

4.5 Civil Aviation

4.5.1 Driving Forces

There are three main reasons why Space Weather is becoming increasingly important for the aviation industry. First, new EU regulations have just come into force that require airlines to assess the radiation dose to aircrew. Some of this radiation dose is due to space weather effects. Second, miniaturization of electronics means that aircraft avionics is becoming more susceptible to radiation damage by cosmic rays and other energetic particles in the earth's environment. Third, the need to increase capacity on selected routes has led to investigations to reduce aircraft separation using GPS, and long-term plans to land aircraft using GPS signals. Space weather causes errors in positioning by GPS.

4.5.1.1 Radiation Dose to Aircrew

Aircrew are exposed to radiation from two main sources, cosmic rays and solar proton events. High-flying aircraft are more susceptible than low-flying aircraft, since there is less shielding by the atmosphere. High-latitude routes are more susceptible due to the orientation of the Earth's magnetic field which enables easier access for energetic particles. Trans-polar routes are most susceptible to radiation exposure due to both cosmic rays and the risk of solar proton events.

New European Union regulations came into force on 13 May 2000 (Directive 96/29/EURATOM). UK interpretation of this legislation is that aircrew are *not* radiation workers and therefore there is no upper limit to the dose they can receive. However, the new legislation requires airlines to assess the radiation dose received by their aircrew and to monitor aircrew individually if the estimated or received dose exceeds 6 mSv/yr. Pregnant aircrew must not receive a dose more than 1 mSv during pregnancy. Passengers are not subject to these regulations at present.

It is estimated that the average dose due to cosmic rays for short haul flights at 26,000ft (8 km) is about 1-3 μSv/hr and about 5 μSv/hr for long hall flights at 35,000 ft (10.6 km). The average typical exposure on a flight between London and New York is approximately 30-40 μSv, and between London and Tokyo is approximately 50-70 μSv [O'Sullivan, 1999, 2000]. For comparison, a chest X-ray is approximately 20 μSv, and the background level of natural radiation is about 2.2 mSv/yr. Since aircrew may fly as much as 600 hours per year at altitude, their exposure due to cosmic rays alone may exceed 1 mSv/yr and could approach the 6 mSv/yr level.

The cosmic ray flux has been monitored for many years. It is known to increase by about 20% above the average solar cycle level during solar minimum and decrease by about 20% below the average level during solar maximum on a timescale of months, but small variations of a few per cent occur over timescales of days. It is highly predictable. The main concern is the risk of exposure on high-latitude routes due to solar proton events. There is no reliable method of predicting when these events will occur. During the solar proton event in 1956 it has been estimated that the radiation dose at 40,000 ft (12 km) on a trans-atlantic flight would have been 10 mSv, and for Concorde 55,000 ft (17 km) it would have been 30 mSv. Thus it is possible for Concorde aircrew to exceed the 6 mSv dose during one flight if no avoiding action were taken. However, events of this severity are rare. It should also be noted that Concorde carries dosimeters which provide an alert if the instantaneous dose exceeds a certain threshold (green for 1-100 μSv/hr, orange for 100 – 500 μSv/hr and red for 0.5 – 10 mSv/hr). During the 24 years of Concorde operations carrying dosimeters, BA and Air France state that they have never had to take avoiding action due to unacceptable radiation levels.

Although the EU has introduced new legislation, they have not provided any means for carriers to calculate the radiation dose. Probability estimates have been determined for solar proton events based on past data, but to comply with new legislation the airlines must still assess the radiation dose received by aircrew.

Procedures to ensure that aircrew are not subject to significant levels of radiation are still being discussed. Current suggestions are that if any aircrew reach a dose level of 1 mSv in any year, then they should be rostered onto other routes to reduce exposure so that they will not exceed to 6 mSv/yr level. This may impose some additional financial expense.

Radiation monitors are flown on Concorde, but are not routinely flown on other aircraft in the BA fleet. Other carriers fly radiation monitors, but mainly for research and experiment. It is technically very difficult to detect the radiation dose due to all the components of cosmic rays (neutron and non-neutron) over the wide range of energies encountered, and identify the component not due to background levels. As a result, radiation monitors only considered accurate to 20-30%. Current work suggests that a similar level of accuracy can be obtained by calculating the received dose from models. Current practice for some airlines is to calculate the radiation dose retrospectively for aircrew after a solar proton event has occurred. This requires the event to be identified, the spatial and temporal scales to be determined, energy spectrum to be calculated and used in a realistic model to calculate the dose for all the aircrew on flights that may be affected. This is a significant undertaking. There is one model, from the University of Arizona, CARI [see CARI, 2000] which can be used to model a solar proton events. Like all models, its accuracy is dependent on the input data, and the assumptions on scale sizes.

Most solar flares emit energetic protons up to energies of 10 MeV. There are about 10 solar proton events per year, 52 were identified between 1966 and 1971 using VLF radio methods [Hargreaves, 1979]. The events tend to follow the sunspot cycle, with a tendency to peak just after solar maximum by a year or two. However, only protons with energies in excess of 500 MeV can reach the ground at high latitudes and there may be between 0 and 6 events per solar cycle.

4.5.1.2 Mitigating Action

During the course of our interviews, carriers showed significant interest in a warning and prediction service for solar proton events. Even identifying an event in progress would enable them to take mitigating action. For example, warning of an event in progress, a nowcast, would enable a 12 hour trans-polar flight to take avoiding action, provided the warning is relayed quickly enough. The types of mitigating action include:

Fly at lower altitudes
Re-route aircraft
Land aircraft
Ground aircraft

Flying at lower altitudes is not always possible, particularly over high terrain. Higher fuel consumption at lower altitudes may prevent this action on some routes, and for some types of aircraft. Diverting aircraft may not avoid the most dangerous regions if the spatial scales of the event are sufficiently large, for example, on trans-polar routes. Landing aircraft is a serious option, but may only be possible with a significant delay on some routes, e.g., trans-polar. Again this highlights the need for accurate early warning

Action to land and ground aircraft would require a high level of probability that the event will occur (> 95%). Only a nowcast could achieve this level of reliability. Similarly once an event has started, there is an important need to continue monitoring to identify the time when it is safe to fly again. Any delay would result in financial loss to the aviation industry. For example, while a solar flare may last for 10 minutes or so, a solar proton event may last for 3 or 4 days.

4.5.1.3 Benefits for Aircrew and Passengers

A space weather warning, prediction and nowcast service would provide significant benefits to the aviation industry, particularly airlines. The most important is that it would enable them to comply with European health and safety legislation to assess exposure by aircrew, and reduce the radiation exposure of their employees and passengers to a minimum. It would help them plan operations during periods of significant risk, and this would enable financial savings.

4.5.2 Radiation Damage to Avionics

Due to miniaturization of electronics, single particle effects can now cause radiation damage in avionics, analogous to single event effects on spacecraft [Dyer and Truscott, 1999]. For example, single event upset rates in CMOS SRAM devices were found to vary from 1.2×10^{-7} per bit-day at 30,000 ft (9.2 km) and 40 degrees latitude, up to 5.4×10^{-7} per bit-day at 65,000 ft (20 km) [Taber and Normand, 1993]. Recent research has shown that single event effects on microelectronics from the neutron radiation environment at aircraft altitudes is in good agreement with upset rates based on ground based testing [Johansson et al., 1998]. The cosmic ray flux is predictable, but there is an additional risk due to solar proton events.

The use of backup and redundancy systems on aircraft provides an effective engineering solution to this problem. However, if an aircraft were to suffer one systems failure and then be informed of a SEP event, the risk of more radiation damage may be too high to continue the flight. More research is required in this area.

The main benefit of a space weather warning system as far as radiation damage to avionics is concerned is to improve flight safety.

4.5.3 Aircraft Navigation via GPS

There are now plans to use GPS for navigating aircraft so that the separation between aircraft can be reduced, and to position the aircraft on approach. There are also studies in progress on the longer-term goal of landing aircraft by GPS. The plan involves using a network of fixed ground based GPS receivers, separated by a few hundred km, to derive a map of the ionosphere using a dual frequency GPS system. The map is then transmitted to the aircraft so that the GPS receiver on board can make an accurate ionospheric correction.

Since the phase and amplitude of GPS signals can be disrupted by space weather, predictions of periods at risk would enable mitigation effects, for example, to increase separation between aircraft as a precaution, or to use alternative methods of navigation.

Flight navigation by GPS is a safety critical system. The main benefit of a space weather programme for airline navigation is improved flight safety.

4.6 Power Generation and Supply

4.6.1 Effects of Space Weather on Power Supply Grids

Space weather events affect the power generation and supply network used for domestic and industrial use. During magnetic storms, very large electrical currents of up to a few million Amperes, flow between the magnetosphere and the ionosphere, and flow through the ionosphere at high latitudes in the auroral region. These currents create magnetic fields up to several hundred nT that can be detected on the ground. During magnetic storms, ionospheric currents are highly dynamic, and induce large electric fields in the Earth and in long conductors such a power lines. In a power grid, there are connections through the transformers between the grid and the ground in order to provide a safe discharge path in case of faults or an unbalanced 3 phase supply. As a result, large electrical currents, called geomagnetically induced currents (GIC), are able to flow from the power grid, through the transformer, to the ground.

When GICs are sufficiently large, they saturate the transformer and create harmonics of the signal waveform. This causes problems in the relays and other equipment, and can cause trip outs in power lines, and on some occasions can bring down the whole power supply network. Saturation of the transformers also creates eddy currents that create hot spots and can damage the transformer windings and supports. In general, GICs reduce the lifetime of transformers on the system with cost implications.

A large fraction of the current in a saturated transformer is reactive, and reduces the ability of the grid to transmit power. The voltage tends to fall, and more power is required from the generators. Thus GICs also have an effect on the generating capacity required during the event. The national grid network supplier must pay to have additional power generating capacity available before the magnetic storm starts in order to maintain supply. Ultimately GICs may trip protection circuits with the loss of power supply.

During the magnetic storm of 12/13 March 1989, the GICs were so large that they caused a series of trip-outs that resulted in a blackout of the Quebec power system leaving 6 million residents without power for over 9 hours [Boteler, 1998]. At the same time as the HydroQuebec system, there was power loss in central and Southern Sweden on six 130 kV power lines. The total cost of losses resulting from the Hydro-Quebec incident is estimated at $6 billion. Incidents such as this may occur about once every eleven years. Since 1989 considerable amounts of money ($1.2 billion) have been spent protecting the HydroQuebec system and it is unlikely that a blackout would occur again on such a large scale. However, in order to manage the power supply network and power generating capacity efficiently there is a requirement for predicting and monitoring GICs. It should be noted that European power supply systems do not have the same amount of protection as HydroQuebec and are therefore still at risk.

The UK National Grid estimate that the cost of a space weather alert is approximately $14M/day, taking into account buying additional generating capacity to maintain supplies. In 2000 they had 2 alerts, and 50-60 warnings where they did not go to alert status, but had to carry out inspections on the network. They estimate that if another Hydro-Quebec incident were to occur today (i.e. a 24 hr blackout), then since the value of the electricity supplied is $4.2 per kW hr (using the official UK regulator figures), and the average electricity supplied during a winters day is $1.2\text{x}10^9$ kW hrs, the value of the unsupplied energy would be $5 billion. Thus the loss to the company itself is small ($5-10M) compared to the loss to society when taking into account lost production etc. as reflected in the UK regulators figures [ESA conference, December, 2000]. Since a Hydro-Quebec incident may occur once every solar cycle (11 years), the annualised loss is about $450 M/year for the UK alone. This figure should be multiplied by 1.5 for France, 1.5 for Germany, 0.5 for Spain and 0.3 for Portugal.

4.6.2 Driving Forces

Power supply companies need to provide uninterrupted power to customers. In some countries, such as the UK, there are financial penalties for not meeting supply targets. Furthermore, as a result of privatization of the industry there are new commercial pressures to reduce costs, and therefore operators now work closer to the margins for supply and demand. This increases the susceptibility of power supplies to space weather events. In addition, the reliability of service significantly affects the stock market price (by as much as 10%), and thus there are more pressures on operators to provide reliable service.

4.6.3 Benefits for Power Supply Industry

A space weather prediction service would enable power supply and power generators to take mitigating action. For example, to have more generating capacity ready from the suppliers in case it is required, to apply circuit protection measures such as capacitors, or to disconnect some system components for protection. This would reduce the risk of transformer damage and minimize interruptions to power supplies, and hence produce cost savings.

In our survey users also stated that collection of data for post event analysis would have several other benefits. For example it would enable them to

Identify of worst case scenario
Identify system behaviour
Identify the total risk
Identify of links to space weather

Analysis of these effects would help some operators who do not use existing prediction services to consider using predictions more seriously.

4.7 Prospecting for Minerals, Oil and Gas

4.7.1 Aerial Surveying

Aerial surveys for minerals, oil and other deposits are often carried out by light aircraft which make accurate measurements of the Earth's local magnetic field. Data from the surveys are used to construct maps from which valuable deposits can be identified from anomalies in the Earth's magnetic field.

There are several types of space weather events may affect the Earth's surface magnetic field. For example, magnetopause compression can change the surface field on the dayside of the Earth by as much as 500 nT. During a magnetic storm the ring current builds up and can change the surface field by as much as a few hundred nT. These effects are most important at low and mid latitudes. At high latitudes, large currents, of the order of a million Amperes, flow into and out of the ionosphere, and through the ionosphere. These currents generate magnetic field that change the surface magnetic field by as much as a few thousand nT. During the great storm of March 1989, the declination of surface magnetic field changed by 6 degrees in the USA, and magnetic surveying in Canada, Australia and South Africa was described as ‘impossible’ [Allen et al., 1989].

Aerial surveying would benefit from a space weather programme that could predict significant changes in the surface magnetic field. During these periods, aerial surveying could be suspended.

4.7.2 Drilling for Oil and Gas

Oil and gas drilling operations are very expensive. Typically new 50 wells are drilled every year world-wide. The bore holes are not generally straight lines but are curved according to geophysical limitations such as rock strata. There are at least two methods of navigating the drill head, one using inertial navigation, the other using the direction of the Earth’s magnetic field. One limitation of inertial guidance is that the gyros must be stopped during the drilling process. Furthermore, using the Earth’s magnetic field is still much cheaper than inertial guidance, and is widely used. It is very important not to drill into a previously drilled bore hole, and on occasions, it is important to drill bore holes very accurately (typically to within 0.1 degrees), for example to intercept a reserve to relieve pressure and to prevent a blow out. During magnetic storms the Earth’s magnetic field may vary by 0.3-4 degrees in the North Sea and disrupt accurate drilling operations.

For bore holes at high latitudes, such as in the North Sea, the largest variations in the magnetic field direction are due to large auroral currents during substorms and magnetic storms. At lower latitudes, and in the equatorial region, changes in the magnetic field arise from magnetopause currents on the dayside during events that cause magnetospheric compression (e.g., increased solar wind pressure, but northward IMF Bz), and from the build up of the ring current during magnetic storms. Typically the ring current may last a few days during the recovery phase of a magnetic storm.

Drilling operations are generally too expensive to cease operations. Therefore companies require a correction for changes in the external magnetic field in order to continue operations. This is an example of a well defined requirement, and organizations such as the British Geological Survey already provide magnetometer data for some drilling operations from their magnetometer sites.

Companies that conduct drilling operations for oil and gas would benefit from a space weather programme that provides real time data on the variation in the Earth’s magnetic field. Prediction of large events would enable them to take preventative action. For example, warnings of rapid variations in the Earth’s magnetic field, such as during substorms, would enable them to apply magnetic corrections taken more frequently. This would enable them to continue operations and reduce losses from errors in navigating the drill head. Drilling operations have specific requirements for measuring the magnetic field deflection at or near the drill sites using ground based magnetometers and therefore require specialized services.

4.8 Oil and Gas Pipeline Distribution

4.8.1 Pipeline Corrosion

GICs are also induced into long pipelines, particularly at high latitudes. The induced current results in corrosion of the pipe through an electrochemical process at points where the current flows from the pipe into the ground. Since the corrosion occurs at the surface of the pipe, pipes are now coated with a high-resistance material. However, in practice, the coating is never perfect and corrosion occurs at holes in the material. The timescale for corrosion is not clear, it has been argued that it is anywhere from a period of months for uncoated systems to years for coated systems [NATO ASI conference, 2000].

To overcome corrosion, pipelines are now protected by a cathodic system whereby the pipe is kept at a negative potential of between about 0.8 and 1.3 Volts with respect to the ground to reduce current flow from the pipe to the ground. It should be noted that these systems were originally introduced to overcome corrosion due to natural geo-chemical effects, not space weather effects. However, ionospheric currents produce both GICs and large potential differences along the pipeline, and between the pipeline and the ground that easily disrupt the cathodic protection system. For example, if the potential is reduced then corrosion will take place, but if the potential is increased then other geo-chemical processes act on the pipe to emit hydrogen from the pipe that leads to separation of the high-resistance material. The problem can actually be made worse by the use of high resistance surface coatings. Using transmission line theory, the potential difference along the pipeline becomes particularly large at the ends of the pipeline. Inserting insulating sections of pipe to reduce the potential difference can reduce the scale of the problem, but needs careful analysis since it can actually make the problem worse and result in additional locations for enhanced corrosion [Boteler, 1998].

In the US and Canada there is about 6,000 km of pipeline costing about US$1 M per kilometer. The cost of the cathodic protection system varies between 0.1% and 0.2% for very large projects (hundreds of millions of dollars). This illustrates the very large sums of money invested in pipelines that can be subject to disruption by space weather effects.

4.8.2 Benefits for Oil and Gas Companies

Oil and gas pipelines would benefit from predictions of space weather events, particularly GICs and induced potentials along the pipeline networks, and post-event analysis. It would enable companies to suspend routine maintenance and measurements of the cathotic protection system during disturbed periods. It will enable them to identify worst case scenarios and the magnitude of the largest events. Analysis of data will enable the effects to be fed back into the design of better protection systems, such as active cathotic control systems. It will enable reduced pipeline corrosion, and financial savings in extended pipe lifetimes.

Protecting pipelines requires detailed modeling taking into account ionospheric current systems, variations in ground conductivity, and the geographical layout of the pipeline network. Although a general warning can be given, this is an area that probably requires a specialist service tailored to the users needs.

4.9 Space Insurance

4.9.1 Driving Forces

The insurance market provides large sums of money for insuring the space industry, in excess of US$1 billion per year. The total estimated value of insured spacecraft in-orbit is now about $16 billion. Europe has more than half the market share of insurance. The policies are usually split into three areas, pre-launch, launch plus 1 year in-orbit, and up to 5 years in-orbit operations. The most important policies affected by space weather are launch plus one year, and in-orbit operations. The space insurance industry has made profits for a period of several years up until about 1997. However, in 1998 there were huge losses. For example, the total space insurance claims for 1998 were about $1.65B compared to premiums of about $850M. Recent figures show that space insurance world-wide has suffered losses overall in the last three consecutive years [Space News, Jan, 2001]. As a result, the market has gone through a period of mergers and some companies have dropped out of the market altogether. The total amount claimed every year has also increased, from about $200M in 1989 to about $1.65B in 1998 showing that the risk has become much higher. To compensate, the insurance industry has had to increase in-orbit premiums from about 1.2% to 2.5% of the value of the satellite over the same period.

Until recently, most of the losses have been associated with launch failures, and most of these failures cannot be associated with space weather. However, the situation has changed recently, and there are now more losses associated with in-orbit failures than with launch. The amount paid out in insurance claims depends on the type of spacecraft, and type of risks covered by the policy, but can be substantial. For example, in1998 Galaxy IV failed during a period when the electron flux in space was enhanced following a magnetic storm. The insurance claim for in-orbit loss was $165M (comparable to the losses arising from a hurricane). This does not take account of knock-on losses, for example, due to loss of revenue for operators and service providers.

The number of launch and in-orbit losses that can be attributed to space weather has yet to be properly evaluated. This is a very sensitive area since the reason for loss may affect insurance claims. There is a view expressed in the insurance industry that virtually all satellite failures are a result of human error. Given that more than 47 satellites have reported anomalies due to electrostatic discharges (ESD) [Wrenn and Smith, 1996], and that there are more than 900 ESD anomalies in the NOAA database, this seems unlikely. Other insurance brokers have suggested that space weather is a cause or contributor to over $500M in insurance claims over the last four years [Kunstadter, 2000]. As far as the insurance industry is concerned, there is a need for more education about space weather and its effects, and for more analysis to identify which satellite failures are due to space weather events.

The space insurance market is highly technical. The lead insurers obtain detailed technical reports from consultants to evaluate the risk for each spacecraft they insure. At present this does not include the risk of damage due to space weather events such as magnetic storms. In some cases the lead insurers decide not to insure all the risk, but to share it with manufacturers or operators. In addition, the lead insurers obtain re-insurance to cover some areas. The re-insurers tend not have detailed specialist knowledge and have little or no awareness of space weather. They are prepared to follow the lead insurers based on their track record, and are prepared to accept high risk for high premiums. This suggests a need for more education about space weather.

The insurance industry is highly competitive. After having evaluated the risks, the insurance company may be able to set a technical rate for insurance. However, since there is overcapacity in the market, i.e., more money available for space insurance than is actually required, and since insurance operates as a market with insurance brokers, if the technical rate offered by one company is more than the market rate offered by other insurers, the broker will take the business elsewhere. Thus in some cases insurance companies are forced to offer a market rate that is lower than the technical rate in order to continue business. This is one of the factors that has contributed to the large losses over the last few years. The companies still operating in the market take the long-term view that space insurance is a growing market with the potential for large profit in the future. One response to market pressures has been to increase the period of in-orbit insurance from approximately 2 to 5 years. Thus insurers have taken on a higher exposure to in-orbit failures than before, and to space weather effects. In view of recent losses, the trend now is to reduce the period of in-orbit insurance back to 1-2 years.

New technology poses new problems for the insurance industry. New technology is very difficult to evaluate for risk assessment since there is no track record. For example, miniaturization of electronics, and incorporating systems on a chip, pose new risks of radiation damage due to single particle effects that were not apparent in older designs. Furthermore, new regulations in the USA known as ITAR now restrict the transfer of technical information on spacecraft built in the US to other countries outside the US. The restriction of information makes risk assessment even more difficult. Since spacecraft insurance is a global business, and since more than 60% of the global satellite insurance is carried out in Europe, this has a direct impact on the profitability of European business. The insurance market would benefit from a space weather programme that included post-event analysis in relation to space weather events to help evaluate risks in new technology, and identify new risks. This would then help them set competitive premiums.

The insurance industry is now starting to take space weather very seriously. The Marham consortium has just funded two research studies in the UK (at the British Antarctic Survey and at MSSL) into analyzing the risks due to space weather on spacecraft, and to construct and fly radiation monitors on spacecraft to characterise the space environment.

In addition, Swiss Re have just published a new brochure publicising the effects of space weather [Jansen et al., 2000].

4.9.2 Requirements

It is not clear that the insurance industry could make direct use of a space weather prediction and warning service. Given a warning of a space weather event 2 or 3 days in advance, it is difficult for an insurer to arrange re-insurance on that timescale. Furthermore, since all risks must be declared, it follows that warning of a space weather event must be declared for insurance purposes. One possibility is that policies could be developed whereby the premium may be lower if the insured accepted more of the risk during space weather events.

Insurers require more post-event analysis to identify the risk to space and ground systems posed by space weather events. It is also in their interest that insured parties are educated and made aware of the potential risks from space weather.

4.9.3 Benefits for Space Insurance

Warning and prediction would be important for insurance policies that cover operators and other service providers. Since insurance policies require the insured to take all reasonable precautions, warning and prediction would enable operators and other insured parties to take mitigating action and reduce the loss risk. Thus the Insurance industry may benefit financially from a smaller number of loss-claims due to the insured taking mitigating action.

Space insurance would benefit from post-event analysis in relation to space weather events. This would provide them with data to identify and evaluate risks in relation to space weather events, and to identify new risks associated with new technology and its relation to space weather. This may enable them to set more competitive premiums.

A space weather programme would also provide new business opportunities, for example, as more systems are identified as being subject to space weather then there will be new opportunities for insurance in other areas, for example in Launch systems, in-orbit operations, satellite service providers, aviation, power supply and distribution, oil and gas prospecting.

4.10 Disruption to Users of GPS Navigation

Signals broadcast from Global positioning satellites (GPS) are used for navigation and for a variety of other uses. By calculating the time delay between four signals broadcast from 4 different satellites, it is possible to calculate the position at the receiver to an accuracy of about 30m. As the signal passes through the ionosphere, the ionospheric density profile causes delays to the signals and thus contributes a source of error. The error depends on the total electron content (TEC) along the signal path. At mid latitudes the error may be a few TEC units, typically < 1 m. GPS receivers include a correction for the ionosphere, but these corrections are limited to average properties of the ionosphere and ignore changes due to the magnetic field. Single frequency systems are the most widely used since a receiver only costs typically £100. Dual frequency systems are also available, but a receiver costs of the order of £15,000.

Space weather events that cause changes in the total electron content produce errors in GPS signals. In particular, ionospheric irregulatities that cause scintillations can increase positional errors by up to an order of magnitude at high latitudes in the auroral regions, and in the equatorial regions. Scintillation also cause amplitude and phase fluctuations, and can result in loss of signal.

GPS spacecraft are operated by the US military for primarily for navigation and other military requirements. There are also plans for a European GPS system called Galileo. At present, outside the military, GPS is widely used by ships and aircraft, and by individual users. There is a large user market, but since the signals can be received free of charge it is not clear whether there is a commercial market that would pay for space weather predictions. It is unlikely that individual users would use space weather predictions. Only in areas where GPS is used for safety critical systems (such as in aviation discussed above) or possibly military use is there a need for reliable predictions.

4.11 Railways

There is some evidence that railways are affected by space weather. Voltages through relays and railway lines are used to control signaling equipment and indicate train on section. The typical dc voltage over the relays is 2.5-6 V. In one instance an induced voltage is believed to have affected signaling equipment in Sweden in 1982 [Jansen et al., 2000]. However, signaling equipment is designed to fail-safe and there is no proof that there have been any fatalities due to GICs.

The railway companies would benefit from a space weather programme that calculated GICs in railway lines so that they could evaluate the risk of disruption to signaling and train control and devise engineering solutions.

4.12 Tourism

Tourism is an area that may benefit from space weather predictions. Already there is one company in Sweden, Kiruna Forskningsturism, that is willing to pay the University of Lund for forecasts of the aurora over Scandinavia, for periods of 1-3 hours ahead. The tourist company collaborates with commercial airlines, at present SAS, so that the forecasts are passed to aircraft so that passengers can see aurora. They are particularly interested in strong auroral activity such as auroral break-up that can be predicted from the solar wind.

A space weather programme that enables more reliable forecasts from a few hours to a day or more would help the development of the tourist market.

4.13 European Defence

Many space and ground based systems for commercial and civilian use have counterparts adapted for military use. It follows that these military systems are also subject to space weather effects. Although these systems are classified, and details of their operation are unknown outside defence circles, we may provide some assessment of the type of systems affected based on reasoned assumptions, and based on what we know from scientific measurements. There are undoubtedly more defence systems affected than we are aware of.

The defence sector are becoming more susceptible to space weather effects for several reasons, including the increased use of space for surveillance, communications and other needs, use of new technology and miniaturization of components.

From scientific research, some of the military systems affected must include:

Ground-to-ground communications at HF.
Over-the-horizon radar for early warning.
Satellite Surveillance and early warning.
Ground-satellite communications for command and control, and spacecraft operations.
Navigation using GPS.
Submarine communications at ELF and VLF.

The response from scientists associated with US defence is that the majority of US defence interests center on HF communications systems and HF radar.

4.13.1 Ground-to-Ground Communications at HF

HF radio waves, at frequencies from 3 - 30 MHz, are used for communications below the ionosphere over long distances. It is cost effective and widely used by the military to communicate between ground troops, and with aircraft over long distances. Given the vulnerability of satellites to attack and interference during periods of conflict, HF is an important back-up system to satellite communications. It is also used for communications with Embassies abroad. HF signals are used for direction finding to locate the source transmitter. This has applications for identifying the location of military units, both friend and foe, and for search and rescue. HF is used by third world armies and therefore Europe maintains expertise is these systems to intercept, monitor and counter any threat.

HF communications are also used for drug enforcement by security services, for example, by direction finding on signals from ships and light aircraft.

HF signal propagation is affected by irregularities (from cm to km scale lengths) in the ionospheric electron density profile. There are two important effects. Increased ionization in the D and E regions increases the collision frequency and hence increases radio wave absorption resulting in loss of signal strength and radio blackout. Secondly, irregularities in the E and F region ionosphere can change the reflection height, scatter the signal, and change the direction of propagation resulting in loss of signal path between receiver and transmitter. The change in signal direction is particularly important for direction finding.

Sources of ionospheric disruptions that are related to space weather events include increased EUV and X ray emissions due to solar flares, solar energetic particle events that penetrate the upper atmosphere, and particle precipitation from the magnetosphere at auroral latitudes. Precipitation and Joule heating are sources of atmospheric gravity waves that propagate from the auroral region around the world causing ionospheric disturbances. Plasma instabilities are also a source of ionospheric irregulatities at high latitudes, and phenomenon such as plasma bubbles at equatorial latitudes, that result in signal scattering and scintillation.

One of the main benefits from predicting ionospheric disturbances is that the military plan how to re-route communications. For example, signals transmitted over the pole from Europe to the USA may be subject to blackout, but could be transmitted by an alternative set of stations at lower latitudes where the disturbances are less severe.

4.13.2 Over-The-Horizon Radar (OTHR)

Over the horizon radar operates at HF frequencies and uses the ionosphere to refract the signals through the ionosphere and detect targets over very large distances, as far as 4,000 km [Judd, 1983]. There are systems in use in Russia, Australia, USA, UK. Typically the operating frequency may be 6 - 30 MHz. OTHR is used for early warning of attack from missiles and aircraft that provide a strong coherent echo along a return path to the radar. Since OTHR operates at HF frequencies, ionospheric disturbances interfere with operations.

OTHR is also used increasingly by the US Drug Enforcement Agency to monitor small aircraft bringing drugs from central and southern America into the southern USA. Similar operations may be envisaged for European drug enforcement across the Mediterranean.

Experience with scientific HF radars such as SuperDARN in the northern hemisphere, and SHARE in the Antarctic shows that over the horizon radars looking over the polar cap are subject to significant amount of clutter caused by plasma instabilities in the ionosphere. Plasma instabilities, such as the gradient drift and two-stream instability produce irregularities that are aligned along the Earth's magnetic field. When the radar signal is refracted almost perpendicular to the magnetic field, a strong coherent echo is returned. This echo is a source of noise for OTHR. Plasma instabilities of this type, and ionosphereic irregularities are most common at high latitudes, above 60 degrees, in the auroral region, and over the polar cap. Large irregularities also occur at important plasma boundaries, at high latitudes, such as at the plasmapause, the auroral zone, the trough region between the plasmapause and auroral region, and at the polar cap boundary, and at the cusp. The irregularities are significantly enhanced during space weather events such as magnetic substorms and storms.

Atmospheric gravity waves, generated by electron precipitation in the auroral regions during magnetic storms and substorms, cause perturbations in the ionospheric density profile and disturb wave refraction through the ionosphere, and thus affect OTHR. Gravity waves are able to propagate from the auroral to equatorial regions and thus perturb the ionosphere over very large distances.

Large space weather events that reduce the capability of OTHR to detect missiles and aircraft and increase the risk of surprise attack. Advanced warning of space weather events would enable the military to go to higher levels of vigilance, and to use alternative early warning systems during disturbed periods. For example, the use of AWACS aircraft is an alternative means of early warning, but very expensive.

4.13.3 Satellite Surveillance

Low Earth orbiting satellites are used for surveillance, particularly during times of increased tension. Several orbits may be used to obtain the required level of coverage over a particular location, depending on the spatial resolution, and the amount of continuous coverage. High resolution requires low Earth orbit, whereas continuous coverage may require highly elliptical orbits such as the molynia type. Thus the military must encounter the same type of space weather problems in controlling, operating and designing spacecraft as commercial satellite operators and designers do. These effects have already been discussed above.

Satellite surveillance may be required in a number of different applications. Here we discuss how space weather may affect two areas: detection of missile launch using optical methods, and eliminating false positive identification.

4.13.3.1 Missile Launch Detection

Since the boost phase of a missile may be short, we assume only a few minutes at most, there is little time to positively identify a hostile intent. The missile radiation spectrum is similar to a continuous black body radiator and therefore should be detectable using infra-red, optical and ultra violet imaging. This signal must be distinguished from the natural sources of radiation, such as emissions from OH, CO_2 and NO. There are three windows where the natural emissions are very low and where a missile may be identified from its emission spectrum. They include window 1, wavelengths between OH (3.5 um) and CO_2 (4.3um) emission spectra, window 2, between CO_2 (4.3um) and NO (5.3um) emission spectra, and window 3, at wavelengths longer than the NO emission spectra. In general the longer the wavelength the less attractive the window due to technological difficulties associated with detector noise and cooling.

Space weather events that give rise to particle precipitation and Joule heating that increase the background levels of natural emission spectra, and result in additional emission spectra that fill-in the detection windows with natural signals. There are two effects, the first results from direct impact of precipitating electrons on NO that raises the NO emission background and increases the radiation levels in windows 2 and 3. It also excites new transitions called overtones that radiate in window 1. The second mechanism is indirect. As a result of direct impact N_2 is left vibrationally excited and cannot radiate energy away because it has no dipole moment. The N_2 collisionally excites CO_2 and increases the CO_2 background levels that extend into windows 1 and 2. The direct mechanism is fast and decays within a minute of the precipitation, but the indirect mechanism is slow and may last for hours after an event. Both mechanisms are important in daylight as well as at night.

Since the energy required to excite these emission only needs to exceed a few tenths of an eV, particle precipitation, optical aurora, and Joule heating that occur during substorms are particularly important. The mean time between substorms is approximately 5 hours. During magnetic storms, the effects are particularly intense. Aurora are produced by particle precipitation, mainly electrons, and therefore can be used as a tracer for precipitation events. Aurora occur along the auroral oval, and sometimes across the polar cap as theta aurora. The aurora can be broad and diffuse, but during substorm disruption, can be highly dynamic. Typically, the aurora may intensify, expand equatorwards, and appear to propagate westward (eastward) from local midnight with the westward (eastward) traveling surge on timescales of seconds. The aurora is highly structured, with filament widths as narrow as 1 km.

Space weather events reduce the capability of surveillance satellites to detect missile launches from auroral latitudes. Submarines and other mobile systems are able to use this reduced detection capability at high latitudes as an advantage. A space weather programme would produce advanced warning of this reduced capability, enable time to use alternative surveillance methods, and enable warnings of periods when a higher state of vigilance is required.

4.13.3.2 Elimination of False Positive Identification

Apart from missile launch detection, satellite surveillance is probably required for a variety of reasons, for example, monitoring the atmospheric test ban treaty, assessment of capability by other nations, intelligence, etc.. By analogy with civilian sensors, optical and other sensors used by the military are probably subject to interference from energetic charged particles during SEP events, and during magnetic storms. Examples of this type of interference have been well documented in the SOHO instruments observing of the sun, where energetic particles create flashes in the instrument detectors. These interference signals could be falsely identified as a missile launch, or hostile act in military applications.

A space weather programme that provides warning of space weather events, and on-line access to data such as the particle flux in space, would help the military eliminate a false positive identification of a hostile act.

4.13.4 Ground-Satellite Communications at UHF

Ground satellite communications, particularly for command and control, must be of the utmost importance for defence. Military communications must be subject to similar problems as civil use, for example, loss of signal due to phase and amplitude scintillations. Prediction and warning would enable the use of alternative systems.

4.13.5 Navigation and Targeting using GPS

The dual frequency GPS system used for military purposes enables real time corrections for the ionosphere and enables an accuracy of less than 1 m. However, scintillation due to plasma instabilities may still cause loss of phase lock and signal amplitude disrupting navigation.

Due to its high accuracy, GPS is probably used for targeting for cruise missiles. For example, although cruise missiles use terrain maps and inertial guidance, the terrain may change during a conflict and inertial guidance may not provide enough precision for a cruise missile to hit a specific target. GPS, with accuracy down to less than 1 m, undoubtedly does provide the required accuracy.

GPS is also used by soldiers and therefore has importance on the battlefield.

A space weather programme that includes predictions of scintillations and disruption to GPS systems could therefore be important for targeting. It may be a factor that would be taken into account for timing of attacks.

4.13.6 Submarine Communications at ELF and VLF

Communications with submarines are conducted at ELF frequencies of the order of 80 Hz, and VLF frequencies at 16 – 24 kHz or so from transmitters located around the globe. ELF and VLF frequencies are used since lower frequencies have a greater penetration depth in sea-water than higher frequencies. Hence submarines can receive signals within a few tens of metres below the surface, but still remain submerged to avoid detection.

ELF and VLF signals can also propagate very long distances around the world. For example, signals from VLF transmitters in the northern USA and Europe are routinely detected in the Antarctic. Direction finding using scientific VLF receivers shows that several countries have VLF transmitters, including USA, UK, France, Germany, Italy, Russia, and have recently started operating in India, and China.

ELF and VLF signals propagate in the Earth-ionosphere waveguide as waveguide modes. The number of modes may vary according to ionospheric conditions. Changes to the ionosphere change the phase and amplitude of the signals, and can cause loss of phase lock. For example, signals propagating across the day-night terminator can experience 180 degree change of phase. ELF and VLF propagation are affected by changes in the electron density profile in the lower ionosphere, in particular by electron density changes caused by electron precipitation from solar energetic particle (SEP) events at high latitudes, precipitation from the magnetosphere (including lightning induced precipitation), enhanced ionization in the lower ionosphere due to solar X ray flares, and gamma rays bursts from neutron stars. While solar X rays may cause disruption to signals for periods of minutes, SEP events may disrupt communications for several days. Gamma ray bursts are sufficient to cause loss of phase lock and changes in signal amplitude by as much as 20 dB [Inan et al., 1999].

A space weather event that disrupts communications with submarines for days may have serious consequences. The submarine may be forced to break surface using buoys to communicate via satellite, thereby increasing the possibility of detection. Space weather predictions may enable the submarine to plan alternative strategies, or re-arrange communications schedules in advance.

5 Strategic Benefits

The growth in the number of spacecraft planned for launch over the next few years shows that European business is making a considerable investment in space systems. The trend for launching larger telecommunications satellites, with longer lifetimes of up to 20 years, the use of new technology in small and micro-satellites, and the miniaturization of electronics that is more susceptible to radiation damage than before, are just some of the reasons why space weather is becoming more and more important in the longer term. Once commercial organizations fully appreciate the importance of space weather and the damage it can do, it is inevitable that there will be a stronger demand for reliable warnings, and for post event analysis to assess cost implications. A European space weather warning and prediction service that has all the necessary elements in place will be ideally suited to respond to these requirements, and ideally placed to develop commercial spin-off companies to exploit the demand. A space weather programme will provide infrastructure for the future protection of space and ground technological systems.

At present there is no coordinated European Centre or network that can match the service provided by the US NOAA center in Boulder. There are several reasons why Europe would benefit from such a Centre or Network of Centers, including the development of commercial spin-off companies, European autonomy, leadership, co-operation within Europe and outside, and European defence. These benefits are discussed below.

5.1 Commercial Spin-off

There are already examples of commercial spin-off companies in the field of space weather. It is interesting to analyse the experience of one of these companies since it can provide important information on more general requirements, and has implications for the structure a European Space Weather programme.

The power supply industry is one example of an industry that uses space weather predictions, and now has well defined needs. It is also an example where there are contracts to companies and University Groups for predictions and analysis. For example, Scottish Power use predictions provided by the British Geological Survey, Edinburgh, and National grid uses predictions of GICs from a US company Metatech. Nuclear power companies also use prediction services, e.g., OKG AB uses IRF Lund for predicting halo CMEs, with a warning of 2-3 days, and Metatech software for predicting GICs. Oil and gas pipeline companies also have contracts with University Groups to provide analysis. Here we examine the experience of the National Grid Company in England, and the services offered by Metatech as an example. The general principles can be applied to other market sectors.

The National Grid uses space weather predictions because they save more money than they lose through the adverse effects of GICs. Typically they spend of the order of £100k/year on these predictions. The same principle of cost-benefit must apply to all commercial companies. Unfortunately, trying to find out how much a company looses due to space weather is very difficult, and is commercially sensitive, particularly where there is strong competition. The National Grid is remarkably open about what it spends on space weather, mainly because it is the only network supplier in England. Given that there may up to 100 such companies world wide, this suggests a market of at most £10M in this particular area.

Companies such the National grid, and oil and pipeline distributors do not employ operators that are skilled in space weather, or solar terrestrial physics. Therefore the type of information provided by some of the space weather centers is of little value. E.g., the predictions that there is a CME, or that the solar wind dynamic pressure has increased beyond a certain level does not convey much meaning. Instead, they need to know how strong the GIC is going to be on all parts of the power grid or pipeline, so that they can decide when to take mitigating action. In other words they require tailored needs. Operators require the data in a form that is easily understandable. For example, it is much easier to understand a map of the grid system, with colour coding for different levels of predicted GIC, so that they can then take action. It should also have feedback.

For example, if part of the network is disconnected, then this should also be reflected in the predicted levels of GIC. This is generally applicable to many other fields. Companies need predictions on a timescale that they can use. Thus if data is required from satellites as input to a model, this must be taken into account. The timescale may rule out the use of certain types of models, such as a physical model that requires extensive cpu time, in favour of empirical models or artificial intelligence. Operators also require reliable predictions, and will not tolerate many false alarms. Reliability may have more than one definition. However, provided the predictions capture a sufficient number of events so that over-all the Company using the predictions saves money, then this gives the baseline for a reliable service.

Companies such as Metatech provide tailored services. They make predictions of GICs at many locations on the power grid network, between 100-1000 locations. They run their own prediction models, the details of which are commercially sensitive and not available. However, the models require data from upstream solar wind monitors, currently provided free by the space environment center at NOAA, and ground conductivity models. The models are used to predict the currents in the auroral current system, and the rate of change of magnetic field associated with changes in the electrojet currents. These predictions are combined with detailed information about the power supply network from the companies concerned in order to calculate the GICs at many different locations. By using data from the L1 position, and relatively simple models that do not require extensive computational time, it is possible to obtain predictions between 3-24 hours ahead.

In summary, spin-off companies, such as Metatech, may grow in number to provide tailored services to specific users. There are possibilities in each market sector where losses have been identified as being related to space weather, and where the losses are sufficiently large to justify paying for specialized services.

A European space weather programme could help the development of spin off companies. It could provide continuous coverage of data from spacecraft and ground based instruments that may be critical for predictions. It can provide basic models and prediction techniques. It could help develop new predictive models with greater reliability that could feed into spin off companies. Where Europe is the only source of data or reliable models, it offers the opportunity of a financial partnership between the Space Weather programme, the spin-off company, and the market; a public private partnership.

5.2 European Autonomy

Several nations have their own space weather programmes, notably the US, Russia and Japan. However, it is noted that in the US nearly all the measurements that are critical for a space weather prediction service are made by US space missions and US ground observatories. For example, NOAA operates its own spacecraft in geostationary orbit, it has 8 dedicated forecasters, data analysts, and a dedicated research effort into space weather forecasting. It has control over critical measurements, except for measurements upstream in the solar wind where it relies on observations from scientific missions such as ACE. At present the data and predictions are freely available. However, Europe is reliant on other nations for continuous coverage of data from critical regions. So long as Europe relies on the US (and other national programmes) for data it will be subject to US interests and political will.

A European space weather programme would provide Europe with some measure of autonomy in protecting its space investment. In some cases there may be measurements that are critical for space weather predictions and may justify observations by more than one spacecraft in case of failure. For example, observations upstream in the solar wind may be considered sufficiently important for predictions and spin-off companies that they require European and US missions. Conversely, if a spacecraft were to fail, replacement missions may take years before they are operational. In other cases measurements by a European spacecraft may complement those made by other nations and provide European autonomy, for example, in the Earth's radiation belts.

5.3 European Leadership

There is scope for European leadership in some aspects of space weather. For example, between 1987 and 1993 there were 126 storm forecasts by SEC Boulder. 27% were correct, 63% were false alarms [Joselyn, 1995]. In 1999 the SEC predicted 3 major storms. In fact there were 5 major storms, and none of these 5 were predicted by SEC. In the first 3 months of 2000, SEC Boulder only managed to get 26% of storm forecasts correct, despite having data from an L1 monitor [J. Joselyn, presentation at NATO ASI Conference, 2000]. These statistics show that the current state of predictions is very unreliable.

Europe has key scientists, world leaders, in every discipline needed for a space weather programme. It has a proven track record of international collaboration in space science through SOHO and CLUSTER and other missions. It has experience with database facilities and is continuing to develop computer models. Given a properly focused space weather programme that takes into account user needs, and continued research, and brings together new ideas and a new perspective, there are opportunities for European leadership.

5.4 Co-Operation

European autonomy can be achieved in the spirit of cooperation and collaboration. Sharing data does not prevent independence. The US example has demonstrated that sharing data leads to exchange of ideas and has strengthened its position as the leading center. A European programme should follow the same principle.

The U.S. space weather programme, 'Living With a Star', has now won presidential approval but has not yet been approved by Congress. It is estimated to cost US$1.5B. A proposal for a European programme that provides complementary missions, data analysis and models to satisfy European autonomy, but collaborates with the US programme to reduce cost, is now timely. It will also enable Europe to be seen as an equal partner.

A European programme would also stimulate collaboration within Europe, and between ESA member states including Canada. Europe has many centres of expertise in solar terrestrial physics, plasma physics, atmospheric physics, modeling, and database centers. It already has university groups and government organizations working of research directly related to space weather, and offering predictive services. However, these groups are geographically spread across Europe. A European programme could stimulate the development of new international teams with complementary backgrounds, and enable cross-fertilisation of ideas, and techniques. It would enable closer European integration for both science and the businesses they offer services to.

6 Benefits for Defence

The US military recognize the importance of space weather. They conduct research at the Air force Research Lab at Hanscomb and provide an operational capability at the 55th Space Weather squadron stationed in Colorado. The 55th SW squadron is staffed by 57 personnel and provides space weather environmental analysis, forecasts and warnings for the US DoD and other Federal agencies. They work closely with NOAA and often provide joint forecasts. The report from the US "Commission to assess the United States National Security Space Management and Organisation" set up by Congress in 1999 has now recommended that the Air force consolidate the various space offices into one single organization [report, 11 Jan, 2001]. Space weather will be an important part.

In addition to the detailed analysis of defence requirements, there are also more general issues. The defence sector in each European country would benefit from an ESA Space weather programme in three ways. First, a European programme would provide additional data, models and interpretation that could be used by each nation. Second, a civilian programme would enable the free exchange of data from the scientific community around the world. The defence sector would be able to draw on these additional sources of data that may not be directly available otherwise. Third, a European programme would draw together scientific expertise and stimulate new research in space weather, and the underlying physics. The defence sector would benefit from new advances in the related fields.

Space weather offers Europe an opportunity for greater co-operation between member states national defence.

7 Benefits for Scientific Research

Space weather is considered by most scientists to be applied research. However, it draws heavily on basic research in solar terrestrial physics, several important branches of plasma physics and some aspects of solid Earth geophysics. Solar terrestrial physics here includes solar, interplanetary, magnetospheric, ionospheric and atmospheric physics.

A European space weather programme will highlight several basic physical processes that need to be understood in order to improve predictions. Examples of where basic understanding needs to be improved to underpin space weather include:

The physics of CMEs,
The evolution of the solar wind from the sun to the Earth
The relationship between storms and substorms
The acceleration of electrons to relativistic energies
The loss processes that govern the structure of the radiation belts
The electrodynamic coupling between the magnetosphere and ionosphere

One of the benefits of stimulating research in these areas is that it will enable the development of better physics based models. These models can then be adapted for more reliable prediction models.

A Space weather programme will also stimulate research into more applied areas. For example, to find better proxy measurements for parameters which are not easily measured, to develop better empirical and artificial intelligence models for prediction.

It has been noted that changes in the solar magnetic field might be related to changes in the Earth's climate [Lockwood et al., 1999]. Such studies on global climate change are an important area of research that has captured public and political attention. They require long-term datasets from a variety of sources, including solar terrestrial physics. A space weather programme also requires long-term datasets from the ground and in space for analysis of risk and feedback into design. Global climate change would benefit from continual long-term measurements that are required for space weather, and for new assessments of energy transfer that a space weather programme, with new models and new observations, could enable.

8 Publicity Benefits

A European space weather programme offers the opportunity for greater publicity and education. This would have several benefits:

One of the results identified from our user study was the need for more education due to market fragmentation, i.e., the trend in recent years for large companies that once provided end-to-end solutions within the same company to be broken down into smaller size companies with greater specialization. One example is the break-up of Bell Labs in telecommunications. There has also been a trend for companies to sub-contract tasks that had once been undertaken inside a larger company. As a result, some of the engineering expertise held in the original companies has not been passed on to sub-contracting companies. In addition, new business managers have been brought in who are driven by commercial pressures and are not familiar with space weather and how affects their business operations.

There is also a need for space weather education in industries and companies that provide services for the space market. For example, during one meeting we attended with Insurance brokers covering a major share of the launch and in-orbit satellite insurance market it was stated on a viewgraph that nearly all spacecraft failures can be put down to human error. However, there are many examples of failures that occurred during space weather events, as cited earlier in this report [e.g., Wrenn, 1995; Wrenn and Smith, 1996; Baker et al., 1998].

A European space weather programme that included European space missions, and a series of space warnings and alerts would gain public attention. The US Space Weather Centre at Boulder, Co., already achieves international media coverage for some of its alerts and warnings, although at present the warnings are unreliable. Similarly, a European programme that issues alerts and warnings, provided they are reliable, could also be used at the same time to promote European science and technology across the world.

A recent report in the UK has highlighted the need to attract students to study physics and engineering at school and University in order to provide a pool of skilled labour for later employment in the space sector [UK House of Commons Select Committee Report, 2000]. The glamour and appeal of astronomy and space science is one of the main reasons why young scientists take up physics based subjects [Wilkinson, 1996]. A strong European space weather programme that includes an educational outreach programme, and a strong publicity element, would help continue to attract good students and fulfill this need.

The general public show great interest in space and space science. This is reflected in media coverage. For example, there was national coverage on TV and radio of the total eclipse of the moon in 1999 in the UK. Again the spectacular failure of CLUSTER in 1996, and the launch of CLUSTER II in July 2000 gained international media attention. A space weather programme that includes a scientific, monitoring, prediction, and post event analysis elements, together with a clear aim to protect our European space investment is more likely to gain public support than a pure science mission. The public could understand the need to carry out basic research into the sun, interplanetary medium, magnetosphere, ionosphere and atmosphere in order to protect technological systems such as telecommunications, and domestic power supplies that affect their daily lives. Continued education and publicity directed towards space weather, and its practical effects, is likely to lead to support for ESA.

The benefits of publicity can be summarized as follows:

1. Education of business managers in the effects of space weather.
2. Promote European science and technology across the world.
3. Attract young scientists and engineers into physics based subjects and provide a pool of valuable labour for the commercial space sector.
4. Provide greater public support for ESA.

9 Timeliness

The number and severity of space weather events will peak during the next few years during the start of the declining phase of the solar cycle. The time is now ripe to highlight the importance of space weather and to put in place the steps needed to develop a European programme. The cost of not doing so will increase, through direct losses and through knock-on effects, as our society becomes more reliant on satellite systems, and as the number and breadth of application of those systems increases

There is evidence for increased awareness of space weather at the international scientific level. For example, this year (2000) there are scientific sessions on space weather at several international meetings, including the Chapman conference in Florida, the NATO ASI on space storms in Crete, the SRAMP meeting in Japan, the EGS meeting in Nice, and the COSPAR meeting in Warsaw. The time is right to build on this awareness and focus scientific effort.

The best way to stimulate research and focus effort is to provide additional research and applications funding for high priority areas.

10 Summary

The benefits identified in this report are summarized by market sector in Table 2, and more generally in Table 3.

Table 2.
Summary of Benefits by Market Sector

Market Sector	**Benefits of a Space Weather Programme**
Satellite Design	Prevent over-design Establish common design standards More reliable satellite operations Achieve longer design life Identify risks due to new technology
Satellite Operators: • Communications • Broadcasting • Navigation • Remote sensing • Science	Reduced risk of anomalies and failures More reliable service provision Reduction in lost revenue Extended satellite lifetime More competitive service Better planning for orbit manoeuvres Reduced risk of uncontrolled re-entry Better station keeping Conservation of fuel Reduced risk of collision damage with debris
Space Agencies: • Man in Space	Reduced radiation exposure to astronauts Reduced cost of re-scheduling astronauts Reduced risk of impact by space debris
Launch Operators	Reduced radiation dose to astronauts Optimisation of launch procedures
Civil Aviation	Reduced radiation exposure to aircrew and passengers Compliance with legislation Reduced cost of having to re-schedule aircrew Increased flight safety
Power Generation and Supply	Better service continuity Minimise lost revenue due to down time Reduced risk of transformer damage Better planning of generating capacity Identify system behaviour Identify total risk Identify links to space weather
Aerial Prospecting	Better planning of aerial surveying Reduced loss of revenue due to corrupt data

Drilling for oil and gas	Reduced interruptions to drilling operations Reduced loss of revenue due to errors in navigating drill heads.
Oil and Gas pipelines	Identify worst case scenarios Better design of protection systems Reduced pipe corrosion Cost savings through extended pipe lifetimes
Space Insurance	Reduced loss-claims due to insured taking mitigation action Data to identify and evaluate risks associated with space weather Identify new risks associated with new technology Identify new business opportunities Development of more competitive policies
Defence	Reduced risk of false positive hostile act Better planning and re-routing of HF communications Better planning of alternative methods for early warning Better planning of alternative methods for detecting missile launch Better planning for targeting and offensive planning Reduced risk of submarine detection
Railways	Increased safety of signaling and train control
Tourism	Enables predictions of the aurora Development of tourist market

Table 3
Summary of Benefits

	Benefits
Economic	Improved satellite design Improved satellite operations Improved health and safety for astronauts and aircrew Improved reliability of utilities Commercial gain to a variety of industries and business
Strategic	Provision of European infrastructure Opportunities for commercial spin-off European autonomy European leadership More collaboration between ESA member states (including Canada) More collaboration between Europe and external countries
Defence	Greater European co-ordination Access to additional data Access to data through scientific networks not otherwise available Draw on advances in civilian research
Research	Stimulate basic research in critical areas Stimulate applied research into prediction and event analysis Stimulate the development of models
Publicity	Education of public and business managers on the effects of space weather Promote European science and technology across the world Attract students into science and engineering to form a pool of skilled labour Provide greater public support for ESA

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Appendix 1

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Consultant	Organisation	Field	Country
Dr D Bartlett	National Radiological Protection Board	Radiation protection	UK
Mr S Clapham	Marham Consortium	Space insurance	UK
Dr T Clark	British Geological Survey	Oil and gas drilling. Pipelines	UK
Dr M Clilverd	British Antarctic Survey	ELF/VFL waves	UK
Dr I A Erinmez	National Grid	Power generation and supply	UK
Dr P Espy	British Antarctic Survey	Defence	UK/Canada
Mr A Fletcher	Wrenn Aerospace	Space Insurance	UK
Dr D Flower	British Airways	Civil Aviation	UK
Dr M Freeman	British Antarctic Survey	Solar Terrestrial Physics	UK
Mr L M Garcia	Eumetsat	Satellite operations	UK
Mr D Hope	Inmarsat	Satellite communications	UK
Dr R Hunter	Civil Aviation Authority	Civil aviation	UK
Dr B Jones	Virgin Atlantic	Civil aviation	UK
Prof T B Jones	U. of Leicester	Ionospheric propagation and Defence	UK
Prof. L Kersley	University of Wales, Aberystwith	Ionosphere and GPS	UK
Prof. S Quegan	University of Sheffield	Remote sensing	UK
Dr A Rodger	British Antarctic Survey	Solar terrestrial physics	UK

Dr N Watkins	British Antarctic Survey	Solar terrestrial physics	UK
Mr J-M Bara	Air France	Civil aviation	France
Mr M Belfort	France Télécom R&D	Satellite operations, Communication	France
Dr C Berthou	Alcatel	Satellite Engineering	France
Dr J Cadet	CEA	Biological effects of radiation	France
Mr O Carel	DGAC	Transport	France
Mr M Chateaureynaud	SNCF	Transport	France
Mr A Dedryvere	DGAC	Transport	France
Mr R Ecoffet	CNES CT	Space environment and radiation effects	France
Mr G Jugie	IFRTP	Consultant	France
Mr P Veyre	Météo-France	Satellite operations, Meteorology	France
Mr L Vigroux	CEA SAP	Nuclear	France
Dr V Bothmer	University of Keil	Solar and heliospheric physics	Germany
Mr B Heini	Swiss Re	Space insurance	Germany
Dr P Maldari	ESOC	Satellite operator	Germany
Mr W Allvin	Kiruna Forskningsturism	Tourism	Sweden
Mr H-E Edwall	Sydgas AB	Gas pipelines	Sweden
Mr M. Palsson	Esrange	Satellite operator	Sweden
Mr P Sigenstam	Sydkraft Elnat AB	Power generation and supply	Sweden
Mr H Swahn	OKG AB	Nuclear power generation	Sweden
Mr L Wallin	Svenska Kraftnat	Power generation and supply	Sweden
Dr D H Boteler	Geological Survey of Canada	Pipelines Power supply	Canada
Mr B Burlton	Telesat Canada	Satellite operations	Canada
Dr J Evans	Telesat Canada	Satellite design Satellite operations	Canada
Dr R Gubby	Telesat Canada	Satellite design. Satellite operations.	Canada
Dr N Fox	APL	Education outreach	USA
Dr P Kappenman	Metatech	Power generation and supply Pipelines	USA
Dr J A Joselyn	NOAA	Space weather	USA
Mr C Kunstadter	US Aviation	Space insurance	USA

	Underwriters		
Dr S Quigley	AFRL	Defence	USA
Dr. G Reeves	Los Alamos	Defence	USA
Dr R Sawyer	Lockheed Martin	Satellite design	USA

Appendix 2

Aide Memoire

Compiled by Dr R B Horne and Mr A Shaw.

QUESTIONS/ POINTS TO COVER	**NOTES**
1. Background information	
1.1 Purpose of the study	We are part of an international team drawn from Science and Industry who are conducting a study on behalf of the European Space Agency (ESA). The object of the study is to evaluate the detailed requirements for an ESA Space Weather Programme, to assess the opportunities and benefits of such a programme, and to establish a cost-effective plan to implement it. We define Space Weather (SW) as *"Events originating from the sun that may damage space-borne and ground-based technological systems in the near Earth space environment and, in the worst case, endanger human life and health"*. We understand that your business or organisation may be affected by space weather events and therefore ask if you would help us by considering the questions below, and by participating in a telephone interview.
1.2 Name of interviewer	
2. Company information	You and your company will be acknowledged in our report to ESA, unless you request otherwise. The information you give will be shared within our consortium and with ESA.
Name	
Position	
Company/ Organisation name	
Telephone Number Email	
Business activities	
Company size in terms of:	• Number of employees

	- Annual turnover (€)
3. Knowledge about Space Weather (SW)	
3.1 *Have you heard about Space Weather before ?*	
3.2 *Do you use a Space Weather prediction service now ?*	(Please also answer section 6 later on)
3.3 *What are the most important problems affecting your operations or business that could be related to SW ?*	(See Table 1 for examples)
3.4 *How do the problems affect your operations or business ?*	Operational impact Economic impact Health and Safety (See Table 1 for examples)
3.5 *Please describe how you deal with the problem now?*	
3.6 *Do the problems you describe represent a significant risk to your business or operations ?*	High Medium Low Not known
4. Prediction of SW events	
4.1 Would some form of prediction or warning help you mitigate the problem ? If so –	
4.2 What action could you	(See Table 1 for examples)

take to mitigate the problems ?	
4.3 What information do you need ?	
4.4 What timescale do you need ?	Event in progress (Nowcast) 0-24 hours (Warning) 2-3 days (Forecast) 1 month Other
4.5 How high does the probability that a given event will occur need to be before you consider taking action ?	> 95 % (2 sigma) > 68% (1 sigma) > 10%
4.6 What type of benefits would you derive from SW warnings or predictions ?	(See Table 1 for examples)
5. Analysis of SW data and events	
5.1 *If your data could be analysed to find correlations with previous space weather events, would this be useful to you ? If so how?*	Help understand the cause of the problem Identify new risks Open up new market opportunities Other
5.2 If your data were found to be linked to space weather events what action could you take ?	No action Develop engineering solutions (long term) Take out insurance Implement new protection procedures Consider using a warning or prediction service Other
5.3 If your data were found to be linked to space weather events, can you give examples of how you would modify your	

operations or engineering programmes	
5.4 If it were possible to provide the following capabilities, which would be of interest to you ?	Data collection on space weather events for your own analysis Modelling of space weather events for impact assessment Specialist service tailored to specific needs Other
6. Users of Existing Space Weather Forecasts or products	
6.1 Which organisation or company provides the forecast or products ?	
6.2 Please provide a contact name	
6.3 What type of forecast or product do you use ?	
6.4 Do you obtain predictions of certain parameters, if so what parameters ?	
6.5 How often do you act on the predictions ?	
6.6 Do you pay for the predictions? If so, how much ?	
6.7 How long have you used predictions ?	
6.8 Do you know of other companies that use SW forecasts or products ?	
7. Potential impacts of SW and level of risk	
7.1 Can the risks of SW be ranked according to	

importance or impact on your operations or business ?	
7.2 Can you quantify the assets and services at risk from a major SW event ?	For example, the magnetic storm of 13 March 1989 that knocked out the power supply in Quebec was estimated to have caused up to $5 billion damage both directly and as an indirect consequence of the event.
7.3 What non-quantifiable risks are there ?	E.g. Impacts on human health
8. Maturity of the Industry	
8.1 How do you rate the maturity of current space weather services ?	Research stage Showing potential Pre-operational Operational Established
8.2 How would you rate the knowledge and understanding of Space Weather products and services by other companies in your sector ?	No knowledge Very little knowledge Good knowledge
8.3 What is your view on the potential for European SW products and services ?	No potential Small potential Good potential
8.4 What is your view on the impact of competitive information sources ?	Difficult to see how Europe could compete Clear opportunities exist Should be complementary with other services
9. Drivers for a European SW programme	
9.1 In principle, would you support ESA in developing a SW programme ?	
9.2 If ESA did develop a SW	Better protection of technological investment

programme for warnings and post event analysis (including new satellite missions, data processing, and modelling), in what way might your business or organisation benefit ? *Tick all that apply*	Opportunity to test new space technology Identify new risks Provide new market opportunities Better understanding of the space environment Cross fertilization between scientific research and industry Other
9.3 In your view, what should be the main objectives of an ESA SW programme?	
9.4 What other partners should be involved ?	
9.5 What could your company or organisation bring as a potential partner in a programme ?	
9.6 What are your views on the most appropriate way for ESA to co-operate with potential users ?	Involve industry representatives in programme operation Encourage commercial services to be brought to market Provide SW services directly to users Provide SW services through a public service entity (e.g. Eumetsat)
10. Closing questions	
10.1 Are there any other questions/points you would like to make?	
10.2 Can you recommend anyone else that we should speak to?	
10.3 Would you like to be involved in future developments of the study?	For example, we are interested in setting up a User Forum – would you be happy to participate in such an initiative? If not, would there be a more appropriate contact (e.g. industry representative body?).

Table 1
Examples of Space Weather effects

Table compiled by Dr R B Horne, British Antarctic Survey.

Market Sector	Problems encountered	Possible Causes	Type of warning or prediction	Possible Action	Benefit
Launchers	Radiation damage	Energetic protons	Radiation environment	Delay launch	Reduced risk of radiation damage
	Increased atmospheric drag on launch	Atmospheric heating. Joule heating. Particle precipitation.	Atmospheric density and temperature profile	Modify launch sequence	Optimised launch
Satellite manufacturers	Anomalies: Satellite surface charging	KeV electrons	Low energy radiation environment		
	Anomalies: Deep dielectric charging	MeV electrons.	Radiation environment		
	Anomalies: Single event Upsets or latch-up	Cosmic rays. MeV protons.	Radiation environment		
Satellite operators: Ground control	Station keeping ?	Increased atmospheric drag	Atmospheric temperature and density	Delay or bring forward orbit manoeuvres	Conserve fuel. Better station keeping.
	Uncontrolled re-entry	Increased atmospheric drag	Atmospheric temperature and density predictions	Orbit manoeuvre	Controlled re-entry.
	Satellite anomalies	KeV and MeV electrons. Cosmic rays.	Radiation environment	Switch off non-essential systems.	Protect satellite systems.
Satellite operators: Navigation	Loss of phase lock and amplitude	Ionospheric disturbances.	Ionospheric disturbances		

(GPS)		Scintillations.			
	Increased error at low elevations	Ionospheric disturbances	Ionospheric disturbances		
Satellite operators: Telecommunications	Loss of data	Ionospheric disturbances. Irregularities.	Radiation environment. Ionospheric disturbances	Re-route communications via other satellites and ground networks	Better continuity for service provider.
Satellite operators: Remote sensing	Loss of data	Ionospheric irregularities	Ionospheric irregularities		
Man in space	Radiation dose	MeV protons. Cosmic rays. Energetic electrons. X rays	Radiation dose	End space walks. Use protective shields.	Reduced radiation exposure to astronauts
Aviation	Radiation dose	MeV protons. Cosmic rays. Energetic electrons ? X rays ?	Radiation dose	Re-route aircraft. Fly at lower altitudes.	Reduced radiation exposure to aircrew and passengers
Power generation	Geomagnetically induced currents	Ionospheric currents. Magnetic field fluctuations	Geomagnetically induced currents. Field fluctuations.	Plan power generation	Service continuity
Power supply networks	Geomagnetically induced currents	Ionospheric currents. Magnetic field fluctuations.	Geomagnetically induced currents. Field fluctuations.	Active potential control ?	Service continuity
Oil and gas prospecting	Magnetic field fluctuations	Magnetopause compression. Changing ionospheric currents.	Magnetic field fluctuations. Ionospheric currents.	Apply magnetic field corrections	

Oil and gas pipeline distribution	Geomagnetically induced currents. Pipeline corrosion.	Ionospheric currents. Magnetic field fluctuations.	Geomagnetically induced currents.	Active potential control ?	
HF radio communications	Loss of signal strength. Loss of signal path.	Ionospheric absorption. Ionospheric irregulatities.	Maximum useable frequency (MUF). Alternative path predictions ?		Service continuity.
Insurance	Launch failure. Loss of in-orbit satellites. Reduced satellite lifetime.	Energetic protons. KeV electrons. MeV electrons. Cosmic rays.	Periods of increased risk to launchers, in-orbit satellite failures, and loss of service.	Re-insurance for periods of predicted high risk ?	Reduced financial loss. Competitive premiums.
Tourism	Optical aurora	Particle precipitation	Probability of optical aurora	Observations	Financial gain. Market development
Railways	Signal failures	Induced currents in the track.	Ionospheric currents. Magnetic field fluctuations		