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Abstract

Space weather is directly concerned with the effects of solar-terrestrial relations on technological systems and human well-being. The benefits to be gained by the implementation of a European Space Weather Programme are described. These benefits can be broadly divided into strategic, technological, scientific, economic and educational categories and affect user groups including pan-European organisations, governments, defence forces, businesses and also individual citizens.

The programme would reduce European dependence on non-European sources of space weather information and by bringing together different areas of expertise, provide a stimulus to the growth of high technology enterprises. The programme execution would encourage advances in space and information technology and the completed system would provide great opportunities for scientific progress. Economic benefits would result from gains in reliability of technological systems such as spacecraft and power grids and in the managed use of radio systems, which include HF and satellite communications, radars and global navigation satellite systems. Additional benefits include the better knowledge of ESA and space issues amongst the general tax-paying public.

Executive summary

Space Weather is defined 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 or health" [1]. This report describes the benefits obtainable from the implementation of a European programme for the monitoring and prediction of space weather effects.

Benefits from a European space weather programme may be felt by a wide range of users: pan-European bodies, governments, armed forces, multi-national companies, small and medium-sized enterprises and individuals. Benefits are: strategic – affecting Europe's industrial, military, technological and scientific independence; economic – affecting the costs consumers must pay for services and the competitiveness of the businesses in which they work; technological – affecting the development of new products and industries; scientific – affecting pure and applied research in a wide range of areas; and educational – affecting people's understanding of science, space and how space weather impacts their lives.

Strategic benefits include:

- The reduced dependence on non-European resources for forecasting, warning, reporting and analysis of space weather effects and hazards. Such information is currently predominantly non-European in origin.
- The strengthening of ESA's role in co-ordinating European space co-operation.
- Improved competitive advantages for pan-European organisations and businesses.
- Improved effectiveness and independence of European defence forces.
- Improved competitiveness of European industry through the bringing together of expertise from a wide range of disciplines.
- Opportunities for growth of European industries in high-technology fields, such as information systems, space platforms, sensors, launch services and ground segment equipment.
- The strengthening of relations with non-European nations through co-operation agreements, industrial partnerships and scientific exchange.
- The raised profile of European capabilities in space.

Technological and scientific benefits include:

- The opportunity to increase the robustness of technology, to optimise its performance and to understand its limitations.
- The development of new sensors, new platform technology, such as micro- and nano-sats, and new data handling technology.
- Monitoring of the effects of technology on the space environment.
- The development of novel technologies that exploit changes in space weather and, potentially, technologies which modify space weather phenomena.
- The stimulus of basic science through improved data availability.
- The improvement of physical modelling and use of data-driven models.
- The improved resilience of scientific missions.

Economic benefits include:

- Reduced satellite operations costs, increased satellite reliability and extended lifetime.
- Greater launcher reliability.

- Reduced radiation exposure of astronauts, giving reduced cancer risk, longer working life, reduced medical costs and lower risk of legal action.
- Decreased risk to aircraft safety and decreased radiation exposure of crew.
- Improved accuracy and reliability of global navigation satellite systems.
- Improved air and marine safety and military effectiveness through better use of radar systems.
- More efficient use of HF and satellite radio communication systems.
- Decreased risk of disruption of terrestrial power grids.
- Improved competitiveness of spacecraft insurers.

Educational benefits include:

- Improved continuing professional development for scientists and engineers.
- A raised profile of ESA and space among the tax-paying public.
- A greater emphasis on space weather in university courses.
- Improved awareness of basic science and space issues among school students.
- A stronger presence for European space activities on the world wide web and thus visibility to the world at large.

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[1] Office of the Federal Co-ordinator for Meteorological Services, "National Space Weather Program Strategic Plan", Report FCM-P30-1995, Washington D.C., USA, August 1995.
http://www.ofcm.gov/nswp-sp/text/a-cover.htm

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1 Introduction

1.1 Purpose

This technical note details the results of WP 110: 'Benefits Evaluation' of the ESA Space Weather Programme Study, ESTEC contract No. 14069/99/NL/SB. It is intended to provide an input to the WP100 report on 'Benefits and Market Analysis', which is a formal contract deliverable. This technical note draws on the description of space weather effects provided by the 'Space Weather Effects Catalogue' ESWS-FMI-RP-0001 created in work package 310 of this study.

1.2 Scope

This report describes benefits achievable both by the implementation of a European Space Weather Programme and by its successful completion. The report is aimed principally at benefits to Europe. However, wider benefits to the global space weather community are mentioned where they provide additional benefits to Europe through potential co-operation agreements. The report includes an assessment of the time-scales in which envisaged benefits may be expected to occur and also of how the benefits depend on the scale or degree of sophistication of the space weather programme that is adopted.

2 Strategic benefits of a European Space Weather Programme

2.1 Benefits of European autonomy in space weather

Europe can be justifiably proud of the contribution that its scientific and academic research community has made and continues to make to the study of space weather phenomena and effects. However, despite this extensive capability, European users of space weather data and services are currently reliant on many non-European organisations for the information they require. The benefit of acquiring an autonomous capability in space weather will be to reduce Europe's dependence on non-European resources for forecasting, warning, reporting and analysis of space weather effects and hazards to the technological systems on which its citizens depend.

There are several space weather centres around the world which provide data and products to their own network of customers. Information on the space environment is also distributed via the International Space Environment Service (ISES) which comprises a network of globally distributed Regional Warning Centres. The NOAA Space Environment Center (SEC) based in Colorado, USA, acts as a key node in the ISES network, providing a wide range of operational services [1]. As in many other scientific and engineering fields, the US currently has a significant lead over other countries in space weather activities, largely as a result of having more spacecraft than any other nation as well as the largest scientific community in the field. In addition to the NOAA SEC, the USAF 55th Space Weather Squadron [2] provides operational space weather services primarily to the US military and the US were the first to establish a National Space Weather Program (NSWP) [3]. Japan also has a national programme funded at about $3 million per year [4].

From a European perspective, it may be considered undesirable for European users of space weather data and services to be dependent on non-European information sources whose availability may not be guaranteed. With the trend towards greater economic and political unity within the European Union (EU), it may be seen as increasingly important for Europe to establish its own autonomous capability in many areas of high technology as a means of ensuring its technical, economic and political independence. This is already happening in many areas. For example, there is currently some concern about Europe's reliance on the US Global Positioning System (GPS) for satellite navigation services which are essential for many existing and planned commercial applications as well as military and private use. Largely because of these concerns and the need for a service guarantee, the EU is currently funding multi-million-Euro Definition Phase studies of a European satellite navigation system termed 'Galileo' [5] which would not only provide an autonomous European capability in satellite navigation but may also be optimised to meet a number of specific user requirements not currently satisfied by GPS. This is just one example of the drive to establish European autonomy in the provision of information systems and services; a European Space Weather Programme could be a similar example of the same concept.

European autonomy in space weather data and services may be considered at a number of levels. Full autonomy, i.e. where European users have *all* their information needs met from sources under European control, would require the development of an appropriate information gathering network (e.g. comprising spacecraft, ground stations, processing and dissemination centres). However, since space weather is a global phenomenon, full autonomy may not be necessary to meet Europe's essential requirements. A lower level of autonomy may be envisaged in which some data is still obtained from sources outside Europe's direct control (such as US or other nation's spacecraft) provided there is a reasonable guarantee of availability and continuity of service. One way of achieving this may be to ensure that Europe has sufficient capability in its own right to provide equivalent data and services wanted by other non-European nations. This capability could support the establishment of reciprocal agreements for data exchange, thereby ensuring genuine sharing and access to data, through the mutual reliance of European and non-European nations on each other's data sources. The important thing would be to ensure that Europe achieves sufficient autonomous capability to meet not only its own core requirements but also to support appropriate reciprocal data exchange agreements.

It is worth noting that the satellite remote sensing systems and data sharing agreements that have been put in place for global atmospheric weather monitoring (which may be considered similar in certain respects to space weather monitoring) could be regarded as setting a precedent for a space weather monitoring service. The current meteorological systems comprise a combination of satellites in geostationary (GEO) and low earth orbits (LEO). In the case of the GEO satellites which carry instruments primarily for imaging and sounding, global coverage is currently provided by 5 satellites operated by the US, EUMETSAT, Japan and Russia, strategically positioned at various longitudes around the equator. (China also operates a geostationary satellite although this is not part of the global network). To complement the GEO satellites, there are also a number of LEO satellites operated by the US and Russia, each of which carry a suite of sensing instrumentation provided by several nations. (A new EUMETSAT system, METOP, is also currently in production). Data from all these satellites is distributed globally with obvious benefits to all nations, most of which could not afford their own individual systems. While no nation can claim complete autonomy, all have assured access to data based on mutual dependence and the sharing agreements.

2.2 Benefits to pan-European organisations

There are a number of pan-European organisations, both public and private, who may expect to benefit from the establishment of a European Space Weather Programme. In some cases the benefit will depend on whether or not the programme includes development of new space infrastructure (which may not necessarily be the case and partially depends on the outcome of the current studies).

On the assumption that new space infrastructure is to be procured, the European Space Agency (ESA) should benefit from a strengthening of its role as promoter of European space systems development and operations. The programme would provide a major opportunity to exploit previous research and development in European space science and technologies, such as the Solar Heliospheric Observatory (SOHO) programme [6], and would further develop the technical expertise which resides in various ESA directorates.

A number of pan-European commercial organisations could expect to benefit from a European Space Weather Programme as users of the information services. Economic benefits are discussed elsewhere (see section 4) but in general arise from either increased cost-effectiveness, through the ability of organisations to provide commercial services more cheaply, or competitive advantage, through the ability to provide better services to customers. Two specific examples are spacecraft operations and launch service provision.

There are a number of pan-European organisations involved in spacecraft operations and launch service provision that may expect to benefit commercially from a European Space Weather Programme. For example, Eutelsat is an organisation formed under international treaty (though planning privatisation circa July 2001) and involving 47 nations in the provision and operation of European telecommunication satellites. As at January 2000, the organisation was managing 15 operational satellites spread across 8 orbital slots, as well as having a further 6 spacecraft under construction [7]. Also in the field of satellite communications, the world's 3rd largest satellite operator in (1998) revenue terms was reported to be SES (Societe Europeenne des Satellites) who operate the Astra satellite fleet currently comprising 9 orbiting satellites (with 3 on order). European meteorological satellites are also operated by EUMETSAT. Among launch service providers, the pan-European Arianespace organisation has established a leading position in the market against strong competition from the US and other nations.

The pan-European commercial organisations who may expect to benefit from space weather data and services are not restricted to those engaged in space-related activities. Companies engaged in terrestrial activities such as oil and gas pipeline operations, power distribution, etc., should also benefit (see discussion in sections 4.8 and 4.10). Such companies are in many (if not most) cases multi-national organisations, often with significant industrial plants and workforces across a number of European states.

Among pan-European government organisations, the Western European Union (WEU) is playing an increasingly prominent role in European defence. Its strategic functions include satellite Earth Observation (EO) imagery interpretation, which is undertaken at a special-purpose facility based at Torrejon, Spain. Since Earth Observation satellites are among the systems that may be adversely affected by space weather, the WEU may be expected to benefit from space weather warning services that support advance planning of its surveillance operations. Multi-national defence forces acting under the direction of the WEU (and/or NATO or the UN) will also benefit from improved communication and navigation services as outlined in the next section.

2.3 Benefits to European defence and security

Modern defence forces are heavily dependent on advanced technology for their operational effectiveness, particularly in the field of communications and navigation. Both are potentially susceptible to space weather effects. Forecasting and warning services, which allow protective measures to be taken to ensure continuity of communication and navigation services - or at the very least allow plans to be made for alternate service provision – should provide significant benefits to European defence forces in helping them maintain a high level of operational effectiveness at all times.

The importance of space weather information in maintaining national defence capabilities is already well recognised by the US Department of Defense (DoD). Warnings, observations and forecasts of space weather effects are provided on a routine basis by the USAF 55th Space Weather Squadron [2] working in conjunction with NOAA SEC. In addition, the USAF Phillips Laboratory and various DoD contracting agencies are active in developing space weather modelling techniques for operational use by the USAF Space Weather Squadron.

Communication systems that are potentially vulnerable to space weather effects include terrestrial HF (High Frequency) networks, which are used by the military for low rate, wide area communications. HF frequencies and below may be subject to loss of communications, change in area of coverage, low signal power, fading and increased error rate. VHF and UHF communication links may also suffer fading and a change in error rate. In addition to terrestrial communications, modern defence forces are also becoming increasingly reliant on satellite communications. At present, three European nations have military satellite communication systems; these are the UK (with SKYNET 4), France (with the SYRACUSE payloads onboard the national telecommunication satellites) and Spain (with the SECOMSAT payloads onboard the HISPASAT satellites). In addition, Italy is set to join this group with the launch of its SICRAL military communication satellites during 2000 while several European nations currently utilise NATO military communication satellites. Commercial satellites are also widely used by many nations for ‘routine’ communications for which a low probability of enemy intercept or exploitation is not a major concern. All these satellites may be vulnerable to space weather effects, and any forecast or warning services that enable the spacecraft operators to implement protective measures or to provide users with advance notice of periods of possible non-availability will be valuable. Apart from communication satellites, France also possesses military earth observation and signals intelligence satellites whose operational effectiveness may similarly be improved by space weather forecast and warning services.

Navigation services are also vital to modern defence forces, at all levels from the individual soldier or small platoon ‘in the field’, to land vehicles, ships, aircraft and missile guidance systems. At present many European nations utilise the US military-controlled GPS (Global Positioning System) satellite navigation system to provide high accuracy navigation services for their defence forces. However, due to concerns within Europe about the USA’s potential capability to deny GPS services over certain regions (which could include all or part of Europe, even if Europe were not the target of such measures), work is currently underway to define a new European satellite navigation system ('Galileo', [5]) which would provide similar navigation and positioning accuracy to GPS with additional integrity monitoring and a service guarantee. Should this programme go ahead, European defence forces would in due course utilise Galileo navigation services either instead of, or in combination with, GPS. In either case, space weather effects will pose a threat to navigation satellite services in much the same way as to communication services, requiring protective measures by the spacecraft operators and non-availability warnings to users. Taking into account the critical importance of satellite navigation services to military operations, the potential benefits of a European Space Weather programme to European defence forces are manifold.

A further dimension would be the increased capability for monitoring either hostile or accidental alteration of the environment. A hostile action, for example, might be the creation of artificial radiation belts in order to damage and reduce the capabilities of space assets such as communication, navigation or earth observation systems (see section 3.1.4).

2.4 Industrial policy benefits

The nature of the opportunities that a European Space Weather Programme will present to industry will depend on a number of issues yet to be determined - in particular, whether the programme is to include procurement of new space infrastructure in addition to ground segment activities.

A minimal European Space Weather Programme may simply involve the exploitation of existing data sources. However, even a minimal programme should still present significant opportunities for companies in a number of fields. Necessary activities will include:

- Information systems hardware procurement (e.g. computing equipment for data reception, processing, product generation and distribution).
- Development of space weather models and algorithms for product generation.
- Software development for implementation of software models and algorithms, database construction, etc.
- Pilot projects / demonstrations of space weather applications.
- Information service provision, including marketing and promotion of space weather products and electronic data dissemination (possibly including 'e-business' data sales).

It is important that any future European Space Weather Programme be consistent with existing ESA and/or EU industrial policy. Current policy objectives include ensuring a fair spread of opportunities/funding across the smaller ESA Member States. This stems from the recognition that smaller nations sometimes find it difficult to find a role in (and hence benefit from) major space programmes which are led by one of the multi-national space companies from the 'large' ESA Member States.

One of the best ways of enabling the participation of smaller nations is to develop opportunities for the involvement of SMEs (Small and Medium-Size Enterprises) in ESA and/or EU programmes. Apart from enabling a fairer distribution of work between large and small nations, a further attraction of SME involvement is that these organisations are often perceived as being more innovative than larger bodies both in the development and exploitation of new technologies. Since information technology and information service provision is a key area in which SMEs often take a leading role, a European Space Weather Programme should present significant opportunities for such organisations (which may include small businesses, universities, research centres and venture capital companies) to make a major contribution. It is worth noting that a number of EU Member States already have industrial policy initiatives aimed at supporting the development of SMEs, while the proposal for the EU Fifth Framework Programme [8] published in 1998 specifically included the promotion of innovation via SME participation as one of its key objectives. One of the benefits of a European Space Weather Programme should therefore be its ability to act as a source of new opportunities for supporting European national as well as ESA and EU industrial policy objectives.

Should a European Space Weather Programme also include the development and operation of new space infrastructure, benefits to industry may be expected to include further opportunities in:

- Space sensor design and development.
- Spacecraft design and development.
- Spacecraft operations (mission control).
- Procurement of new ground segment facilities and/or exploitation of existing facilities for spacecraft TT&C (tracking, telemetry and command) and data reception.
- Launch procurement (potential to support European launch manufacturers).

The beneficiaries of new opportunities in the above areas may be expected to include large European space manufacturing companies and launch service providers, although SMEs should also benefit from significant sub-contract opportunities. SMEs may also be in a leading position to undertake innovative development of space sensors and sub-systems, possibly based on new micro or nano-technologies.

2.5 Co-operation benefits

The potential benefits of co-operation depend on the nature of the co-operative measures adopted. As a minimum, a European Space Weather Programme would have the effect of bringing together the considerable but scattered capability that already exists within Europe in the field of space weather science and related space and ground systems engineering. While it is highly unlikely that any single European nation could muster the financial and other resources needed to develop a space weather programme, a co-operative programme under ESA's leadership could exploit and develop Europe's existing capabilities to the benefit of all.

Co-operation may also extend beyond Europe's boundaries, either at government level via data exchange or technology transfer agreements with other nations or, at industry level, via the placement of contracts with non-European organisations. Apart from the direct benefits of increased access to scientific and technological resources, other less tangible but nonetheless important benefits include the promotion of understanding and trust between nations which can derive from international links of this type. In some cases, co-operative agreements with specific nations may already exist and a European Space Weather Programme may be a means of fulfilling or strengthening the existing arrangements. For example, an 'Agreement on Partnership and Co-operation' between the European Union and the Russian Federation was signed in June 1994, representing a commitment by both sides to promote and encourage political, economic and scientific partnerships. A European-led Space Weather Programme which included some contribution from Russia could provide a means of realising the objectives of this agreement.

The fact that both the US and Japan have already established national space weather programmes makes these countries obvious candidates for co-operative working or data exchange agreements with Europe. In the case of the US, considerable benefits could accrue to Europe from collaboration with NOAA/SEC, which has an established capability in operational space weather monitoring, and the National Aeronautics and Space Administration (NASA), which has a long track record in space science missions. ESA already has considerable experience of working in collaboration with NASA on space weather science projects, notably SOHO, Cluster and Solar Orbiter. In the case of SOHO [6], the spacecraft was built in Europe by an industrial team led by Matra, but instruments were provided by both European and American scientists. The project has 9 European Principal Investigators (PIs) and 3 American ones. Large engineering teams and more than 200 co-investigators from many institutions across Europe and the USA are also participating through development of instruments and in instrument operations and data analysis. The NASA contribution includes launch and mission operations. Looking to the future, the proposed NASA 'Living with a Star' programme [9] is worth $500million over 5 years [10] and has recently been approved for a $20million start in US FY 2001 [11]. This is a major NASA science programme of significant interest to space weather scientists in Europe as well as the US. A European Space Weather Programme could provide a powerful negotiating tool in gaining European participation in such a programme or access to its results.

Canada also has substantial Space Weather activities, these include its network of geomagnetic observatories, the CANOPUS programme, Canada's SuperDARN involvement, space instrumentation development, theoretical work and modelling. The Canadian Space Agency's 'Long Term Space Plan III' maps out a 10-year strategy for space environment research which includes provision for international collaboration [12]. There is thus an opportunity for mutually beneficial collaboration with a European Space Weather Programme.

Co-operation may take a number of forms within the following three main categories:

1. Co-operation in space weather science and technology development.

This type of co-operation is equally applicable to groups working both within Europe and around the world. It is already happening to some extent in academic circles but could be considerably strengthened if a European Space Weather Programme were to be established. For example, co-operation could include:

- Information exchange in space weather science and modelling (e.g. understanding of effects and development of forecasting models).
- Technology transfer between nations in a number of high-technology fields such as Information Technology (IT), micro and nano-satellite technology, sensor design, etc.
- Exchange of scientific and engineering staff between academic institutes and possibly industrial organisations.

2. Co-operation in infrastructure design, development and procurement.

Within Europe, recent mergers between a number of major space hardware manufacturing companies (eg. in France, UK and Germany) have made multi-national project teams the norm on European space projects. Opportunities arising from a European Space Weather Programme may be expected to help foster this type of co-operative working. Sub-contracts placed by the prime contractors on any ESA development contracts should also provide further opportunities for teaming across European national boundaries.

Outside Europe, the leading 'space' nations (ie. USA, Russia and Japan) clearly have capabilities in space hardware design and development that Europe could potentially benefit from. Co-operation could take a number of forms, a typical example being the supply of instruments to fly on other nations' spacecraft (as was the case for the ESA/NASA co-operation on SOHO, which has already been discussed). Apart from the major space nations, a growing number of countries have some capability in space system design, space and ground system operations and satellite launches. All of these may be considered potential contributors to a European Space Weather Programme.

Many developing nations have growing space industries and capabilities in small satellite and sensor design. For example, Brazil has a number of government programmes focussed primarily on Earth Observation missions, e.g. the SCD (Satelites de Coleta de Dados) environmental monitoring satellites and the SSR (Satelites de Sensoriamento Remoto) imaging satellites, while India has an established track record in remote sensing through its IRS (Indian Remote Sensing) satellite series. These nations (and other similar developing nations) could potentially contribute either complete spacecraft or individual instruments required for a space weather monitoring system. Depending on the nature of the co-operative agreement, such items could either be developed for full integration into the European system, implying subsequent operations under European control, or provided as complementary elements to a European system, remaining under national control.

Several nations, including Russia, China, India and Brazil, have satellite launch capabilities which could form part of an international co-operation agreement. The potential benefits include free or subsidised launches of European space weather satellites. In exchange, Europe could expect to be asked to provide access to some of its space weather science and technology, including data from an operational system.

3. Co-operation in space weather service provision / data exchange.

A potential benefit of a European Space Weather Programme would be to stimulate and support co-operation within Europe in the supply of space weather data and services. For example, there may be opportunities for the creation of space weather service provider organisation(s) that would supply data and products to users across international boundaries. There could also be significant benefits to Europe as a whole through participation in co-operative agreements with non-European nations for provision and/or exchange of space weather data and products. In this case it is clear that Europe must have something to offer other nations and this is likely to depend on the size of the European programme. For example, a large programme involving the deployment of new space hardware for space weather sensing could potentially generate a significant volume of data not available to other nations from their own resources. However useful data might also be generated with a less extensive programme, eg. based on the deployment of 'hitchhiker' payloads. A small programme based on the use of existing space assets could continue to support existing international links (eg. into ISES, see below) but may have limited scope for achieving further co-operative benefits.

A European Space Weather Programme could help foster and develop existing links to international organisations such as the International Space Environment Service (ISES) and the US National Science Foundation. ISES [13] is a joint service of the International Union of Radio Science (URSI), International Astronomical Union (IAU) and International Union of Geodesy and Geophysics (IUGG) and a permanent element of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). At present the service is supported by a number of globally distributed space weather Regional Warning Centres (RWCs). Within the ESA member states there are RWCs in Belgium (Royal Observatory) and Sweden (IRF-Lund). In France, the CLS company is an associated member of ISES. Two RWCs are in European countries that may shortly become members of the EU (Prague, Czech Republic and Warsaw, Poland). There is also a centre in Canada (Ottawa) which is an Associate Member of ESA; the others are in USA (Boulder), Russia (Moscow), India (New Delhi), China (Beijing), Japan (Tokyo) and Australia (Sydney). To support its services, data is exchanged on a regular basis between the ISES RWCs , with the Boulder facility acting as a hub for data exchange and forecasts and fulfilling the role of 'World Warning Agency'. One of the benefits of a European Space Weather Programme would be to increase the amount of data emanating from European sources and thereby the importance of the European ISES facilities within the global network. Making European-sourced information freely available over the ISES network may be expected to encourage reciprocal arrangements with other complementary data sources, and generally to foster co-operation among the community.

2.6 Summary of strategic benefits

The table below provides a concise summary of the main strategic benefits of a European Space Weather Programme that have been discussed in this section. It should be noted that some of the identified benefits clearly depend on the size of the future programme (which has yet to be decided). In broad terms, three sizes of programme are being considered:

- Small – in which only existing space resources are utilised.
- Medium – in which additionally, 'hitchhiker' space weather payloads are placed on otherwise non-space weather spacecraft.
- Large – in which additionally, dedicated space weather spacecraft are flown.

In the table below, an assessment has been made about which benefits will accrue at which programme size. In many cases some benefit will be realised irrespective of the programme size, although the extent of the benefit may be increased with a larger programme. As a rough indicator of how the benefit depends on programme size, one, two or three ticks are indicated, corresponding to minimum, intermediate and maximum benefit.

An attempt has also been made to estimate the timescale(s) in which the identified benefits may be expected to accrue. Since the details of a ESWP's likely scope and development schedule have yet to be established, the suggested timescales assume that any new space segment assets developed under the programme would enter operation around 3 years following programme approval (however it is recognised that ground segment developments may be achieved much more quickly than this, even with a small programme). Subject to this assumption, the timescales are defined as follows:

- Short-term (<3 years) – benefits that could be expected to accrue during the early stages of a European Space Weather Programme, during the development but prior to operational use of any new space segment assets.
- Medium-term (3-10 years) – benefits that could be expected to accrue as soon as new space segment assets became operational.
- Long-term (>10 years) – benefits that depend on further developments in space weather science or technology that are not expected to be achieved for at least ten years.

Benefits	Programme Size			Timescale		
	Small	Medium	Large	Short (<3 years)	Medium (3-10 yrs)	Long (>10 yrs)
Reduced dependence on non-European resources for forecasting, warning, reporting and analysis of space weather hazards to technological systems on which European citizens depend.	√	√√	√√√		√	√
Strengthening of ESA's position as leader of European space systems development and operations, with opportunities for both ESTEC and ESOC involvement.			√√√	√	√	√
Improved operational effectiveness and hence competitive advantage to pan-European organisations engaged in satellite operations, launch operations, oil and gas pipeline operations, strategic defence.	√	√√	√√√		√	√
Improved ability of European defence forces to maintain a high level of operational effectiveness through advance warning of potential communication and navigation service outages.	√	√√	√√√		√	√
Opportunities for European industry in information systems hardware procurement, development of models and algorithms, software development, pilot projects and demonstrations.	√	√√	√√√	√	√	√
Opportunities to involve and support the growth of SMEs.	√	√√	√√√	√	√	√
Potential opportunities for European industry in spacecraft and sensor design and development, spacecraft operations, provision of ground segment equipment and facilities, launch services.		√	√√√	√	√	√
Improved ability to exploit and develop Europe's capabilities in the field of space weather science and related space and ground systems engineering through the bringing together of currently scattered resources.	√	√√	√√√	√	√	√
Opportunity to promote understanding and trust between nations through new co-operation agreements with non-European nations.	√	√√	√√√	√	√	√
Opportunity to fulfil or strengthen existing international partnership and co-operation agreements.	√	√√	√√√	√	√	√
Opportunity for individual European scientists, engineers and industrial groups engaged in the development of space weather science and technology to benefit from information exchange, technology transfer and collaborative working with non-Europeans.	√	√√	√√√	√	√	√
Increased importance of the European ISES facilities within the global network due to increased flow of European-sourced data.		√√	√√√		√	√
Opportunity to support international co-operation in the provision of space weather services and to secure access to non-European data through reciprocal data exchange agreements.	√	√√	√√√		√	√

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3 Technological and Scientific Benefits

3.1 Technological Benefits

Benefits to technology include both the stimulus that a space weather programme would provide to advances in technology and the ability to protect advanced technology against environmental extremes enabling more rapid insertion into operational systems. The latter case clearly has economic consequences which are discussed further in section 4.

3.1.1 Application of mini-, micro- and nano-satellites

Monitoring the space weather environment at a large number of points is important for modelling and forecasting. Deployment of constellations of low-cost, small satellites would provide a significant stimulus to European industry and universities. Europe already has an excellent reputation in mini- and micro-satellites (e.g. Astrid-1 and –2, Freja, UoSAT series, STRV series, Oersted, TUBSAT, BIRD and MITA) and this could provide a good springboard for a European Space Weather Programme to deploy a multi-point observation system. Mass production and miniaturisation of sensors and instruments would also be required and would provide significant benefits.

3.1.2 Application of nano-technology

Micro- and nano-technology is a growth area which could derive particular stimulus from the widespread deployment of small satellites in a Space Weather Programme. ESA has already organised two workshops in this area [1]. Besides miniaturisation of subsystems, such as attitude and orbit control, certain sensors can also be improved. For example magnetometers utilising magnetic films on silicon substrates could fit within 200x200 μm and detect 3nT fields [2].

3.1.3 Stimulus to ground-based information technology

The requirements for data handling and dissemination could provide a significant stimulus to the information technology industry. Although a small perturbation to a large market, a Space Weather Programme would require a seamless system, taking data from a multitude of sources, providing analysis and prediction and disseminating the output in near real time to a multitude of users. This is likely to push the envelope of IT systems and may impact standardisation of data formats.

3.1.4 Monitoring and controlling man-made influences on space weather

Human activity already influences the space environment and a Space Weather Programme would assist in monitoring, understanding and moderating such activity. It is also conceivable that beneficial modifications could be performed, subject to international treaty. Some examples are as follows:

i) In 1962, exoatmospheric nuclear tests performed by the USA (Starfish) and the USSR (USSR 1 to 3) significantly enhanced the trapped electron belts [3]. These had not been adequately mapped prior to the tests and the contamination has confused belt modelling ever since. On the other hand determination of electron lifetimes in these artificial belts has assisted in the understanding of the natural belts. In addition these belts led to the rapid demise of a number of spacecraft, including the first UK scientific spacecraft, Ariel-1, which was monitoring the belts at the time [4]. Modern spacecraft would be very vulnerable to such enhanced belts and it has been pointed out in the open literature that even quite modest nuclear devices would have a dramatic economic impact by reducing the lifetime of many space assets [5]. The long electron lifetimes in the inner belt could render low earth orbits unusable for years.

The widespread deployment of radiation monitors (e.g. X-ray, gamma-ray, neutron, electron) in a space weather system would provide very sensitive early detection of nuclear bursts or artificial injection of charged particles. It is conceivable that they could form part of a world-wide treaty monitoring system and could be something of a deterrent to rogue states who might wish to attack space assets. If such attack were to occur, the understanding of radiation belt dynamics and the monitoring of particle fluxes would be of key importance to the rehabilitation of space.

ii) Space-borne nuclear power sources have been deployed for both civilian and military purposes. The issues of safety of re-entry and space contamination are extremely important. It is difficult to hide an operating power reactor due to emissions of gamma rays, neutrons, electrons and positrons. The uncharged species are seen by line of sight while the charged particles are channelled by the geomagnetic field. For example the series of Russian Radar Ocean Reconnaissance Satellites were detected in this way by the NASA Solar Maximum Mission. This detection capability was in fact classified for a number of years before open publication was permitted [6]. Clearly such radiation monitors deployed for space weather purposes could very effectively monitor the clandestine use of space nuclear power and could possibly monitor radioactive debris in danger of intersecting spacecraft orbits or re-entering the atmosphere.

iii) Man-made transmissions at ELF/VLF are able to precipitate electrons from the earth's radiation belts [7]. In fact one theory of the slot region between the belts at L=2.6 ascribes the short lifetimes in this region to resonance with such waves. At no time in the history of radiation belt research have these waves been absent. Clearly radiation belt dynamics are entwined with human activity and it is important to understand the processes. Deliberate belt reductions or removal of artificial belts could be envisaged. Of course the precipitating electrons have to go somewhere and they can interfere with LEO spacecraft as well as disturbing the ionosphere and leading to ozone depletion [8]. Another benefit could be the deliberate generation of artificial aurorae. Deliberate injections of plasma via chemical release can create instabilities and particle losses. Experimental environmental modifications of this type were made by the Combined Release and Radiation Effects Spacecraft (CRRES).

iv) High-power transmitters can also be used to deliberately modify the ionosphere. For example the high latitude facilities in Europe (EISCAT or European Incoherent Scatter Facility), USA (HAARP for High frequency Active Auroral Research Program) and Russia (SURA) are used to perform research on the ionosphere via a small amount of deliberate local heating [9]. Use of higher powers could significantly modify the ionosphere. Such modifications could be used for benefit or for military attack on communications and it is important both to understand interactions and to regulate activity.

v) Space debris is removed by atmospheric drag, which is modified by space weather. The influence must be understood and there is the possibility of deliberate intervention by modifying the upper atmosphere.

3.1.5 Improved resilience of modern technology

Many advances in technology result in increased susceptibility to environment effects and space weather. Estimation of the rate of occurrence of extreme space weather events is important for design, while adequate warnings, if available, would benefit many applications by enabling protective measures and work-around procedures. Regulatory changes are requiring many operators to take greater account of space weather while fear of litigation is forcing organisations to be able to prove in court that they have paid adequate attention to risk assessment. Some examples are given below.

Modern microelectronic devices are rapidly evolving and moving to sub-micron feature sizes and lower operating voltages. This is leading to increased susceptibility to both single event effects from ionising particles and to electromagnetic effects, including discharges caused by electrostatic charging processes. Modern memories of 256 Mbits are estimated to experience one single event upset per month from sea-level neutrons. Evidence of sea-level events has been obtained from major computer installations [10] and from medical devices such as cardiac defibrillators [11]. Power diodes are experiencing neutron-induced burn-out and failures have been recorded in European high speed trains [12]. In space applications electronics are exposed to the full vagaries of space weather and failures and anomalies are being observed from single event effects and electrostatic charging effects. At aircraft altitudes the environment can be as severe as in certain low earth orbits. In the atmosphere variations due to space weather are decreased with respect to space with a reduced cosmic-ray modulation and significant enhancements from solar particle events reduced to two or three major events in every solar cycle. However massive solar particle events, such as occurred in February 1956, can lead to fifty-fold increases on the ground and to even greater enhancements at aircraft altitudes. Also of concern are long-term changes to the geomagnetic field which alter the access of cosmic rays. Ultimately a field reversal would allow full access to low latitudes.

For conventional aircraft there is a movement towards use of higher altitudes for fuel efficiency and use of near polar routes to save both time and fuel. Both trends increase the radiation burden and the risk of exposure to large solar particle events. In addition the aircraft of the future will make increasing use of microelectronics and fly-by-wire systems which are more vulnerable to single event effects. The aircraft industry continues to study the possibilities for future supersonic passenger aircraft for which solar particle events would be extremely significant. In all cases, the ability to predict cosmic-ray modulation and solar particle events is important.

There is increasing reliance on satellite navigation (GNSS) in both military systems and civil aircraft. High reliability requires the ability to forecast extreme events and possible outages so that back-up or alternative systems may be employed.

In older power distribution networks the voltage decayed gracefully as the load increased. However modern power distribution networks use special devices (essentially huge capacitor banks) to maintain normal voltages up to high load levels and then decay rapidly when some critical level is exceeded. Thus sudden load increases, such as those arising from transformer imbalances induced by space weather effects, can cause the collapse of the system. This is what happened in Quebec in March 1989 when collapse occurred in 90 seconds. Adequate space weather warnings are clearly required.

3.2 Scientific Benefits

3.2.1 Stimulation of basic research

Space weather is an area where science performed for understanding will find increasing application and a European Space Weather Programme would provide a major stimulus to basic research in terms of financial support, industrial interest and job satisfaction among scientists.

A vast increase in the quantity and types of data available would result from the Space Weather Programme and this should offer many new research opportunities. For example the detection of observable precursors to coronal mass ejections and charged particle acceleration at the sun are key research areas which require multi-wavelength observations at a wide range of heliolongitudes and heliolatitudes.

As another example, the understanding of electron acceleration in the magnetosphere is a key area due to the large number of satellite anomalies and losses which result from such "killer" electrons. This requires multi-point observations within the magnetosphere of both electron fluxes and waves as well as measurement of solar wind parameters upstream from the earth.

Other topics that would benefit directly through the stimulation of basic research include:
- Solar particle acceleration processes.
- Acceleration of particles at CMEs and shocks in the interplanetary medium.

- Solar wind / magnetospheric coupling.
- Diffusion and loss processes within the radiation belts.
- Geomagnetic shielding and particle entry to the magnetosphere.
- Auroral electrojet formation.

Europe already has a strong international presence in space science, geophysics and information technology. Scientific fields expected to benefit substantially from a space weather programme include: solar physics, interplanetary physics, cometary physics, magnetospheric physics, ionospheric physics, atmospheric physics, astrophysics, the physics of geomagnetism, mathematical modelling and information science. Modelling of solar-terrestrial relations will, naturally, benefit and from this field may come models that could usefully feed into a European Space Weather Programme. European groups are already active in this area and their work to date constitutes a valuable European resource. Some of these groups are already producing real-time space weather forecasts on the world wide web. At the time of writing, these include:

- DERA's Ionospheric Forecast Demonstrator, giving predictions of the critical ionospheric frequency f_0F2 (rasp.dera.gov.uk/ifs).
- The Rutherford-Appleton Laboratory's Short-term Ionospheric Forecasting (STIF) service, giving Europe-wide maps of total electron content, f_0F2 and maximum usable frequency (MUF) (www.rcru.rl.ac.uk/iono/stif.htm).
- The Danish Meteorological Institute's prediction service for Linear Modelling of Ionospheric Electrodynamics (LiMIE) and Dst (dmiweb.dmi.dk/fsweb/solar-terrestrial/).
- The Swedish Institute of Space Physics, Lund Space Weather Center's predictions of the *AE* and Kp indices (www.irfl.lu.se/HeliosHome/forecastpage.html). (This site gives access to a host of other information, including other prediction services.)
- The Swedish Institute of Space Physics, Kiruna's predictions of Dst (sukiyaki.irf.se/rt-dst/).
- British Geological Survey's Geomagnetism Information and Forecast Service (GIFS), providing predictions of geomagnetic and solar activity (www.nerc-murchison.ac.uk/gifs/on_line_gifs.html.)
- The Royal Observatory of Belgium's, Sunspot Index Data Center (SIDC), providing predictions of the sunspot index, flare activity, proton fluxes, magnetic activity and solar radio flux (sidc.oma.be/)
- The Observatoire de Meudon's Centre de prévision de Meudon, which provides forecasts of sunspot number (www.dasop.obspm.fr/previ/).

3.2.2 Improvements in predictive techniques

These will require both improvements in modelling of the physical processes and application of artificial intelligence tools such as neural networks. Modelling of the basic physics has to reach a high level of maturity before valuable predictions can be obtained. However even a crude understanding can provide informed input into neural networks.

An example of an area in which both techniques are being applied is the above-mentioned problem of predicting electron enhancements in the outer radiation belt. Currently numerous theories abound which need bounding by observations. Both linear and non-linear predictive techniques are being applied with modest success and the latter include neural networks using both multi-layer perceptron and radial basis function techniques. Good coverage of all techniques is provided by reference [13].

Artificial neural networks are being applied to other aspects of Space Weather as well as to many other applications. Their general development would benefit from the stimulus of Space Weather programmes.

3.2.3 Developments in sensors for hazard warning

Improvements will be required in solar monitors across the full electromagnetic spectrum while improvements in charged-particle detectors should be stimulated. It is likely that this will involve a few specialised instruments with improved sensitivity, discrimination and resolutions as well as the mass production and miniaturisation of simpler detectors for wide ranging deployment. Numerous compact radiation detectors are currently being developed and flown [14]. Examples of radiation detectors in compact packaging are the CREDO-3 (Cosmic Radiation Effects Dosimeter) [15], the CEASE (Compact Environment and Anomaly Sensor) [16], the SREM (Standard Radiation Environment Monitor) [17], and the Radiation Monitoring System developed for the X-ray Multi-Mirror (XMM) mission. Deliberately sensitised devices are even more compact but yield less discrimination and sensitivity. Examples of the latter are RadFETs [18,19], Scintillating Fibre Dosimeters [20], Optically Stimulated Luminescence Dosimeters [21], EPROMs [22], RAM chips [23] and Charge Coupled Devices (CCDs). Charging environments can be monitored by direct measurement of electron fluxes or by accumulated charging currents or voltages [24].

3.2.4 Improved resilience of space science missions

The ability to provide better predictions of space weather effects would have significant benefits in the improved performance of space science missions.

Astronomical and remote-sensing instruments, ranging from gamma rays to the infra-red, are susceptible to sensitivity-reducing background resulting from interactions of the charged particle environment [eg 25,26,27]. Such background can be both prompt and delayed (e.g. due to induced radioactivity in the detectors and surrounds). Periods of total black-out can result from solar particle events or from passage through the South Atlantic Anomaly. The ability to optimise operations and take protective measures (e.g. by use of protective shutters or filters) would be greatly enhanced by improvements in space weather prediction. Surprises still occur when new types of technology are deployed. For example the Chandra X-ray telescope is subject to a surprisingly high level of degradation due to exposure of the CCD detectors to magnetospheric or solar soft protons (<200 keV) scattering down the telescope. This discovery required last minute investigation and has enabled preventive measures to be taken for the ESA X-ray Multi-Mirror (XMM) mission. However the variability and predictability of this previously neglected proton population has now assumed a new importance. X-ray observations are also subject to magnetospheric or solar wind keV electrons or ions, either by direct impact on the detector or by the background produced by X-rays generated when such particles hit neighbouring surfaces.

Certain techniques for planetary remote sensing rely on the emissions stimulated by solar X-rays or charged particles and the ability to predict these would enhance mission success.

Manned planetary exploration is critically constrained by the radiation environment. For example a mission to Mars would probably have to be constrained to the years around solar minimum and even then prediction of solar particle events would be required.

Electrostatic charging can perturb particle and field measurements by orders of magnitude and considerable improvements to geophysics and solar system science would result from full knowledge of the electrodynamic environment of scientific spacecraft.

3.2.5 Improved recruitment into scientific disciplines

By improving scientific education at school and in universities, a European Space Weather Programme could potentially increase the numbers and quality of graduates wishing to enter science as a career. This aspect is discussed further in section 5.

3.3 Summary of technological and scientific benefits

The major technological and scientific benefits discussed above are summarised in the following table. The programme size and timescales are as discussed in section 2.6.

The programme size is the minimum required to yield any benefit. Although many have thresholds in the small programme category, the benefit, in most cases, would increase with programme size.

Benefits	Programme Size			Timescale		
	Small	Medium	Large	Short (<3 years)	Medium (3-10 yrs)	Long (>10 yrs)
Increased robustness of new technology	√	√√	√√√		√	√
Development of new sensors		√√	√√√	√	√	√
Development of new platform technology			√√√	√	√	√
Development of new data handling technology	√	√√√	√√√	√	√	√
Monitoring of human influence on environment	√	√√	√√√		√	√
Beneficial modification of environment			√√√			√
Stimulus for basic science	√	√√	√√√	√	√	√
Improvements to artificial intelligence algorithms	√	√√√	√√√	√	√	√
Improved resilience of scientific missions	√	√√	√√√		√	√

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4 Economic benefits

4.1 Quantifying economic benefits

This section of this report deals with the economic benefits that it is anticipated will arise from a European Space Weather Programme. In planning such a programme, it is clearly valuable to assign a quantitative financial value to each space weather problem being addressed. To make such an assessment, one needs to know:

A - The rate of occurrence of the problem;

B - The percentage by which the problem would be alleviated due to the space weather programme;

C -The cost incurred each time the problem occurs.

The added value of the service is thus $\Sigma(AxBxC)$, where Σ indicates that the calculation is integrated over all the users involved. Where the problem is not of the yes/no variety (e.g. a satellite working or not), a further integration over the magnitude of the problem is required (e.g. the magnitude of location error in GNSS). For certain problems, reasonable estimates exist in the literature for A, B and C and the group of users is quite homogenous, e.g. where the problem is satellite failure in orbit and the users are operators of commercial satellites. However for most other problems, the cost of the problem (C) is highly dependent on the type of user, the user group is highly diverse and users do not usually reveal the cost of the problem because it would pass commercially sensitive information to competitors. For similar reasons, users often conceal the rate of occurrence of the problem (A).

A survey to discover A, B and C for all users and all problem magnitudes, for just one of the many problems covered in this report, would constitute a major market analysis study and is far beyond the scope of activity permitted within this study. It is also strongly against the ethos of the authors to make estimates without such information. Hence, in this section, we describe such relevant quantitative information that is publicly available, and explain in qualitative terms how economic benefits would be generated where the quantitative information is not available.

4.2 Increase in satellite reliability and lifetime

Anticipation of environmentally induced spacecraft anomalies can minimise the costs associated with damage and recovery. Most importantly, accurate space weather information allows accurate anomaly diagnosis which can help spacecraft designers improve the reliability of future satellites.

Anticipation of environments likely to cause anomalies via SEEs, surface charging and internal charging can minimise the time required to recover from spurious commands. Where this involves loss of service to customers, this can be expensive both in terms of immediate revenue and in customer confidence. Economic benefit is achieved by facilitating a heightened awareness in operators, allowing experienced staff to be brought in and allowing established recovery procedures to be at hand. Prediction of hazardous environments also allows risky manoeuvres to be delayed and vulnerable sub-systems to be put into a safe mode. This lowers the risk of mission loss or shortening of lifetime. However, since turning off the payload is generally unacceptable, the ability to make systems safe has practical limitations.

At the present time, satellite anomaly diagnosis is mainly ‘educated guesswork’. Because environmental information is incomplete, broad assumptions have to be made and diagnosis is seldom reliable, unless frequent repetition of the same type of anomaly allows a clear statistical correlation with one parameter or another to be established. The most significant economic benefit to satellite operators comes from accurate anomaly diagnosis as a result of accurate space weather information. This means that systems may be made more immune to environmental effects (i.e. in terms of fewer anomalies) without expensive over-engineering.

Anomalies may be considered in two categories, i.e. those involving transient changes in state and those due to permanent failures. For transient anomalies:

- At the lowest level, many data errors may be corrected by on-board error detection and correction (EDAC), at no direct cost. However, this leads to an overhead in design and, to be cost-effective, needs an assessment of the space weather threat.
- ‘Nuisance’ anomalies, such as changes in state of non-critical systems, have little effect but must be monitored on the ground and may require registers to be reset. This requires staffing and command up-link capability and also limits savings through autonomous satellite operation.
- Many anomalies, e.g. many attitude control problems, result in the spacecraft being put into safe mode. It takes generally a few hours of ground commanding to recover from uncommanded safe mode. This requires staffing and command up-link capability and creates a higher risk of more serious problems occurring while the spacecraft is not in its standard mode. It may also require expenditure of fuel, which may shorten the spacecraft lifetime. During this procedure a commercial spacecraft is unable to earn revenue and the operator may incur penalties due to the interruption of service. Scientific satellites lose data at such times, causing a reduction in value of the mission. For military systems, loss of service at critical times could have severe military consequences of which large financial losses would be just one component.

With regard to permanent failures:

- Some anomalies, e.g. loss of gyros on ANIK-E2, can be worked around using a ground-loop. This may require expensive software development.
- RF amplifier anomalies are common on communications spacecraft and result in a loss of capacity of the spacecraft and hence decreased revenues.
- A permanent decrease in available power due to solar array degradation may result in reduced capability of the spacecraft, e.g. loss of capacity in a communications spacecraft, or reduced lifetime.
- Permanent failure of critical spacecraft sub-systems is frequently anticipated and redundancy is provided. Loss of redundancy due to environmental anomalies has no immediate effect but may shorten spacecraft life and may accelerate the replacement of the spacecraft. Failure of a complete satellite requires a replacement spacecraft. In-orbit redundant spacecraft are frequently provided in commercial communications, weather and military systems. This minimises costs of loss of service but further redundancy then has to be provided. However, in-orbit failures are not always caused by space weather effects and so the costs of redundancy cannot be avoided completely.

Complete satellite failure as a result of space weather is rare and is not the main economic effect. There have been 11 reported cases in the last 25 years [1]. Assuming that each lost half its useable lifetime, and each cost $50million, then the annual benefit of avoiding losses could be very crudely estimated to be around $11 million. This estimate ignores classified satellites whose failures are not reported.

The economic benefit from quicker recovery from spurious changes in satellite state is associated with the cost of providing alternative services via purchase from competitors or from back-up spacecraft. The benefit from minimising loss or life shortening of a satellite or subsystem is related to the cost of replacement satellites and redundant subsystems. Costs may be particularly high where duplicate systems on the same or different satellites are affected, since this may cause both primary and back-up systems to be lost. The benefit of greater immunity to anomalies derives from lower operational costs associated with anomaly recovery, lower costs of system outages, lower costs from redundancy and less frequent replacement of satellites.

Atmospheric drag effects also have an impact on operational costs for satellites in low Earth orbit. Space weather induced increases in atmospheric scale height result in increased drag which may cause loss of attitude control of the spacecraft and may induce loss of tracking by ground controllers, requiring the re-acquisition of the spacecraft. The scale height of the atmosphere is also of crucial importance in atmospheric breaking and in the controlled re-entry of defunct spacecraft.

The US DoD estimates that the increased costs of US government satellite operations due to space weather effects are around $100million per year [2]. Whilst it is envisaged that a 50% decrease in these costs is possible through improved anomaly diagnosis, complete elimination of these costs is unlikely, since technology is continually evolving and the vulnerability of new components may not be discovered until they are in service.

In 1997 the total value of the commercial space market was estimated at around $18billion per year [3]. One study has estimated the annual value of space-based communications to be $15billion and remote sensing services $350m [3]. Another study has valued the market in GPS services at around $2billion in 1999 in North America alone [4]. The sector as a whole is rising at around 14% per annum [3]. Even a 1% gain in efficiency, in terms of continuity and availability of user services would be worth $180m per year. In practice, the advantages created by better space weather information may be greater than this.

Listed below are just a few examples of satellite anomalies with financial implications:

- All Telesat Canada satellites have experienced at least some space weather anomalies. Anik-C3 experienced over 100. Anik-D2 experienced one serious outage. Anik-E1 experienced failure of one momentum wheel and Anik-E2 experienced two momentum wheel failures. The ANIK-E1 and -E2 failures led to outages of hours and months respectively. The cost of the ANIK-E2 outage has been estimated at $10million. Both of these satellites also had RF amplifier failures, leading to a loss of capacity. Recently MSat has experienced many phantom commands and a very large number of amplifier failures [5].
- The DoD/NASA Tracking and Data Relay Spacecraft (TDRS-1) experienced several upsets per day in the satellite central memory from Cosmic Rays, increasing to several hundred per day during the September/October 1989 solar particle event. Expensive ground operation procedures had to be invoked.
- The Hispasat 1A and 1B spacecraft suffered failures in X-band antennas for military communications and the cost of an associated insurance claim was estimated at $40million. [6]

The level of benefit to satellite reliability varies with the level of space weather service. Most benefit is obtained by accurate post-event knowledge of the environment at the satellite itself, i.e. not simply a related global activity index, like Kp, or the actual environment at GOES-8 or -10, positioned in geostationary orbit over the USA. (These GOES spacecraft are NOAA's existing space weather monitors for geostationary orbit. The position of these spacecraft means that they characterise the environments of satellites positioned over the USA better than those over Europe). Local environment information is required for accurate anomaly analysis. Greatest benefit to current satellite technology derives from knowing energetic electron flux and plasma characteristics. However, benefit is also derived from knowing solar proton flux and its importance may increase if electronic technology continues to evolve as at present.

Where spacecraft operations can be changed to take account of the environment, economic benefit increases with the accuracy and length of the warning. An hour in advance could allow risky operations to be delayed. A day in advance could allow changes in personnel to be made. A week in advance could influence a weekly operations plan.

4.3 Decrease in environmental risk during spacecraft launches

Launch represents a critical high-risk period in the life of a satellite. Timely space weather information can minimise costs associated with launch failures and postponed missions.

The risk of SEE during launch is minimised by not launching during solar proton events. The level of solar proton flux must be monitored in the pre-launch preparations. Predictions are required to be accurate, since there are costs associated with cancelling launches at a late stage. A disturbed magnetosphere is not generally a hazard to a launch, since the launch phase generally terminates at low altitude with the spacecraft either in low earth orbit or injected directly into a transfer orbit. However, it is not recommended to launch into a severely disturbed magnetosphere, since this would require that the satellite launched would have to make its first mission-critical manoeuvres under adverse conditions.

Cost benefit is related to the probability of a serious anomaly during a solar proton event and the cost of the loss of both satellite and launcher. The single event effect risk from galactic cosmic rays cannot be realistically controlled since launching only during solar maximum is not an option.

The value of decreased risk of Ariane V failure by avoiding launches during solar proton events has been estimated at 3 million French francs (around $450,000) per launch during an event like that in August 1972 for sun-synchronous orbit, and 30 million francs ($4.5million) for GTO [26]. Solar proton events occur at a rate of around 10 per year, on average, and last typically 2 days. However, most are smaller than the very large 1972 event. Comparable events occur typically once per solar cycle. Assuming a launch rate of 12 per year (that achieved by Arianespace in 1998 [7]), with 75% to GTO, then an upper limit on the potential value to Arianespace may be crudely estimated by assuming all events to be equally hazardous, as around $2.5million per year. Arianespace accounts for only around a sixth of all launches, so the global benefit is larger.

Space weather information can also be used to optimise the performance of launchers, it is reported [26] that certain US launch providers make use of predictions of atmospheric scale height to allow earliest jettisoning of the payload shroud and hence to minimise fuel consumed before orbit is achieved.

Greatest economic benefit derives from a space weather service that gives now-casting of atmospheric scale height and predictions of solar proton events, the main avoidable threat to launches. Most benefit would come with a warning of about 2 days, so that time-scales would be similar to weather forecasts, which also affect launch schedules. Warnings less than 6 hours ahead, when filling of cryogenic tanks is in progress or completed, are less valuable because considerable cost is incurred in delaying a launch at that stage.

4.4 Decrease in risk in manned space missions

Although the main consequences of reducing risk to man are health and safety, there are economic consequences in terms of the number of missions able to be flown by each astronaut and the decrease in medical costs and litigation.

Considerable investment in manned space has been made in recent years. The International Space Station (ISS) programme is a 16-nation programme involving substantial hardware contributions from the USA, Russia, Japan, Europe, Canada, Italy and Brazil [27]. The NASA ISS budget is $35billion, including 10 years of operation [28]. ESA's contribution to the development phases (mainly in the form of the Columbus Laboratory) will cost up to €2.6billion and a further €250million is budgeted for the 10–year operational phase [29]. Russia's contribution is subsidised by the US to a value of over $1billion [7]. Italy, in addition to its ESA involvement, is contributing the Multipurpose Laboratory Modules (MPLM) at a cost of around $300million [7]. Canada's hardware contribution, the Mobile Service System, costs around C$250million [7].

Astronauts work in a radiation environment and an increase in total dose exposure, over that experienced on the ground, cannot be eliminated. Limits on permissible total dose have decreased in recent years and affect the number and duration of space missions that each astronaut can fly. US astronauts in Earth orbit have a career dose limit of 4000mSv, although expeditions to the

Moon and Mars would currently have more relaxed limits. However, US astronaut radiation is managed on the ALARA principle (i.e. As Low As Reasonably Achievable) because any unnecessary exposure is considered unacceptable. Astronaut exposure to an equivalent dose of 4000mSv is possible in a single solar proton event and would be fatal if not treated. Large events occur about once per solar cycle, whilst smaller events are more frequent.

If severe solar proton events are not encountered, astronauts in near-equatorial LEO get about 2/3 of equivalent dose from galactic cosmic rays and about 1/3 from trapped radiation. ISS differs from recent Space Shuttle experience in that it intercepts the outer belt and so, as well as trapped protons, trapped electrons may play a part in extra-vehicular activity (EVA) exposure. A reduction in equivalent dose would be achievable with good predictions of increases in the proton and electron belts by enabling astronauts to avoid EVA during enhancements. Similarly, with predictions of the occurrence of solar proton events, it would be possible for occupants to move to a less dangerous part of the spacecraft, terminate a mission early or delay launch if the warning time was sufficient. Space weather information can also be used to quantify exposure of the different organs more accurately than could be achieved with a passive total dose monitor. Economic benefit is related to the cost of training more astronauts, medical costs and possible litigation if reasonably achievable reductions in exposure were not obtained.

Whilst savings are not easily quantifiable, the cost of training an astronaut is estimated to be several million dollars. Hence an increase in useful lifetime is valuable. In the event of severe illness or death caused by space radiation, medical costs and/or costs from litigation are potentially very high. There is also a potential financial cost to agencies arising from public disquiet, e.g. public inquiries, suspension of operations and the imposition of new checks and procedures, such as were experienced by NASA after the Challenger explosion.

The most intense recorded solar proton event recorded in space took place in August 1972. This would have caused a dose equivalent of around 4000mSv to astronauts, inside a spacecraft in interplanetary space. This occurred between Apollo missions 16 and 17 and is thought capable of killing the crew [8]. An event in February 1956, before measurements in space were possible, was slightly less intense but its harder spectrum would have penetrated spacecraft and geomagnetic shielding, to be a severe threat to astronauts, even in low Earth orbit.

An event in October 1989 was comparable to the 1972 event. Simulations of astronaut radiation exposure in the International Space Station (ISS) during this event have been made [9]. These show that an astronaut carrying out EVA will experience a 637% increase in skin dose and an 873% increase in dose at blood-forming organs, over an astronaut remaining in the ISS habitation module.

The level of benefit depends on the level of space weather service and the type of mission being flown. Knowledge of solar proton and trapped proton fluxes are of most use in low Earth Orbit. In interplanetary flight, only solar proton fluxes are important. Post-event knowledge has some benefit since it improves on information from on-board total dose monitors. However, greater benefit comes from now-casting and greatest benefit comes from prediction, a few days in advance.

4.5 Decreased radiation risk to aircraft

Commercial and other aircraft are susceptible to single event effects caused mainly by secondary neutrons. Crew and ‘frequent flyers’ also have a dose-equivalent risk. Space weather information can allow altitude and course changes when severe solar proton events are expected.

Single event effects, similar to those seen on spacecraft, affect avionics at high altitude, particularly on routes that cross the poles and the South Atlantic Anomaly. Olsen et al. [10] reported that a commercial computer was temporarily withdrawn from in-flight service when SEU bit-errors were found to accumulate in 256 Kbit CMOS SRAMs. Similar observations [11] have been made with memory devices on a Boeing E-3/AWACS aircraft and at high altitudes (65000 feet) on a NASA

ER-2 aircraft. Boeing have reported SEUs in commercial autopilot systems at high altitudes and latitudes [12].

Limits on aircrew exposure to radiation mean that there is a benefit in minimising exposure. These limits have been tightened by the implementation of European Union Council Directive 96/29/EURATOM, which took effect in May 2000. This demands that aircraft operators take account of exposure of air crew who are liable to be exposed to more than 1 mSv (milliSievert) per year. Tighter limits apply to pregnant women. Whilst the above directive applies also to military pilots, they are, in general, less affected by these effects because they spend fewer hours in the air.

Economic benefits from improved space weather information are related to the reduced risk of catastrophic failure of electronic systems, improved manpower utilisation and reduced damage to equipment. There is also a potential cost of litigation where airlines have not obeyed the new EU directive.

In September and October 1989 a series of solar proton events led to enhancements of up to a factor 6 at Concorde altitudes. Dose-rates would have been of order 100 microSieverts per hour at Concorde and 10 microSieverts per hour at conventional altitudes. The largest ground level event observed, so far, was that of February 1956. It is estimated that aircraft dose rates could have been as high as 100 milliSieverts per hour so that very serious doses could have been received. The consequence of a several orders of magnitude increase in the rate of single event effects on aircraft electronics could be very serious as would the dose-equivalent consequences to passengers and crew.

The US Federal Aviation Authority (FAA), Civil Aeromedical Institude (CAMI) distributes software which estimates doses for flights between any two destinations, based on galactic cosmic rays. This software is reported to be in use by EU airlines, individual airline personnel and the US AirForce. CAMI also publishes information on solar proton events in progress [13].

The main benefit to aircraft and crew comes from warnings of solar proton events. Warnings more than 12 hours ahead would allow flight plans to be modified but even now-casting would be useful, as it would allow high-flying aircraft to descend. Post knowledge is also useful for diagnosis of SEUs.

4.6 Greater accuracy and reliability of GNSS systems

Single frequency civilian global navigation satellite systems (GNSS) experience loss of accuracy which can be compensated for by knowledge of space weather information. Warnings of locations and times, where GNSS may be unavailable due to scintillation effects, would allow alternative navigation systems to be used.

Single-frequency GNSS can experience position errors of up to 35 metres as a result of variation in total electron content (TEC) of the ionosphere. Knowledge of TEC could allow this error to be recovered. This brings single frequency systems up to the accuracy of dual frequency systems like the military GPS system. Since the removal of ‘selective availability’ in May 2000, which artificially degraded GPS accuracy for non military users, ionospheric changes are the main limitation on the accuracy of single–frequency GNSS. Ionospheric corrections are broadcast with the civilian GPS signal but are based on models which do not take account of space weather effects.

Scintillation in the equatorial and auroral zones causes loss of phase lock and hence less regular updating of GNSS information for both single and dual frequency systems. This can lead to inaccuracies in position measurements. Knowledge of when GNSS is thus degraded would enable other systems, such as inertial navigation, to be used. Significant economic benefits could result from improved safety of aircraft and ships and improved navigation accuracy for cars and freight vehicles. Related effects occur in the ground-based LORAN C radio-navigation system. This uses

LF and VLF frequencies. Reflections from the lowered ionosphere during magnetically disturbed periods can lead to errors of up to 1km in position accuracy [14].

The existing GPS system is provided free to all users. However, GPS is estimated to have cost $12 billion to develop and deploy [24] and the proposed European Galileo system is expected to cost several billion. The market in ground receiving equipment has grown rapidly, with civilian users far out-numbering the original military user community. An inexpensive satellite navigation receiver terminal can be bought for less than $100. However, the total market has been estimated as worth $2.0 billion annually [15]. Users will benefit if they require better than 30m position accuracy and if space weather information allows them to avoid using expensive differential GPS systems. In differential GPS, a correction is broadcast from a local ground station. Where high positional resolution has safety consequences, such as airport landing system, then differential GPS is likely to be preferable. However, there are many applications, e.g. prospecting in remote areas, where high positional accuracy is required but differential systems are impractical.

In one example of space weather effects on GNSS, enhanced scintillation during the Gulf War meant that US troops lost full use of GPS at times and suspected that jamming by the enemy was taking place [16].

The economic value of space weather information to GNSS depends on location and level of service. Now-casting of TEC is useful for single-frequency GNSS everywhere. Forecasts of enhanced scintillation can be useful for predicting when the service is degraded and are particularly valuable in equatorial and auroral regions.

4.7 Improved radar operations

Radar systems can be disrupted due to ionospheric disturbances. Warnings and now-casting of when radar is degraded has an effect on radar remote sensing and aircraft and shipping safety, as well as military capability, and thus has an economic benefit.

Radio waves from over-the-horizon radars, operating in the HF range and below, are reflected from the ionosphere. As this region changes in density, the height at which reflection occurs, and thus the range of the radar, varies. Radars used for space surveillance from the ground and space-based remote-sensing radars are affected by scintillation and change in phase as the waves pass through the ionosphere. For synthetic aperture remote-sensing radars, this leads to loss of coherence which decreases the size of the aperture that can be synthesised and hence the spatial resolution of the imagery. For a single frequency radar, changes in these effects can also lead to absolute errors in range. Knowledge of the total electron content (TEC) can enable phase information to be corrected, allowing full correction of coherence. Range errors can be corrected by knowledge of TEC and by the use of dual frequencies. Terrestrial radar is principally used in safety and military systems, for aircraft and ships. Awareness of when degraded performance affects radar systems can have a significant effect on safety and a very large effect on military effectiveness.

Economic benefit is related to the value of increased resolution and height accuracy from remote sensing spacecraft and the value of knowledge of when the range of over-the horizon radars is restricted.

Post-knowledge of TEC can let the full accuracy of space-based radar be recovered. Now-casting is also valuable, where users need to know that their radar performance is degraded. For remote sensing applications where high resolution is required, forecasts may allow observations to be re-scheduled or alternative systems, e.g. aircraft-borne radar, to be brought in.

4.8 More reliable radio communications

Radio transmissions at HF frequencies and below are able to travel around the curvature of the

Earth by being reflected from the ionosphere. Space weather effects control the critical frequency for ionospheric reflection and can cause fade-out. At higher frequencies, satellite to ground communications can be degraded by ionospheric scintillation effects.

The critical frequency for reflection of radio waves from the ionosphere typically varies between 1 and 10MHz. Radio waves below this frequency can travel vast distances by being reflected between the ionosphere and the ground. However, users in the HF bands typically must check ionospheric conditions before selecting the frequency to be used. A lower ionosphere can temporally cause signal strength to weaken dramatically in a process called short wave fade-out. Events lasting several days occur around the auroral zones and are called polar cap absorpsion events. Scintillation effects degrade satellite to ground communications up to 2GHz in much the same way as has been discussed for GNSS and space radar systems. During October 1989, world-wide interference of HF and satellite communications occurred. This caused military communications problems during the Gulf war and the loss of contact with Airforce 1, the US presidential plane [17].

Based on data from NOAA/SEC, the Federal Aviation Authority (FAA) issues warnings that HF, VHF, UHF, and SATCOM may experience interference in the following few days [13]. This need for space weather information is already partially met through organisations such as NOAA and the Australian IPS. Economic benefit will vary with the level of space weather information available. Significant benefit comes from now-casting of ionospheric critical frequency. This allows better choice of transmission frequencies. Forecasts of scintillation effects are of use if the time ahead is sufficient for alternative systems to be employed. This is liable to be of particular importance for military systems.

4.9 Improved reliability of power systems

Geomagnetically induced currents (GICs) can cause damage to power system equipment and interruption to power supplies. Warnings of large geomagnetically induced currents in ground systems can enable power system operators to take appropriate action to mitigate their effects.

Induced currents in long conducting systems such as power lines and telephone cables have been recorded over many years. In fact, disruption to electrical telegraph systems in 1860 was the first recorded space weather effect [18]. Although telegraphs and telephones continued to be affected for many years, modern telephone networks are not generally sensitive to these effects. Power cables have continued to suffer, especially at high magnetic latitudes. e.g. north-eastern USA , Canada and Scandinavia. Post-event space weather information has identified problems as space-weather related and led to the development of more tolerant systems. This benefit is expected to continue. Hardware measures to prevent damage from GICs can be expensive and hard to implement. Hence there is a need for accurate forecasts of disturbed geomagnetic conditions. Armed with these predictions, operators of generating equipment can minimise the risk of damage by reducing the output of generators to, say, 80% of full load (to reduce thermal loading) and enable tripping of the equipment if early signs of damage, e.g. gas accumulation in oil-cooled transformers, are detected. Highly vulnerable equipment can even be turned off for the duration of the event. Operators of power distribution systems can suspend maintenance work and restore transmission lines, reduce the load on high-voltage distribution cables, distribute generating capacity, bring reserve power supplies on-line and co-ordinate action with adjacent systems [19].

Economic benefit is related to the cost of down-time of the power system and the cost of replacing damaged generating and transmission equipment. Power supplies are of critical importance to virtually all economic activity and interruption poses additional risks in health and safety, e.g. winter heating, hospitals, passengers in lifts, and traffic lights, and has public order consequences. Failure to make adequate provision for space weather effects may result in expensive litigation for the companies involved.

The cost to HydroQuebec of the March 1989 outage is estimated at over $10million and the cost to its customers is estimated at $10s to $100s million. This cost is comparable to hurricanes and earthquakes and was this high because 6 million people were affected [20]. Oak Ridge National Laboratory estimated that a similar failure in NE USA would cost $3 to $6 billion. A nuclear plant in New Jersey had a transformer fail during the same March 1989 event. The plant took 6 weeks to get back into operation. This short period was only possible because there was an identical transformer available at a cancelled nuclear power plant. Transformers are estimated to cost $10m each and spares are not kept ready for failures. Analysis of transformer failure rates in the USA [21] has shown that excess failures of up to 60% occur in regions where GICs are found. Their occurrence is also correlated with geomagnetic activity. The cost in transformers alone is estimated at >$100m over 25 years. Many of these costs could be avoided by accurate diagnosis of which systems are being damaged by GICs and by accurate forecasts which would allow systems to be managed more carefully during active periods.

There already exists a market for space weather information in this field. NOAA/SEC publishes on-line data aimed at this section of industry. Stattnet, the Norwegian power grid company has been active in measuring space weather effects [14]. The UK National Grid has purchased a computer tool, called PowerCast, which attempts to forecast the consequences of geomagnetic activity and which takes, as input, solar wind data from the ACE spacecraft [22]. To date this power company is the only purchaser of this tool and so the current market appears small. Since the price paid is not public information, a quantitative assessment, in financial terms, is not possible.

Benefits require accurate prediction of geomagnetic activity at least 1 hour in advance. Predictions of GICs local to the transmission lines in question are most valuable. Now-casting is less beneficial since users are already able to monitor currents in their own systems.

4.10 Improved competitiveness of insurers

Space weather effects are a significant component of the risk of in-orbit failure of spacecraft and have caused expensive losses in ground power systems. Accurate space weather information could enable insurance firms to calculate risks more effectively.

The insurance market underwrites most commercial satellites, particularly up to injection into orbit but often also for in-orbit operations. The space market is a specialised area with a core of seven to ten companies playing a major role [25]. Europe has the largest share of the insurance market, perhaps 50 or 60%, and includes companies such as Lloyds, AXA, Munich Re, AGF, SCOR and La Reunion Spatiale. Scientific and military satellites are often not insured.

The total insured value of satellites is about $16 billion [25]. In-orbit premiums are typically 1.2 to 1.5% per year of the total satellite value [25] while launch insurance is typically 12 to 15%. Insurance premiums total $800 million to $1billion annually. Over the last decade premiums have exceeded losses by about 20%. However, in 1998, losses exceeded premiums almost two to one. Most losses are associated with launcher unreliability however, and losses of satellites in orbit are frequently from causes other than space weather [23]. Hence space environment effects are only a small part of the overall risk.

The capability of space weather information to lower costs appears quite marginal based on experience to date. However, space weather has an unusual characteristic, compared to other loss mechanisms, in that it could potentially affect a great many spacecraft simultaneously. The possibility that an environment worse, say, than the 1972 solar proton event, could take whole constellations of satellites out of service is something for which the insurance industry needs to prepare.

Financial risks associated with disruption of power systems are not generally covered by insurance companies and are treated as ‘acts of God’. The dependence of society on electrical power, and hence the cost to users of disruption, continues to rise. Hence this appears to be a market that could be exploited by insurers with strong expertise in space weather and GICs in particular.

The principal benefits to insurers of accurate space weather information come from better risk assessment. This involves the assessment of the susceptibility of different types of space and ground technologies to environmental effects. Insurers also require statistical information on the frequency and severity of enhanced environments in all orbits where insured spacecraft may be found. Just as insurers define a 1 in 100 years hurricane, they need to define a 1 in 100 years solar proton event, outer belt enhancement and magnetic storm.

Under a British government initiative called 'TSUNAMI', aimed at improving the competitiveness of the insurance industry, a study is being carried out into the space environment factors causing satellite anomalies. The setting up of this study, where government and industry share costs, shows that there is a perception within the industry that improvements to risk analysis can be achieved. The Norwegian insurance group Storebrand commissioned a report on solar eruptions and space weather effects from the University of Oslo after the large geomagnetic storm in January 1997 [14].

Most economic benefit to insurers is derived from post-knowledge of the environment from which broad climatological models may be constructed and to infer which systems are more vulnerable than others. The parameters of most interest in satellite insurance are solar protons, plasma characteristics and outer belt electron fluxes and for power systems it is geomagnetic activity. Forecasts may be used by insurers to ensure that, during disturbed periods, the insured parties do not carry out procedures that will increase the risk, e.g. satellite launches and power system maintenance.

4.11 Reduced corrosion in pipelines

Space weather information can be used to assess levels of corrosion in pipelines and tell when monitoring of cathodic protection systems is corrupted.

Pipelines in contact with the ground are subject to corrosion which is enhanced by positive pipeline potential. To counteract this, the pipes are covered with insulators and held at a small negative potential. Geomagnetically induced currents (GICs) can overcome this potential and, in theory, allow corrosion to take place at spots where the insulator is punctured. The extent to which this is a practical problem has not been well quantified and estimates are said to vary over a wide range. GICs also invalidate testing of cathodic protection systems.

A study of a pipeline in northeastern Australia showed a GIC-induced corrosion rate at coating defects consistent with a loss of 10% of pipeline thickness in 14 years. At this level of corrosion, the pipeline would need replacement 4 times more often than planned. Construction of an oil pipeline costs typically $2million per km [30,31] in total. However, this cost must include land clearance, surface preparation, access roads, bridges etc. so the cost of the metal pipe itself is only a fraction of the overall outlay.

Benefit comes principally from post-knowledge of geomagnetic activity from which GICs can be modelled. This would allow the possible level of corrosion to be assessed. Now-casting has some benefit because it would allow operators to postpone tests of cathodic protection systems.

4.12 Improved magnetic geological prospecting

Magnetic surveys are a valuable tool in geophysical exploration. However, corruption of magnetic data, due to temporal changes in the geomagnetic field, leads to data being inaccurate. Space weather information can allow planning of surveys and correction of corrupted data. Oil drilling platforms routinely use magnetism to define the direction of drilling. Space weather information is required to ensure accuracy.

Magnetic surveys are an essential tool in finding information about subsurface rocks. This information is typically used in mineral and petroleum exploration and has applications in earthquake fault analysis. Most surveys are carried out by aircraft, equipped with magnetometers, flying linear tracks, separated by typically a kilometre. At sea, measurements are carried out by ship. The results of these measurements are used to generate a contour map of magnetic intensity that can be compared with other information to make inferences on the underlying rocks.

Space weather variations in the Earth’s magnetic field lead to corruption of these data and corrections have to be made before the data are useful. Over land, local space weather corrections can be made by subtracting variations, measured at a fixed location. However, this works only over a limited area, is ineffective in auroral regions and has its own problems (e.g. data can be corrupted if a vehicle drives close to the reference location). Benefits are achievable if space weather information allows accurate subtractions to me made. Some benefit also arises if periods of severe disturbance can be forecast so that unnecessary flights can be cancelled.

When drilling for oil, prospectors typically use models of the Earth’s magnetic field to steer the drill bit in the required direction. Space weather information is required to make corrections due to the additional temporally varying component of the geomagnetic field.

The oil and mineral extraction industries are of great economic value and accurate magnetic information is very valuable to them. This is clear from the extensive networks of geomagnetic measurements carried out by national authorities, such as the British Geological Survey (BGS) and by international collaborations, such as INTERMAGNET. It is also clear that there is already a market for space weather information, which is being partially met e.g. through BGS’ CGIFS (Commercial Geomagnetism Information and Forecast Service).

The economic value of space weather information comes from accurate post-knowledge of the temporal component of the magnetic field. This allows correction of both survey data and drilling direction. Forecasts of geomagnetic disturbances are of lower importance but could influence scheduling of survey measurements.

4.13 Summary of economic benefits

The table below provides a concise summary of the main economic benefits of a European Space Weather Programme that have been discussed in this section.

In considering programme size, the definitions of small medium and large have been used as described in section 2.6. The threshold programme size, required to yield benefit and as indicated in the table below, occurs at the small level, since existing data sources, if appropriately used, could provide some useful information in all these areas. However, the degree of benefit depends on the accuracy and timeliness of the information provided and it is to improve these areas that larger programmes are being considered.

In the estimation of timescale of the benefits, the definitions of short, medium and long-term have again been used as described in section 2.6. The economic benefits described will only occur once a space weather service begins to come into operation. Hence benefits start in the medium term but should improve in the longer term if space weather products improve.

Benefits	Programme Size			Timescale		
	Small	Medium	Large	Short (<3 yrs)	Medium (3-10 yrs)	Long (>10 yrs)
Improvements to spacecraft operations	√	√√	√√√		√	√
More robust spacecraft components	√	√√	√√√		√	√
Risk avoidance during launch	√	√√	√√√		√	√
Reduction of radiation exposure during of manned missions	√	√√	√√√		√	√
Reduced risk of SEUs in avionics	√	√√	√√√		√	√
Reduction in radiation exposure to aircrew and passengers	√	√√	√√√		√	√
More robust avionics components	√	√√	√√√		√	√
Improved accuracy of GNSS	√	√√	√√√		√	√
Warnings of GNSS non-availability due to scintillation	√	√√	√√√		√	√
Warnings of radar degradation	√	√√	√√√		√	√
Recovery of synthetic aperture radar accuracy	√	√√	√√√		√	√
Choice of VHF transmission frequency	√	√√	√√√		√	√
Knowledge of when scintillation effects will adversely affect radio communications	√	√√	√√√		√	√
Reduced damage to power systems from geomagnetically induced currents	√	√√	√√√		√	√
Development of climatological models for insurance purposes	√	√√	√√√		√	√
Analysis of system vulnerability for insurance purposes	√	√√	√√√		√	√
Assessment of corrosion in pipelines	√	√√	√√√		√	√
Improved accuracy of geological surveys	√	√√	√√√		√	√
Improved accuracy of drilling operations	√	√√	√√√		√	√

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5 Educational Benefits

5.1 School courses

Scientific awareness begins at school and there are many aspects of space weather which can be used to illustrate basic scientific principles, for example; subatomic particles, electric charge, magnetism, electromagnetic induction and light. This is a field in which school students can follow the link from these basic physical concepts to practical every-day effects. Appreciation of the Earth as a planet in space, our dependence on the Sun, our local star, and the fact that it is variable in output should be fundamentals for all school children. As well as providing the opportunity for gaining scientific knowledge, there are plenty of valuable exercises in mathematics and scientific skills, such as data handling, statistics and correlation of effects.

The need for better school education in science is set against what is regarded as 'a deteriorating state of physics literacy amongst Europeans at all levels' [1].

In the USA, both NASA and NOAA operate "Outreach" programmes which aim to bring their science to schools and to the general public. In both cases there are strong components of space weather containing much valuable teaching material for schools. ESA also has an outreach programme but, at present, without a strong space weather element.

In the UK, the Particle Physics and Astronomy Research Council (PPARC) is committed to the public understanding of science and operates a 'Schools and Education' web-site with links to many resources in the space field. A schools information pack on solar-terrestrial physics relates many important phenomena to aspects of the UK National Curriculum in science. Research students are encouraged to share their knowledge and enthusiasm in school visits.

Within Europe, a strong space weather programme would provide greater access to more complete space weather information, enabling more widespread and better co-ordinated use of educational material, resulting in greater understanding of science, and space weather in particular, among school students.

5.2 University courses

Many physics and astrophysics courses have modules on sun-earth connections, while satellite engineering courses usually acknowledge the significance of the environment. The benefits of a European space weather programme include enhanced awareness and accuracy in such courses and increased opportunity for student participation in aspects of the programme.

5.3 Continuing professional development

There is a need for the continuing education of professional scientists and engineers involved in the design and operation of systems which are potentially vulnerable to space weather. A European space weather programme would provide a stimulus for more professionals to obtain and develop such knowledge. By providing better quality space environment information, it would facilitate the development of material to satisfy this need. Use of websites is of great importance here (see below).

5.4 Public awareness

In an era where the public is often seen as increasingly distant from or distrustful of science, the dramatic nature of major space weather events provides a focus to remind people of the importance of science in every-day life and the value of understanding the Earth's space environment in particular. Public awareness of space weather has, at times, been temporarily raised by good media coverage but the imperfect state of forecasting up to now has led to many false predictions. For instance, recent events of 7-12 June 2000 attracted significant media attention but have had few, if any, significant effects. A more effective space weather service would be able to attract public notice without being alarmist.

In recent years European space weather scientists have played major roles in television documentaries on space weather - for example, "Sun Storms" produced for Equinox and "Cosmic Storm" produced for Discovery Ultrascience. A European space weather programme would provide further opportunities for and improved effectiveness of this type of public education. The programme could be expected to generate interesting information on science and its impacts on society and would greatly benefit displays concerning space in science museums and space centres.

By improving public understanding of space weather, a European space weather programme would provide positive public relations with the benefit of raising the profile of European space activities among the taxpaying public.

5.5 Websites

The increasing use and accessibility of the world wide web means that websites are a very effective means of advancing the above aims. Many have an element of education in terms of raising public awareness. However only a few contain much basic education. Organisations currently supporting such facilities include the following:

- NASA has a wealth of educational material which can be found under its International Solar Terrestrial Physics Outreach site, http://www-istp.gsfc.nasa.gov/istp/outreach/. Information on NASA's current "Living with a Star" programme can be found at (http://www.sec.gsfc.nasa.gov/lws).

- NOAA has plenty of educational material on space weather including materials for teachers and students (http://www.sec.noaa.gov/info).

- The PPARC Public Understanding of Science programme can be found at (http://www.pparc.ac.uk/PUS).

- The University of York operates an aurora watch site at (http://www.aurorawatch.york.ac.uk). The dramatic visual impact of aurorae is an excellent way to excite the public about space weather.

- ESA has set up a space weather website at (http://www.estec.esa.nl/wmwww/spweather) with strong connections to the Finnish Meteorological Institute's site at (http://www.geo.fmi.fi/spee/links). Plenty of information is available through the site at the University of Lund, Sweden (http://www.irfl.lu.se/HeliosHome/spwo) but the only basic education component is provided by a link to Stanford Solar Center, USA (http://sola-center.stanford.edu).

With a properly funded European space weather programme, the ESA associated sites could be expanded to become a valuable resource for Europe. Basic education could particularly benefit as there are many fundamental principles illustrated by space weather. This is an area in which the USA currently appears to be far ahead of Europe. A European space weather programme could help develop a stronger European presence on the world wide web to match the existing US facilities.

5.6 Summary of educational benefits

The programme size and timescales are as defined above in section 2.6. While all benefits could start to be realised with a small programme, there would be scaling with programme size.

Benefits	Programme Size			Timescale		
	Small	Medium	Large	Short (<3 years)	Medium (3-10 yrs)	Long (>10 yrs)
Improved awareness of scientists and engineers	√	√√	√√√	√	√	√
Improved space weather courses in universities	√	√√	√√√	√	√	√
Improved awareness of space weather at school	√	√√	√√√		√	√
Stronger presence of European space activities on the world-wide web	√	√√	√√√	√	√	√
Raised profile of ESA and Space amongst general public	√	√√	√√√		√	√

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10a. Abstract. (An abstract should aim to give an informative and concise summary of the report in up to 300 words).

Space weather is directly concerned with the effects of solar-terrestrial relations on technological systems and human well-being. The benefits to be gained by the implementation of a European Space Weather Programme are described. These benefits can be broadly divided into strategic, technological, scientific, economic and educational categories and affect user groups including pan-European organisations, governments, defence forces, businesses and also individual citizens.

The programme would reduce European dependence on non-European sources of space weather information and by bringing together different areas of expertise, provide a stimulus to the growth of high technology enterprises. The programme execution would encourage advances in space and information technology and the completed system would provide great opportunities for scientific progress. Economic benefits would result from gains in reliability of technological systems such as spacecraft and power grids and in the managed use of radio systems, which include HF and satellite communications, radars and global navigation satellite systems. Additional benefits include the better knowledge of ESA and space issues amongst the general tax-paying public.

10b. Abstract classification: UL	FORM MEETS DRIC 1000 ISSUE 5