ESA Space Weather Programme Study
Alcatel Consortium

Space Weather Parameters Required by the Users
Synthesis of User Requirements

WP1300 and WP1400

Richard B. Horne

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

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ESA Officer: A. Hilgers, ESTEC

R. B. Horne
British Antarctic Survey
Madingley Road
Cambridge, CB3 0ET
U.K.
Email R.Horne@bas.ac.uk

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1. Introduction

1.1 Objectives

There are two objectives to this workpackage. The first is to identify the space weather parameters required by the users, and the second is to provide a synthesis of requirements from the user point of view. To avoid too much duplication with other workpackages, the results are mainly summarised in tabular form and include a large set of appendices for reference.

This workpackage is based on an information gathering exercise outlined below, and draws on work set out in WP1100 Benefits of a Space Weather Programme, and WP1200 Market Analysis. The results of this workpackage feed into WP 2000 Space Segment, and WP4000 First Iteration.

1.2 Definition of Space Weather

We define Space Weather (SW) as

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

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

1.3 Information Gathering

The approach used in this workpackage is a bottom-up user approach. Members of the Alcatel consortium identified more than 75 contacts covering each market sector affected by SW and including defence and scientific research, and spanning countries in Europe (UK, France, Germany, and Sweden) and Canada and the USA. We obtained a response from more than 49 people, via meetings, telephone interviews, and written responses to an aide memoire questionnaire. This pro-active activity was very time consuming, but has provided essential information and focussed our attention on the needs of the users.

In addition, members of the Alcatel team provided additional input by attending conferences (including EGS, Nice, 2000; NATO ASI, Crete 2000; COSPAR, Warsaw, 2000; SRAMP, Japan, 2000). Conferences were a very valuable forum to discuss issues and to obtain a balance of what is required and what is possible to provide; they were particularly important source of information. Information was also obtained from previous reports and web based documents.

The list of users who provided input to this study is given in the Acknowledgements. The response by market segment is given below in Table 1.1.

1.3 Definition of the Users

We identified several different market sectors that are affected by space weather. They are set out in Table 1.1, together with the number of interviews and responses received by market sector. Despite contacting four different launch operators we could not obtain any response. Every market sector listed in Table 1.1 either receives information on space weather from the Space Environment Centre, Boulder Colorado, buys information from companies, or has commissioned research from research institutes and University Groups.

Market Sector	**Number of interviews and responses**
Satellite Design	4
Satellite Operators including: • Communications • Broadcasting • Remote sensing • Navigation • Science	6
Space Agencies including: • Man in space	2
Launch Operators	0
Defence including: • HF communications • Over the horizon radar • Surveillance • Navigation • Submarine communications	4
Civil Aviation	7
Ground based systems including: • Power generation and supply • Prospecting for minerals oil and gas • Oil and gas pipeline distribution • Railways	 6 1 2 1
Insurance	4
Tourism	1
Research	5
US Space Weather/Education	2
Other	4
Total	**49**

Table 1.1. Market sectors and number of interviews and responses

In this approach we have tried to identify the market sectors with a potential for buying services or commissioning research, and not groups of users who may be similarly affected by space weather. For example, HF communications and GPS navigation aids are used by the public and by Defence and are subject to disruption by a disturbed ionosphere. However, while the public form an important interested sector they are unlikely to form a market sector that would buy space weather services.   On the other hand, Defence has a strong interest in space weather services and commissions research in this area; Defence can be regarded as a market sector in its own right. Similarly, we have identified tourists, rather than the general public, as a market sector that will (and already does) pay for space weather predictions.

1.4. Classification of the Users

The results of our analysis suggest that the users can be classified into four types, with different driving forces.   They are given in Table 1.2.

Type of user	**Objective**	**Driving Force for Space Weather**
Commercial Companies	Provide goods and services	Cost-benefit
Commercial Companies, Agencies and Organisations	Protect life and health	Health and Safety
Defence	Maintain effective capability	Need to know
Scientific Research	Problem solve, understand, and advance knowledge	Interesting and challenging problems with commercial applications
Tourist/public	Enjoyment and understanding	Curiosity

Table 1.2. Classification of the users

Understanding the driving force is useful for assessing the financial impact (covered separately in WP1200 on market assessment) and for determining the relative priorities for a space weather programme:

- Most commercial companies are driven by cost-benefit analysis. They are mainly interested in space weather if better mitigation procedures can be used to reduce their losses and protect their employees, or if data analysis can be used to develop better products, and new markets.
- There are several companies, mainly airlines but also Space Agencies, which are driven by Health and Safety.   They need to minimise radiation exposure to their employees, and to meet new legislation.
- Defence users are driven by the need to know. For example, if a satellite fails or a radar system is blinded, or if they cannot communicate with their remote forces, they must know whether cause is due to a hostile act, or to space weather, and they must know as soon as possible.

- Research scientists are mainly driven by interesting and challenging problems. Space weather provides exceedingly challenging problems for both basic and applied research. Space weather also provides problems that have a direct commercial application which is an additional driving for some scientists.
- The public show great interest and curiosity in the effects of space weather. Tourism is a developing market in Scandinavia where tourists pay for predictions of the aurora.

2. User Problems

2.1 Problems Related to Space Weather

A detailed analysis of user problems caused by space weather is given in WP1100 Benefits, and WP1200 Market Analysis and is not repeated here. Instead, a summary is provided in Table 2.1. More detail for each market sector is provided in the tables in the Appendix.

Market Sector	Problem	Cause	Result	Location and Space Weather related Events
Satellite Design **&** **Satellite Operators** **(including Space Agencies)**	Internal charging resulting in electrostatic discharges.	Accumulation of charge, mainly electrons > 0.5 MeV	In-orbit anomalies. Phantom commands. Parts failure.	Radiation belts and south atlantic anomaly - Variations in flux due to magnetic storms, substorms, magnetopause compression, fast solar wind streams. SEP events.
	Total radiation dose.	Accumulated radiation damage due to all ionizing radiation mainly electrons (> 0.5 MeV), protons (> 1 MeV) and all ions (mainly He+ and O+ > 1 MeV/ nucleon).	Reduction in solar cell power. Reduction in satellite lifetime.	All locations, but mainly radiation belts - Variations in flux due to magnetic storms, substorms, magnetopause compression, fast solar wind streams. Cosmic rays. SEP events.
	Single event effects	Protons > 50 MeV Ions > 10 MeV/nucleon Electrons > 500 keV	Corruption of memory. Parts failure.	All locations, but mainly radiation belts. Cosmic rays - Variations due to solar cycle. SEP events.
	Surface charging resulting in electrostatic discharges.	Solar illumination. Thermal electrons and ions (1-50 eV) and spectrum up to plasmasheet energies (1eV – 100 keV electrons and ions). Changing plasma density.	In-orbit anomalies. Phantom commands. Parts failure.	All locations, especially plasmasheet and outside plasmapause during early morning, south atlantic anomaly region, auroral precipitation region. Changes in solar UV during Eclipse. Variations in keV plasma, especially during magnetic storms and substorms. Plasma boundary crossings.

Market Sector	Problem	Cause	Result	Location and Space Weather related Events
	Solar cell degradation and displacement damage.	Electrons > 100 keV and protons 1 – 10 MeV.	Reduction in power.	Cosmic rays – variations due to solar cycle. SEP events. Radiation belts as above. Ring current – magnetic storms.
	Surface material degradation, sputtering and erosion.	As for total dose, but including protons 0.1-1 MeV and atomic oxygen	Spacecraft heating through loss of reflectivity.	Cosmic rays. SEP events. Radiation belts – as above. Ring current – magnetic storms.
	Sensor interference and degradation	As for total dose.	Increase in sensor noise.	Solar wind, magnetosphere, lower ionosphere. SEP events. Cosmic rays. Radiation belts – as above. Ring current – magnetic storms.
	Micro-particle impact	Space debris and meteoroids	Parts failures. Trigger for electrostatic discharge	All earth orbits. Result of orbit perturbations due to geomagnetic storms.
Satellite Operators **(including Space Agencies** **and** **including Remote sensing, GPS and other navigation systems, altimetry)**	In-orbit anomalies, Phantom commands. Mode switching, (See also satellite design).	Internal electrostatic discharge. Surface electrostatic discharge. Single event effects.	Partial or complete loss of service. .	All locations, but especially radiation belts, south atlantic anomaly region, auroral region, morning magnetospere. - Variation due to magnetic storms, substorms, magnetopause compression, fast solar wind streams. SEP events.
	Orbit perturbations. Loss of spacecraft stability.	Atmospheric expansion.	Increased atmospheric drag Early re-entry in LEO. Additional use of fuel to correct.	Thermosphere. Enhanced solar EUV during flares. Joule heating in the ionosphere and particle precipitation during substorms and storms.
	Loss of tracking space debris.	As above	Risk of collision between spacecraft and space debris.	As above
	Loss of attitude control.	Magnetic field reversals (for spacecraft with magnetic torquers).	Loss of directional coverage for broadcast signals.	Magnetopause compression inside GEO, related to CMEs and periods of increased solar wind pressure.
		Spurious signals in star sensors	As above	Solar wind and magnetosphere. SEP events.

Market Sector	**Problem**	**Cause**	**Result**	**Location and Space Weather related Events**
	Loss of signal phase and amplitude lock.	Ionospheric scintillations. Radio interference.	Errors in navigation. Loss of useable data.	Mainly equatorial and auroral ionosphere. Enhanced solar EUV during flares. Joule heating and particle precipitation during substorms and magnetic storms, plasma instabilities. SEP events.
Space Agencies (man in space)	Increase in ionizing radiation	Electrons and ions > 10 MeV/nucleon	Increased radiation dose to astronauts.	Low altitude portion of the radiation belts and south atlantic anomaly region. Variations due to magnetic storms, substorms, magnetopause compression, fast solar wind streams. SEP events. Galactic cosmic rays.
Launch Operators **(including Space Agencies)**	Increase in ionizing radiation	Electrons and ions > 10 MeV/nucleon	Increased radiation dose to astronauts, radiation damage to payload.	As above.
	Errors in launch trajectories	Atmospheric expansion	Increased atmospheric drag	Thermosphere. Increased EUV radiation. Joule heating. Particle precipitation.
Civil Aviation	To asses radiation dose to aircrew	Ionizing radiation, E > 10 MeV (primary and secondary), Neutrons	Radiation dose to aircrew.	Polar routes, and high altitude aircraft. Galactic cosmic rays, variations during solar cycle. SEP events.
	Single event effects	As above	Radiation damage to avionics.	As above
	Interruption to GPS and other positioning systems for navigation	Ionospheric scintillations.	Errors in positioning on landing approach.	Mainly equatorial and auroral ionosphere. Enhanced solar EUV during flares. Joule heating and particle precipitation during substorms and magnetic storms, plasma instabilities. SEP events.
	Interruption to HF communications	Ionospheric irregularities	Unable to make position reports.	As above
Power generation and supply	Geomagnetically induced currents.	Time varying ionospheric currents	Power surges and outages in distribution networks. Transformer damage and reduced lifetime. Reduction in transmitted power.	Auroral latitudes. Changes in auroral current systems caused by magnetic storms and substorms.

Market Sector	**Problem**	**Cause**	**Result**	**Location and Space Weather related Events**
Oil and gas pipeline distribution	Geomagnetically induced currents.	Time varying ionospheric currents.	Pipeline corrosion. Build-up of electric potential along pipeline.	As above.
Aerial surveying for minerals oil and gas	Variations in the direction of the surface magnetic field.	Changes in magetospheric current systems.	Corruption of data.	Changes in auroral current systems at high latitudes due to magnetic storms and substorms. Low latitude field variations due to the ring current and tail currents during magnetic storms, and magnetopause compressions.
Drilling for oil and gas	Variations in the direction of the surface magnetic	As above	Errors in navigating the drill head.	As above.
Railways	Geomagnetically induced currents	Time varying ionospheric currents.	Possible disruption of signaling.	Auroral latitudes. Changes in auroral current systems caused by magnetic storms and substorms.
Insurance	Problems as for design, launch and operation of spacecraft.		Insurance claims for in-orbit loss, loss on launch, and loss of service provision.	
	Problems as for power generation and supply.		Insurance claims for direct damage. Indirect claims from domestic users due to knock-on effects.	
Defence:	Problems as for design, launch and operation of spacecraft, and power generation.			
Defence: **HF communications**	Loss of signal path between transmitter and receiver. Radio wave absorption and blackout.	Ionospheric irregularities. Changes in peak plasma density. Increase in ionospheric collision frequency.	Loss of communications. Loss of direction finding.	All locations, especially auroral region and day/night terminator. Particle precipitation, plasma instabilities, gravity waves caused by Magnetic storms. Substorms. Solar flares.
Defence: **Over the horizon radar**	Enhanced clutter at high latitudes.	Coherent scatter from plasma irregularities.	Reduced detection capability for satellites and aircraft.	As above

Market Sector	Problem	Cause	Result	Location and Space Weather related Events
Defence: **Satellite Surveil-lance**	Increased atmospheric drag for satellites in low orbit.	Atmosphere heating.	Reduced detection capability for missile launch.	Thermosphere. Enhanced solar EUV during flares. Joule heating and particle precipitation during substorms and storms.
	Increased noise in optical sensors.	Auroral light emissions.	Reduced detection capability for missile launch.	Magnetic storms. Substorms.
Defence: **Navigation by GPS and other positiong systems**	Loss of phase lock and amplitude.	Ionospheric scintillations.	Loss of targeting accuracy for cruise missiles.	Mainly equatorial and auroral ionosphere. Enhanced solar EUV during flares. Joule heating and particle precipitation during substorms and magnetic storms, plasma instabilities. SEP events.
Defence: Submarine communicati ons	Disruption to ELF and VLF signals.	Irregularities in the bottomside ionospheric density profile.	Loss of communications with submarines.	Long distance across plasma boundaries. SEP events. Solar flares.
Tourism	Predicting the aurora.	Electron precipitation	Missed observations	Auroral regions, during magnetic storms, and substorms.

Table 2.1. Summary of user problems due to space weather

2.2 Mitigating Action

A space weather prediction service only makes sense to the users if they can take some avoiding action to minimise loss, or in some cases, develop new business. There are several types of actions that the users can take, and these are given in the Appendix for each market sector, together with an assessment of how they can be improved. In general terms predictions enable better planning of operations such as:

- Having more staff available and on alert to deal with problems
- Suspending non-routine operations
- Switching off non-essential systems
- Having back-up systems immediately available for use
- Curtailing activities
- Optimising existing operations
- Using alternative systems

3. User Requirements for Measurement and Prediction

3.1 Types of Information Required

From the interviews conducted as part of this workpackage, and from our own assessment, we have identified several user requirements. They generally fall into the following categories:

- Prediction of Space Weather events
- Prediction of physical quantities that directly impact the users
- Continuous measurements of the system
- Post-event analysis (PEA)

Post-event analysis is just as important as predictions, and in some market sectors such as satellite design and insurance, much more important.

3.2 Prediction of Space Weather Events

Events originating from the sun and solar wind impact the magnetosphere, ionosphere and thermosphere over a variety of timescales, from a few minutes to a few days. There are several different types of events, but in general there are two main reasons why they should be identified, predicted and recorded:

- Event identification provides some measure of warning before technological systems are disrupted.
- Event recording provides important information for use in post-event analysis for assessing impact and developing new models, and feedback into design.

The events that should be identified and recorded, together with an assessment of relative priority, are given in Table 3.1.

User No.	**Event**	**Pri-ority**	**Action**	**Primary Reason**
E1	CMEs	1	Warn and record	Operational. Pre-cursor to strong magnetic storms.
E2	Magnetic storms	1	Warn and record	Operational. Provide major impact on a large range of technological systems according to severity.
E3	Solar Flares	1	Warn and record	Operational. Associated with strong radio emissions that disrupt the ionosphere.
E4	Solar energetic particle events	1	Warn and record	Operational. Source of highly energetic protons that disrupt satellite systems.
E5	Change in solar magnetic field	2	Record	Pre-cursor to CME lift-off, and solar flares.
E6	Substorms	2	Record	Impact a wide range of systems, but on much shorter timescale than magnetic storms (hours).
E7	Interplanetary shocks	2	Record	Source of radio emission that could be used for better storm predictions.
E8	Magnetic clouds	2	Record	Associated with a rotation of the interplanetary magnetic field that may

User No.	Event	Pri-ority	Action	Primary Reason
				enable better storm predictions.
E8	Fast solar wind streams	2	Record	Associated with energetic electron enhancements in the radiation belts and may enable better flux predictions.
E10	Solar wind pressure pulses	3	Record	Associated with magnetopause compressions that affect the surface magnetic field.

Table 3.1. Space Weather events to be identified and recorded

3.3 Predictions of Physical Quantities that Directly Impact the Users

In order to quantify the severity of a space weather event, and the location where it will impact the users, predictions of several physical parameters are required. They are given in Table 3.2. The symbols provide an indication of the relative importance for each market sector high (1), medium (2) and low (3).

User No.	User Required Predictions	Satellite Design	Satellite Operators	Space Agencies (Man in Space)	Launch Operators	Defence	Civil Aviation	Ground Based Systems	Insurance	Tourism	Research
P1	Prediction of enhanced electron and ion flux in the radiation belts, including spectrum, peak flux and duration.		1	1	2	1					1
P2	Prediction of SEP flux, including spectrum, peak flux and duration.		1	1	1	1	1				1
P3	Predictions of atmospheric density profile.		1		2	1					1
P4	Predictions of magnetopause compression and field reversals at GEO.		3			3		3			1
P5	Predictions of the radiation dose to aircrew and astronauts due to SEP events and cosmic rays.			1			1				1
P6	Predictions of the ionospheric current systems, rate of change of the current systems, and GIC on the ground.					1		1			1
P7	Predictions of ionospheric electron density profile, peak density, and		2			1	3				1

User No.	User Required Predictions	Satellite Design	Satellite Operators	Space Agencies (Man in Space)	Launch Operators	Defence	Civil Aviation	Ground Based	Systems Insurance	Tourism	Research
	radio blackout.										
P8	Predictions of ionospheric scintillations, radar clutter and TEC errors, location and severity.		1			1	3				1
P9	Predictions of the aurora, including location and duration.					1				1	1
P10	Predictions of all clear conditions		2	2				2			
P11	Predictions of the magnetic field deviations and fluctations			2		1		1			

Table 3.2. Summary of user predictions required

3.4 Timescales and Reliability

The timescale for warning depends on the nature of the event. For example, Table 3.3 gives an estimate for the time delay between an event being detected on the sun and its effects on the earth for the most important events. It is an estimate of the maximum prediction timescale possible at present.

Event	Warning timescale currently possible after event detected on the sun	Comment
Solar flares, X-ray, EUV, UV and radio emissions	None	Research required to develop reliable predictions
Solar energetic particle event	< 1 hour	If detected by radio/optical techniques on the sun
Disturbances due to magnetic storms	2-3 days	If CME, shock, or magnetic cloud can be identified and tracked.
Radiation belt enhancements	1-2 days after the start of a magnetic storm	For 90% of magnetic storms
Recurrent storms	27 days after first storm	Research required to develop reliable predictions

Table 3.3 Prediction timescales possible now

Research into the precursors of these events on the sun is required to increase the prediction timescales possible, and to increase reliability.

Almost all commercial operators require warnings of events a few days in advance so that they have plenty of time to plan operations, warn staff, and take mitigating action as set out in section 2.2. However, warnings a few days in advance are very unreliable at present. In our research, most operators wanted reliable warnings up to 24 hours in advance at the 68% confidence limit or higher. Some operators (such as power generation and supply) currently receive warnings up to 1 hour ahead based on data from the L1 position and are still able to act upon them. This is an absolute minimum timescale for warnings. Some companies stated that they require very high reliability before they take action, at the 95% confidence limit. The only way to achieve this level of reliability is via a nowcast. Nowcasts are still very valuable, for example, airlines can decide to ground aircraft during a SEP event if the risk of radiation exposure is too high on a trans-polar route.

We suggest that warnings of disruptions should be issued over a variety of timescales with an initial target reliability given in Table 3.4.

Warning timescales	**Target Reliability**
Warning – 2-3 days	65%
Warning – 3-6 hours	65-95%
Warning – 1 hour	95%
Nowcast	95%

Table 3.4. Warning timescales required

To achieve reliable warnings on a timescale of more than 1 hour, serious consideration should be given to in-situ observations upstream of L1. This would provide Europe with a unique capability, and would provide the additional warning time required by the users.

We note that even using data from the L1 position may afford more than 1 hour warning for some ground based systems in special circumstances. For example, a storm may hit the magnetosphere while the European sector is on the dayside so that it may be several hours before the European secotor rotates to the nightside where the full impact of the storm is felt by ground-based systems. Secondly, electron flux enhancements in the radiation belts occur on two timescales, large fluctuations during the storm main phase, and significant enhancements (3 or 4 orders of magnitude) above the pre-storm level during the recovery phase. This enables longer timescales of many hours for predictions.

3.5 Long-Term Predictions

A system of long-term predictions is also required for some market sectors such as satellite design and insurance. We suggest:

- Long term predictions – 1 month ahead
- Long term predictions – 1 year ahead
- Long term predictions – 3 years ahead

The predictions should include solar activity and the number of important events that are likely to occur, such as SEP events and magnetic storms.

3.6 Continuous Measurements

In order to predict events, and predict the parameters required by the users, continuous measurements are required. In addition, continuous measurements are also required for:

- **Nowcasting and ground truth**. It is important to confirm predictions of events, and their severity, when they are in progress. Users also require secure access to data in real time for system monitoring.
- **Model development**. Models can be developed to predict physical parameters which can be compared to observations as a test of validity. This provides a feedback loop for model development.
- **To characterise the state of the system**. Continuous measurements are needed to determine when the system is in a disturbed state, and when it has returned back to its nominal quiet-time level.
- **Research**. Many of the relationships between different parts of the system are not understood, and measurements are required for research to feedback into better predictions and for post-event analysis.
- **Post-event analysis**. Users require data to determine whether systems failed as a result of space weather (see Section 4).

Not all the parameters shown in Table 3.2 are sufficient to fulfil these needs. Table 3.5 gives a more complete list of the measurements required based on input from scientists in solar-terrestrial physics.

User No.	Measurement/Parameters	Reason
M1	Solar magnetic field. Solar X-ray, EUV, and UV emission	Provides a measure of the suns activity. Impacts the ionosphere.
M2	Solar radio emission	Directly impacts the users, see table 3.2
M3	Sunspot number	Provides a measure of the phase of the solar cycle
M4	Cosmic ray flux	Directly impacts the users, see table 3.2
M5	Solar energetic particle flux	Directly impacts the users, see table 3.2

User No.	Measurement/Parameters	Reason
M6	Interplanetary magnetic field vector, velocity vector, electron density, electron and proton temperature.	Provides a measure of energy coupling to the magnetosphere. Required to determine geo-effectiveness.
M7	Geomagnetic indices Kp, Dst, AE, AL, AU, Aa, Pc.	Provides a measure of geomagnetic activity, storm activity and substorm activity. Aa is required for compatibility with historical records to measure long-term evolution.
M8	Location of magnetospheric boundaries: • Open/closed magnetic field boundary • Equatorward edge of electron precipitation boundary. • Plasma-sheet boundary layer. • Magnetopause boundary. • Plasmapause boundary.	Provides a measure of energy input, storage and release in the magnetosphere. Provides a measure of stress in the system.
M9	Radiation belt electron and ion flux. Ring current particle flux. Plasmasheet electron and ion flux. Ion composition (H+, He+, O+) Thermal electron and ion density.	Directly impacts the users, see table 3.2
M10	Level of magnetospheric wave activity, ULF, ELF, VLF, LF.	Provides a measure of electron and ion loss rates, and substorm activity. Provides a measure for electron acceleration timescales in the radiation belts.
M11	Auroral electron precipitation flux at ionospheric altitudes.	Directly impacts the users, see table 3.2
M12	Polar ionosphere electric field distribution.	Provides a measure of energy coupling from the interplanetary medium into the magnetosphere.
M13	Ionospheric currents	Directly impacts the users, see table 3.2
M14	Rate of change of surface magnetic field dB/dt	Directly impacts the users, see table 3.2
M15	Peak ionospheric electron density, and density profile.	Provides a measure of ionospheric disturbance. Directly impacts the users, see table 3.2
M16	Electron density perturbations dNe/Ne	Directly impacts the users, see table 3.2
M17	Total electron content	Directly impacts the users, see table 3.2
M18	Neutral density profile	Directly impacts the users, see table 3.2
M19	Global optical and UV auroral emissions.	Provides a measure of energy input into the neutral atmosphere.

Table 3.5. Continuous measurements required for an effective space weather programme.

3.7 Issues for a Prediction Service

In summary, users require the following information when predictions are made:

- The probability that the event will occur
- When the event will occur
- How severe the disruption will be
- Where the disruption will occur
- How long the disruption will last

There are several factors that must be taken into account. For example, the users require:

- **Continuous coverage**. Users require continuous measurements and a continuous prediction service, 24 hours/day, 365 days a year. This has implications for the manpower required for an operation service.
- **Continuous access**. Users require continuous real-time access, or close to real-time access (within 10 minutes or so), to measurements for their operations (e.g., Defence, and satellite operators). The data access system must be able to withstand high loading at peak times via the network.
- **Reliable data**. Some users require data to make their own predictions and risk assessment. It is essential that the data collected are accurate and reliable and that the satellites and instruments are robust enough to withstand space weather events.
- **Back-up and redundancy**. An operational space weather service must have back-up and redundancy in every aspect. For example, if observations from a given location are critical (such as the L1 point), then more than one spacecraft is required. This is particularly important for maintaining Defence capability. Back-up suggests opportunities for collaboration with other Agencies and countries.
- **Reliable predictions**. Predictions must be reliable otherwise they will cost the users money and will reflect badly on ESA. Similarly, users will not tolerate many false alarms. For very high cost operations 95% reliability is required. Only a nowcast can achieve this level of reliability at present. Any prediction service must strive for 95% reliability and any warnings must be issued with a statement of probability so that users can make their own risk assessment whether to take action.
- **Timely predictions**. Predictions must be provided in time for the users to take action. This sets constraints on the timescale for obtaining and analysing data to identify events, and then for issuing warnings. It also sets constraints on the timescale for models to predict physical parameters and hence determine the severity of events. Timescales may determine whether the most effective model is physical, empirical, or based on artificial intelligence.
- **Understandable predictions**. Users are not experts in solar-terrestrial physics and require predictions in a form they can understand. For example, a prediction of the solar X ray flux, or particle flux will not convey much

meaning. Instead, users require a dual-system approach which combines a clear, concise assessment, such as Red, Amber, Green warning system, together with more detailed information that can be accessed as users become more experienced.

- **Visualisation**. Users require visualisation as a key to understanding. By analogy with terrestrial weather, colour-coded maps of the solar wind-magnetosphere-ionosphere system are required to illustrate the warnings and indicate the regions they apply to. A system of maps is required to illustrate the regions at risk for each important parameter (e.g., particle flux, currents, scintillations), for varying levels of detail and information..
- **Authoritative predictions**. Some warnings and nowcasts will be used to protect human health and safety, and therefore must be issued through an authoritative body, such as ESA.
- **Coordinated and quality controlled predictions**. The users require a co-ordinated issue of warnings and nowcasts. This is important if ESA adopts a distributed space weather network, where different centres have different specialisations. There must be quality control to resolve conflicting predictions.
- **Tailored predictions**. Some users require specific predictions requiring detailed knowledge about their operations, such as the power supply and distribution companies. This provides opportunities for specialised services.
- **All-Clear announcements and predictions**. In many cases users require an all-clear signal in order to continue normal operations, and to carry-out special operations. The all-clear may not apply to all systems at risk at the same time. For example, the timescale for the radiation belts to return to normal is very different to that for ionospheric current systems.

The reliability issue is crucial and deserves further comment. The requirements for reliability may differ between market sectors depending of the driving forces set out in Table 1.2. For commercial companies, a sufficient level of reliability may be obtained when the company can save more money by acting on predictions than it would otherwise lose, even though some warnings may be false alarms. This requires a detailed assessment by the companies involved, and a close monitoring and evaluation by ESA. It requires re-assessment every year. It also highlights the need to educate the users in the damaging effects of space weather so that they are prepared to spend time and effort to make this assessment.

Back-up and redundancy is also a very important issue. Over-reliance on satellite and ground based research facilities that are short term, or nearing the end of their operation life is unsatisfactory. For an operational service the there must be a clear replacement and upgrade plan to maintain continuity into the future. Back-up instruments and replacement spacecraft should be available for immediate operation, or launch, to cope with failures and seriously degraded systems. For systems that are shared with other countries, or are currently used for short-term research projects, there must be agreements in place for continued operation as part of a SW programme after the research programme is completed.

4. User Requirements for Post-Event Analysis

From the users point of view, post-event analysis is an essential part of a space weather service. For example, it enables:

- Long-term feedback into design.
- Development of more reliable models and predictions
- Better risk assessment
- Better mitigation procedures
- Better understanding and education

An assessment of user requirements for post-event analysis is summarised in Table 4.1.

User No.	User Requirements for Post-Event Analysis	Satellite Design	Satellite Operators	Space Agencies (Man in Space)	Launch Systems	Defence	Civil Aviation	Ground Based Systems	Insurance	Tourism	Research
PEA1	Data on the radiation environment for various orbits (particularly GEO, sun-synchronous, MEO, LEO and Molynia) to identify the cause of satellite anomalies.	1	1	1	3	1			3		1
PEA2	Data analysis to identify the extremes of the radiation environment, including peak flux, time variability, duration of event, probability of occurrence, and determination of the controlling factors for feedback into design, risk assessment and models.	1	1	1	2	1			2		1
PEA3	Development of better radiation environment models for average and extreme conditions for every phase of the solar cycle for various orbits (particularly GEO, sun-synchronous, MEO, LEO and Molynia).	1	1	1		1					
PEA4	Development and maintenance of a satellite anomaly database for analysis in relation to space weather events.	1	1			1			1		1
PEA5	Development of analysis tools for research with the anomaly database.	1	1			1			1		
PEA6	Data analysis to identify and characterize space weather events (including CMEs, solar flares, SEP events, magnetic storms, substorms), their geo-effectiveness, probability of occurrence, and impact potential on commercial systems.	1	1	1	2	1	1	1	1	2	1
PEA7	Research and analysis to provide more reliable forecast, warning, and nowcast capabilities.		1	1	1	1	1	1	2	1	1
PEA8	Establish an agreed set of design standards and practice to overcome the causes of satellite anomalies, particularly internal charging.	1	1			1			3		

User No.	User Requirements for Post-Event Analysis	Satellite Design	Satellite Operators	Space Agencies (Man in Space)	Launch Systems	Defence	Civil Aviation	Ground Based Systems	Insurance	Tourism	Research
PEA9	Development of better models to predict the atmospheric density profile.		1		1	1					
PEA10	Development of better real time models to predict the intensity and location of SEP events.		1	1	1		1				
PEA11	Development of better models to quantify the radiation dose due to cosmic rays and SEP events to astronauts and aircrew along different flight paths.			1			1				
PEA12	Improved measurement techniques for dosimeters.						1				
PEA13	Improved models of the ground conductivity for calculating GICs.							2			
PEA14	Data analysis to identify the thresholds and extreme GICs and induced potentials in power supply networks, pipelines, and other ground conductors, for feedback into engineering design.							1			
PEA15	Development of best practice procedures to minimize risk for all market sectors affected by space weather.	1	1	1	1	1	1	1	1		
PEA16	Development of better prediction models for HF radio communications, radar clutter and scintillations.		2			1					
PEA17	Data on the ionosphere (including current systems, density profiles, density irregularities, scintillations and optical emissions) to distinguish between a hostile act and space weather cause resulting in loss of HF communications, HF radar clutter, loss of positioning accuracy, loss of VLF/ULF communications and enhanced noise in optical instruments.					1		1			
PEA18	Data on solar UV, EUV, and X ray emission to identify the cause	1	1			1					

User No.	User Requirements for Post-Event Analysis	Satellite Design	Satellite Operators	Space Agencies (Man in Space)	Launch Systems	Defence	Civil Aviation	Ground Based Systems	Insurance	Tourism	Research
	of anomalies and interruptions to communications.										
PEA19	Data on solar energetic particles for post-event analysis of anomalies and radiation dose.	1	1	1		1	1				
PEA20	Data on the thermosphere for post-event analysis of changes in orbit drag.		1		1	1					

Table 4.1. Summary of user requirements for post-event analysis

Data for post-event analysis must be provided in a timely fashion. For example, in the civil aviation industry the radiation dose to aircrew is currently assessed after the event. Any delay in making the data available increases the risk of aircrew exceeding the recommended limits. It should be a goal to make the data available within a few days of collection, ready for analysis.

Data on satellite anomalies is commercially sensitive and very difficult to obtain. However, analysis of anomalies is very important for satellite operators, defence, insurers and for feedback into satellite design. It is very important for quantifying the effects of space weather. Even if commercial data cannot be obtained, all data on scientific satellites should be stored in a central database available for analysis.

5. Education and Outreach

There is an important need for education about Space Weather. There are several reasons:

- **Market fragmentation**. Many companies that once provided end-to-end solutions have now been split up into smaller companies specialising in certain areas. As a result, a lot of the knowledge and expertise on space weather has not been passed on.
- **Loss of expertise.** Since space weather is cyclical; turnover of personnel within a solar cycle results in loss of knowledge.
- **Cost-benefit analysis**. Many businesses are not aware of the true cost of space weather on their operations. Education about space weather will encourage more businesses to spend time and effort doing cost-benefit analysis.

- **Public support**. An education programme is likely to enhance public support for ESA since space weather directly affects them, and since the public show great interest in space generally.

An education programme should encompass the following user groups:

- Commercial users
- Research community
- Schools and Universities
- The general public
- News media

It is essential that any space weather programme focuses on the needs of the users, and re-assesses their needs periodically. An education and outreach programme enables continued contact with the users, and enables them to provide feedback. It will enable ESA to develop and evolve a more effective programme as needs change.

One type of outreach activity that could be particularly important is the creation of User Groups focused on particular space weather related problems. The most important areas include radiation dose to aircrew and astronauts, geomagnetic induced currents in ground conductors, and satellite anomalies.

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Consultant	**Organisation**	**Field**	**Country**
Dr D Bartlett	National Radiological Protection Board	Radiation protection	UK
Mr S Clapham	Marham Consortium	Space insurance	UK
Dr T Clark	British Geological Survey	Oil and gas drilling. Pipelines	UK
Dr M Clilverd	British Antarctic Survey	ELF/VFL waves	UK
Dr I A Erinmez	National Grid	Power generation and supply	UK
Dr P Espy	British Antarctic Survey	Defence	UK/Canada
Mr A Fletcher	Wrenn Aerospace	Space Insurance	UK
Dr D Flower	British Airways	Civil Aviation	UK
Dr M Freeman	British Antarctic Survey	Solar Terrestrial Physics	UK
Mr L M Garcia	Eumetsat	Satellite operations	UK
Mr D Hope	Inmarsat	Satellite communications	UK
Dr R Hunter	Civil Aviation Authority	Civil aviation	UK
Dr B Jones	Virgin Atlantic	Civil aviation	UK
Prof T B Jones	U. of Leicester	Ionospheric propagation and Defence	UK
Prof. L Kersley	University of Wales, Aberystwith	Ionosphere and GPS	UK
Prof. S Quegan	University of Sheffield	Remote sensing	UK
Dr A Rodger	British Antarctic Survey	Solar terrestrial physics	UK
Dr N Watkins	British Antarctic Survey	Solar terrestrial physics	UK
Mr J-M Bara	Air France	Civil aviation	France
Mr M Belfort	France Télécom R&D	Satellite operations, Communication	France
Dr C Berthou	Alcatel	Satellite design	France
Dr J Cadet	CEA	Biological effects of radiation	France
Mr O Carel	DGAC	Transport	France
Mr M Chateaureynaud	SNCF	Transport	France
Mr A Dedryvere	DGAC	Transport	France
Mr R Ecoffet	CNES CT	Space environment and radiation effects	France
Mr G Jugie	IFRTP	Consultant	France
Mr P Veyre	Météo-France	Satellite operations, Meteorology	France
Mr L Vigroux	CEA SAP	Nuclear	France
Dr V Bothmer	University of Keil	Solar and heliospheric physics	Germany
Mr B Heini	Swiss Re	Space insurance	Germany
Dr H Klinkrad	ESOC	Satellite operator	Germany
Dr P Maldari	ESOC	Satellite operator	Germany
Mr W Allvin	Kiruna	Tourism	Sweden

	Forskningsturism		
Mr H-E Edwall	Sydgas AB	Gas pipelines	Sweden
Mr M. Palsson	Esrange	Satellite operator	Sweden
Mr P Sigenstam	Sydkraft Elnat AB	Power generation and supply	Sweden
Mr H Swahn	OKG AB	Nuclear power generation	Sweden
Mr L Wallin	Svenska Kraftnat	Power generation and supply	Sweden
Dr D H Boteler	Geological Survey of Canada	Pipelines Power supply	Canada
Mr B Burlton	Telesat Canada	Satellite operations	Canada
Dr J Evans	Telesat Canada	Satellite design Satellite operations	Canada
Dr R Gubby	Telesat Canada	Satellite design. Satellite operations.	Canada
Dr N Fox	APL	Education outreach	USA
Dr P Kappenman	Metatech	Power generation and supply Pipelines	USA
Dr J A Joselyn	NOAA	Space weather	USA
Mr C Kunstadter	US Aviation Underwriters	Space insurance	USA
Dr S Quigley	AFRL	Defence	USA
Dr. G Reeves	Los Alamos	Defence	USA
Dr R Sawyer	Lockheed Martin	Satellite design	USA

APPENDIX

A1 Commercial Satellite Design

The most important space weather related problems to overcome, reported by satellite designers, are how to design for internal (deep dielectric) charging, and total dose. Secondary problems include surface charging, sensor effects, and surface erosion.

The main requirement is to measure the important parameters in the space environment and to build better models of the environment. Designers stated several times that existing models are based on old data from the 1960s that have questionable accuracy, and incomplete coverage of the regions of interest. The extrapolation used in the models is of great concern to them. Furthermore, they are aware of the very large variability in the measured particle fluxes, particularly during magnetic storms and SEP events, and need to know the maximum flux and its duration. Their approach is to eliminate the effects of space weather by careful design.

Characterisation of the environment is essential for their needs. They need to know the radiation environment before they decide on the amount of sheilding and radiation hardening of spacecraft parts. The probability of events such as SEP events and the total dose is very important for designing the satellite for a specified lifetime.

Table A1.1 provides a summary of the problems, the direct cause and the relationship to space weather events.

Table A1.2 provides an assessment of current practise.

Table A1.3 suggests some possible space weather services

Table A1.1. Commercial satellite design problems related to space weather.

Problem	**Cause**	**Space Weather related source**
Internal charging resulting in electrostatic discharges.	Electrons > 0.5 MeV Accumulation of charge.	Radiation belts - Variation due to magnetic storms, substorms, magnetopause compression, fast solar wind streams. SEP events.
Total radiation dose limiting satellite lifetime.	Accumulated radiation damage during lifetime of spacecraft due to all ionizing radiation, including fluence spectra of electrons (> 0.5 MeV), protons (> 1 MeV) and all ions (mainly He+ and O+ > 1 MeV/nucleon).	Radiation belts - Variations due to magnetic storms, substorms, magnetopause compression, fast solar wind streams. Cosmic rays. SEP events. Auroral electrons.
Single event effects (SEE) including: Single event upset Single event latchup Single event burn-out	Protons > 50 MeV Ions > 10 MeV/nucleon Electrons > 500 keV	Cosmic rays - Variations due to solar cycle. Radiation belt particles. SEP events.
Surface charging resulting in electrostatic discharges.	Solar illumination. Thermal electrons and ions (1-50 eV) and spectrum up to plasmasheet energies (1eV – 100 keV electrons and ions). Changing plasma density.	Change in UV during Eclipse. Variations in keV plasma, especially plasmasheet, and auroral electron precipitation regions, during substorms and magnetic storms. Boundary crossings into different plasma regiemes such as plasmapause and plasmasheet boundary.
Solar cell degradation and displacement damage.	Electrons > 100 keV and protons 1 – 10 MeV.	Cosmic rays – variations due to solar cycle. SEP events. Radiation belts as above. Ring current – magnetic storms.
Surface material degradation, sputtering and erosion.	As for total dose, but including protons 0.1-1 MeV. Atomoc Oxygen. UV radiation.	Cosmic rays. SEP events. Radiation belts – as above. Ring current – magnetic storms.
Sensor degradation	As for total dose.	SEP events. Cosmic rays. Radiation belts – as above. Ring current – magnetic storms.

Table A1.2. Assessment of current practice.

Problem	**Current practice**	**Assessment**
Internal charging resulting in electrostatic discharge	Models are used to calculate the trapped electron and proton flux, and fluence. Vital components are shielded. Radiation hardened parts are used. Systems are duplicated at unit level.	Internal charging is now regarded as the most important design problem. Models do not take into account the time dependent nature of the radiation belts. Models are based on old less accurate data. Existing data does not cover all regions of interest nor complete solar cycle. Shielding may pose important weight restrictions. Impractical to duplicate all systems.
Total radiation dose limiting satellite lifetime.	Spacecraft are designed according to the intended orbits. Models are used to calculate the total dose. Other comments as above.	Regarded as second most important problem to overcome. Comments as above.
Single event effects (SEE) including: Single event upset Single event latchup Single event burn-out	Models are used to calculate the particle flux due to galactic cosmic rays and radiation belts. Radiation hardened components are used according to peak flux. Vital components are shielded.	Cosmic ray flux depends on solar cycle and is predictable. No models available for heavy ions. Reduction in size means devices are more susceptible. Impossible to shield against high-energy cosmic ray flux.
Surface charging resulting in electrostatic discharges.	Outer surface is made conducting as far as possible.	Conducting layers are punctured due to meteors. Surface charging still causes anomalies.
Solar cell degradation and displacement damage.	Models of peak flux and number of SEP events used to estimate degradation. Solar cells are designed to provide a 5% margin of power at end of working life.	Communications satellites are now designed for up to 15 years – more than 1 solar cycle. Statistics on number of SEP events, peak flux, and duration required through solar cycle.
Surface material degradation, sputtering and degradation		
Sensor degradation		

A1.1 User Needs

- Measurements of the average radiation environment for various orbits including GEO, sunsynchronous, MEO, LEO and Molynia (including MeV electrons, heavy ions, data on peak flux, spectrum and probability of occurrence) throughout the 11 year solar cycle.

- Measurements of the extreme radiation environments, time variability, duration of event, and determination of the controlling factors.
- Development of improved radiation belt models to calculate average and extreme variations, including peak flux, spectrum, probability of event occurrence and total dose, for every phase of the solar cycle.
- The establishment of an agreed set of design standards and practice to overcome internal charging and other related problems (see table above).
- Creation of a satellite anomaly database.
- Collection of data to identify and characterize space weather events including magnetic storms, CMEs, substorms, solar flares, UV flux in order to determine the number and type of anomalies that are caused by space weather.

Table A1.3. Possible space weather services.

	Input	Output	Actions	Benefits
Forecast (1-several days)				
Warning (0-24 hrs)				
Nowcast				
Post-event analysis	Measurements of particles and fields in GEO, Sun synchronous, MEO, LEO, and molynia orbits Measurements to identify and characterise substorms, magnetic storms, ring current, CMEs, magnetopause compressions, SEP events, cosmic rays.	Characterisation of the space environment, including time variability. Development of more reliable models, including those to describe largest events. Identification of space weather events responsible for anomalies.	Use new models for satellite design	Achieve longer design life. More reliable operations. Reduced cost of over-design.

A2 Satellite Operators

The overall philosophy of satellite operators is to identify the cause of satellite anomalies, determine whether they are related to space weather effects, and then develop procedures to modify the design of future satellites. The primary objective is to minimize the effects of space weather by feeding back information into future design.

The most controversial issue is the identification of the cause of each satellite anomaly. All anomalies are carefully recorded by operators. Reports are written on all serious anomalies and provided to insurers and designers. Data on anomalies are kept by operators and designers and are highly confidential and commercially sensitive.

Table A2.1 provides a summary of the problems, the direct cause and the relationship to space weather events.

Table A2.2 provides an assessment of current practise.

Table A2.3 suggests some possible space weather services

Table A2.1. Satellite operator problems related to space weather.

Problem	Cause	Space Weather related source
In-orbit anomalies resulting in phantom commands, mode switching, corrupt memory parts failure.	Internal electrostatic discharge. Surface electrostatic discharge. Single event effects. (See satellite design).	Radiation belts - Variation due to magnetic storms, substorms, magnetopause compression, fast solar wind streams. SEP events.
Reduced satellite lifetime.	Accumulated radiation damage (total dose) during lifetime of spacecraft due to all ionizing radiation, including fluence spectra of electrons (> 0.5 MeV), protons (> 1 MeV) and all ions (mainly He+ and O+ > 1 MeV/nucleon).	Radiation belts - Variations due to magnetic storms, substorms, magnetopause compression, fast solar wind streams. Cosmic rays. SEP events. Auroral electrons.
Increased atmospheric drag and re-entry in LEO.	Atmospheric expansion.	Enhanced solar EUV during flares. Joule heating and particle precipitation during substorms and storms.
Unexpected orbit manoeuvres for satellites with magnetic torquers, (loss of pointing for broadcast signals).	Magnetic field reversals.	Magnetopause compression inside GEO, related to CMEs and periods of increased solar wind pressure.
Loss of phase and amplitude lock for remote sensing applications, GPS navigation and altimetry.	Ionospheric scintillations, mainly at equatorial and polar latitudes.	Enhanced solar EUV during flares. Joule heating and particle precipitation during substorms and magnetic storms.

Table A2.2. Assessment of current practice.

Problem	Current practice	Assessment
In-orbit anomalies resulting in phantom commands, mode switching, **corrupt memory,** parts failure.	Anomalies are recorded. Operators try to identify cause, but this is often very difficult. Any identified cause is fed back to designers to improve future design. Some warnings and nowcasts are monitored so that staff can be on alert.	In general operators do not have expertise in space physics and enough data on the plasma environment at the spacecraft at the time of anomaly to identify the cause as space weather reliably. Some operators assign cause to space weather if all other causes can be eliminated. Feedback into design is very important but takes years. Requires data on SW events to identify any SW cause of anomalies.
Reduced satellite lifetime through reduction in solar cell power and degradation of parts.	Operators switch off some systems (e.g., transponders) to reduce power consumption and optimize lifetime.	Needs better assessment of severity and frequency of SW events.
Increased atmospheric drag and re-entry in LEO.	Operators correct with orbit manoeuvres.	Fuel consumption limits lifetime of satellite.
Unexpected orbit manoeuvres for satellites with magnetic torquers, (loss of pointing for broadcast signals).	During reversals, automatic torquing systems are switched off for some spacecraft.	Careful monitoring is required to keep control of some spacecraft. Most normally operating communications spacecraft are only slightly affected.
Loss of phase and amplitude lock for remote sensing applications, GPS navigation and altimetry.	Data may need to be corrected on the ground by users using total electron content.	Only average models of the ionosphere are used in GPS receivers.

A2.1 User Needs

Operators require a prediction service and post-event analysis.

User needs for operator are very similar to those for designers. The primary object is to identify the cause of the anomaly. The main requirement here is to identify whether it is related to space weather events. This requires data on space weather events from a variety of different ground and space instruments.

Operators also place orders for satellites. To do this they have to write a specification and this requires knowledge of the space environment.

- Measurements of the average radiation environment for various orbits including GEO, sunsynchronous, MEO, LEO and Molynia (including MeV electrons, heavy ions, data on peak flux, spectrum and probability of occurrence) throughout the 11 year solar cycle.
- Measurements of the extreme radiation environments, time variability, duration of event, and determination of the controlling factors.

- Development of improved radiation belt models to calculate average and extreme variations, including peak flux, spectrum, probability of event occurrence and total dose, for every phase of the solar cycle.
- The establishment of an agreed set of design standards and practice to overcome internal charging and other related problems (see table above).
- Creation of a satellite anomaly database.
- Collection of data from a variety of sources to identify and characterize space weather events including magnetic storms, CMEs, substorms, solar flares, UV flux in order to determine the number and type of anomalies that are caused by space weather.

- Predictions of magnetopause compression and field reversals.
- Predictions of enhanced electron and ion flux.
- Predictions of SEP events.
- Predictions of atmospheric heating.

Table A2.3. Possible space weather services.

	Input	Output	Actions	Benefits
Forecast (1-several days)	Solar activity	Probability of an event	Put staff on alert	
Warning (0-24 hrs)	Detection of flares, CMEs and radio signals	Revised probability of an event Prediction of radiation belt particle flux. Prediction of neutral density profile. Prediction of scintillations.	Plan orbit manoeuvres	Conserve fuel.
Nowcast	Identification of increased particle flux. Identification of duration of event.	95% reliability	Prevent orbit manoeuvres. Prevent uploading of new software. Switch off magnetic torquing. Switch off non-essential systems (e.g., sensors on scientific satellites).	Minimise risk of anomaly and service interruption.
Post-event analysis	Measurements of particles and fields in GEO, Sun synchronous, MEO, LEO, and molynia orbits Measurements to identify and characterise substorms, magnetic storms, ring current, CMEs, magnetopause compressions, SEP events, cosmic rays.	Characterisation of the space environment, including time variability. Development of more reliable models, including those to describe largest events. Identification of space weather events responsible for anomalies.	Use new models for specifying satellites	Feed back information to achieve more reliable design.

A3. Space Agencies (Man in space)

The primary concern of space agencies as far as space weather is concerned must be the health and safety of astronauts, and the safe and relaible operation of equipment to support them to and from orbit, and whilst in orbit. A second concern is the successful and reliable operation of space missions.

The requirements for launch services and the design and operation of satellites are covered elsewhere in the report. Therefore, only the requirements for astronauts are considered here,

Table A3.1 provides a summary of the problems, the direct cause and the relationship to space weather events.

Table A3.2 provides an assessment of current practise.

Table A3.3 suggests some possible space weather services

Table A3.1. Space Agency problems related to space weather.

Problem	Cause	Space Weather related source
Radiation dose to astronauts	Electrons and ions > 10 MeV/nucleon	Galactic cosmic rays. SEP events. Low altitude portion of the radiation belts - variations due to magnetic storms, substorms, magnetopause compression, fast solar wind streams and South Atlantic anomaly.

Table A3.2. Assessment of current practice.

Problem	Current practice	Assessment
Radiation dose to astronauts during construction of the international space station.	Warnings of SEP events are used to take mitigating action. Probability estimates of SEP events are provided to assess risk of exposure.	The time between a solar flare and an SEP event may be less than 1 hour providing very little warning for astronauts. Probability estimates show that 2 out of 43 construction flights for the international space station will co-incide with an SEP event.

A3.1 User Needs

The main threat to astronauts is from SEP events that can occur within an hour of a solar flare or CME giving very little time to react.

- Early warning of SEP events to curtail EVA activity.
- Analysis of SEP events throughout the 11 year solar cycle to construct probability of occurrence SEP events and peak flux and duration.
- Development of real time models to predict the intensity and location of SEP events.
- Research into pre-cursors of events on the sun for early warning.

Table A3.3. Possible space weather services.

	Input	Output	Actions	Benefits
Forecast (1-several days)	Solar activity	Probability of an event	Put ground staff and astronauts on alert	
Warning (0-24 hrs)	Detection of flares, CMEs and radio emissions.	Revised probability of an event	Plan EVA activities	
Nowcast	Identification SEP event. Identification of duration of event.	95% reliability	Curtail EVA activities.	Minimise radiation dose to astronauts
Post-event analysis	Measurements of particles and fields to characterize SEP events	Assessment of probability of occurrence of SEP events and radiation dose. Develop better prediction models based on solar activity.		Financial savings through not having to reduce flight opportunities for astronauts, and training of additional astronauts. Carry out duty of care as required by Health and Safety legislation.

A4 Launch Services

The probability of launch failure during an SEP event is estimated to increase by a factor of 200 for launch into sun-synchronous orbit and by a factor of 10 into geostationary orbit [Boscher et al., 1999]. The are two main areas where these risk may become unacceptable, the launch of manned missions and the risk of radiation damage to launcher payloads not designed for high radiation environments. Knowledge of atmospheric heating may also be useful in optimising the launch.

Table A4.1 provides a summary of the problems, the direct cause and the relationship to space weather events.

Table A4.2 provides an assessment of current practise.

Table A4.3 suggests some possible space weather services

Table A4.1. Launch problems related to space weather.

Problem	Cause	Space Weather related source
Unacceptably high radiation dose to manned missions.	Electrons and ions > 10 MeV/nucleon	Galactic cosmic rays. SEP events. Low altitude portion of the radiation belts - variations due to magnetic storms, substorms, magnetopause compression, fast solar wind streams and South Atlantic anomaly.
Radiation damage to launcher payload	Energetic electrons and ions	As above
Increased atmospheric drag	Atmospheric expansion	Increased EUV radiation. Joule heating. Particle precipitation.

Table A4.2. Assessment of current practice.

Problem	Current practice	Assessment
Unacceptably high radiation dose to manned missions.	Warnings of SEP events are used in the launch of manned missions.	The time between a solar flare and an SEP event may be less than 1 hour providing very little warning.
Radiation damage to launcher payload		As above.
Increased atmospheric drag		Predictions of the amount of atmospheric drag could help optimize launch procedures.

A4.1 User Needs

Launch services require prediction and warning of space weather events.

The main threat to launcher is from SEP events and increased energetic particle flux in the radiation belts.

- Early warning of SEP events.
- Nowcast of SEP events and radiation belt enhancements for reliability.
- Development of real time models to predict the intensity and location of SEP events.
- Models of the atmospheric density profile.

Table A4.3. Possible space weather services.

	Input	Output	Actions	Benefits
Forecast (1-several days)	Solar activity	Probability of an event	Put ground staff and astronauts on alert	
Warning (0-24 hrs)	Detection of flares, CMEs and radio emissions.	Revised probability of an SEP event. Neutral density profile.	Optimise launch sequence for density profile.	
Nowcast	Identification SEP event. Identification of duration of event.	95% reliability	Delay launch	Minimise radiation dose to astronauts on manned missions. Reduced risk of radiation damage to launcher and payload. Optimize launch procedures
Post-event analysis	Measurements of particles and fields to characterize SEP events	Assessment of probability of occurrence of SEP events and radiation dose.		

A5 Aviation Industry Summary

The aviation industry is subject to three types of risk from space weather events. First, radiation exposure to aircrew at high altitude and high latitudes, second, radiation damage to avionics, third, loss of GPS signal for positioning on approach, and fourth, loss of HF communications for position reporting.

EU legislation requires aircrew to be assessed for radiation dose and to be monitored individually if the radiation dose exceeds 6 mSv/yr. Airlines plan re-roster aircrew onto other routes if their radiation dose approaches 1 mSv/year, so as not to exceed these levels.

The average dose received by an aircrew over a year depends on the route followed by the aircraft (latitude, altitude, duration), the galactic cosmic ray flux, the phase of the solar cycle, and the impact of solar energetic particle events (SEPs). However, in an extreme case, such as a repeat of the 1956 SEP event, the radiation dose on a transatlantic flight at 40,000 ft would be approximately 10 mSv, and would exceed the recommended levels.

Present plans are to assess radiation dose after an SEP event has occurred.

Table A5.1 provides a summary of the problems, the direct cause and the relationship to space weather events.

Table A5.2 provides an assessment of current practise.

Table A5.3 suggests some possible space weather services

Table A5.1. Aviation industry problems related to space weather.

Problem	**Cause**	**Space Weather related source**
To asses radiation dose to aircrew as a result of EU legislation.	Ionizing radiation, (primary and secondary) Neutrons	Galactic cosmic rays SEP events E > 10 MeV
Radiation damage to avionics	As above	As above
Interruption to GPS navigation for positioning on landing approach.	Ionospheric scintillations	Particle precipitation at auroral latitudes, caused by magnetic storms and substorms.
Interruption to HF communications for position reporting.	Ionospheric irregularities	As above

Table A5.2. Assessment of current practice.

Problem	**Current practice**	**Assessment**
To asses radiation dose to aircrew as a result of EU legislation.	Calculate radiation dose due to galactic cosmic rays from models. Calculate dose due to SEPs using models after an event. Calculate dose on Concorde and some aircraft from dosimeters. Reduce altitude of Concorde during an event. Roster aircrew onto low risk routes if they approach 1 mSv/yr.	Cosmic ray flux depends on solar cycle and is very predictable. Forbush decrease lasts only a few days and varies by up to 5%. Flux is highly variable and could be enhanced for days during an event. Calculations are retrospective and could result in aircrew exceeding recommended limits due to a SEP event. Models require reliable data at top of atmosphere for input. Dosimeter measurements are technically very difficult due to the broad energy spectrum and different types of radiation. Only accurate to 30-50%
Radiation damage to avionics	Use computer redundancy and back-up systems.	Needs more assessment in relation to space weather events.
Interruption to GPS navigation for positioning on landing approach.	System being evaluated for use.	
Interruption to HF communications for position reporting.	Aircraft asses risk of being unable to report position during transatlantic flights.	Aircraft do not usually stop flying due to loss of HF communications.

A5.1 User Needs

The aviation industry has a requirement for predictions and for post-event analysis. Calculation s of radiation dose to aircrew must come from an authoritative source, ripe for Agency level provision.

- Reliable system of warnings over a range of timescales for SEP events.
- Reliable predictions of the radiation dose to aircrew.
- Post event analysis to quantify risk of SEP events.
- Improved models to calculate the radiation dose at different altitudes along flight paths.
- Improved measurement techniques for dosimeters.

Table A5.3. Possible space weather services.

	Input	Output	Actions	Benefits
Forecast (1-several days)	Solar activity measurements	Probability of a SEP event.	Risk assessment. Roster aircrew on to low risk routes.	Ensure aircrew do not exceed recommended radiation dose.
Warning (0-24 hrs)	Detection of flares and CMEs.	Revised probability of a SEP. Prediction of the radiation dose.	Put staff on alert. Implement procedures to minimize airline service disruption.	Minimise service disruption.
Nowcast	Identify SEP event on the ground and in aircraft. Continuous monitoring of SEP in progress.	95% reliable calculation of radiation dose with a few hours delay.	Take avoiding action such as reducing aircraft altitude, diverting and grounding aircraft.	Minimise radiation dose to aircrew and passengers.
Post-event analysis	Characterize parameters of SEP (energy spectrum, flux, duration, location).	Model calculations of the radiation dose received by aircrew on different routes and altitudes. Determine probability and severity of occurrence. Improve risk assessment.		Compliance with EU regulations in assessing radiation dose. Minimise loss of revenue through re-rostering of aircrew. Development of more reliable models for assessing radiation dose.

A6 Ground Based Systems

There are several market sectors that are affected by the same type of space weather phenomena, namely magnetic field fluctuations and geomagnetically induced currents. These market sectors include

- Power generation and supply
- Prospecting for minerals, oil, and gas
- Oil and gas pipeling distribution
- Railways

These market sectors are considered together here since their user requirements are very similar.

Table A6.1 provides a summary of the problems, the direct cause and the relationship to space weather events.

Table A6.2 provides an assessment of current practise.

Table A6.3 suggests some possible space weather services

Table A6.1. Effects on ground based systems.

Market Sector	Problem	Cause	Space Weather related source
Power generation and supply	Power surges and outages in distribution networks. Transformer damage and reduced lifetime. Reduction in transmitted power.	Time varying ionospheric currents resulting in geomagnetically induced currents.	Substorms. Magnetic storms. Magnetopause compressions.
Oil and gas pipeline distribution	Pipeline corrosion. Build-up of electric potential along pipeline.	Time varying ionospheric currents resulting in geomagnetically induced currents.	Substorms. Magnetic storms. Magnetopause compression.
Aerial surveying for minerals oil and gas	Variations in the direction of the surface magnetic field.	Time varying ionospheric currents, magnetopause currents, magnetotail currents and ring current.	Magnetic storms. Substorms. Magnetopause compressions.
Drilling for oil and gas	Variations in the direction of the surface magnetic field used for drilling operations.	As above	As above
Railways	Possible disruption of signaling	As above	As above

Table A6.2. Assessment of current practice.

Market Sector	Problem	Current practice	Assessment
Power generation and supply	Power surges and outages in distribution networks. Transformer damage and reduced lifetime. Reduction in transmitted power.	Some companies now employ prediction services from private companies, Universities and Government Institutes.	Prediction services rely critically on data from the solar wind L1 point, and ground-based magnetic field observations. Reliability of models is unknown.
Oil and gas pipeline distribution	Pipeline corrosion. Build-up of electric potential along pipeline.	Companies now employ active cathotic protection systems to keep pipe at 1 volt potential with respect to the ground. Pipes are coated in high resistance material. Insulating sections are inserted into pipelines.	Surface coatings are not perfect. GICs still disrupt cathotic protection systems. Insulating sections reduce electric potentials, but can make additional locations for corrosion.
Aerial surveying for minerals oil and gas	Variations in the direction of the surface magnetic field.	Predictions of magnetic field disturbances are used.	
Drilling for oil and gas	Variations in the direction of the surface magnetic field used for navigating bore holes.	Some companies use measurements of the local magnetic field to correct for changes in the external field.	Drilling operations are too expensive to halt. Magnetic field observations local to drilling sites are required.
Railways	Possible disruption of signaling		This is a very sensitive safety issue. Extent of the problem is unknown. More research is required.

A6.1 User Needs

Users require a prediction and post-event analysis.

- Measurements upstream in the solar wind to provide warnings of events likely to change current systems in the magnetosphere and ionosphere and coupling between the two.
- Measurements of the ionospheric current systems, and rate of change of the current systems to provide nowcast, over entire power supply, or pipeline networks.
- Models of the ground conductivity for calculating geomagnetic induced currents.
- Analysis of largest events, and duration of largest events for feedback into engineering design for worst case.

Table A6.3. Possible space weather services.

	Input	Output	Actions	Benefits
Forecast (1-several days)	Solar activity	Probability of an event		
Warning (0-24 hrs)	Detection of flares, CMEs and radio signals	Revised probability of an event	Put staff on alert. Plan power generating capacity. Suspend maintenance.	
Nowcast	Identification of increased ionospheric currents, and rate of change of currents.	95% reliability	Suspend aerial surveying. Use magnetic field corrections for drilling operations	Minimise risk of service interruption.
Post-event analysis	Measurements to identify and characterise substorms, magnetic storms, ring current, CMEs, magnetopause compressions,	Characterisation of the space environment, including time variability. Development of more reliable models, including those to describe largest events.		Feed back information to achieve more reliable design.

A7. Space Insurance

Space insurance covers several areas that may be directly affected by space weather. For example, launch services and in-orbit operations, power supply and distribution, and other market sectors set out in the introduction to this workpackage. Insurers are also affected indirectly, by the cost of knock-on effects, for example, through the total or partial loss of broadcast services, and, as in the case of the 1989 power outage in Quebec, through claims resulting from the power outage.

Space insurance has a clear need to assess the risk posed by space weather, and therefore the main requirement is to identify previously unknown risks and hence for post-event analysis. It is not clear whether there is a strong requirement for prediction of events. However, insurers have a strong interest to ensure that designers, operators, launchers, and other sectors develop procedures to minimise risk due to space weather.

Table A7.1 provides a summary of the problems, the direct cause and the relationship to space weather events.

Table A7.2 provides an assessment of current practise.

Table A7.3 suggests some possible space weather services

Table A7.1 Space Insurance interests related to space weather.

Problem	Cause	Space Weather related source
Space weather effects that affect the design and construction of spacecraft.	See tables for Commercial satellite design.	
Space weather effects that increase the risk of launch failure.	See tables for Launch services.	
Space weather effects that damage spacecraft in-orbit, reduce operational lifetime, or may cause multi-satellite failure. Insurance claims through loss of service.	See tables for Satellite operators.	
Space weather effects that may increase the risk to human health and safety.	See tables for Space Agencies (man in space) and Aviation (radiation dose to aircrew).	
Space weather effects that increase the risk of interruption to power supplies, damage to transformers and supply networks, pipeline networks, and disruption to drilling operations for oil and gas. Insurance claims resulting from loss of service.	See tables for Ground based systems.	

Table A7.2 Assessment of current practice.

Problem	Current practice	Assessment
Space weather effects that affect the design and construction of spacecraft.	Reports on engineering design are evaluated by consultants.	Engineers are aware of some but not all of the range of space weather effects. The cause of anomalies is very difficult to identify and many remain unknown. Evaluation of risk in relation to space weather is in progress by some research groups such as BAS and MSSL.
Space weather effects that increase the risk of launch failure.		
Space weather effects that damage spacecraft in-orbit, reduce operational lifetime, or may cause multi-satellite failure. Insurance claims through loss of service.		Insurers have funded some operators to recover spacecraft for partial operations which has required using real time space weather information such as monitoring the direction of the magnetic field for reversals.
Space weather effects that may increase the risk to human health and safety.		
Space weather effects that increase the risk of interruption to power supplies, damage to transformers and supply networks, pipeline networks, and disruption to drilling operations for oil and gas. Insurance claims resulting from loss of service.		

A7.1 User Needs

Insurers have a requirement for post-event analysis to identify new risks, and disaster scenarios. It is not clear that insurers have a direct requirement for warning and prediction, but they do have an interest to see that the operators they insure have access to warning and prediction to take mitigating actions.

- Collection of data to identify and characterize space weather events including magnetic storms, CMEs, substorms, solar flares, UV flux in order to determine the number and type of satellite anomalies that are caused by space weather, and to identify the risk to human health, and disruption to ground based systems.
- Creation of a satellite anomaly database.
- Development of analysis tools for research with the anomaly database
- Development of best practice procedures to minimize risk for market sectors affected by space weather.

Table A7.3. Possible space weather services.

	Input	Output	Actions	Benefits
Forecast (1-several days)				
Warning (0-24 hrs)				
Nowcast				
Post-event analysis	Measurements to identify and characterize space weather events including substorms, magnetic storms, solar flares, CMEs, magnetopause compressions, SEP events, and particle flux enhancements.	Characterisation of the space environment, including time variability. Identification of space weather events responsible for anomalies.	Analysis to identify new risks in different market sectors.	Reduced loss-claims due to insured taking mitigating action. Data to identify and evaluate risk associated with space weather. Identify risks associated with new technologies. Identify new business opportunities. Develop more competitive premiums.

A8 Defence

Defence has many areas that are affected by space weather. Although these systems are classified, we can provide some assessment based on reasoned assumptions and what we know from scientific measurements. There are many areas of Defence affected by space weather – see WP1100. Satellite design, launch services and in-orbit operations are already covered in the commercial market sectors elsewhere in this report. Here we cover the following areas:

- **HF communications**
- **Over the horizon radar**
- **Surveillance**
- **Navigation via GPS and other positioning systems**
- **Submarine communications**

Table A8.1 provides a summary of the problems, the direct cause and the relationship to space weather events.

Table A8.2 provides an assessment of current practise.

Table A8.3 suggests some possible space weather services

Table A8.1. Effects on Defence.

Sector	**Problem**	**Cause**	**Space Weather related source**
HF communications	Loss of signal path between transmitter and receiver. Loss of direction finding. Radio wave absorption and blackout.	Ionospheric irregularities Changes in peak plasma density. Increase in ionospheric collision frequency.	Magnetic storms. Substorms. Solar X ray flares.
Over the horizon radar	Enhanced clutter at high latitudes.	Coherent scatter from plasma irregularities, particle precipitation, plasma instabilities, gravity waves.	Magnetic storms. Substorms.
Surveillance	Increased atmospheric drag for satellites in low orbit. Increased noise in optical sensors.	Neutral atmosphere heating and expansion from Joule heating and particle precipitation. Auroral light emissions.	Magnetic storms. Substorms. Solar X ray flares.
Navigation by GPS and other positiong systems	Scintillations.	Ionospheric irregularities	Magnetic storms. substorms.
Submarine communications	Disruption to ELF and VLF communications.	Irregularities in the bottomside ionospheric density profile.	SEP events. Solar X ray flares.

Table A8.2. Assessment of current practice.

Market Sector	Problem	Current practice	Assessment
HF communications	Loss of signal path between transmitter and receiver. Loss of direction finding. Radio wave absorption and blackout.	Military use predictions for HF propagation.	On-going need for predictions. The US experience is that the major interest in space weather is for HF predictions.
Over the horizon radar	Enhanced clutter at high latitudes.	As above – otherwise unknown.	As above.
Surveillance – detection of missile launch.	Increased atmospheric drag for satellites in low orbit. Increased noise in optical sensors.	Probably use alternative methods of missile detection such as OTHR above, otherwise unknown.	
Navigation by GPS and other positioning systems	Scintillations.		May be important for targeting on battlefield and for cruise missiles
Submarine communications	Disruption to ELF and VLF communications.	Submarines may be forced to use alternative means such as releasing buoys and using other frequencies.	Use of buoys may increase risk of detection.

A8.1 User Needs

Defence is already a user of the NOAA system. About 80% of the US defence interest is reported to be in ionospheric predictions and events affecting the ionosphere.

Defence requires prediction and post-event analysis. However, it is very difficult to assess exactly what services they may require since this information may be classified. Defence must design and operate their own satellites and therefore some of their requirements are already covered elsewhere in this report. Otherwise we can only assess some of their expected requirements in very general terms.

- Same requirements as for satellite design
- Same requirements as for satellite operators
- Same requirements as for launch services
- Warning of events that disrupt the ionosphere.
- Prediction of electron density profile, peak density, radio blackout, auroral emissions.
- Warning of events that may disrupt military power generation and supply, such as GICs.

- Collection of data to charactrise the state of the sun, solar-wind, magnetospherei, ionosphere, atmosphere system for evaluation of defence systems and how they are affected by space weather.

Table A8.3. Possible space weather services.

	Input	Output	Actions	Benefits
Forecast (1-several days)	Solar activity	Probability of a space weather event		
Warning (0-24 hrs)	Detection of flares, CMEs and radio signals	Revised probability of an event	Put staff on alert. Plan alternative methods for communications at HF, ELF/VLF.	Better planning for targeting.
Nowcast	Identification of events	95% reliability	Re-route communications or use alternative means. Use alternative means to identify missile launch and for early warning. Ensure additional cross-checks to eliminate false positive identification.	Minimise risk of service interruption. Minimise risk of false identification of nuclear attack. Reduced risk of submarine detection.
Post-event analysis	Measurements to identify and characterise substorms, magnetic storms, ring current, CMEs, magnetopause compressions,	Characterisation of the space environment, including time variability.		Development of more reliable models, including those to describe largest events.

A9 Tourism

Tourism is a more specialized and very small market at present (see WP1100). The main activity is to see the aurora. Therefore space weather does not provide problems, but provides opportunities.

The main requirement is already covered in other areas, namely the prediction of events, primarily large magnetic storms, and the probability of observing the aurora at different latitudes which is dependent of the severity of the magnetic storm.