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RATIONALE FOR A EUROPEAN SPACE WEATHER PROGRAMME

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Abstract

The underlying physical causes of space weather are discussed in order to define a rationale for a European Space Weather Programme. The investigation deals with several aspects of the observable space weather environment, including the Sun, solar wind, solar and galactic cosmic rays, the magnetosphere, the ionosphere, and the atmosphere, as well as man-made space weather environments. The systems affected by space weather both in space and on the ground are identified and the interrelationships between space weather domains, phenomena, and affected systems are tabulated in catalogue form.

The main space weather effects are analysed in terms of critical observable parameters and forecasting, nowcasting, and modelling capabilities; spacecraft charging, single event effects on spacecraft, effects on humans in space, drag, and effects on RF communications, aircrew and avionics, and ground-based systems. It is concluded that in practically all these fields significant efforts on basic research, enhanced observations and data systems, as well as model development are needed. To facilitate this a coherent European Space Weather Programme is called for.

The study is concluded by several comments on issues that need to be considered when developing a European Space Weather Programme. It is noted that it is useful to make a clear distinction between a broad Programme and a service-oriented European Space Weather System which should be a practical enterprise growing from a limited beginning toward a more comprehensive system as awareness and practical user needs evolve.

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Executive summary

This report discusses the underlying physical causes of space weather in order to define a rationale for a European Space Weather Programme. The rationale is based on the fact that the time-variable solar-terrestrial interaction affects technological systems in space and on the ground and can have consequences to human life and health. During the last few years space weather activities have expanded with an increasing pace world-wide and it has become commonly accepted that improved space weather services are important and expected to become much more useful in the near future. At the same time scientific communities have strengthened their efforts toward better understanding of the physical foundations of space weather and it has been remarked that without strong emphasis on improved scientific understanding, the promises for, and dreams of, improved space weather products may not be fulfilled. Thus the scientific solar-terrestrial physics community and the users of space-sensitive systems are intimately coupled to each other.

The source of space weather is the Sun that controls the electromagnetic and particle environments in the entire solar system. The control is time-variable due to the strong temporal variations in the solar UV and particle emissions. These variations have time scales from seconds to years and longer. Typical space weather phenomena take place in time scales up to days or weeks whereas there are also important space climatological effects spanning over solar cycles and even centuries.

Space weather is, however, not synonymous with solar-terrestrial physics. Without the effects on technological systems and humans the whole concept would be useless. In fact, space weather effects are critical to

- spacecraft on orbit, both interplanetary and within the magnetosphere
- humans in space
- launchers of spacecraft
- RF communications and satellite positioning systems
- aircrew and avionics
- power and information transmission systems on ground

To address the space weather effects on these systems a great variability of observations and models are needed. In some cases it is sufficient, but not trivial, to specify the space environment "after the fact" in order to find ways of avoiding space weather-induced problems, as, e.g., within spacecraft engineering. In other cases reliable warnings and forecasts are required, such as assessing the space weather risks during long extra-vehicular activities on space stations.

As the Sun is the main source of space weather, focussed and continuous solar observations are the key element of space weather specifications, warnings, and forecasts. Presently this is done in an excellent way by the SOHO spacecraft but useful space weather activities require long-term commitments to observe such critical elements of space weather as coronal mass ejections (CMEs), the shock structures associated with them, and solar energetic particle events (SEPEs). Our physical understanding is not yet good enough to forecast these phenomena to any useful accuracy.

The solar energetic particles may directly cause problems with spacecraft electronics or human bodies if not protected appropriately whereas the CMEs are the contributors of

major magnetic storms in the near-Earth space. However, we are not yet able to tell from observations of a CME close to the Sun whether it will be geoeffective, or not. Thus continuous in situ observations of solar wind parameters, e.g., at the L1 point, where presently SOHO and ACE spacecraft are located, are needed.

The magnetospheric storms lead to strong particle acceleration within the magnetosphere producing particles causing, sometimes fatal, surface charging of spacecraft and relativistic electrons that can penetrate deep into the spacecraft electronics. Much of the dynamics of these particles is poorly understood and, in addition to in situ observations of the particles, improvements in the energetic particle models are called for.

The storms perturb the ionospheric conditions critical to radiowave communications and satellite navigation applications. The storm-time ionospheric current systems have rapid temporal variations, which can induce harmful currents, e.g., in ground-based electric transmission systems and gas and oil pipelines. Furthermore, the upper atmosphere is heated resulting in increased drag on low-altitude space vehicles. Also here both continuous observations and improved modelling are needed.

While the galactic cosmic ray background is rather steady, the solar variability modulates the penetration of the particles to the upper atmosphere. Cosmic radiation is a concern already at the commercial altitudes around 10 km and increases rapidly for higher-altitude airflight. Radiation is not only harmful for aircrew and passengers. The increasing miniaturisation makes the aircraft electronics vulnerable to single event effects caused by space weather.

There are also man-made space environmental concerns related to space weather, the most important being space debris. Collisions with pieces of space debris can be extremely hazardous. Space weather effects modify the orbits of debris in, so far, unpredictable manner.

At present Europe is strongly dependent on external space weather observations and there is no coherent approach to space weather services. However, there is strong enough European expertise in solar-terrestrial physics and in space environment modelling to establish an own European Space Weather Programme, a part of which could be a European Space Weather System directed toward particular services, growing from a limited start toward a more comprehensive structure in the future.

1. Introduction

1.1.Purpose and scope of this document

This Report is the final deliverable product of work package WP 300: "Establishment of detailed rationale" of the ESA Space Weather Study (ESWS) (ESTEC/Contract No. 14069/99/NL/SB). In addition to its role as a stand-alone report, it is intended to provide input to system definition studies in WP 400, in particular to the System Requirement Definition document (ESWS-DER-SR-0001) to be produced within WP 410, and to programme definition studies in WP 500 and WP 600.

The underlying reason for space weather is the fact that the time-variable solar-terrestrial interaction affects technological systems in space and on the ground and can have consequences to human life and health. As the well-being of European people are dependent on these issues, there is a strong rationale for establishing a European Space Weather Programme. As the benefits and economic consequences of European space weather activities are addressed elsewhere in the present project (WP 100, Benefits and Market Analysis), the present document concentrates on observations and modelling of physical phenomena with space weather relevance.

The present document contains three main sections:

- Section 2 discusses the observable space weather environment and space weather effects on various systems. The goal of this discussion is to give a comprehensive overview of space weather and the effects without quantitative details. The section includes catalogues of space weather effects produced in a sub-package of this study (WP 310, Range of space weather and its effects, reported in Space Weather Effects Catalogue, ESWS-FMI-RP-0001).
- Section 3 ties space weather effects to observations and comments on possibilities of modelling and forecasting the effects. The discussion aims at giving detailed and quantitative facts. However, as the field of space weather is very wide and the level of detail knowledge in various sectors of space weather is rather variable, a fully comprehensive presentation is outside the resources of this work package and thus beyond the scope of the present document. In particular, detailed requirements for practical space weather observations are discussed in WP 410.
- Finally Section 4 puts these items in the context of a future European Space Weather Programme. As the Programme Proposal will be a task of a separate part of the Study (WP 500 and WP 600), no practical proposals are made here. Instead Section 4 shall be seen as input to these particular work packages.

Note that in this Report we make a distinction between European Space Weather Programme (ESWP) and European Space Weather System (ESWS). The former is a wider context including independent activities, e.g., research and scientific missions, whereas the latter means some, to be defined, system focussed on space weather services. The Rationale discussed in this Report is for the ESWP that, however, would remain too abstract without simultaneously considering implementations in terms of ESWS. We note also that some of the present conclusions are based on personal opinions of the authors whereas more thoroughly motivated suggestions have to wait for the completion of later work packages (WP 500, WP 600).

1.2. Basics of space weather

Quite generally (and according to the Statement of Work for this study) the term "space weather" refers to the time-variable conditions in the space environment that may damage space-borne or ground-based technological systems and, in the worst case, endanger human health or life. The most important aspects of space weather are related to being aware of the consequences of space weather events and possibly avoiding them either by system design or by efficient warning and prediction systems that allow preventive measures to be taken. While these economically and socially important aspects have a negative connotation, space weather is also related to the beautiful auroral displays and the fascinating pictures of the active Sun as provided by the SOHO satellite. Furthermore, space weather provides an excellent avenue of educating the wider public on space science and technology.

During the last few years space weather activities have expanded with an increasing pace world-wide and it has become commonly accepted that improved space weather services are important and expected to become much more useful in the near future. At the same time scientific communities have strengthened their efforts toward better understanding of the physical foundations of space weather and many scientists have remarked that without strong emphasis on improved scientific understanding the promises for, and dreams of, improved space weather products may not be fulfilled. This way the scientific Solar-Terrestrial Physics (STP) community and the users of space-sensitive systems are intimately coupled to each other.

The design of future space weather activities may be able to utilise the experience from meteorological services, at least concerning real-time operations, input data management, and nowcast and forecast services. The most extensive operational space weather centres today, the Space Environment Center (SEC) of NOAA, and the 55th Space Weather Squadron of the US Air Force, both in Colorado, USA, already operate in this fashion, although in much smaller scale than typical meteorological services.

However, there are important differences between the atmospheric and space weather systems:

- While many meteorological processes are localised and it is possible to make good limited-area weather forecasts, space weather is always global in the planetary scale. Perturbations originating from the Sun disturb the Earth's plasma environment, the magnetosphere, which responds to these disturbances globally.
- Space weather events occur over a wide range of time scales: the entire magnetosphere responds to the solar-originated disturbances within only a few minutes, global reconfiguration takes a few tens of minutes, and sometimes extreme conditions remain for much longer periods. Ground-based magnetometers react immediately when an interplanetary shock hits the magnetosphere whereas enhanced fluxes of energetic particles in radiation belts decay in time scales of days, months, or even years.
- Our means to monitor space weather are much more limited than our ability to install weather stations on the Earth's surface: Our prediction schemes must be capable of functioning with input from only a few isolated measurements of the upstream solar

wind conditions and magnetospheric parameters. While the present (e.g., magnetic activity indices, interplanetary scintillations) and future (e.g., energetic neutral atom imagery, ionospheric tomography) observations have a global character, they still remain rather far from the detailed and continuous observations of the atmospheric weather. As a consequence, successful space weather activities need to be performed on a global scale, merging a variety of space-borne and ground-based observational capabilities.

All these aspects put significant requirements and constraints to present and future space weather service systems both in space and on the ground. While the monitoring system cannot be as complete as one would like, it must be extensive enough for reasonable specification of the space environment. This introduces the crucial question of costs versus benefits. On the other hand, data collection and assimilation, and the service product processes have to be very efficient and fast which calls for well-designed and maintained space and ground segments. Further analyses of all these questions are topics of other parts of the present ESWS study (WP 400, WP 500, WP 600) and reported in separate documents.

1.3. Why create a European Space Weather Programme

During the 1990's space weather became an established part of space research and applications and there is no return to times before that. As understanding of the space environment, its temporal variability, and the consequences of this are an essential part of competence of space organisations such as ESA, it is clear that ESA will have to address these issues in one way or another. It would, of course be possible to continue without a well-defined approach where application-oriented studies are conducted separately, space scientists continue with their programmes, and the efforts of national organisations remain incoherent. Most likely this would be the least efficient approach and a more coherent programme finally arising from the recommendations of the present and related studies is desirable.

The benefits and markets of space weather have been studied in a separate part of this investigation (WP 100) and reported in "Report of Benefits and Market Analysis for Space Weather (ESWS-MMS-RP-0001). The report identifies a long list of benefits (economic, defence, strategic, etc.), whereas the market situation shows a need for more focused and better quality education about space weather and how it affects commercial markets and technical systems in order to develop their level of understanding and overcome their scepticism.

From the "rationale" viewpoint a coherent European Space Weather Programme (ESWP) is highly desirable. While it is possible to conduct useful research on the physics of space weather and its technological impacts within various science and technology programmes, a system directed toward services requires continuous monitoring, data processing, and distribution of products, which are not the responsibilities of, e.g., the ESA Science Programme, or national science organisations.

A comprehensive and well-formulated ESWP is expected to contain both the service-oriented ESWS and the support from space science, which is necessary for improved space weather products. On the other hand the request for improved products also challenges the STP science to increased efforts to gain deeper and more detailed knowledge of the basic space physics.

Finally, an ESWP will provide a very useful avenue to educate students, general public, and policy makers across Europe on space issues. Hazards and beauty awake the curiosity and explanations tying the Sun, near-Earth space and technological systems together can show the strengths of rational, scientific approach to natural phenomena and hazards.

2. Space weather and its effects

This section is a qualitative description of space weather as a natural phenomenon and its effects on different technological systems and humans. Subsection 2.4 summarises the effects in a catalogue form. This catalogue focuses on qualitative description as our current quantitative knowledge varies greatly between different phenomena and their effects. Indeed, some are still very difficult to quantify at all. Thus, quantitative information is put in Section 3 to the extent it has been found feasible within this particular part of the ESWS study.

2.1. Observable space weather environment

Figure 2.1 illustrates the spatial domains where such space weather effects take place and have effects on technological systems or human beings. There are two main natural sources of space environment: the Sun and the interstellar matter. While the activity of the Sun controls all space weather processes, the role of the interstellar matter is to provide galactic cosmic rays and meteoroids to the system. In addition there are man made effects related to space weather, in particular debris and electromagnetic "pollution". For complementary information on space environment, see the recent publication by ECSS on Space engineering standards (ECSS, 2000).

Practically everything in space weather is related to the variability of the Sun. In addition to being a source of matter and radiation, the Sun also controls the changes in the atmosphere and ionosphere, entry of the cosmic rays into the vicinity of the Earth, the evolution of low-altitude debris, and the loss of energetic charged particles from the radiation belts.

In the following subsections we identify several key parameters from the space weather viewpoint from each of these environments.

2.1.1. The Sun

The effects of the Sun on space weather arise both from electromagnetic and particle emissions. The steadiest emission is the visible light, which has led to the concept of the "solar constant". While there are small variations in the solar constant over the solar cycle and recently a slight increase of the solar brightness during the last 100 years (Lockwood and Stamper, 1999; Lockwood et al., 1999; Solanki and Fligge, 1999) has been found, it is not clear what their impacts on space weather or space climate are. However, the UV/EUV part of the spectrum, which creates the planetary ionospheres, varies much more strongly and has a direct impact on ionospheric space weather. Furthermore, the solar UV variability of the Sun is directly associated to the active processes in the solar atmosphere, which in turn are responsible for the release of both energetic particles as well as strong solar wind disturbances, such as coronal mass ejections (CMEs). Thus, the solar UV flux is one of the key parameters in space weather.

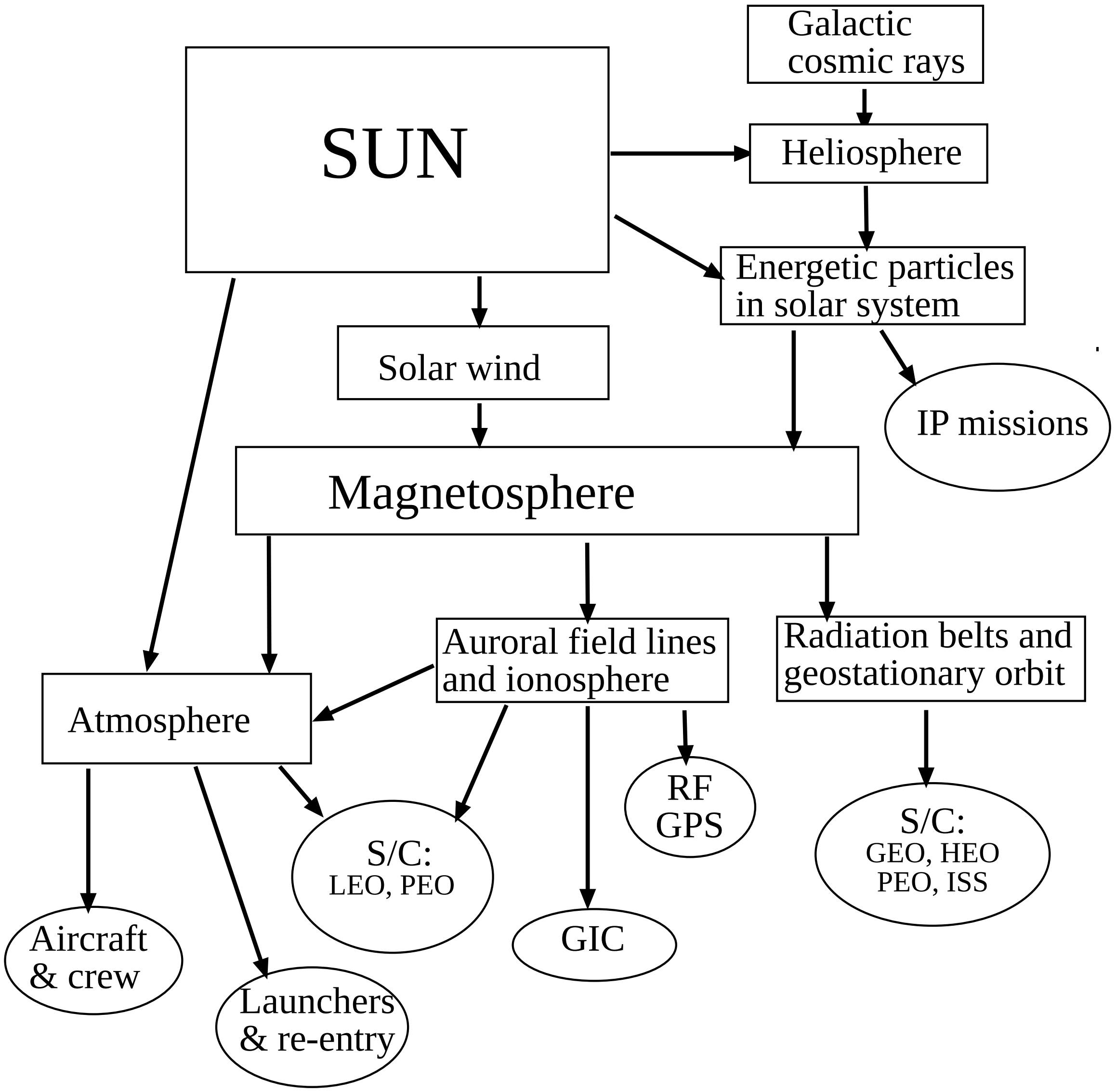

Figure 2.1. The domain of space weather. Note that the Sun affects the atmosphere directly through electromagnetic radiation but also through the magnetosphere. Furthermore, the solar system energetic particles may cross the magnetosphere with little deflection until they hit the atmosphere. There are also two-way interactions between atmosphere, ionosphere and magnetosphere.

Before continuous UV-observations above the terrestrial atmosphere, it was not possible to monitor directly the UV-flux and its variability. Already before the physical relationship between the UV-variability and solar radio emissions was known, it was found empirically that the properties of the terrestrial ionosphere were related to 10.7-cm radio emissions (F10.7). Now we know that the solar activity, seen, e.g., by the Extreme Ultraviolet Imaging Telescope (EIT) of SOHO, is associated with strong magnetic perturbations which give rise to the radio emissions through the cyclotron radiation by energetic electrons. Although the present ionospheric and atmospheric models mostly use F10.7 as input, it is merely an easily derivable proxy. If available, the direct UV flux is preferable (see, e.g., Feynman and Gabriel, 2000).

Solar activity, and in particular solar flares, produces X-ray emissions. X-ray flux is one of the standard solar activity parameters provided routinely by the GOES spacecraft of NOAA and available through the NOAA web site (http://sec.noaa.gov).

Today CMEs have become appreciated as the main drivers of large geomagnetic storms. They have, actually, a two-fold role. In addition to being storm drivers CMEs also contribute to the acceleration of solar energetic particles (SEP). The tens to hundreds of MeV protons can reach the Earth in a few tens of minutes, whereas the main storm effects are mediated with CMEs arriving typically in 1.5–3 days after the ejection. It is evident that visual CME monitoring with a LASCO-type instrument assisted with an instrument like EIT to observe the source regions on the solar disc (both presently onboard SOHO) should be seen as the most important task for space weather systems. In fact there is no acceptable return to times before SOHO. How this requirement could be met is discussed in Section 4.

Whether a CME drives a geomagnetic storm or not, depends on the speed of the CME (i.e., whether it is fast enough to produce a shock in front of it) and on the orientation of the magnetic field in the sheath region behind the shock and/or within the CME structure. The solar wind energy is transferred most efficiently to the magnetosphere when the magnetic field has a strong and long-duration southward component. Thus some CMEs drive only weak storms and some others are not geoefficient at all. Vice versa, weak and intermediate storms take place also in the absence of CMEs provided that the solar wind magnetic field has a strongly enough southward component for long enough time (typically more than 3 h). This often happens when the fast solar wind emerging from the large polar coronal holes impinges the Earth. These storms are often recurrent with a 27-day period as the coronal holes are quite persistent features, in particular around the solar minimum.

Finally the SEPs belong to major causes of effects on space systems. Prediction of individual SEP events (SEPEs) is very difficult, their acceleration mechanisms and interplanetary scattering before reaching the environment of the Earth are not fully understood, and their passage through the geospace is a complicated issue as most of them do not become trapped in the dipole field of the Earth. The characterisation of SEP fluxes in various parts of space is among the key parameters for space weather effects.

2.1.2. The solar wind

The velocity, density, and magnetic field (IMF) of the solar wind plasma are the most important in situ-measurable parameters affecting the magnetospheric activity. Once the upstream parameters are determined, fairly reliable predictions of the general level of magnetospheric activity can be made. The problem is that the lead-times for predictions are short. Before a possible future sub-L1 mission with, e.g., solar sail techniques, the optimal position in situ observations is the halo orbit around L1 where presently SOHO and ACE spacecraft are placed. From L1 a fast CME proceeds to the magnetopause in about half an hour and more typical solar wind in one hour. Thereafter it takes a variable time to set up a magnetic storm and the warning times are of the order of one hour.

An additional difficulty with single-point upstream observations is that the shape of the proceeding perturbation front cannot be determined uniquely and contact with the magnetopause can be established faster than the direct propagation time from L1 to the subsolar magnetopause would suggest.

For scientific purposes there have been solar wind monitors closer to the Earth, most notably the IMP-8 spacecraft which has served since 1973. For space weather purposes the advantages of an L1 monitor over a near-Earth satellite are continuous observations from the same relative position and more time to react to observations.

Interplanetary scintillations (IPS) can, in principle, be used for characterisation of global solar wind properties. However, the scintillations do not yield information of the IMF and the technique needs much work to improve spatial coverage and time resolution, and to remove the ionospheric contamination.

2.1.3. Solar and galactic cosmic rays (SCR, GCR)

The galactic cosmic-ray source is relatively uniform and constant. There is a predictable solar cycle modulation in the GCR flux, which can be classified as a space climate effect. Individual solar events modify the penetration of GCRs close to the Earth. Thus cosmic-ray fluxes both on ground (neutron monitoring) and at GEO are among essential space weather parameters. The latitude effect is important and calls for neutron monitoring at high-latitudes.

Solar cosmic rays are the high-energy end of SEPs, discussed in section 2.1.1. The strongest recorded SCR event took on February 23, 1956, when a factor of 50 increase on the ground at high-latitudes (rigidity cut-off 1 GV) was recorded.

2.1.4. The magnetosphere

The magnetosphere is the venue of most of space weather-sensitive spacecraft. Solar, solar wind, and cosmic-ray parameters discussed above are all important also from the magnetospheric point of view.

The large-scale state of the magnetosphere is expressed in terms of a great variety of activity parameters (for details, see Mayaud, 1980). For space weather applications the most used are the planetary activity indices Ap and Kp, the storm-time disturbance index Dst, and the auroral electrojet indices AL, AE, and AU. For climatological studies an often-used parameter is the aa-index. These are derived from ground-based magnetometers at various places from low geomagnetic latitudes (Dst) to the auroral region (AL, AU, AE). The key role of these indices in space weather is to indicate magnetic storms and substorms that are known to give rise to electron acceleration to relativistic energies, to efficient transport of charged particles to trapped orbits in the ring current and radiation belts, to enhanced ionospheric precipitation to change the ionospheric density, and to enhanced ionospheric currents affecting the ground-based systems. The accurate derivation of these indices takes time, as the determination of the correct base-line requires in many cases the knowledge of the longer-term averages, e.g., the whole month in question. Thus for real-time purposes predicted proxies based, e.g., upstream solar wind observations are widely used (for example, see the discussion of the MSFM model in section 3.1.2.).

The most important in situ space weather parameters within the magnetosphere are the fluxes of energetic particles. As there are several spacecraft on GEO, these parameters are readily available at that particular altitude but the lower altitudes (ring current, centred around 4 R_E, and the radiation belts) are monitored much more sparsely. The characterisation of protons in tens of MeV and above is particularly difficult because they can be trapped for long times only in the inner belt whereas the transient events can be missed by too sparse observation grids.

The radiation belts are mostly embedded within a cold (about 1 eV) and dense plasmasphere co-rotating with the Earth. The outer boundary of the plasmasphere is characterised by a rapid plasma density drop from 1000 cm^{-3} down to below 1 cm^{-3}. The location of this plasmapause depends strongly on magnetospheric activity. During strong activity it can be compressed down to dipole field-lines crossing the equator at a distance of about 3 R_E whereas during quiescence it can reach beyond 8 R_E.

2.1.5. The ionosphere

The critical parameters for the ionosphere are the total electron content and the peak electron densities at various ionospheric layers. TEC can be derived from GPS signals whereas the critical frequencies of various layers (e.g., foF2) can be found from ionosonde measurements of the local peak electron density. For space weather purposes keeping up of a dense enough ionosonde network is important although their role in scientific investigations has decreased during the years. This trend may reverse in the future as modern digital ionosondes are becoming more common and provide much better resolution of the complex patterns of ionsopheric behaviour.

Good characterisation of ionospheric currents is needed to understand the substorm and storm dynamics and is critical for useful GIC applications.

2.1.6. The atmosphere

For space weather applications the most important atmospheric parameter is the scale-height as it is related to the drag effects both on low altitude space vehicles (satellites, space stations, shuttles, launchers) and on debris. The scale-height is mostly dependent on solar EUV fluctuations and correlates also with the Kp index during magnetic storms. The drag is usually calculated using solar EUV- or F10.7-dependent atmospheric models.

There is also an increasing interest on the coupling of space and atmospheric weather phenomena through climate effects as well as on the effects on ozone through energetic particle precipitation. Furthermore, there are increasing efforts to understand the nitric oxide production through energetic particle precipitation and subsequent effects on stratospheric and cloud chemistry. While these are not direct concerns of space weather systems, there are mutual interests to give motivation for increased efforts on studying all aspects of space weather, also the long-term trends, and increased understanding of the upper forcing of the atmosphere can lead progress in the field of atmospheric sciences as well.

2.2. Non-standard space weather environments

2.2.1. Man-made environment (debris, EM noise)

Human activities have an increasing effect on our space environment and some aspects of this are directly coupled to space weather and climate. Probably one of the most serious is the occurrence of space debris, the distribution of which needs to be carefully monitored. The number of objects larger than 1 cm is estimated to between 30000 and 13000 and there is a far larger number of smaller pieces (e.g., ECSS, 2000). Variation of the population is closely related with the change in the density of the upper atmosphere, depending on space weather. Here the natural space weather has actually a positive effect as the increased drag cleans up the low-altitude debris population.

The second effect is the electromagnetic noise. The VLF waves emitted by naval communication systems interact with radiation belt particles moving them into the atmospheric loss-cone and thus continuously weaken the radiation belts. In fact such a wave background has been there longer than direct observations of radiation belt particles have been possible and we have never seen the radiation belts in their natural state. For example, it has been speculated if the slot region in electron flux between the inner and outer radiation belts would, at least partly, be a man-made phenomenon.

The wave-particle interactions could also, in principle, be used to remove part of the energetic particles from the radiation belts. This might be desirable after some very strong storm-time injections but before doing so the costs vs. benefits need to be carefully evaluated. Another idea to produce a similar effect is to move a long conductor (tether) across the geomagnetic field and let the induced electric field move the particles into the loss-cone (e.g., Danilov et al., 1996).

Finally in the history there have been significant man-made radiation belt components resulting from high-altitude nuclear explosions. These had a useful spin-off as they allowed detailed studies of particle loss from the trapped orbits.

2.2.2. Meteoroids

Meteoroids and micrometeoroids are the smallest objects left over by the formation of our solar system. Most of them are particles ejected from collisions between the asteroids or are particles ejected by cometary nuclei upon their closest approach to the Sun. The flux of meteoroids can be divided into three components: (a) Sporadic flux, omnidirectional background, fairly stable; (b) Streams, temporary periodic increase (by a factor of ten in the average) over the sporadic level associated with the orbits of short period comets (for instance the Perseids stream in August) and (c) Storms, linked to the temporary increase of the activity of a stream (for instance the Leonids storm in November, with a period of 33 years). Fluctuation in the environment is therefore linked to the presence of meteoroid streams. As the streams are associated with the orbit of past or present comets, the main parameters of the streams are known with a good accuracy (flux density, orbital elements, size distribution of particles within the stream) and the meteoroid models used in the environment engineering tools incorporate these parameters. Enhancement by a factor of ten is common, during a period of a few days or a few hours. However, the models are statistical and do not allow an actual short term forecast (in space and in time). There is no direct interaction of solar activity with the meteoroid flux. However, meteor rates (provided by visual, radio, or radar observations) can be used for potential hazard predictions. Actually, electrostatic discharges could be triggered by the plasma produced upon hypervelocity on spacecraft surfaces (Levy et al., 1997).

2.3. The systems affected by space weather

The space weather effects on various systems are discussed in detail in the documents "Space Weather Effects Catalogue" ESWS-FMI-RP-0001 produced as a part of the present study. In this section we briefly summarise the systems affected by space weather. The phenomena, the effects, the systems, and the critical spatial domains are tabulated in section 2.4.

2.3.1. Spacecraft

All spacecraft in orbit are always under space weather influence but the potential effects are strongly dependent on the orbit in question. Furthermore, the sensitivity to space weather depends critically on the design and thus the same environment may lead to different effects on different spacecraft.

In the interplanetary space the main space weather effects are due to direct solar energetic particles and, less frequently, the meteoroid populations. For a recent example, it has been estimated (unconfirmed), that during the July 2000 storm, the solar panels of SOHO aged due to SEPs as much as during one whole year under normal conditions. There is nothing dramatic with this effect as the event fits within the total exposure estimates over the whole lifetime of SOHO. Similarly, the November 2000 storm has been estimated to have reduced the power supply of the Cluster satellites 1–2 %.

Within the magnetosphere the picture is more complicated. The SEPs have access to variable altitudes, depending on their energy, and provide transient impacts of particles penetrating deep into the spacecraft subsystems, resulting in various single event effects (SEE).

On the other hand, magnetospheric storm processes enhance energetic particle populations in the radiation belts. In particular, the enhanced relativistic electron fluxes have often been associated to spacecraft or subsystem failures and there is a good statistical correlation between satellite anomalies and storm-time energetic particle enhancements (see discussion in Koskinen et al., 1999), which are known to cause surface and deep dielectric charging. These effects are important to GEO satellites as well as the satellites at lower altitudes crossing the magnetic flux tubes of radiation belts.

Spacecraft on polar Earth orbits (PEO) may also encounter auroral electron precipitation. As shown, e.g., in the case of the Freja satellite (Koskinen et al., 1999), even a spacecraft designed against spacecraft charging, can experience charging up to kilovolts when hitting the auroral electron beam (energy of a few keV) in eclipse.

2.3.2. Manned spaceflight

There is an increasing concern of space weather in the manned spaceflight community as the construction of the International Space Station (ISS) implies a strongly growing human presence in space. The required long extravehicular activities will increase the risk of exposure to intense solar energetic particle events. As the space suit and skin give only a 0.5-mm shielding, the same particles that cause deep discharges in electronics are dangerous to humans as well. As the time to seek cover after an observed SEPE is only a few tens of minutes, there is a genuine need for improved means of forecasting. While most technological risks may well be possible to avoid by better design, this is not possible in case of humans. As found out in the SPEE study (Koskinen et al., 1999) the manned spaceflight is expected by many to become one of the most important future space weather service customers.

Possible future long-term presence in the Moon or long interplanetary flights, such as manned flights to Mars pose also several requirements to take care of space weather. The crew will need well-protected areas to spend their time when not needed to be active elsewhere.

2.3.3. Launchers

Launchers experience specific space weather effects which are due to neutrons resulting from the interaction between the atmosphere and solar energetic particles (producing SEEs), or to the drag related to the opening of the launcher protecting shroud. Otherwise, launchers as they move higher and higher are subject to nearly all other space weather effects (surface charging, global drag, SEEs by energetic particles from radiation belt as well as solar energetic particles and cosmic rays, internal charging). Nevertheless, normally these effects have not enough time to perturb the launcher, except during solar energetic particle events or when crossing during a long period of time the radiation belts (near the South Atlantic Anomaly), which is the case for Ariane V launches to GTO or interplanetary orbits (Bourdarie and Bourrieau, 1999).

2.3.4. RF communications

The ionosphere, an area of the atmosphere which extends from ~80 to ~1000 km, can significantly affect the propagation of radio frequency (RF) signals which pass through it or are reflected by it. The effects are varied but include absorption, refraction, retardation and scintillation. At frequencies above ~1 MHz, the lower *D* region causes absorption and the higher *E* and *F* regions cause a variety of other effects. These effects, which include refraction, signal group delay, signal phase advance, pulse broadening and Faraday rotation of the polarisation vector, all follow an inverse power law and are significant only up to a frequency of ~2 GHz. Below ~1 MHz radio systems bounce their signals from the tenuous *D* region; consequently, although the height of the layer is important for system operation, absorption is not an issue.

The diverse set of affected systems include ground-ground high frequency (HF) communications, ground-space communications, GPS (Global Positioning System; particularly single-frequency navigation systems), HF over-the-horizon radars, satellite altimeters and space-based radars. HF communications and radar systems rely on the ionosphere for their operation but also have to contend with its effects. Most other systems are degraded by the ionosphere but for certain specialist systems detailed knowledge can be of great benefit. Loss of phase lock and range errors in GPS are examples of such deleterious effects.

2.3.5. Ground-based systems

The variations of magnetospheric and ionospheric currents are seen as geomagnetic disturbances or storms at the Earth's surface, and in accordance with the basic electromagnetic theory (Faraday's law of induction), a geomagnetic variation is accompanied by a geoelectric field (Weaver, 1994). Although the auroral electrojet system is of particular importance concerning geomagnetic disturbances, similar effects are also experienced at lower latitudes (Rastogi, 1999). The Earth consists of conducting material, so the geoelectric field drives currents within the Earth. These also affect the geoelectromagnetic disturbance observed at the Earth's surface, and especially in the electric field the Earth's contribution is significant.

The geoelectric field implies the existence of voltages between different points at the Earth's surface. For example, there is a voltage between the grounding points of two transformers, and a current will flow in the power transmission line connecting the transformers. Such a current is known as a geomagnetically induced current (GIC). Besides power systems, GIC flows in other technological conductors, like oil and gas pipelines, telecommunication cables and railway equipment (Lanzerotti et al., 1999). In general, GICs are a source of problems to the system: in power systems transformers are saturated leading to disturbance of the system or even to permanent damages, in pipelines problems associated with corrosion and its control occur, telesignals may be interfered and overvoltages can damage the equipment (Boteler et al., 1998). On railways signalling problems have occurred.

2.3.6. Avionics

While the Earth's atmosphere shields out most of the primary cosmic rays at conventional altitudes (30000–40000 feet; 9–12 km), there is a build up of secondary particles (neutrons, mesons and electrons) which reach a maximum at around 60000 feet (18 km) and are only a factor of three diminished at 30000 feet (9 km). By sea level there is a further factor 300 diminution. As a result of this mechanism the radiation hazard at aircraft altitudes is as severe as in certain low-earth orbits. During the past ten years there has been increasing evidence of single event effects on aircraft electronics as well as in sea-level systems.

At the same time there is new legislation on the allied problem of the effects of radiation on aircrew and frequent flyers. Ionising events in cells lead to free radicals and DNA rupture and increase the risk of cancers. Probabilities are related both to the ionising energy deposited per unit mass and to the density of ionisation as measured by LET (linear energy transfer or energy deposited per unit pathlength). Increasing awareness of health risks has led to the European Union Council Directive 96/29/EURATOM, which took effect in May 2000. Article 42 demands that aircraft operators must take account of exposure of air crew who are liable to be exposed to more than 1 mSv (milliSievert) per year. Exposure must be assessed and reduced by rostering where appropriate and workers must be educated on the health risks. Pregnant women must not be exposed to more than 1mSv during pregnancy and crew exceeding 6 mSv per year must be carefully monitored and given health checks. At altitudes up to about 60000 feet (18 km) there are approximately equal contributions from directly ionising particles (protons, electrons, muons) and indirectly ionising neutrons. Above 60000 feet (18 km) ions have to be considered. For aircraft flying above 49000 feet (15 km), where there is a significant probability of increased dose rates resulting from solar particle events, Air Navigation Orders demand that an active warning monitor should be carried. If such a monitor is non-operational, flights may take place only if favourable space weather forecasts are obtained

2.4. Space weather effects catalogues

This section presents various space weather phenomena and effects in a catalogue form. Information is organised according to three different schemes: Domain-oriented catalogue, Phenomenon-oriented catalogue, and System-oriented catalogue, in order to serve the wide variety of interests in space weather. The primary objective of these catalogues has been to organise the complicated web of natural phenomena and technological consequences to support further parts of the present project. It does not intend to restrict or reinterpret the actual scope of Space Weather Programme as described in the Statement of Work of this study.

2.4.1. Domain-oriented catalogue

Spatial domain	Systems affected	Effects	Measurable parameter
Interplanetary space	Spacecraft	SEE, radiation damage, noise, charging	charged particle flux & composition, UV, X-rays
		meteoroid impact	mass, velocity
	Manned spaceflight	tissue damage	dose equivalent
Magnetosphere	Spacecraft	SEE, radiation damage, noise, current loos	particle flux & composition
		charging, ESD	mass, velocity, charge
		debris/meteoroid impact	
	Manned spaceflight	tissue damage	dose equivalent
Ionosphere and thermosphere	Spacecraft	Drag, high latitude charging	density, precipitating particle flux, UV
	Communications HF & below	loss of communications	mainly D-region electron density
		change in area of coverage	E & F region electron density
		low signal power	mainly D-region electron density
		fading	mainly E-F region bulk electron density and irregularities
		error rate change	mainly E & F-region irregularities
	Communications VHF/UHF	fading	E&F-region irregularities
		error rate change	E&F-region irregularities
	Navigation	dispersion, scintillation, loss of phase-lock	total electron content scintillation via S4 & Sigma-phi

Domain-oriented catalogue (continued)

Neutral atmosphere	Aircraft and crew	SEE, tissue damage	neutron , ion, electron, meson fluxes and spcetra, dose equivalent
	Launchers	SEE	neutron, ion electron, meson fluxes
Earth surface	Power transmission systems	saturation of power, transformers reactive power consumption, harmonics, stray flux voltage drops, relay trippings, overheating, black-out	geomagnetically induced current, (time derivative of the) ground magnetic field geoelectric field
	Gas and oil pipelines	pipe-to-soil voltage variations disturbance to the cathodic protection system corrosion	geomagnetically induced current pipe-to-soil voltage (time derivative of the) ground magnetic field geoelectric field
	Telecables	overvoltages interference	geomagnetically induced current voltage between groundings of the system (time derivative of the) ground magnetic field geoelectric field
	Railways	overvoltages signalling problems	geomagnetically induced current (time derivative of the) ground magnetic field geoelectric field neutron fluxes
	Geophysical surveys	interference	(time derivative of the) ground magnetic field geoelectric field

2.4.2. Phenomenon-oriented catalogue

Phenomenon	Dynamic Process	Measurable parameter	Predictability
Energetic electron flux	Magnetospheric Storm	peak flux, fluence, spectrum	nowcast (at GEO), prospects of day ahead
Energised plasmasheet	Substorm	density, temperature	nowcast, prospects of day ahead
Trapped proton flux in LEO	Atmospheric removal, solar cycle	flux, spectrum	days ahead plus solar cycle
Trapped proton flux in slot	SPE + magnetic storm	flux, spectrum	not enough knowledge yet
Debris	Evolution, atmospheric drag	orbit & size distribution	weeks
Meteoroids	Streams, storms	size distribution, flux, orientation	months, weeks
RF disturbances	mid-latitude ionospheric storm	electron density, total electron content, scintillation via S4 and sigma4	nowcast, forecast hours to days
	high latitude ionospheric variations	all above	even nowcast is difficult
	equatorial ionospheric variations	all above	nowcast, forecast hours to days
Cosmic radiation	Solar cycle, Forbush decreases	Primary flux & composition, atmospheric secondaries	year ahead using sunspot number decreases via CME
Solar Particle Event	Solar flare, Coronal Mass Ejection	peak flux, fluence, composition	difficult
GIC	Substorm related ionospheric currents	dB/dt on ground geoelectric field GIC pipe-to-soil voltage voltage between groundings of the system	
Atmospheric weather	Ionisation by cosmic rays		
Atmospheric drag	Solar UV, particle precipitation	10.7-cm radio flux, UV flux sunspot number	solar cycle, nowcast

2.4.3. System-oriented catalogue

System	Phenomenon	Effect	Predictability
Spacecraft	Energetic electrons, protons and ions, plasma	SEE, charging, dose, damage, noise	cosmic rays good, SPE poor, relativistic electrons 1 day ahead in prospect trapped protons in LEO good trapped protons in slot not possible
	Debris	Damage, stimulated discharge	statistical predictions
	Meteorites	Damage, stimulated discharge	weeks (statistical)
	Magnetic field	Induced currents, attitude control	hours
	Atmosphere	Drag	after solar eruptions solar cycle
Manned space flight	Energetic ions, protons, electrons from cosmic rays, SPE and trapped radiation	Tissue damage	cosmic rays good, SPE poor trapped protons in LEO good
Launchers	neutrons, ions, protons from cosmic rays & SPE	SEE	cosmic rays good, SPE poor (nowcast prevents launch)
Aircraft	Neutrons, ions, protons, electrons, SEE & Tissue damage mesons from cosmic rays & SPE		cosmic rays good, SPE poor

System-oriented catalogue (continued)

Communications	RF disturbance	HF and below loss of communications change in area of coverage low signal power fading, error rate change VHF/UHF fading, error rate change	nowcasts and forecasts are possible except at high latitudes
Navigation	Scintillation, dispersion	loss of phase lock, position errors	nowcasts, forecasts hours to days
Power transmission systems	Geomagnetically induced current	saturation of power transformers reactive power consumption harmonics stray flux voltage drops, relay trippings, overheating black-out	nowcast
Gas and oil pipelines	Geomagnetically induced current	pipe-to-soil voltage variations disturbance to the cathodic protection system corrosion	nowcast
Telecables	Geomagnetically induced current	overvoltages interference	nowcast
Railways	Geomagnetically induced current	overvoltages signalling problems	nowcast
Geophysical surveys	Variations of the ground magnetic field	interference	nowcast

3. From observations to effects

We can divide the space weather observations into two different classes: those that are needed for research and further model development (scientific observations) and those that can be used in operational space weather activities (monitoring). This division is not exclusive; scientific observations are often excellent for space weather operations (e.g., LASCO on SOHO) and data from monitoring missions is useful for various research topics, in particular for statistical and/or long-term purposes.

It is important to understand the consequences of this division. Scientific observations are not always straightforward to use in operational context as they may require too much special expertise. Furthermore, they are seldom available beyond the end of the given mission. The operational observatories, in turn, require special commitment to routine data production, which is not always the responsibility of scientific organisations and problems in long-term fulfilling of such commitments are not rare. For example, many ground-based neutron monitors have been shut down, which severely limits the possibilities for reliable nowcasting of cosmic-ray events in order to protect air-crews in case of strong space weather events. Furthermore, it is practically impossible to include routine monitoring missions within the ESA Science Programme. This is an important motivation for an ESWP independent of, but in collaboration with, the Science Programme.

Not all observations are equally important and different observations are needed for different applications. In Section 4 we discuss the various observations in the context of a potential ESWS. Here we discuss the key observations and forecasting/nowcasting for various operational purposes starting from the effect viewpoint.

3.1. Spacecraft charging

An important space weather effect on spacecraft is spacecraft charging due to energetic particles. A recent extensive study (Koons et al., 1999) based on 326 anomaly records, containing thousands of individual events, concluded that spacecraft charging has caused by far the most environmentally related anomalies and the most serious ones, i.e., those that have led to the loss of mission, have been due to surface charging.

3.1.1. Critical parameters

Spacecraft charging is a result of the demand by nature to keep the electric current source-free. Thus all charged particles either incident on a spacecraft or emitted by it (e.g., photoelectrons or secondary electrons) contribute to the charging, but electrons, being the most mobile are responsible for the largest potentials. There are two main types of charging: Energetic electrons and ions impacting and leaving the S/C but not penetrating through the surface can result in negative surface charging, whereas particles delivering their charge deep inside the system can cause deep discharges. The threshold between these two depends on the particle energies; a typical 0.5-mm shielding will stop electrons below 300 keV and ions below 8 MeV on the surface. Surface charging takes some time to accumulate and potentials of about 1 kV are required before discharges occur. The actual charging depends very much on the materials used in different surface elements (e.g., Koskinen et al., 1999, and references therein).

The problems with spacecraft charging arise when the accumulated charges discharge, which may lead to various anomalous effects on the subsystems. One way of avoiding too large surface charges accumulating and creating large potential differences is to make the spacecraft surface as conductive as possible, which is not always feasible, in particular for large vehicles.

The most important population to cause surface charging are 10–100-keV electrons. The population varies rapidly (within minutes) in response to magnetospheric activity but enhanced populations can remain trapped for long times (hours and longer) in the inner magnetosphere.

Magnetospheric activity, in particular the so-called substorm injections play a decisive role in the production of these particle populations. The activity is characterised by several activity indices based on ground-based magnetic observations. The most widely-used parameter in spacecraft charging studies is the 3-hour planetary K-index Kp. Some other parameters (AE, AL) would have a more direct substorm association but their local characteristics and rapid temporal variability makes them more complicated to use in charging studies. During strong storms increased fluxes of relativistic electrons are produced in the inner magnetosphere. These MeV electrons penetrate deep into the spacecraft systems. They may generate arcs behind EMC shields and are therefore sometimes called "killer electrons".

As spacecraft charging depends on the balance between particle currents flowing into and away from the spacecraft, the ambient plasma density has an important role, in particular at low altitudes where the ambient density is typically large. However, when a spacecraft crosses the auroral field lines on LEO/PEO, the surrounding plasma density can drop by several orders of magnitude. If the crossing takes place in eclipse, even a spacecraft carefully designed for these conditions may acquire negative potentials up to the kV range. In the SPEE study (Koskinen et al., 1999) the Freja charging events were found to be caused by electrons around 10 keV which are quite typical in the auroral regions, in particular during substorm activity.

In summary the key parameters to be measured for spacecraft charging applications
- activity indices based on ground-based observations or proxies predicted from solar wind observations (velocity, density, and IMF)
- surface charging at high altitudes: electrons 10–100 keV with good spectral resolution
- surface charging on LEO/PEO: electrons 1–10 keV, cold plasma density
- deep discharges: MeV electron fluxes with spectral information (0.3–5 MeV)

For detailed studies, either forecasting of post-analysis, a number of ancillary data are needed. These are discussed in the following subsections.

3.1.2. Forecasting

The possibilities of forecasting conditions that induce negative surface charging depend on the ability to forecast storm or substorm activity and even at very detailed level as substorm injections are of variable intensity.

There is a class of intermediate level storm periods that are related to fast solar wind streams from large polar coronal holes. As these holes are relatively persistent structures, in particular around the solar minimum, similar solar wind conditions occur with about 27-day recurrence. Thus there is a limited predictability that a storm period will follow 27 days after an observed storm period. The prediction can be refined when the hole reappears on the eastern limb using, e.g., a space-borne EUV imager.

Forecasting of magnetospheric activity days ahead has to be based on solar observations (e.g., coronagraph images of halo CMEs, EUV and X-ray images of solar disc, flare X-ray and radio emissions). Presently, such forecasts are poor and merely warnings can be issued. One-hour ahead forecasts can be based on in-situ solar wind observations at, e.g., L1. Dynamical magnetospheric MHD models can be driven with upstream parameters but their predictive efficiency is yet rather weak. Good predictions of general activity level as expressed in terms of indices such as Kp, AE, Dst can be achieved from upstream observations using various AI techniques, including linear or non-linear prediction filters and neural networks. The advantage of these methods is that they are fast to compute. The flipside is that they do not directly predict the appearance of the harmful particle populations. In Europe such forecasts are delivered routinely in the ineternet by the Lund Space Weather Center (http://www.irfl.lu.se/).

The most comprehensive forecasting model today is the Magnetospheric Specification and Forecasting Model (MSFM) which has been developed for operational purposes under contracts from the US Air Force. Although the model is not publicly available its structure illustrates the main elements that a comprehensive model needs, it illustrates in particular a set of critical observable parameters

- activity indices: Kp and Dst
- magnetospheric state: equatorward boundary of the diffuse auroral oval at midnight (MEB), polar cap potential (PCP), and the polar cap convection pattern
- solar wind input: density, velocity, IMF

Note that PCP is an important parameter in MSFM (as well as MSM discussed below) as it is related to the plasma convection in the magnetosphere. For example, during magnetic storms the strong convection can push ring current particles deep into the inner magnetosphere. PCP can be determined by direct polar-orbiting satellite observations or ground-based radar measurements. Such measurements, however, a very average picture and cannot describe the bursty nature of magnetospheric convection nor the strong acceleration events related to strong induction fields. These are presently topics of intense scientific research and cannot yet be implemented in operational models. MEB is most accurate to determine by polar-orbiting electron detectors, presently onboard DMSP satellites. One of the strong points of the MSFM is that it is based on a good magnetic field model (Hilmer and Voigt, 1995) whereas many other models of the inner magnetosphere still are based on dipole magnetic field. On the other hand, the evolution of convection patterns following changes in the solar wind parameters is still an open scientific issue.

The MSFM flow chart is given in figure 3.1. The model output includes both electrons causing surface charging as well as daily averages of relativistic (> 2 MeV) electrons that can cause damage inside spacecraft systems. The forecasting capability is based on a neural network driven by the solar wind parameters. Based on publicly available information it is difficult to determine how good the model is from a user viewpoint, but it is evident that MSFM is not very powerful concerning relativistic electrons nor energetic ions. Presently there is no competing model in Europe.

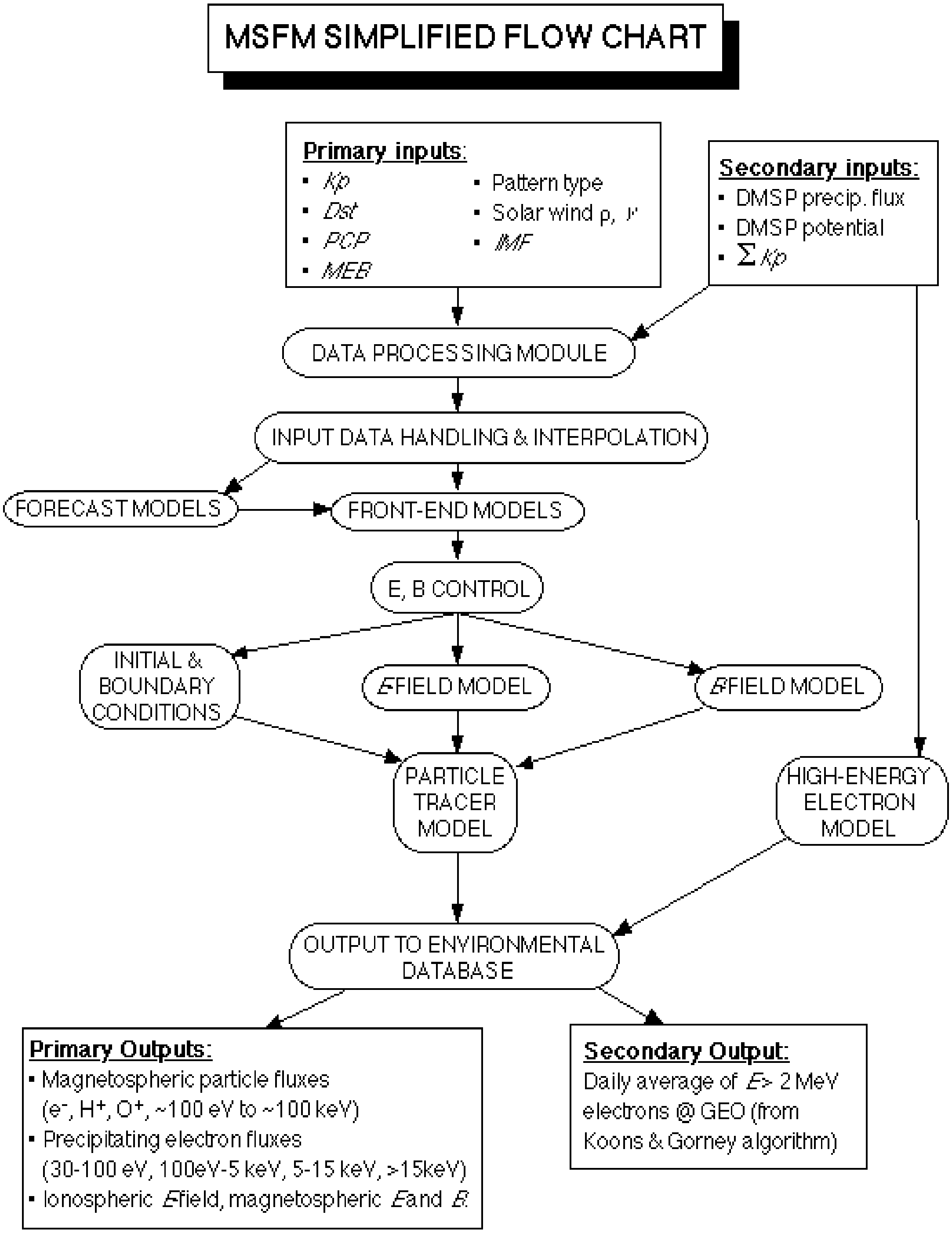

Figure 3.1. Flow chart of MSFM

A study of anomaly forecasting on GEO using neural networks based on local and non-local observations was conducted as a part of the SPEE study (Koskinen et al., 1999; for more details, see http://www.geo.fmi.fi/spee/sc_anomalies.html). The anomalies were recorded on two gestationary spacecraft. The non-local Kp and Dst indices were found to be good for both anomaly and non-anomaly simultaneously whereas relativistic electron flux (> 2 MeV) was good for anomaly forecast but not nearly as good for forecasting of non-anomalies. It is important to note that such a forecast is always a trade-off between forecasting of anomalies to occur and avoiding false alarms. Which one should have a higher weight depends on the system in question and the needs of the user. Furthermore, different spacecraft suffer from different types of anomalies and the results are very satellite-dependent, including the age of the satellite and its subsystems. This study continues as a separate ESTEC contract, see http://www.irfl.lu.se/saaps/

3.1.3. Nowcasting

Nowcasting of charging electrons requires reliable mapping of particle distributions measured somewhere to other parts of the magnetosphere. This is a considerably easier task than forecasting. The predecessor of MSFM the Magnetospheric Specification Model (MSM) developed at Rice University is in operative use at NOAA/SEC and has also limited predictive capacity. It is run with the same input parameters as MSFM. The actual practical value of any nowcast model today is unclear.

There are efforts to mate the MSM type models with global MHD models but this work is still at research stage (R. Wolf, talk at the COSPAR Assembly, 2000).

3.1.4. Reconstruction of environmental parameters for post-analysis

The need to specify the space environment after an observed charging event may be different. An important distinguishing factor is the time within which the analysis has to be performed. Long-term environmental parameter reconstruction studies are also important for statistical studies of satellite anomalies needed for future mission planning and satellite design.

Most rapid reconstruction is needed when, after a system malfunction, the operator may quickly want to know if the event could have been caused by environmental conditions and should immediate measures to be taken to avoid more damage. In such cases the specification resembles nowcasting and thus the forecasting or nowcasting models described above would be useful.

As the detail accuracy of forecasting and nowcasting models yet is very limited, a more thorough post analysis requires, however, more powerful tools, and more detailed data available, e.g., from scientific instruments, have to be added. As there often is more time for such an analysis, it is possible to collect more accurate and comprehensive environmental information. Trend-corrected activity indices can be used, more observational data from both operational and scientific payloads can be assimilated, different types of models (including scientific models) can be compared, the input parameters to the models can be varied, etc. Such an approach is not very different from scientific event analysis.

In Europe a particularly important effort toward good characterisation of the energetic particle environment is the Salammbô code (see, e.g., Bourdarie et al., 1997; Vacaresse et al., 1999; Boscher et al. 2000). The model is probably the most advanced research tool in this field but not yet applicable to operational purposes. It is important that the success of codes of type MSM and Salammbô depends on the inner magnetospheric magnetic field models where the dynamical behaviour and spatial asymmetries of the ring current are yet insufficiently included.

3.2. Impacts and single event effects on S/C

Single event effects (SEE) include a large number of anomalous behaviours of spacecraft systems from harmless to fatal. The events arise from solar energetic particles or galactic cosmic rays. SEE effects are also a concern of launchers as solar protons create neutrons at low altitudes, which can penetrate deep into the electronics of the launchers.

Also collisions with space debris or meteoroids can be considered as single events on spacecraft systems and humans in space. Small pieces of debris can destroy solar cells or induce electrostatic discharges. Larger particles can easily destroy entire satellite systems.

3.2.1. Critical parameters

The spatial distribution of debris is the given parameter that has to be kept track of. This is an increasing concern at low altitudes. The most important meteor showers (e.g. Leonids) are known in principle. However, the detailed calculation of the showers is not easy as was illustrated by the relatively poor public predictions of the November 1998 shower.

The most common causes of SEEs are protons in the energies above 10 MeV. There are two main source populations: solar energetic particles (SEP) and galactic cosmic rays (GCR). A relatively constant GCR background is always there with certain solar cycle modulation, and thus the phase of the solar cycle is the most important parameter. The prediction of GCR fluence is straightforward.

The SEPs are directly related to solar activity and thus a space weather system needs information about the developing solar activity and status of flares and CMEs. There is no simple parameter that can cover all aspects of this group of complex phenomena. For mission planning the phase of the solar cycle gives important input.

Distribution of SEPs within the magnetosphere can be characterised at GEO. A significant amount of SEEs are caused by protons above some 10 MeV, which are not on trapped orbits. The trapping boundary of 10 MeV protons is at about L = 5.5, 100 MeV at about L = 4. The mapping of non-trapped populations based on a limited number of observations is quite difficult, if not impossible.

The intense relativistic electron fluxes on GEO and inside are produced by magnetospheric storms and substorms. Once they have been injected to trapped orbits they remain there for several days and contribute to the total radiation dose on spacecraft. However, their distributions are asymmetric with strong gradients and reliable modelling of the evolution of this population would require much denser observational grid than is available today.

The intensity of the inner radiation belt protons characterises the most serious radiation environment of low-altitude spacecraft, including the ISS. The protons can be on trapped orbits up to energies of 100's of MeV. Above 50 MeV the CRAND (Cosmic Ray Albedo Neutron Decay) mechanism is a significant source of protons. It depends more on the solar cycle modulation of the GCR fluxes than individual solar events. However, as the terrestrial magnetic field at these altitudes deviates from the dipole (e.g., the South Atlantic Anomaly), accurate modelling with sufficiently distributed radiation monitoring is necessary.

In summary, the key observables for single event effects are
- solar protons: 10 MeV – 1 GeV (passing through the system)
- trapped ions: 10–100 MeV
- GCR: > 1 GeV

and for larger particle impacts
- distribution of debris
- distribution of meteoroids

3.2.2. Forecasting

The SEPs need to be forecast from several-year periods down to arrival of protons from a single SEPE (Solar energetic particle event, often abbreviated by SPE). For mission planning the JPL 1991 fluence model (Feynman et al., 1993; 2000) is widely used. It predicts the fluence for a specified time period within given confidence levels. The model is statistical and cannot be used to forecast individual SEPEs.

There are no reliable models to predict appearance of SEPEs on the Sun. This is one of the most important voids in our understanding of the main driver of the space weather system. The SEPE predictions have an additional difficulty on the top of difficulties to predict flares or CMEs as actual acceleration of energetic particles is yet a topic of intensive research and debate. Different CME events can have very different high-energy proton fluxes as shown, e.g., by Torsti et al. (1998) using SOHO/ERNE observations.

Once a solar event is in progress time for forecasting is very short. The energetic protons propagate to the Earth in only a few tens of minutes. The onsets of solar flares are traditionally monitored using X-ray observations.

Thus presently the predictions based on solar observations remain at the level of rather unreliable warnings. Useful observables for warnings are
- general solar activity: SSN, F10.7
- development of active regions (optical and UV solar monitoring)
- solar X-rays: 0.05–0.8 nm (e.g., GOES)

Note that while the solar activity is in principle possible to parameterise using SSN, F10.7, or X-ray fluxes, the comprehensive specification of solar activity requires synoptic maps of the entire solar disc and their phenomenological description. In fact, this is similar to atmospheric weather reports – it is not enough to give measured numbers from various weather stations, but also the weather patterns need to be described.

3.2.3. Nowcasting

After the energetic particles are observed, they can be mapped around the magnetosphere with energetic particle models. However, as gyroradii of 10's of MeV protons are large, they do not get trapped at high altitudes (e.g., GEO) and transient modelling, taking the time-dependent magnetic field into account, becomes necessary. The task is formidable and reliable nowcasts require very extensive in-situ coverage.

The high-energy protons remain trapped in the inner radiation belts where they can be mapped using available radiation belt models. Further development of models such as Salammbô (section 3.1.4) are expected to be very useful in this respect.

3.2.4. Reconstruction of environmental parameters for post-analysis

Similarly as in section 3.1.4 above, the nowcasting and post-analysis requirements are partially overlapping. As the post-analysis does not require immediate output, e.g., the Salammbô model is a a strong European asset. In fact, in the field of radiation belt modelling Europe is not as far behind the USA due to the TREND and SPENVIS projects conducted by IASB/BIRA under ESTEC contracts have produced valuable tools for nowcasting and specification of radiation environments. These models are discussed briefly in section 3.8.3 below.

3.3. Effects on humans in space

The effects on humans in space are in principle similar to SEE on technological systems. Skin and a space-suit give the same protection as a 500-micron shielding of S/C structure. Thus during extravehicular activities (EVA), whether outside a space station or on the Moon, the same parameters as for the SEE events have to be considered but more strict criteria for protection are necessary. Debris impact can easily be fatal and long-term dose effects are a major concern during long-duration flights, during which the astronauts will need special protection. During extreme solar events it is important to have well-shielded shelter, to which the astronauts can quickly return.

3.3.1. Critical parameters

In principle these are the same as for SEE on electronics. However, for humans the total dose effects are particularly critical.

3.3.2. Forecasting

Forecasting requirements are similar to those for SEE, but more attention must be paid to warnings based on solar observations as it may take a long time to interrupt an EVA. Possible neural networks weighing successful event predictions against false alarms are likely to have a strong bias in favour of issuing warnings in doubtful cases.

3.3.3. Nowcasting and post-analysis

Also this is, in principle similar to the SEEs. In addition, continuous radiation dose monitoring is mandatory.

3.4. Drag

Atmospheric drag is a result of an increased temperature and consequently increased atmospheric scale-height due to solar EUV and energetic particle precipitation. It affects all objects at LEO, spacecraft and debris alike. For example, after strong magnetic storms NORAD has lost tracking of thousands of objects for several days.

3.4.1. Critical parameters

As the main driver of the scale height is the solar EUV radiation, it is the given parameter to monitor. If not available the F10.7-cm radio flux is a useful proxy which, in fact, is used by most present ionospheric and thermospheric models. Finally SSN can be used if neither F10.7 nor EUV is available.

The average neutral density at 400-km altitude increases by a factor of 10 from solar minimum to solar maximum. This can decrease the lifetime of a spacecraft at an initial altitude of 400 km from 4 years at solar minimum to 6 months during solar maximum (c.f., Hastings and Garrett, 1996). Thus the determination of neutral density either by ground-based radars or through modelling is important. Also the monitoring and forecasting of debris in LEO is closely related with atmospheric drag.

Atmospheric models are quite well developed, but are not presently suited for the prediction of short-term variations of, e.g., the upper atmospheric density. Presently the leading models in this field are the COSPAR International Reference Atmosphere (CIRA-86), Mass Spectrometer Incoherent Scatter (MSIS-86) model and the higher-altitude extension of the latter MSISE-90. These are related to each other but different models are suitable for different applications. The models are described and publicly available at NSSDC: http://nssdc.gsfc.nasa.gov/space/model/atmos/. Note that MSIS-86 includes geomagnetic activity as an input parameter but inclusion of observed solar UV flux in these models is needed.

Note that the neutral thermosphere and the ionised ionosphere occupy the same physical space. Their coupling through momentum transfer is a complicated process and the relevant parameters, in particular the neutral winds, are difficult to determine experimentally. This calls for quite involved modelling. There are several modelling attempts toward comprehensive thermosphere-ionosphere-magnetosphere coupling. Europe is well-represented in this field, e.g., the Magnetosphere-Thermosphere-Ionosphere Electrodynamics General Circulation Model (MTIE-GCM) by Peymirat et al. (1998) and the work with the Coupled Thermosphere Ionosphere Model (CTIM) at the University College London (http://cat.apg.ph.ucl.ac.uk/model1.html). However, the development of these models is still at the research stage and their transfer to practical applications is somewhere in future.

3.4.2. Forecasting

Predictability over a solar cycle is good but short-term forecasts meet the same problem as all other solar activity dependent predictions, namely the poor understanding of the physical foundations of the solar EUV variability.

3.4.3. Nowcasting and post-analysis

The atmospheric density variations have time-scales of hours. Thus nowcasting is possible based on observations of increased solar activity and use of atmospheric models.

3.5. RF communications (including GPS)

The space weather effects on RF communications and satellite positioning and navigation applications are determined by ionospheric electron density structure and total electron content (TEC). The community dependent on ionospheric propagation effects is among the largest regular users of space weather forecasts, in particular the military communications, which partly explains the strong involvement of the US Air Force in the US space weather efforts.

3.5.1. Critical parameters

The ionospheric ionisation level is determined by the interplay of sources, losses and transport. The main source is solar EUV radiation with some additional production by particle precipitation, especially in polar regions. Thus solar EUV-flux, and in its absence the F10.7 as a proxy, is a critical driver parameter. In fact, most ionospheric/ thermospheric models use the F10.7 as input as it has been available for much longer time than the direct EUV flux. Loss is largely determined by dissociative recombination, which requires the presence of molecular species. Loss rates above 200 km are enhanced during geomagnetic storms due to upwelling of molecular species. During geomagnetic storms enhanced heating of the upper polar atmosphere (by particle precipitation and the electrojets) alters the global pattern of thermospheric winds, and via neutral-ion momentum coupling, the transport of ionisation. Thus geomagnetic activity is also a critical parameter.

For propagation through the ionosphere (UHF, GPS) TEC is the critical parameter but also plasma density irregularities are important to the signal propagation. For HF and lower-frequency communications the ionospheric reflection properties are crucial. These include D, E, and F region peak electron densities and their irregularities.

3.5.2. Forecasting

Climatological prediction models of both the bulk ionospheric electron density distribution and small-scale ionospheric electron density irregularities are fairly mature. The

ITU-R provides recommended expressions for the median prediction of the ionospheric characteristics such as the critical frequencies of the E, F1 and F2 regions being respectively foE, foF1 and foF2 for any location, month, time-of-day and solar epoch (ITU-BR, 1997; ITU-R, 1997). Errors in the E region predictions are low at mid-latitudes being typically 100 kHz; the mid-latitude F-region errors on the other hand can be several MHz corresponding to many tens of percent. At high- and low-latitudes the deviations from the median values can be higher still.

The availability of a model of the electron-density height profile (rather than just points on the profile) is, however fundamental to many applications. These climatological profile models can be divided into three categories: theoretical, parameterised and empirical. The theoretical models are complex and time consuming to run but are more accurate than the empirical models. Empirical models (e.g., Bradley and Dudeney, 1973; Bilitza, 1990) provide generally adequate monthly median estimates of the electron density or TEC. The International Reference Ionosphere (IRI) can be found at http://nssdc.gsfc.nasa.gov/space/model/ionos/. The parameterised models use analytic approximations to the theoretical models maintaining some of their accuracy but with vastly improved run times. In addition, a model, WBMOD, has also been developed to predict the effects of ionospheric scintillation (Secan et al., 1997; Secan et al., 1995).

The above models are generally parameterised by a simple solar activity index and sometimes a magnetic index on the assumption that the important characteristics of the ionosphere are well correlated with those indices. This is successful, to first order, and provides useful planning and design information but cannot model the actual day-to-day variability. In order to forecast this variability it is first necessary to accurately specify (measure) the current ionosphere and this requires the use of a sophisticated instrumentation and data assimilation suite. This being available an understanding of physics in combination with time series analysis can provide a useful forecast capability over several hours. For example, Francis et al. (2000) have generated a neural network model which is able to predict foF2 one day ahead with a root mean square error of around 0.5 MHz which compares favourably with a persistence model error of ~1 MHz.

3.5.3. Nowcasting and environmental specification

Nowcasting or environmental specification requires the assimilation of real-time ionospheric measurements into models or alternatively (and perhaps ideally) a dense network of instrument measurements which can be combined without recourse to models. The problem has never been satisfactorily solved since the medium is currently grossly undersampled – a common problem with these strategies is the generation of artificial hills and valleys in the geographical distribution of TEC or electron density. The best practical hope for nowcasting involves a combination of ground and space based instrumentation optimally combined with physical (not empirical) models of the ionosphere.

3.6. Aircrew and avionics

There are two aspects of space weather effects on airflight. One is the health of the crew and passengers, the other is the aircraft electronics. The main effects are caused by

GCRs. The atmosphere shields most of the primary cosmic rays at conventional altitudes 9–12 km (30000–40000 feet). The collisions with atmosphere produce secondaries (neutrons, mesons, electrons) which peak at the altitude of about 18 km (60000 feet). The flux of secondaries diminishes only by a factor of 3 down to 9 km and a further factor of 300 down to sea level.

3.6.1. Critical parameters

Cosmic-ray flux is the most critical parameter. A particular problem is that current GEO monitors have relatively low energy thresholds (e.g., 100 MeV on GOES). Higher energy thresholds, e.g., 360 MeV provided by Cerenkov telescopes would be important. Ground-based neutron monitors are essential for cosmic-ray energies of GeV and above and these both track the cosmic-ray modulation and show those solar particle events which produce increases at aircraft altitudes. Unfortunately, during recent years several neutron monitors have been closed and near real-time data are available from only a very limited number of sites. For space weather purposes a high-latitude neutron monitor is essential as the geomagnetic cut-off rigidity is below 1 GV in the polar region.

3.6.2. Forecasting

For long-term needs, e.g., in route planning and crew rostering the forecasts can be based on the solar cycle modulation of the GCR flux. There are possibilities for predicting the level of modulation several months in advance using sunspot number (e.g., Dyer et al., 2000) The main problems are the transient solar energetic particle events that are very difficult to predict in advance.

3.6.3. Nowcasting

As the forecasting possibilities are rather limited, the countermeasures against transient events must be based on nowcasting using both onboard radiation monitoring and rapid dissemination of information of events in progress. For example, Concorde is required to take action when the onboard monitor shows dose rate of 0.5 mSv per hour. The present EU criteria for annual exposure limit for radiation workers is 20 mSv while pregnant women shall not be exposed to more than 1 mSv during their pregnancy. Indeed any aircrew subject to more than 1 mSv per annum must have their exposure controlled. Note that during the largest recorded ground-level event on 23 February 1956 the dose rate has been estimated to be 30 mSv per hour at Concorde altitude and 10 mSv per hour at conventional altitudes (Foelsche, 1974). Such an event would also result in a thousand-fold increase in single event upset rates in susceptible electronics. Unfortunately, aircraft operators are unwilling to bear the cost of onboard monitors unless compelled. Current Air Navigation Orders require a monitor only for operation above 49000 feet (14.9 km).

3.6.4. Reconstruction of environment parameters after the event

Improved estimates of aircrew dose can be made retrospectively using actual measurements of cosmic-ray modulation from neutron monitors in conjunction with calculations based on radiation transport codes (e.g., CARI-6, see http://www.cami.jccbi.gov/AAM-

600/610/600radio.html). This is the approach being adopted by most airlines and aviation authorities. A similar approach has also been proposed to calculate the additional doses from solar particle events (Lantos et al., 2000). This is made difficult by the huge variability of intensity and spectral hardness from event to event. The approach given in (Lantos et al., 2000) is based on observations from two neutron monitors (Kerguelen and Terre Adelie). However, a wider range of neutron monitors in combination with spacecraft measurements would appear to be required in order to give adequate spectral definition and to allow for the directional response of the ground-based monitors in the presence of significant anisotropies in the particle fluxes. At the very least, such a technique requires validation against data from airborne monitors and currently such observations have been made only for a few events observed by monitors on Concorde. Given the possibility of very severe doses in a single flight, it would appear desirable to have active monitors distributed amongst the vast volume of air traffic. This would afford the possibility of taking avoiding action in extreme events as well as improving the computational methods employed for event reconstruction.

3.7. Ground-based systems

Space weather effects on ground-based systems are in most practical cases induced by ionospheric currents. Of course, individual GCR events might, in principle, cause SEE in electronics but this is a rather remote possibility. Failures in space-borne systems may also have ground-based consequences, e.g., through problems in navigation systems. We do not deal with these second-order effects here.

3.7.1. Critical parameters

Ionospheric currents can be monitored by ground-based magnetometers and the relevant components are the horizontal ones (X and Y, or H and D). As the effects are rather localised, it is important to have magnetometer near the system in question. The relevant frequency range of GICs is 0.001–0.1 Hz, thus sampling does not need to be faster than one sample in a few seconds. Of course, direct observations of GICs when available are useful. The measurement ranges of the key parameters are:

- GIC: 1–100 A
- pipe-to-soil voltage: 1–10 V
- dX/dt, dY/dt: 10 nT/s
- geoelectric field: 0.1–10 V/km
- time resolution: 10 s
- spatial resolution: 50–100 km

The variations of ionospheric currents are due to magnetospheric activity and thus activity indices are among the relevant parameters.

3.7.2. Forecasting

There are no real forecasting models of GIC effects. The large events take place during strong magnetospheric disturbances and thus warnings can be issued based on general criteria for storm warnings, using similar methods as discussed in section 3.1.2. However, the scientific research in the field of GIC modelling is intensive (e.g., Viljanen et al., 1999). Monitoring solar wind conditions at the L1 point by a satellite (e.g., ACE) permits forecasting of a magnetic storm with a lead-time of typically one hour. This has been applied to constructing a warning system of large GIC (Kappenman et al., 2000) The chain of physical processes from L1 to GIC at a particular site of, e.g., a power grid is, however, very complicated and difficult to handle in an accurate and fast manner. Thus, forecasting still remains more or less qualitative.

3.7.3. Nowcasting and post analysis

There is at least one commercial nowcasting model (Kappenman et al., 2000) that calculates the geoelectric field from magnetic field observations and derives the induced currents in a given network. Note the GIC predictions always need the knowledge of the actual network. However, after the geoelectric field is calculated correctly, this is rather straightforward. Other, and more complicated, technological issues are how GICs affect particular transformers of introduce corrosion in pipelines.

Post analysis of an intensive GIC event can be done if the network structure is known and the magnetic field is measured close enough to the place where the high GIC was detected. However, the really large events are still difficult to calculate even afterwards.

3.8. Requirements for progress

We identify three main areas where major efforts are needed for improving future space weather services. The European Space Weather Programme (ESWP) must thoroughly address these items whereas a European Space Weather System (ESWS) must find a suitable selection from these where practical solutions can be worked out and upon which further evolution of the system can be based.

As the first complex we discuss the *need for research efforts*. Within parts of the space weather community there may be naïve hopes that once we get more efficient numerical codes and simulation systems, the problems will be solved. As our basic understanding of several key processes of space weather is far from sufficient, this impression is wrong. Of course, model development is often closely associated to the fundamental research.

The second complex is the *continuous need of data, rapid data input to the system, and management of large databases*. The third is the *model development* where the progress is dependent on progress in scientific research. Finally, the usefulness of the models is critically dependent on the data systems and their performance.

3.8.1. Need for research effort

The scientific research on space weather can be seen as a part of the more general topic of solar-terrestrial physics (STP). While most of STP evidently leads to improved understanding of physics behind space weather (e.g., the Cluster mission, whose main emphasis is in the small-scale physics of magnetospheric boundary layers and how particles and energy penetrate through these boundaries), the long-term success of the ESWP will depend on progress in research of the key problems for space weather. This does not mean that the establishement of such a programme should be subject to parallel scientific efforts. However, it is important that means of co-ordinating the ESWP with the Science Programme of ESA and with the national European programmes shall be identified during the early phase of ESWP evolution.

As the purpose of this document is not to promote the science of space weather on its own, we just give a brief list of some of the most important holes in our present understanding of the processes that are fundamental for space weather phenomena:

- *Solar atmosphere, where and when events take place:*
  This is a major problem to be solved to obtain reliable warnings and forecasts in the time scale of days.

- *Acceleration of solar energetic particles:*
  This is a fundamental scientific problem related to the above. Different CME events produce different high-energy ion fluxes toward the Earth, and we do not know why.

- *Prediction of the structure and interplanetary propagation of CMEs:*
  Even after observation of a CME around the solar disc, we still cannot be sure if it will hit the Earth, and even if it will, without upstream in situ observations we cannot tell if the event will be geoeffective. Critical features are whether the CME is fast enough to produce a shock ahead of it and how strong is the southward component of the magnetic field behind the shock and/or within the CME structure itself.

- *Magnetospheric acceleration (killer electrons, storms/substorms):*
  These belong to the major unknowns in magnetospheric physics. To reconstruct a major acceleration event is still very difficult even afterwards, as the events take place during most active phases of magnetospheric storms and require setting up very strong localised and transient electric field structures.

- *Storm dynamics:*
  This is a wide complex of insufficiently solved problems, in particular in the near-Earth region (inside the geostationary orbit). Storm dynamics are usually described in terms of global geomagnetic indices, but it is still uncertain how different magnetospheric current systems contribute to these indices, and what factors in storm dynamics are the most critical to space weather effects. Problems are related to storm drivers, acceleration events, magnetosphere-ionosphere coupling, etc. In addition to warning and forecasting, this is also a major issue in after-the-fact reconstruction of the space environment.

- *Exceptionally big GIC events:*
  Serious damages on ground are associated with particularly large GICs. However, as these events are very localised, they are extremely hard to predict, making development of useful warning systems difficult.

- *Dynamics of the upper atmosphere:*
  The dynamical response of the upper atmosphere to magnetic activity is very complex and is important both for drag and for ionospheric effects. Good progress is being made but further work, particularly in terms of model development is required.

- *Coupling to the lower atmosphere:*
  Finally, space weather is coupled to the atmosphere through complicated processes, ranging from penetration of GCRs to long-term relationship between solar activity and climate. These processes are still poorly understood, which slows down useful space weather product development.

- *Studies of planetary magnetospheres, ionospheres and thermospheres*:
  The study of these domains around other solar system bodies is of great value for space weather - especially in terms of model development. The basic physical principles are the same as for the domains around the Earth, but the greater range of physical parameters allows better testing of those models and their underlying concepts. This may be see, e.g., in the development of models of the thermospheres of Mars and Titan.

While this list is not exhaustive, it illustrates that the most important physical problems in space weather belong simultaneously to the most challenging problems in space physics. It is clear that these problems cannot be solved by a space weather programme alone but they require long-term scientific efforts. The present and near-future space weather activities must be built upon existing knowledge and on progress derived from present science missions (in the case of ESA, these are SOHO and Cluster). Europe has considerable capability to contribute to future research missions for space weather. ESA's newly selected Solar Orbiter mission is already recognised by NASA as an international partner for their Living with a Star programme. Furthermore, several European groups have Co-I roles on NASA's STEREO mission and on the Japanese Solar-B. If further opportunities for space weather research missions arise, perhaps as a result of the ESA Space Weather Initiative, there are a number of well-developed European mission concepts that can be considered. The best-developed of these is the STORMS proposal to study the inner magnetosphere behaviour during magnetic storms; this proposal was assessed during the recent F2/F3 selection and study report is available (STORMS, 2000). Some of the other F2/F3 candidates (e.g., Maxwell, SWARM) could also provide a basis for future space weather research missions.

3.8.2. Observations and data systems

The present European weather observation and data system resources are studied in WP 500 (European Co-ordination) of the present study and listed in the Catalogue of European Space Weather Resources (ESWS-RAL-RP-0001). Here we discuss the need for further developments in this field.

Any weather service needs an extensive data system somewhere in the loop, beginning with observations. Forecasting and nowcasting services depend on real-time 24-hour observations and also model development and post-analysis activities often require continuous 24-hour data coverage although the data may not need to be brought together immediately. Furthermore, there must be guarantees that certain key observations are continued uninterrupted by replacing old monitors when necessary. For space segment this is an important cost issue.

Presently a considerable part of space weather relevant data comes from various scientific payloads that often are much better than needed for monitoring but which only seldom provide continuity for monitoring purposes. A prime example is the SOHO mission. It is an unquestioned landmark mission in the solar research and has been the first spacecraft giving real-time warnings about the Earth-directed CMEs. However, after the LASCO instrument ends its observations, the day-to-day space weather services will need something else. The scientists can continue research based on several years of data but warnings and forecasts always need real-time observations.

Another problem with scientific spacecraft is that there is no 24-hour coverage of critical data. The Cluster II mission has been heavily marketed as a space weather mission by ESA but, in fact, its data-taking operations are constrained to about 50% by budget limitations, by telemetry considerations, and by the orbit. Thus it is possible that the satellites may completely miss important space weather events. No operational space weather services can be made dependent on such missions, although these services can certainly make excellent use of these when available.

After observations at least some key features of them must sent to the space weather system immediately. These include prompt information on

- solar eruptions (e.g., X-ray fluxes, information on CME releases),
- in situ solar wind parameters (at minimum velocity and IMF),
- current magnetospheric activity (real-time indices, preferably based on ground-based observations but also predicted from solar wind parameters),
- increased energetic particle fluxes in the magnetosphere, etc.,

depending on actual products that the system is delivering to its customers. With present technology this is technically feasible but to make such a system comprehensive enough would evidently be quite expensive. Related issues are

- common and efficient data formats,
- efficient data base management structure, and
- further data dissemination to various users.

These are all important issues of the present study but we consider them to belong to the realm of practical implementation instead of the rationale itself, and thus they are dealt with in other work packages (WP 400).

Note that the SEDAT project managed by RAL under an ESTEC contract is a step toward this direction. For more information, see http://www.wdc.rl.ac.uk/sedat/. For more information see also http://www.estec.esa.nl/wmwww/wma/seds_RT/.

3.8.3. Model development

The model development is often seen as the major occupation in space weather activities. It is likely that any space weather organisation should have some level of own model development, at least at the level of tailoring the existing models to their own particular needs. On the other hand, in the case of an ESWS there are good arguments for having a strong emphasis on model development as there are several first class efforts in scientific space weather modelling in Europe (e.g., Salammbô mentioned in section 3.1, or the 3D magnetospheric MHD model GUMICS-3 at FMI, see http://www.geo.fmi.fi/~pjanhune/gumics3/).

European examples of more practice-oriented modelling efforts are the BIRA/IASB-led ESTEC Contracts on Trapped Radiation Environment Model Development (TREND, TREND-2, TREND-3). These studies have utilised the static NASA radiation belt models AE8 and AP8, developed already in the 1960s, and the ESA sponsored UNIRAD. An important part of the TREND studies was the incorporation of the Russian radiation belt modelling effort at the Institute for Nuclear Physics (INP) of the Moscow State University based on the NASA models and data from the Soviet and Russian spacecraft missions.

The applications of these developments are included in the Space Environment Information System (SPENVIS, also developed under an ESTEC Contract). SPENVIS is a WWW-server (http://www.spenvis.oma.be/spenvis) which can be used to generate a spacecraft trajectory or a co-ordinate grid and then to calculate, for example:

- the geomagnetic coordinates B (magnetic field) and L
- trapped proton and electron fluxes and solar proton fluences
- radiation doses
- damage equivalent fluxes for Si and GaAs solar panels
- linear energy transfer (LET) spectra and single event upsets
- trapped proton flux anisotropy
- atmospheric and ionospheric densities and temperatures
- atomic oxygen erosion depths
- spacecraft charging

Magnetic field line tracing is implemented, as well as the generation of world maps and altitude dependence plots of the magnetic field and the current models of the neutral atmosphere and the ionosphere. The server is continuously updated.

With some exceptions of certain spacecraft engineering or ionospheric propagation models, most space weather models originate from the scientific community where they have been developed for specific scientific research problems. The transformation of such models from research to operations is a nontrivial task that cannot be left for the responsibility of the science community. The implementation of operational models will require good software engineering discipline - especially with respect to incomplete data, robustness and reliability as well as maintainability and documentation. The prototyping of new models is one of the key tasks of NOAA/SEC (http://sec.noaa.gov/rpc/index.html) and it should be one of the foci of an ESWS as well.

4. Toward a European Space Weather Programme

This section discusses the requirements for a space weather programme (ESWP) from the physics and modelling point-of-view. This is not a formal requirement document but more a summary of the previous sections. The requirements for ESWS are reported elsewhere as a result of WP 410 of the present study.

We repeat that the European Space Weather Programme (ESWP) should not be synonymous to any particular space weather system or service (e.g., ESWS). Systems and services can be many and their interfaces should depend on particular needs.

ESWS can have different extensions and levels of ambition. In fact, an evolution from a less ambitious start toward a more comprehensive system is expected. As a minimum level requirement we assume that the system needs to be able to process input data to one or more users. Given the global and international context of space weather ESWS is expected to have efficient interfaces to external data sources.

4.1. Input to a space weather system

4.1.1. Space-borne monitoring

The Sun is the single-most important element in space weather. Solar observations can be made from the ground (optical and F10.7) and from space. The L1 point is an optimal location but for improved 3D resolution in CME observations from L4 and L5 are called for. This is the prime motivation of the STEREO mission of NASA which has significant European instrument participation. An advantage of L1 is that it is possible to combine the optical observations with in situ solar wind observations on the same spacecraft.

For space weather the CME observations together with identification of the source location are the most critical. Thus an instrument complex similar to LASCO and EIT on SOHO has the highest priority. This can be facilitated also from an orbit closer to the Earth, either from a polar halo orbit or by more than one spacecraft. It is essential to have continuous coverage.

The EUV and X-ray monitoring can be made either in the solar wind or in the magnetosphere. For example, NOAA gets their X-ray fluxes from the Geostationary Operational Environmental Satellites (GOES). Selection between L1 and near-Earth orbit as the monitor location is mostly a cost issue. A comprehensive space weather system requires both upstream and GEO observations and the monitors should be placed on these following some optimal strategy.

The solar wind must be monitored in situ upstream of the Earth. Interplanetary scintillations (IPS) can be used for supplementary information but it is questionable if they can give detailed enough information to be useful alone. Prior to the present L1 missions (WIND and ACE), the upstream conditions were usually determined using the IMP spacecraft, most importantly IMP-8 since 1973, much closer to the Earth. While the smaller distance to the Earth may sometimes be useful for scientific studies, the advantage of L1 is that from there it takes about 1 h for 300-km/s solar wind to reach the Earth, thus one gets a 0.5–1-hour lead time from the in situ observations before the perturbation reaches the magnetopause. With a solar sail it would be possible to keep a spacecraft at a sub-L1 position increasing the lead-time but the technical feasibility and costs of such a mission are not yet clear.

It looks reasonable that the solar and solar wind monitoring are done in international co-operation, in particular as there is no reason to have different data sources for different space weather systems. On the other hand, two different systems would provide redundancy although for much higher total cost.

The magnetosphere is the venue of most important space weather phenomena and there is the largest user community. While there are excellent scientific motivations to make observations almost everywhere in the system, the essential needs for space weather monitoring are more focussed.

Observations of energetic electron and ion fluxes from *geostationary orbit* are among the most evident space weather observations. Presently these data are obtained from the GOES and US military spacecraft (with Los Alamos National Laboratory particle detectors). There is enough instrument expertise in Europe to become a partner in the observing system either by providing a monitoring spacecraft in one time sector or instruments to spacecraft external to ESA.

With the REM and SREM projects ESTEC has already useful equipment *for radiation belt* observations. Such monitors can be carried by various spacecraft and it would be useful to try to establish a policy that any ESA-assisted satellite of reasonable size should carry such monitors. In addition an ESWS would need information form a polar-orbiting satellite that crosses a large number of L-shells as, e.g., the SAMPEX mission of NASA. As shown by SAMPEX such a satellite does not need to be large and could thus be realised as an ESWS mission.

For comprehensive observations of the dynamics of magnetic storms in the inner magnetosphere a constellation of spacecraft on *elliptical nearly-equatorial orbits* such as the recent STORMS proposal to the ESA flexi-missions (F2/F3) would be desirable (STORMS Assessment Study Report, 2000). As the STORMS was designed for the research on storms and space weather, the model payload was much more extensive than a space weather monitor on a similar orbit will require. Again such a satellite system is within the reasonable resources of an ESWS. The optimum number of spacecraft is not easy to give as very detailed description of spatial asymmetries and gradients at radiation belt boundaries would require a dense spatial sampling. Three S/C on STORMS-type orbits is probably a minimum goal.

Another flexi-mission proposal related to the science and monitoring of space weather was SWARM (Space Weather Advanced Research Mission), which consisted of 30 microsatellites on six different types of orbits both in the solar wind and various key regions in the magnetosphere. A combination of STORMS and SWARM with comprehensive ground segment and 24-hour operations would provide an excellent space segment for space weather fulfilling the needs of both monitoring and scientific progress toward more useful products. One should, however, be realistic with the operational complexities and consequent costs of such a system. In this respect ESA's experience in building, commissioning and operating Cluster puts it ahead of NASA in terms of running multi-spacecraft missions. For future space weather operations careful analysis and documentation of these experiences should be very valuable.

4.1.2. Ground-based monitoring

Ground-based observations of various space weather parameters are always much less expensive than their space-borne counterpart. While, as described in the WP 500 Catalogue of European Space Weather Resources, some European countries (in particular, UK and France) possess overseas observing facilities, Europe is within a limited time sector. Thus the ground-based monitoring of the Sun and solar wind (through IPS) as well as the determination of the magnetospheric activity indices or the state of the ionosphere require global international co-operation. The ESWS could play an important role the European link in this enterprise; Monitoring of local geomagnetic effects could be one of the ESWS activities in collaboration with the local national interests.

4.1.3. Data management

Efficient data management is a critical issue in space weather. Presently there is no structure in Europe that would be expected to lead and co-ordinate this effort. Thus this is a given task for ESWS. It is being discussed in WP 430 and will be reported in a Technical Note on space weather service (ESWS-RAL-TN-0001).

4.2. Processing of space weather information

Data management is closely related to the processing of space weather information, which should be an important occupation of ESWS. It includes model development, routine modelling and forecasting, and services tailored according to user needs. A European example of a small research unit routinely processing space weather infromation is the Lund Space Weather Center. It provides information of the present status of the space environment and limited nowcasting and forecasting products through internet (http://www.irfl.lu.se/).

4.2.1. Model development

As discussed in section 3 the most sophisticated present day models are often research tools rather than models optimised for routine services. Furthermore, even the best models need considerable further development, in particular those used for warnings and forecasting. While this already is in progress for some magnetospheric models, the atmospheric models have not yet really been adapted for space weather purposes. A task that should be seriously considered as a responsibility of ESWS would be a prototyping activity, as is the case at the SEC of NOAA. As prototyping would be closely related to basic research, it is expected to get significant intellectual support from the research community.

4.2.2. Routine modelling

Continuous routine specification (nowcasting) of the space environment, as is done by atmospheric weather centres, is an ambitious but a worthwhile goal for ESWS in the longer time perspective. Such activity is necessary also for detailed forecasting and high-accuracy warnings. Furthermore, a system capable of high-quality nowcasting would, of course, be able to give strong support to any needs for reconstructing environmental conditions for past events or for spacecraft design requirements.

4.2.3. Tailor-made services

Specific users have specific needs. As building up a comprehensive space weather service in Europe will take a long time, the ESWS could grow stepwise by providing tailored services to various users, including ESA's own S/C engineering at ESTEC. Provision of tailor-made services is an important opportunity for market provision of space weather services. In an environment where services are commercially viable smaller and medium enterprises could add specialist value to data provided by a publicly funded infrastructure (such as ESWS), as is increasingly happening with meteorological services.

Products not requiring prohibitively large resources could include

- auroral forecasts for tourists
- real-time prediction of activity indices (already done by various scientists)
- consulting services to space engineering
- "today's space weather" service for public
- etc.

4.3. User contacts

As the potential user community still is not well-identified, hesitant, and poorly informed of the possibilities of space weather, one of the primary tasks of a developing ESWS should be to create and maintain user contacts. Without improved interaction between space weather providers and users the present positive evolution of space weather activities may slow down and the whole activity risks getting a questionable reputation.

4.4. Research on space weather

It has been mentioned repeatedly in this document that in order to improve space weather services enhanced effort in science of space weather is needed. This is a particularly urgent task as there are no actual plans for any future STP missions in the ESA Science Programme other than Solar Orbiter, and this is only in the time frame of 2011–2013. Basic research needs to be a focal point in the European Space Weather Programme (ESWP) but only partly to be covered by ESWS activities.

Space weather research is, however, not only research in the underlying reasons but also research in engineering solutions to space weather problems. This is another central issue to include in ESWP and, for suitable parts, in ESWS.

4.5. Education and outreach

As the underlying reason of space weather is the physically highly complicated interaction between the active Sun and the terrestrial environment, space weather has excellent potential to educational purposes throughout the education system from kindergartens to university science and engineering and also to advancement of science to general public.

List of acronyms

ACE	Advanced Composition Explorer -spacecraft
AE	Auroral electrojet index (contains AL and AU)
AE8/AP8	Radiation Belt Models
AI	Artificial intelligence
AL	See AE
AU	See AE
CIRA-86	COSPAR International Reference Atmosphere
CME	Coronal mass ejection
COSPAR	Committee on Space Research
CRAND	Cosmic Ray Albedo Neutron Decay
DMSP	Defence Meteorological Satellite Program
DNA	Deoxyribonucleic acid
D-region	Lower ionosphere below a height of about 90 km
Dst	Ring current index
EIT	Extreme Ultraviolet Imaging Telescope
EM	Electromagnetic
E-region	Upper ionosphere between 95km and 140 km
ERNE	SOHO energetic particle instrument (Energetic and Relativistic Nuclei and Electron)
ESD	Electrostatic discharge
ESWP	European Space Weather Programme
ESWS	European Space Weather System
EUV	Extreme ultraviolet
EVA	Extra vehicular activities
F10.7 cm	10.7 cm radio emission
F1-region	Upper ionosphere between 140 km and 200 km
F2-region	Upper ionosphere between 200 km and 400 km
F2/F3	Flexi missions
F-region	Upper ionosphere between 140 km and 400 km
GCR	Galactic cosmic rays
GEO	Geostationary Earth orbit
GIC	Geomagnetically induced currents
GOES	NOAA meteorological satellite series
GPS	Global positioning system
GTO	Geostationary transfer orbit
GUMICS-3	Grand Unified Ionosphere-Magnetosphere Coupling Simulation
HF	High frequency
IMF	Interplanetary magnetic field
IMP 8	Interplanetary Monitoring Platform spacecraft
INP	Institute for Nuclear Physics
IP	Interplanetary
IRI	International Reference Ionosphere
IPS	Interplanetary scintillations
ISS	International space station
Kp	Planetary magnetic activity (K) index
L1	First Lagrange point
L4	Fourth Lagrange point
L5	Fifth Lagrange point
LASCO	Large Angle and Spectrometric Coronagraph Experiment in SOHO instrument
LEO	Low Earth orbit
LET	Linear energy transfer
MSFM	Magnetospheric Specification and Forecasting Model
MSIS	Mass Spectrometer Incoherent Scatter
MSISE	Mass Spectrometer Incoherent Scatter Extension
MSM	Magnetospheric Specification Model
NOAA	National Oceanic and Atmospheric Administration

NORAD	North American Aerospace Defence Command
PCP	Polar Cap Potential
PEO	Polar Earth orbit
REM	Radiation environment monitor
RF	Radio frequency
S4	Standard deviation of the signal power
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SEDAT	Space Environment Database and Analysis Tools
SEE	Single event effect
SEP	Solar energetic particle
SEPE	Solar energetic particle event
SEU	Single event upset
Sigma-phi	Standard deviation of phase
S/C	Spacecraft
SCR	Solar energetic rays
SEC	Space environment center
SOHO	Solar and Heliospheric Observatory
SPE	Solar particle event
SPENVIS	Space Environment Information System
SSN	Sunspot number
SREM	Standard Radiation Environment Monitor
STEREO	NASA mission
STORMS	Three-spacecraft constellation for studies of magnetospheric storms (proposal for F2/F3)
STP	Solar terrestrial physics
SWARM	Space Weather Advanced Research Mission (proposal for F2/F3)
TEC	Total electron content
TREND	Trapped Radiation Environment Model Development
UHF	Ultra high frequency
UNIRAD	Trapped Radiation Software Package developed by BIRA/IASP
UV	Ultraviolet
VHF	Very high frequency
WIND	NASA solar wind satellite
VLF	Very low frequency
WBMOD	WideBand MODel (ionospheric scintillation model)

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Important references to WWW-pages:

http://nssdc.gsfc.nasa.gov/space/model/atmos/

http://nssdc.gsfc.nasa.gov/space/model/ionos/

http://sec.noaa.gov/rpc/index.html

http://sec.noaa.gov/

http://www.cami.jccbi.gov/AAM-600/610/600radio.html

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http://www.wdc.rl.ac.uk/sedat/

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