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State of the art of space weather modelling and proposed ESA strategy

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Abstract

State of art of space weather modelling capabilities world-wide and in Europe are investigated. While it is clear that in the US space weather activities are farther ahead than in Europe there are certain fields where Europe is strong and it is possible and even desirable to formulate an European space weather programme built on these strengths.

The European solar-terrestrial physics community has strong scientific competence in the fields relevant to space weather modelling and forecasting. On the technological side Europe has good expertise in modelling of the effects of space environment. However, the cross-fertilisation between scientists and engineers is much weaker in Europe than in the US. While more dialogue between these communities is necessary for advancement of space weather, space weather activity can, in turn, foster this dialogue.

In the field of space weather modelling Europe has already established impressive activities in the modelling of energetic particles and their effects in the ring current and radiation belt regions of the inner magnetosphere. Also in the field of applying modern analysis methods, such as neural networks, Europeans are at high international level. Furthermore, the Solar and Heliospheric observatory (SOHO) provides good possibilities for European scientists to take a leading position in the studies of the solar origins of space weather. Joining the European expertise in global magnetospheric dynamics it is quite feasible that competitive global magnetohydrodynamics (MHD)-based modelling activity could be initiated in Europe.

A specific weakness in Europe is that the resources are scattered and it is unlikely that any single group or country could form a significant independent space weather activity. Consequently this study proposes a formulation of European Space Weather Strategy based on the following three suggestions:

1. ESA Science Programme should take space weather on its agenda.

2. Form a formal Science/Technology Interdisciplinary Space Weather Programme which reports to SPC/SSWG and IPC.

3. ESA should initiate work to establish a European Space Weather Data and Model Centre (either centralised or distributed with a central core). This Centre should have as its goal to become a European Data, Model, and Specification Centre, and it should look for a workable solution for a full-scale European Space Weather Centre.

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1. Introduction

1.1 Purpose of this document

This document is a Technical Note describing the results of the WP 310: "State of art of space weather modelling" of the Study of energetic electron environments and effects (ESTEC/Contract No. 11974/96/NL/JG(SC)).

The scope of the present document is defined to deal with modelling of short-term "weather"-type events in the solar-terrestrial plasma system, leaving out the questions of long-term "climatological" trends. The border between weather and climate is, however, unclear. The 11-year solar cycle is the most significant cycle of space climatology whereas the 27-day solar rotation is much more closely related to space weather. Especially during the phase of low solar activity in the 11-year sense, the 27-day recurrence is one of the most predictable features of space weather. The goal of this document is to give a comprehensive overview where the modelling stands today world-wide and what is the role of the European activities in this picture. The intended readers of this document are all who are interested in developing the European approach to space weather modelling for the needs of both space engineering and forecasting.

Note: In the text below we have included a number of references to various WWW-servers. There is no guarantee that these sites will be updated and maintained, as space weather WWW-servers is a rapidly evolving and uncontrolled process. For more information we refer to the WWW-server that is developed as a part (WP 330) of this ESTEC Contract (http://www.geo.fmi.fi/spee/). After installation at ESTEC the server will have a guaranteed maintenance at least to the summer of 2000.

1.2. What is space weather?

Space weather is a relatively new concept and as such its content and meaning are still under development. Quite generally it is understood as the time-variable conditions in space environment that may damage space-borne or ground-based technological systems and, in the worst case, endanger human health or life. While this definition is quite negative, the physical phenomena relevant for space weather are extremely interesting and under active basic research, and also include positive effects such as the beautiful auroral displays in the polar regions. The most important social and economical aspects of space weather aim at avoiding the consequences of space weather events either by system design or by efficient warning and prediction systems allowing for preventive measures to be taken.

The ultimate source of most space weather phenomena is the Sun and a control of space weather effects requires thorough understanding of Solar-Terrestrial Physics (STP), the physics of the intercoupled plasma environments of the solar wind, the magnetosphere, the ionosphere, and the atmosphere. Although closely linked, the distinction between space weather and STP is the more practical flavour of space weather research. Thus, if needed, a distinction between these concepts can be made: Basic research in the field of STP is necessary to deal with space weather, whereas space weather research is an application-oriented discipline stimulating research of various problems in STP. This distinction has been implicitly assumed in the preparation of this Technical Note, although we do not claim that it would be fully adapted by all parties in the space weather field. However, any space weather activity must ultimately address the needs of the applications community, e.g., engineers and operators. Identification of user needs is paramount but, as yet, one of the most unclear parts of the activity.

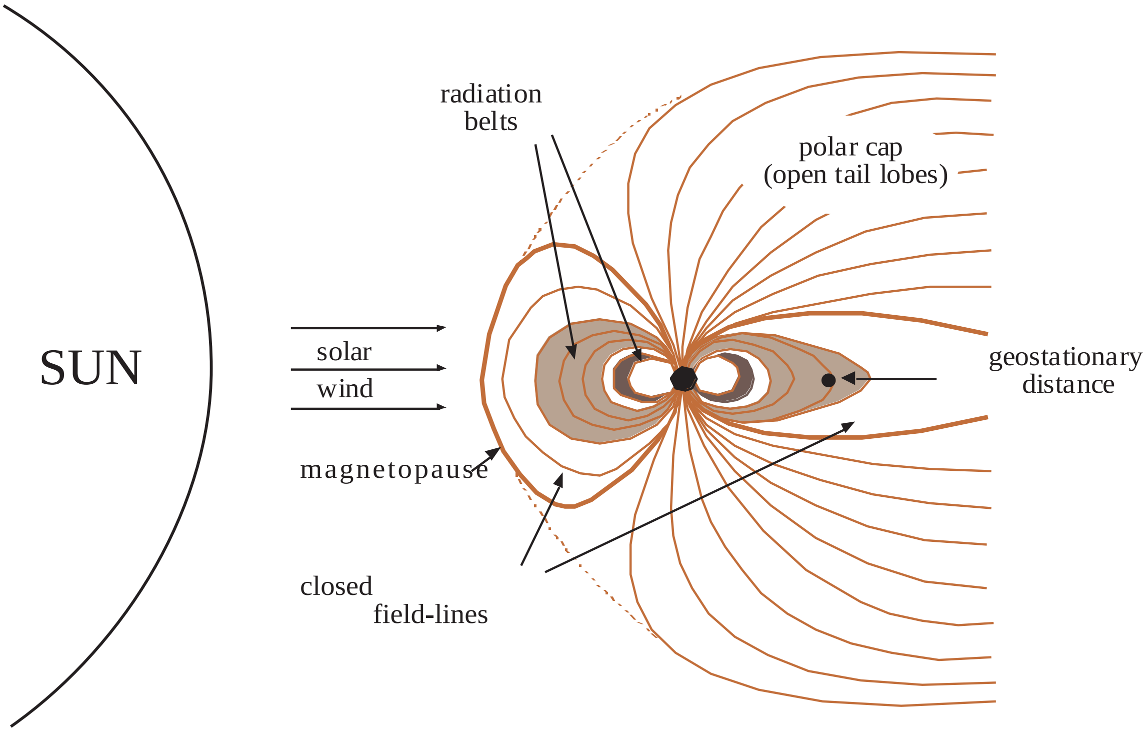

Figure 1.1. Main physical domains of space weather

1.3. What are space weather activities?

Space weather has many similarities with atmospheric weather; thus the design of future space weather activities will, to a large extent, utilise the experience from meteorological services. This is already now a fact at the only operational space weather centres, the Space Environment Center (SEC) of NOAA, and the 50th Space Weather Squadron of the US Air Force, both in Colorado, USA.

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

1) 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. This arises from the large spatial scale-sizes of the solar-terrestrial plasma systems and the long correlation times of these plasmas. The most important and most dramatic effects originating from the Sun disturb the Earth's plasma environment, the magnetosphere, which responds to these disturbances globally.
2) 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 may remain for much longer periods. The fastest signal in the global magnetospheric system is associated to the so-called Storm Sudden Commencement (SSC): ground-based magnetometers react immediately to a significant change in the magnetopause current system when a strong solar wind disturbance hits the magnetosphere. At the slowest end the enhanced fluxes of energetic particles in the radiation belts decay in time scales of days, months, or even years.
3) Our means to monitor the 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 measurement points in the upstream solar wind conditions and magnetospheric parameters. These aspects are discussed in more detail below in the section dealing with the physics requirements for space weather modelling. As a consequence of these properties, successful space weather activities are performed on a global scale, merging space-borne and ground-based observational capabilities.

There is no doubt that at present the US is further ahead in space weather activities than other countries: They have the largest number of spacecraft, their scientific STP community is the largest, and they already have some operational space weather activities. This is demonstrated by the documentation of the National Space Weather Program (NSWP), which is a result of an initiative from the American space science community in 1993. The Strategic Plan of the NSWP was published in 1995 and the Implementation Plan in 1997. While the programme is not directly suitable for European needs, the latter document provides useful reference material and has been extensively used in the preparation of this Technical Note.

The European activities and capabilities for an extended European approach are analysed below. At present, while Europe has a strong scientific community in the field of STP, there are only few attempts toward space weather, and the resources are scattered to relatively small groups in different countries. Furthermore, Europe is not as independent in space-borne facilities as the US is. The US STP community has also always maintained synergies with the applications community. Space physicists often act as consultants on space environment issues for aerospace companies and military organisations (Boeing, Lockheed, Aerospace, McDonnell-Douglas, Naval Research Laboratory, Air Force laboratories, Los Alamos National Laboratories, NOAA, NASA Science groups, etc.). This kind of ties are much weaker in Europe. These facts are important to keep in mind when discussing the future European space weather activities.

As space weather is a global phenomenon, it is not clear that Europe should aim at full autonomy in this field. Actually, although the US NSWP has a strong national flavour, there is a general understanding that the programme must be widened to become international. This was discussed much during the 1997 General Assembly of IAGA in Uppsala. Because the meeting was a scientific one, the discussions were dominated by the scientific and modelling viewpoints. On the other hand, most of the present space weather activities are driven by the scientific community and the awareness of the users is only beginning to emerge. When the user awareness increases and more space weather tools and products are developed, the needs to safeguard national (or e.g., ESA) technological assets and commercial interests extends the space weather modelling activities beyond the scientific interests. This is one reason why ESA should have a clear space weather policy to support and guide the European space weather activities in their integration to the international space weather community.

On the truly international level there actually already exists an organisation that covers most of the world, The International Space Environment Service (ISES).
(see: http://www.sel.bldrdoc.gov/ises/ises.html)
ISES is a joint service of URSI, IAU and IUGG and a permanent service of the Federation of Astronomical and Geophysical Data Services (FAGS). At present, there are ten Regional Warning Centres (RWC) scattered around the globe. These centres are located in Beijing (China), Boulder (USA), Moscow (Russia), Paris (France), New Delhi (India), Ottawa (Canada), Prague (Czech Republic), Tokyo (Japan), Sydney (Australia), and Warsaw (Poland). A data exchange schedule operates with each centre providing and relaying data to the other centres. The centre in Boulder plays a special role as "World Warning Agency", acting as a hub for data exchange and forecasts. For

some reason the awareness of ISES among the present day space weather activists has remained smaller than expected, regardless of the fact that ISES has organised well-attended Solar Prediction Workshops, the latest one in Japan 1996.

It is worth noting that some RWCs are directly run by organisations having their own industrial interest in space weather, e.g., USA and Japan, whereas the only RWC in an ESA member state is run by an academic organisation. Nevertheless, the European ISES centre in Paris is most active in space-based applications, in particular providing services for spacecraft orbits, altimetry, as well as launch and re-entry calculations (see: http://previ.obsm.fr/previ/).

1.4. What is space weather modelling?

This Technical Note deals mainly with questions around space weather modelling. Improved modelling is crucial both for engineering solutions to avoid space weather damage and for all types of forecasting: Whether analysing space environment conditions that led to a space weather event or making a forecast, we need models which can use the relatively sparse observations as input and produce a reliable global map of charged particles and electromagnetic fields in the geospace region of interest.

A "grand unified" model encompassing the Sun, the solar wind, the magnetosphere, the ionosphere, and the atmosphere, is probably beyond our horizons. However, for all these regions we already now have a large number of different models, the most advanced of which also address the coupling between adjacent domains.

Longer-term (more than ~1 hour) forecasting requires good models for the solar activity. Forecasts extending to 1–2 days utilise models of generation and propagation of solar flares and coronal mass ejections, their propagation through the interplanetary medium, and their interaction with the magnetosphere. The solar wind-magnetosphere interaction is one of the key issues in the magnetospheric dynamics and simultaneously one of the most difficult problems in STP. In order to protect technological systems against space weather events, warning systems and models of trapped radiation during enhanced magnetospheric activity are needed. Theoretical and/or empirical models are needed in advance for spacecraft design and mission planning, whereas operational purposes require models running in real time utilising real-time data input. Modelling of the electromagnetic coupling to the auroral ionosphere is needed for avoiding communication problems and for warning of the induced current effects on the ground systems. Coupling to the neutral atmosphere is an important issue, as enhanced energetic particle precipitation during solar activity heats the atmosphere, leading to order of magnitude increase of atmospheric drag which may cause problems for low-altitude satellites or for the re-entry of manned spacecraft. Furthermore, recent studies have shown that the energetic particles precipitating in the Earth's upper atmosphere may change the atmospheric chemistry and thus influence the ozone content shielding the Earth's surface from UV radiation. Many of these effects are also functions of the long-term variability in the Sun, the 11-year (or actually 22-year) solar cycle, thus belonging both to the realm of space climatology and space weather.

In order to assess the risk to either space-borne or ground-based technologies, we need models for the effects of ground-induced current loops in power grids or gas pipe lines, models for determining how the spacecraft electronics are harmed by energetic particles, and models for assessing how the spacecraft charging affects the satellite subsystems. All these models are important tools for both the technical design and operational use.

As discussed below, there are separate models for these and many other space weather purposes. In many cases they have been developed from purely scientific motivation and will require considerable effort to be made operational. Other models have been developed for specific space environment problems for engineering use. The natural goal, a more integrated effort of combining various models, has to be approached in a stepwise manner, as all partial models still require development and many of them are and will remain incompatible with each other.

1.5 What is a space weather product?

A way of categorising space weather can be based on the warning time allowed for users to react to the possible hazard.

Space weather **forecasts**, like their atmospheric weather counterpart, cover a variety of time scales and accuracies. The long-range solar cycle forecasts are based on models of solar activity, but lack accuracy in timing of actual events. Shorter term forecasts may cover a period from several hours to a few days, and are based on solar and solar wind observations, in-situ magnetospheric data, and modelling.

Warnings are needed for events that have the potential to harm satellites, equipment, and humans in near-Earth space environment and on the ground. The warnings are based on solar observations and modelling techniques for prediction of geomagnetic activity, and are given less than 24 hours in advance, often only minutes in advance.

Nowcasts are based on in-situ real-time data assimilation techniques and models capable of running in real time. They provide global information about the state of the magnetosphere based on a measurements in different regions of space.

Post-event analysis is used to assess the possible factors that may have caused operational anomalies. Post-event analysis utilises all available information of a given event to gain an accurate understanding of the sequence of events. This is valuable both for assessing damage and for future improvements of spacecraft design.

In a questionnaire discussed in section 7.1. below one of the questions concerned the concept of space weather product. It was somewhat surprising to find out that most respondents understood the models, more than their output, as products. This may partly display the fact that most active in this field today are those who themselves develop models, often more for scientific than operational use. This attitude may change when more real end-users become more involved in the dialogue. A model is the product of a model developer but the customer paying for space weather services wants products of the models categorised above.

1.6. Who are the users?

The identification of users of space weather products or space weather modelling is one of the most critical issues for the development of space weather activities. This is partly related to the fact that until useful products become available, there will be no well-defined market for them. Most likely the awareness of the potential users will develop in parallel with the developing space weather services. Both sides of the development, i.e., products and the market, gain if the space weather community gives a high priority to education and public outreach. Also in this field the US space weather community is far ahead Europe. NOAA/SEC organises frequent user conferences where their needs and the development of scientific models to applications are discussed.

The needs of the various users, actual or potential, are very variable, and, for the time being, rather poorly specified. Perhaps the most clear end-users of present space weather products are spacecraft engineers and spacecraft operators. The spacecraft development is based on accumulated knowledge of space environment and its effects. It is important that both non-critical and, especially, hazardous satellite anomalies are carefully analysed using the best available modelling tools. Spacecraft operators need information to avoid critical manoeuvres during critical conditions. Spacecraft launches are avoided during bad space weather conditions and the re-entry of Space Shuttle depends on the atmospheric drag conditions.

Other users are telecommunication operators, users of the global positioning system (GPS), electric power industry, etc. Commercial airlines must be careful not only with the radiation doses for their crew and passengers but also consider the potential radiation damages to the increasingly miniaturised electronic components. Often the end-user is just interested in receiving useful information from a space weather service provider. There is, however, a large group of users who wish to get pre-processed data for further modelling work. For example, a spacecraft engineer may want to analyse a spacecraft failure by varying the input parameters around the state of the radiation belts specified by a space weather centre. Also the scientific community sees themselves often as users because efficient data dissemination and modelling services are useful for them in one of the most tedious steps of scientific analysis, namely rapid access to data, model results, and coordinated observations using different observatories.

With all hazards the insurance questions are important. With society's increasing dependence of space technology the insurance industry is becoming an increasingly important customer of space weather services. Due to the very high unit price of spacecraft the correct risk analysis is important for the insurance companies as well as their customers.

Another contributing factor is that the space weather models are of very variable size and level of sophistication, and will remain so. The most extensive physics-based models will always be run in supercomputers, and the most advanced models will follow the most advanced computer evolution. On the other hand, there is a great number of simpler models which can be used locally by the users themselves. Examples of these are various artificial intelligence systems, such as neural networks or non-linear filters. These models can be run by the users given that suitable interfaces and input data bases are developed.

2. Impact of space weather effects on technological systems in space and on the ground

Space weather effects change the Earth's plasma environment on time scales varying from minutes to days and weeks. Dynamic magnetospheric processes may enhance the existing energetic particle populations to levels which are hazardous to the electronics onboard Earth-orbiting satellites. Solar activity and particle acceleration through cosmic processes create very energetic ions that can enter through the magnetospheric shield, again posing a hazard to both humans and technological systems in space.

Space weather effects are by no means limited to space-borne systems. The strong currents in the auroral region induce large Geomagnetically Induced Currents (GIC) in the long power lines. The increased and irregular plasma density in the ionosphere disturbs high-frequency (HF) and very-high-frequency (VHF) communications, the future satellite telephone communications, and satellite-based positioning systems (e.g., GPS). Furthermore, increased radiation doses on electronics and human beings on high-altitude air-flights, especially over polar regions can reach harmful levels.

2.1. Examples of hazardous space weather events

2.1.1. Historical examples

The first space weather events reported to harm technological systems took place around 1850 when electric telegraph communications were disturbed and in some cases completely stopped during strong auroral activations (Prescott, 1860). For a long time the telegraph and later the telephone communications were the most susceptible technological systems for space weather problems. The first reported effect on power systems took place on March 24, 1940 (Davidson, 1940). A great geomagnetic storm caused voltage dips, large swings in reactive power, and tripping of transformer banks in the US and Canada. During the same event 80% of all long-distance telephone connections out of Minneapolis, Minnesota, were out of operation.

A widely-known event took place on March 13, 1989, when a severe geomagnetic storm caused the failure of a complete electric distribution system in Quebec, Canada. Several million people lost their electric power for up to 9 hours and the estimated peak power lost exceeded 20 GW. The effect spread throughout the network very rapidly, from the first signs of problems to the system collapse in about 90 seconds. At the same time HF communications were blocked world-wide, whereas VHF signals propagated unusually far creating interference problems. A Japanese communication satellite lost half of its redundant communication circuitry, a NASA satellite dropped about 5 km in altitude due to increased atmospheric drag, and several other satellites experienced various types of upsets.

2.1.2. Recent satellite failures

As a consequence of a high-speed solar wind stream impacting the Earth's magnetosphere on January 20, 1994, at 1735 UT, the Anik E-1 spacecraft at geostationary orbit suffered an operational anomaly causing a loss of attitude control. Telesat Canada operators were able to finally switch to the backup momentum wheel controller and resume reasonably normal operations. The Anik E-2 satellite also experienced failure of its momentum wheel control circuitry at 0210 UT the following day. Anik E-2's backup circuitry was found to be non-functional, and therefore normal operational control of the spacecraft was lost. TV, radio, telephone, and scientific operations within the American continent were affected for hours to days by these spacecraft anomalies: The news, weather, and entertainment programming were affected, daily newspapers' information gathering systems were inoperative, and telephone services were interrupted in Canada (Baker, 1996).

During an extended (about two weeks) period of greatly enhanced electron fluxes present in the outer trapping region, the same Anik E-1 communication satellite suffered a severe operational problem on 26 March 1996. The satellite lost all power from its south solar panel array when the array was effectively disconnected from the satellite payload at 2047 UT. The 50% power loss reduced the spacecraft's capacity significantly. The lost communication capability affected a broad range of video, voice, and data services throughout North America. Service to Telesat Canada customers was restored after about six hours by link switches to other spacecraft and by using backup systems such as fibre optics ground links. During the same period, several other spacecraft operators also reported problems. Direct measurements showed that the operational anomalies were due to deep dielectric charging caused by elevated fluxes of very high-energy electrons (Baker et al., 1996).

A coronal mass ejection emerging from the Sun formed a magnetic cloud, which impacted the Earth on January 10, 1997. On early morning of January 11, 1997, AT&T lost contact with its Telstar 401 satellite. Telstar 401, one of the two Skynet satellites, was fully functioning before the incident. The other, Telstar 402R, took re-routed network signals right away following 401's difficulties. Satellites like the Telstars transpond TV programmes, telephone calls, and computer data. The magnetic cloud caused an exceptionally strong enhancement of relativistic electron fluxes in the Earth's magnetosphere detected both by geostationary and low-altitude polar-orbiting satellites. These electrons remained within the radiation belts for over a week after the incident. Evidence suggests that the increased levels in the radiation environment were connected

to the malfunction of the AT&T Telstar satellite although it has remained unclear what the immediate cause of the failure was.
(see http://www-istp.gsfc.nasa.gov/istp/cloud_jan97/event.html)

2.1.3. Other effects on spacecraft

Interference and other hazards (SEUs, problems with start tracking, etc.) are much more common than the most publicised examples discussed above. Examples of space weather related problems on European satellites include radiometer stops of Meteosat, SEUs on most satellites (ISO, Hipparcos, ERS, SOHO, etc.), ISO experienced problems in its star tracker, and so on. Exact information on anomalies is difficult to get. The commercial companies consider this information confidential and within international organisations (such as ESA) there is no systematic investigation of anomalies by space environmental experts. However, when available, various effects have been traced directly to space weather events. As a part of this ESTEC contract, extensive anomaly databases from two operational spacecraft Meteosat-3 and Tele-X were used to study the problem of determining empirical anomaly indices (Andersson et al., 1998a, 1998b; Wu et al., 1998). Another useful reference is Wrenn and Smith (1996) which includes a table of reported anomalies due to electrostatic discharges (ESD) from 47 spacecraft.

2.2. What causes these effects?

The exposure of Earth-orbiting satellites to the hot plasma and energetic particle populations is the major environmental cause for anomalies in spacecraft systems and operations. In the inner part of the magnetosphere these effects are primarily due to the stably trapped radiation belt particles. In the outer magnetosphere the major contributor are intense but transient phenomena: high energy ions from the Sun, galactic cosmic rays, very high energy electrons (1–10 MeV) accelerated within the magnetosphere, and energetic ions and electrons (tens to hundreds of keV) produced by magnetospheric substorms.

2.2.1. Trapped radiation belt particles

The quasi-dipolar magnetic field of the Earth is capable of confining and trapping large fluxes of energetic electrons and ions, which bounce back and forth between magnetic mirror points in northern and southern hemisphere and drift around the Earth. As negative charges drift eastward, and positive westward, this motion produces a westward current encircling the Earth. In the dipolar region, particles can be stably trapped for extended periods, even years, as was demonstrated in connection with atmospheric nuclear tests. The inner Van Allen radiation belt consists mainly of energetic protons, whereas the outer belt hosts mostly energetic electrons. While the inner belt is rather stable, the outer belt can be quite variable both in intensity and radial extent. The energetic (tens of keV to many MeV) electron and ion populations, at variable intensity levels, are always present in the near-Earth space environment.

2.2.2. Magnetospheric substorms

Magnetospheric substorms are large-scale dynamic events in the magnetosphere, which lead to injections of energetic (tens to hundreds of keV) electrons and ions into the inner magnetosphere as well as to a global reconfiguration of the magnetospheric magnetic field. Substorms are well correlated with the orientation of the interplanetary magnetic field: they are known to occur after a period of southward interplanetary magnetic field (IMF) when part of the solar wind energy has been loaded into the magnetosphere. Under average conditions there are several isolated substorm events per day. The energetic particle populations created during substorms obviously constitute a quasi-continuous hazard for the spacecraft. Furthermore, substorms are associated with strong ionospheric currents at auroral latitudes, which in turn can cause problems at the high-latitude power lines and communication systems.

2.2.3. Coronal mass ejections and geomagnetic storms

Large, non-recurrent geomagnetic storms develop as a consequence of aperiodic solar disturbances, such as coronal mass ejections (CME). These are large expulsions of material from the Sun, usually associated with solar prominences and flares. Fast CMEs can be thought of as large plasma blobs moving rapidly outward from the Sun. The rapid motion through the ambient solar wind leads to a forward shock wave in front of the CME. The interplanetary magnetic field is draped over the CME, which creates a strong northward or southward magnetic fields ahead of the CME. A strong southward IMF, combined with the high velocity of the structure, constitute an efficient driver for magnetospheric activity.

Major geomagnetic storms cause strong distortion of the geomagnetic field as well as hours or days of hot plasma enhancements in the outer trapping region. These injected particles strongly enhance the ring current encircling the Earth. The ring current intensity can be monitored by ground-based magnetometers at low-latitudes: The Dst index composed of data from several stations around the world is an approximate measure of the total ring current energy content. It has been shown that the ring current decays usually in a time scale of 2–10 hours. Radiation belt particles can also be monitored by low-altitude, polar-orbiting satellites equipped with energetic particle sensors. These have shown that storm-generated populations can last for weeks or even months.

Large interplanetary shock waves driven by CMEs can also have pronounced effects in the inner magnetosphere, causing strong particle acceleration on a time scale of minutes. The compression and relaxation of the Earth's magnetic field caused by the arrival of the shock can lead to strong, highly time-variable electric fields, which can efficiently accelerate electrons in the outer trapping region.

Geomagnetic storms are most frequent before and after solar cycle maxima, and typically occur much more infrequently during quiet solar conditions. In the energetic particles the most significant difference between substorms and storms is that while substorms accelerate electrons mainly up to hundreds of keV, the storm-time acceleration reaches several MeV.

2.2.4. High-speed solar wind streams and recurrent storms

Fast solar wind streams, when they interact with the Earth's magnetosphere, cause acceleration of energetic electrons: The lower-energy (below hundreds of keV) particle fluxes are well-correlated with solar wind velocity variations. These electrons appear as a product of magnetospheric substorm activity driven by the high-speed solar wind.

The highest energy electrons (several MeV) show a strong recurrence tendency at the 27-day rotation period of the Sun. These electrons are produced during geomagnetic storms driven by recurrent high-speed solar wind streams, which occur most often during times when the coronal holes extend to low latitudes during the declining phase of the solar cycle. The acceleration mechanism of the MeV electrons in the magnetosphere is still unknown, the substorm activity may play a role but the acceleration processes are most likely more complicated than the injections at substorm onset (Blake et al., 1997).

2.2.5. Solar particle events

Coronal mass ejections and flares often accelerate particles to very high energies. If a magnetic connection between the disturbance site on the solar surface and the Earth exists, the energetic solar protons travelling at speeds close to the speed of light can enter the near-Earth space within tens of minutes, and the peak flux can reach the Earth in a few hours. These particles constitute the largest risk for missions outside the magnetosphere, e.g., Moon and the planets. These very energetic protons also have an access to the polar cap regions and the outer magnetosphere where the shielding effect of the geomagnetic field is weakest. It is interesting to note that the solar physicists do not agree upon where the main acceleration takes place: at the flare site, on the shock wave ahead a CME, or behind the CME where it loses its magnetic connection to the Sun.

2.2.6. Galactic cosmic rays

The galactic cosmic ray population consists mostly of protons and alpha particles, but it also contains significant levels of heavier ions. A specific component in the galactic radiation is the so-called anomalous cosmic rays which are singly- or doubly-ionised heavy ions picked-up from the interstellar neutral matter by the solar wind. These ions enter the inner solar system after being accelerated at the heliospheric termination shock. The galactic cosmic ray energy spectrum near the Earth peaks in the energy per mass range 1–10 GeV/nucleon but the tail of the distribution contains ions of much higher energies. The integral intensity of galactic cosmic ray particles shows a 5–10% modulation with the solar cycle.

Galactic cosmic rays are shielded from directly reaching the low-altitude magnetosphere by the terrestrial magnetic field, and the Earth's surface by the thick neutral atmosphere. However, the galactic cosmic rays have a direct access to the polar regions through the polar cusp and can be transported from there to high equatorial altitudes in the magnetosphere (e.g., to geostationary orbit).

2.3. Which systems are damaged and how?

2.3.1. Effects of trapped radiation belt particles

The most obvious effect on Earth-orbiting spacecraft is the radiation dose on satellites traversing the trapped radiation belts. The almost stable inner radiation zones have been extensively modelled in the past (e.g., the NASA AE8 and AP8 models although there are well-known shortcomings in these models). The environment obviously is a major contributor to operational problems, but evaluation of the risk is possible. The possibilities of predicting operational anomalies using local and non-local data were investigated as part of the present ESTEC contract (Anderson et al., 1998a, 1998b; Wu et al., 1998). The results of this investigation show that useful satellite anomaly warning indices can be developed.

Although many problems with trapped radiation belt particles could traditionally be accounted for by radiation hardening of the spacecraft components, there is a drive to use advanced components which are more sensitive to radiation effects. The radiation also causes interference in sensors which cannot always be shielded against radiation. In addition, radiation effects to the growing astronaut population have to be very carefully monitored.

Intense long-term exposure to high-energy proton fluxes, particularly in the inner radiation belt, produces crystal-lattice structure damage in solid state devices, which can become completely inoperative after a certain integrated dose. The effects of heavily ionising radiation on electronics have been extensively investigated, and models for the damage as a function of fluence are available.

2.3.2. Effects of magnetospheric substorms

Spacecraft charging occurs as a result of the trend to reach current balance between the spacecraft surface and the ambient plasma medium. Both positive and negative charging occurrences are possible. Positive charging occurs mainly when the spacecraft is immersed in tenuous sunlit plasma and the incident particle flux is balanced by the current of photoelectrons. During magnetospheric substorms the plasma density around a geostationary satellite may drop by several orders of magnitude. The energetic electrons can then drive surface potential negatively to several kV, especially in eclipse or shadowed insulated surface. Negative charging can also become a problem when the spacecraft is immersed within an auroral electron beam, which cannot be compensated by photoelectrons. This is a problem especially in eclipse. The risk for this effect is also strongly enhanced during substorm activity when the electron beams are strongest and most frequent. This kind of charging events were studied as a part of this ESA Contract (Wahlund et al., 1998a, 1998b; Eriksson et al., 1998).

Differential charging of spacecraft surfaces can lead to arcing, which in turn introduce noise into the system. This noise can interrupt normal spacecraft operations or represent false commands, or the discharge can change the thermal properties, conductivity, optical parameters, or chemical properties of the materials. In addition, the material released from the discharge location is a source of spacecraft contamination.

Magnetospheric substorms and storms create significant fluxes of field-aligned energetic (tens of keV) particles (mainly electrons), which precipitate into the auroral regions encircling the magnetic poles. At the same time the ionospheric currents in the auroral region enhance and may exhibit strong temporal variations. Transformers in the high-voltage electric transmission lines can be saturated by the current induced by the changes in the local magnetic field caused by ionospheric currents. The saturation can lead to overloading, overheating, or false relay tripping in the transformers, or disturbances in the reactive power balance of the transmission lines. This is a risk mostly in Fenno-Scandia and Canada, but the effects can reach lower latitudes during strong disturbances. Also the increasingly complicated interconnectivity of the power distribution systems increases the risk of propagation of the effects in the network.

Pipelines carrying natural gas are also affected by the changing geomagnetic conditions, as currents induced between the pipe and earth cause corrosion. To protect the pipes, they are kept at a potential lower than that of the surrounding earth in order to prevent current flow from the pipe to earth.

2.3.3. Effects of non-recurrent and recurrent geomagnetic storms

The strong driving of the solar wind during storms can cause the magnetospheric boundary to move inside the geostationary orbit. In such cases geostationary satellites on the dayside lose the shielding the magnetosphere provides against solar wind particles. Furthermore, storms include series of repetitive and often intense substorms, posing similar hazards as discussed in the previous subsection.

The very high energy electrons created by storms and especially by the interactions with the high-speed solar wind streams can cause deep dielectric charging of internal spacecraft components. In this process, the high energy electrons bury themselves in dielectric materials (such as coaxial cables), giving rise to high electric fields (potential differences of several kilovolts) in their vicinity until an intense breakdown occurs.

The high energy (>1 MeV) electron population in the radiation belts intensified by the storm and high-speed stream-associated activity constitute a primary integrated dose problem for operation of spacecraft within the inner magnetosphere. They also interfere with sensors, e.g, as flashes in glass and impacts on detectors.

2.3.4. Effects of solar particle events

Solar energetic particle events (SEPE) may have important effects on passengers, crew, and electronics onboard polar-crossing aircraft and manned spacecraft. Furthermore, the planned orbit of the International Space Station is such that it will be influenced by solar proton events. The damaging aspects of solar energetic particles on spacecraft comes from fluence effects. Energetic protons and other ions (tens to hundreds of MeV) are highly penetrating, and one large event can be as damaging as years of operation in the normal near-Earth environment. Particularly vulnerable are systems and human beings outside the magnetosphere, e.g., on interplanetary flights or on the future Moon base. An astronaut has less than 20 min to seek cover after an event is observed on the surface of the Sun.

Solar protons can also penetrate directly into spacecraft sensor systems. The energy deposition by the protons may cause malfunction in the instruments at times when the fluxes are sufficiently high. A variety of proton-induced disruptions have been directly traced to solar energetic particles.

2.3.5. Effects of galactic cosmic rays

Ground-based systems at polar latitudes and low-altitude polar-orbiting spacecraft can be strongly affected by galactic cosmic rays. Humans in polar-transiting airplanes or on long-duration spaceflights can be subjected to strong galactic cosmic ray influence. The most hazardous part of the cosmic rays is the highly ionising and relatively abundant Fe nuclei. These heavy ions can cause severe tissue damage in humans and major single event upsets in space electronics.

Single event upsets occur in microelectronics when an individual charged particle, usually a heavy ion, deposits enough charge at a sensitive portion of the circuit to cause the circuit to change state, e.g., when the particle passes through a depletion region of a transistor in a flip-flop circuit. Even protons can cause the same effect in the circuit by causing a nuclear reaction in or very close to the sensitive region. In very sensitive electronics, a proton can cause a single event upset directly.

Single event upsets can be also caused by protons and heavy ions from solar particle events or in trapped radiation belts. Upsets caused by neutrons have often been observed in aircraft. These neutrons are secondary products of cosmic rays impacting the atmosphere.

2.3.6. Summary of damaged systems

Effects on spacecraft components:
- Spacecraft charging
- Deep dielectric charging
- Anomalies
- Gradual degradation
- Electronic and sensor upsets
- Sensor interference

Effects on spacecraft orbits
- Altitude decrease due to increased atmospheric drag
- Problems in attitude control systems

Effects on communications
- GPS disturbances
- Satellite - ground communications
- Radio communications on the ground

Effects on humans
- Effects on manned space flight
- Effects on air flight

Effects on ground-based systems
- Effects on electric power systems
- Effects on natural gas pipelines

2.3.7. Outlook for effects

The future society will increasingly rely on space systems. Various positioning needs are already now fulfilled using GPS and these applications are continuously expanding. The same happens with communications. Today's geostationary communication systems will be completed by low-altitude polar telecommunications spacecraft networks of which the Iridium of the Motorola company is right now being deployed with several new S/C every month. Even larger new type of telecommunications services, based on hundreds of S/C, will be deployed to take care of wide-band multimedia applications (e.g., Celestri of Motorola and Teledesic of Microsoft). Polar orbiting or high-inclination geosynchronous satellites cross the low-altitude ends of the radiation belts and auroral regions several times every day and thus encounter hazardous conditions more regularly than geostationary S/C.

In the field of commercial air traffic only the crew and passengers were until recently considered to be threatened by radiation damages. This, of course, remains a concern, e.g., the airline companies have to take into account the new EU directive concerning radiation doses to workers. In addition, the development toward smaller electronic devices increases the risks as consequence of single event upsets. These effects become even more serious if the long-haul flights move to higher altitudes.

With the building of the International Space Station the human presence in space will grow. The orbit of the space station will routinely cross high fluxes of radiation belt particles. Space weather events are particularly serious during extravehicular activity (EVA). In planning of EVAs the space weather forecasts are needed and there must be effective systems to rapidly warn the astronauts of unexpected SEPEs. The precautions for SEPEs are of course critical for any long-duration activities outside the magnetosphere, be they during a trip to Mars or while working outside a future lunar base.

3. Current space weather modelling capabilities

Space weather has its origin in the variable activity of the Sun. The consequences of the solar activity propagate from the solar surface, through the interplanetary medium to the Earth orbit, interacting with the magnetosphere, the ionosphere, and the upper atmosphere. There are hundreds, if not thousands, of models to address important aspects of the various parts of this chain. Most of these models are developed for purely scientific purposes, and often it has been more important to study and illustrate the fundamental physical processes than to attempt to reproduce the processes with such a detail accuracy as is necessary in operative space weather applications. It is both impossible and not very useful to consider all models in detail here. Instead we pay the main emphasis to those which are deemed to be closest to be useful to cope quantitatively with the problems discussed in Section 2.

3.1. Models for solar activity

The solar activity is the driver of space weather. Thus it is important to be able to predict the violent eruptions such as coronal mass ejections (CME) and solar flares, as well as solar energetic particle events (SEPE). In the longer, climatological, time scales the modelling of the 11-year sunspot cycle (or 22-year magnetic cycle) is of considerable interest, but we do not discuss this aspect further.

From the modelling point of view CMEs, flares, and SEPEs are closely related to each other because the acceleration of energetic protons to several tens of MeV is associated with CMEs and/or X-ray flares, although the details are not yet fully understood. From the forecasting and warning viewpoint these phenomena are different due to the very different time scales in which they reach the Earth orbit. For example, a 50-MeV proton can move along the magnetic flux tube from the Sun to 1 AU in 25 min whereas the plasma and magnetic clouds of a CME reach the Earth in 3-4 days. Thus a warning time for SEPEs from a flare observation is very short and there is a need to predict the events that can produce SEPEs. The direct effects of CMEs are mostly due to their strong perturbation of the magnetosphere and there is ample time to take protective measures once a CME heading toward the Earth is observed. A major problem here is that we cannot yet reliably predict whether an observed CME will hit the Earth or not, and how geoeffective it will be, until it is observed, e.g., at L1 from where the CME moves to the magnetopause in about 1 hour. From the first effects at the magnetopause it takes some tens of minutes more before the damaging effects have propagated to the various regions of the geospace.

3.1.1. Solar proton models

For interplanetary missions the most important long-term hazard is posed by the accumulative effect, the fluence, of SEPEs. At present the most widely used statistical model of solar proton fluence is the JPL-91 model (Feynman et al, 1993). It predicts, on a probabilistic basis, fluences at integral energies of 1, 4, 10, 30, and 60 MeV, for mission lengths of 1 to 7 years. The selection of the confidence level is a critical issue. If one wants to have high, say 90%, confidence that the dose will not exceed a given level, the model gives for a 5-year mission about 2 order of higher fluence than if only 50% confidence level is required (cf. Gabriel et al., 1996). Improvement of SEPE statistical model is undergoing in a frame of an ESTEC TRP contract, SEDAT. (http://www.wdc.rl.ac.uk/sedat/)

In order to be able to predict individual SEPEs the generation of CMEs and X-ray flares and the associated particle acceleration have to be understood much better than today. So far, there are no first-principle physics-based simulation models which would yield useful predictions (NOAA/SEC regularly evaluates their SEPE and flare forecasts; see section 4.1. below). Work is underway in application of neuro-fuzzy techniques to use long-duration X-ray flares as input and predict the SEPEs one hour in advance (cf. Gabriel et al, 1996). Note further that there are no models to describe the duration of SEPEs which is another parameter of interests of spacecraft engineering.

3.1.2. Modelling of CMEs and flares

A CME carries some 10^{12}–10^{13} kg mass away from the Sun. Nevertheless, they were basically unknown (unobserved) until early 1970s. Before that it was commonly held that the most geoeffective form of the solar activity were the flares. Even after the observations it took quite a long time before the wide STP community, beyond those actively involved in the CME research, fully realised the importance of the CMEs. A landmark paper was Gosling (1993). Presently SOHO is producing unprecedented data of CMEs, examples of which are easily available on WWW:
http://sohowww.nascom.nasa.gov

Physics-based models of CMEs are still in their infancy. A recommendable and up-to-date collection of papers is the AGU Geophysical Monograph; 99 "Coronal Mass Ejections" (1997). The book provides an extensive review of the current observational, theoretical, and modelling status of CMEs. Present-day models are directed toward the understanding of the production of CMEs in general terms and have not yet been transformed toward space weather applications. However, strong efforts toward this goal are underway. Linker and Mikic (1997) discussed the possibilities of accurate MHD modelling of the corona to 1 AU and demonstrated their ability to determine the current sheet crossings of Ulysses during its first perihelion pass from the south to the north. (Note that the perihelion of Ulysses is beyond 1 AU!) Furthermore, there is a clear and increasing awareness of the importance of the goal toward application oriented CME models (e.g., NSWP Implementation Plan; Luhmann, 1997).

Although our understanding of CMEs is still behind our knowledge of the magnetosphere, the situation from the forecasting and warning point of view is not hopeless. Actually, the implementation plan of the NSWP gives the least pessimistic view on this field. It is, in fact, possible to make meaningful forecasts and warnings of CME-driven effects in geospace without understanding the actual origin of CMEs. For all practical purposes it will be sufficient to detect an approaching CME after it has left the Sun and base the predictions on that information. This is still quite difficult because only a few CMEs hit the Earth and only about 1 of 6 CMEs hitting the Earth produce major geomagnetic storms (e.g., Gosling, 1997).

It is more than obvious that the SOHO mission already has turned a new page in this part of space weather modelling and forecasting (for first SOHO results, see Solar Physics, vol 175, part 2, 1997). The January 1997 CME was the first major event heading toward the Earth predicted on basis of SOHO observations. The warning was neglected, e.g., by NOAA/SEC. Now SEC continuously checks SOHO quick-look data as a part of their forecasting activity. There have also been false alarms from SOHO. As noted above, only some CMEs hitting the Earth have sufficient momentum and favourable geoeffective magnetic field orientation to lead to major storms. At this preliminary stage false alarms have to be accepted but on the long run too many false alarms will turn against the development of space weather warnings.

With SOHO European scientists have an opportunity to undertake leading activities in the modelling of the origins of space weather. The present activities could and should be enhanced. An important improvement for a SOHO-like observatory would be to carry at least a simple plasma and magnetic field monitoring package to probe the local IMF and plasma conditions. This is one of the positive return of a space weather programme to foster interaction between solar and mangetospheric physics communities.

3.2. Models for solar wind properties

Modelling of the solar corona and the solar wind are closely tied to each other. A key issue is the shape of the interplanetary current sheet and the magnetic spiral which determine whether or not an energetic particle burst from the surface of the Sun can propagate along the magnetic flux tube to a given location, e.g., to the surface of the Moon where a future astronaut may be outside the protection of the lunar base. Another important issue is the shape of the solar wind current sheet and the location of sector boundaries. So far these have usually been modelled by the source surface models (e.g., Wang and Sheeley, 1992) but the discussion by Linker and Mikic (1997) indicates that MHD models are soon to become the standard.

There is also a need for more detailed solar wind models closer to the Earth. In many ways the optimum solar wind monitoring point is L1 which is 1.5 million km from the Earth. The advantages of this point are its stability and about 1-hour warning time. Disadvantages are the problems of deducing the three-dimensional structure of the local solar wind from single-point observations. Interplanetary shock fronts may have very variable orientation and the local direction of the magnetic flux tube may be quite different from the average. These make the modelling from L1 to the Earth a formidable task (e.g., Ridley et al., 1998). For the model development it would be highly desirable to have more spacecraft closer to the Earth, e.g., on a 30-40 R_E orbit. The IMP-8 satellite has made, since its launch in 1973, an exceptional service exceeding all expectations, but it is bound to cease functioning some time quite soon. For space weather it is most unfortunate that the STP community has not been able to persuade any space organisation to take the responsibility for continuous near-Earth solar wind monitoring. Because exact information of upstream conditions will be needed also in future scientific studies, the continuation of IMP-8-type observations is essential for science as well as for space weather applications.

Modelling of solar wind propagation from L1 to the terrestrial magnetopause requires more fine-tuned approach than is possible for the modelling of the entire corona. Most of the present flow models involving the planetary bow shock are based on the magnetogasdynamic model by Spreiter and Stahara (1980). This approach is applicable for Mars and Venus as well as for the Earth. With detailed enough input it gives sufficient description for the flow up to the magnetopause. However, dealing with the magnetopause and the transfer of solar wind plasma and magnetic field requires a more extensive approach with massive solar-wind magnetosphere interaction models discussed in the next section.

3.3. Models for solar wind - magnetosphere interaction

Different magnetospheric domains are coupled to each other and models describing some specific region are not independent of physics of the surrounding regions. We organise the discussion of these domains so that this section deals with empirical models describing the magnetopause and the magnetospheric magnetic field and the large-scale MHD approach to magnetospheric dynamics. Section 3.4. discusses models whose goal is to model the inner magnetosphere including radiation belts and geostationary orbit.

3.3.1. Empirical models for magnetospheric configuration

The boundary separating the shocked solar wind plasma in the magnetosheath and the region dominated by the terrestrial magnetosphere is the magnetopause. Its subsolar point it is typically at the distance of 10 R_E whereas in the nightside tail the boundary is identifiable at distances of several hundred R_E. During exceptionally strong solar wind dynamic pressure the dayside magnetopause may become compressed inside geostationary orbit (6.6 R_E) as happened during the January 1997 CME event. There are several empirical models for the bow shock and magnetopause, including other planets (e.g., Slavin and Holzer, 1981). A recent well-documented model based on fresh data is that of Shue et al. (1997). The model has a simple functional form and two adjustable parameters, the stand-off distance in the solar direction and the tail flaring. It has been applied, e.g, to the above mentioned CME event of January 1997. See: http://www-istp.gsfc.nasa.gov/istp/cloud_jan97/event.html.

In recent years, several empirical magnetic field models for the magnetospheric field have been developed, which are based on both magnetospheric magnetic field measurements and mathematical modelling of the extra-terrestrial current systems (e.g, Tsyganenko, 1990; 1995; Hilmer and Voigt, 1995). The external fields are superposed to a description of the geomagnetic field, which is usually described by the regularly updated IGRF model. These purely statistical models utilise the vast database of magnetic field values accumulated over the years, parametrised by indices describing the level of geomagnetic activity (Kp, Dst, AE). Time-evolving models developed for post-event analysis utilise, in addition, the field measurements taken at the time of the event to adjust the statistical model to best describe the actual field configuration (Pulkkinen et al., 1992).

Statistical models are already widely used both by the scientific and by the space weather communities. For example, they form the basis of the MSFM (see section 3.4.1 below). The models are continuously updated to account for more complex processes in the magnetosphere, for example, the most recent version of the Tsyganenko models (Tsyganenko, 1997) can model the configuration changes during magnetospheric substorms. However, as the magnetospheric dynamics depends on both the solar wind conditions and the previous history of the magnetosphere and these models use only the present values as input, they are not very reliable predictors of the magnetospheric state.

The time-evolving event-oriented models utilise all available information of a particular event to determine the large-scale magnetospheric configuration. The input for these models are various indicators of the magnetospheric state, such as the auroral boundary, or the measured magnetic field values. Through an iterative process, a best-fit configuration is arrived at. The models have been developed and used in scientific problems, but can be developed to produce real-time global maps if implemented together with real-time magnetospheric observations.

3.3.2. Three-dimensional MHD simulations

Fully three-dimensional magnetohydrodynamic models, which include the solar wind, the magnetosphere, and the ionosphere, have been developed for scientific use by a number of groups. These models involve heavy numerical computing requiring supercomputer capabilities including parallel processing if real-time running is needed. Probably the best known of the models, that are also closest to implementation for operational use, although not necessarily scientifically or numerically the most advanced ones, are those developed at the University of Maryland (see Mobarry et al., 1996) and at the University of California at Los Angeles (there is no published record of the model itself, for a recent application, see Raeder et al., 1997). At UCLA there is also another MHD model (see Walker et al., 1993), but Raeder's model is the one which people usually refer to in space weather context. In Europe there is an advanced model at the Finnish Meteorological Institute (Janhunen, 1996) but it is currently developed for scientific use only. Furthermore, the group at CETP, France, is doing fundamental research on MHD simulations. In summary, the field is in a state of continuous evolution and the state of art is not easy to assess. Several groups are developing their models further and they do not publish the details of their models too early, if at all.

Global MHD models accept solar wind density, velocity, and interplanetary magnetic field as input parameters. From these time series, they predict the dynamic response of the magnetosphere-ionosphere system. The inner boundary of the magnetosphere is typically set to somewhat above 3 R_E, and physical quantities are mapped along field lines to a two-dimensional ionospheric surface. The details of how the ionosphere is included vary from one model to another.

These models replicate the global response of the magnetosphere to increased solar wind energy input deduced from observations: energy loading followed by an explosive energy release into magnetospheric particle energy, into the ionosphere, and out from the magnetosphere in the form of a plasmoid. However, the timing of these events is critically dependent on various model parameters, e.g., diffusion, which are not uniquely determined from the underlying physics.

The problems related with the MHD simulations are mostly concerned with the inner magnetosphere and the thin current sheets. The model boundary at 3.5 R_E and the inherently non-MHD processes dominant in the inner magnetosphere prohibit the proper description of the plasmasphere, the ring current region, and the radiation belts. Note, however, that the numerical inaccuracies are, in most cases, still more severe than those introduced by the MHD approximations. It is not always appreciated that the

MHD equations are structurally much more complicated than the corresponding Euler equations of neutral gas. Furthermore, the coupling with the ionosphere is as yet poorly understood, and only crudely modelled in the simulation codes. Thin current layers, on the other hand, require dense grid spacing. The increase of grid points in 3D simulations costs both memory and computing time. E.g., increasing the resolution by a factor of 10 in all directions requires that the time stepping is also made 10 times more frequent. In total this means a factor of 10000, which is a difference between 1 s and 3 h in computing time. It is possible to define a different grid spacing in different parts of the magnetosphere, putting the best resolution where it is mostly needed (e.g., Janhunen, 1996). This adaptation should also be made dynamic, e.g., to follow the moving magnetopause or tail current sheet but the efficiency of this method has not yet been thoroughly tested in a supercomputer environment. However, this will soon be used in most advanced models (P. Janhunen, private communication, 1998).

The UCLA group has recently run a test case of an isolated substorm event (February 9, 1995). Solar wind and IMF data from WIND were used as input and the simulation results were compared with data from GEOTAIL, which was located around 35 R_E in the anti-sunward direction from the Earth. Results from the simulation compared well with the GEOTAIL observations (plasma sheet thinning and recovery, fast tailward and earthward flows, and plasmoid signatures), but the expansion phase onset occurred too early in the simulation. Examination of the effects of different ionospheric conductance distributions and the effect of different models of anomalous resistivity on tail evolution confirmed that both ionospheric conductance and the parametrisation of microscale processes in the tail current sheet affect the substorm development in the model (see http://omicron.igpp.ucla.edu/sps/nightside.html).

Comparisons between the University of Maryland and UCLA MHD code performance are in progress: recently a comparison was made of simulations run for a case study (October 9, 1984), which involved multiple magnetopause crossings by AMPTE/CCE and AMPTE/IRM spacecraft within a one-hour period. The results showed only qualitative agreement (see http://omicron.igpp.ucla.edu/sps/compare.html). From a scientific point of view, the point-by-point comparisons between simulation and data or between two different simulations, may lead to pessimistic conclusions because the initial conditions are not quite complete. For post-event analysis these problems may be possible to overcome iteratively, but for forecasting the exactness of the simulations is a critical issue.

3.4. Models for the inner magnetosphere

Models describing particle fluxes in the inner magnetosphere, say inside 10 R_E, are for understandable reasons of particular interest to spacecraft engineers and operators. Because the global MHD simulations described in the previous section are computationally too heavy for computation of the electric and magnetic fields needed to calculate the energetic particle trajectories, these models take another approach. The underlying fields are determined using statistical magnetic and electric fields and the particle orbits are calculated from these. The evaluation of complete particle distributions are still numerically demanding and problems arise particularly during exceptional conditions when the fields deviate from the statistical models. At the same time, these exceptional conditions are often the most important from space weather viewpoint.

3.4.1. Magnetospheric Specification and Forecast Model (MSFM)

Of the large-scale physical models, the MSFM is probably closest to being an operational space weather model. It is an update of a series of earlier models capable of following particle drifts through the inner magnetosphere in model electric and magnetic fields. It is being developed for operational use by the US Air Force. Its predecessor, the MSM (Magnetospheric Specification Model), has been installed also at NOAA/SEC and is used in daily space weather services. The most up-to-date easily available document of MSFM is the WWW-document by Freeman et al. (1995). A recent example of its use in scientific analysis is Lambour et al. (1997).

The MSFM is designed to specify fluxes of electrons in the energy range responsible for spacecraft charging, ~100 eV to ~100 keV, and also H^+ and O^+ fluxes in the same energy range. The model output gives electron and ion fluxes in the inner and middle magnetosphere, fluxes of electrons precipitating into the ionosphere, ionospheric electric fields, and magnetic-field mapping information. As a secondary parameter it furthermore gives daily average of more than 2-MeV electrons, based on an empirical extrapolation of the electron spectra (cf. Freeman and O’Brien, 1998).

The major advancement of the MSFM over the earlier models is the complexity of the electric and magnetic field models and its capability to run in real time. The primary input parameters for the model are the Kp-index, the Dst-index, the polar cap potential drop, the auroral boundary index, the solar wind density and speed, which define the magnetopause stand-off distance, and the IMF, which is used to select the appropriate convection pattern in the polar cap. These parameters determine the used magnetic and electric field models. Secondary input parameters include precipitating particle flux and polar cap potential profile from the operational DMSP satellites and the sum of Kp, which is an indicator of the longer-term activity level. The model can operate with reduced sets of input parameters, particularly, it can be run using Kp alone. The MSFM also includes neural network algorithms that predict the input parameters empirically from solar-wind measurements, which gives the code some capability for short-term space weather forecasting.

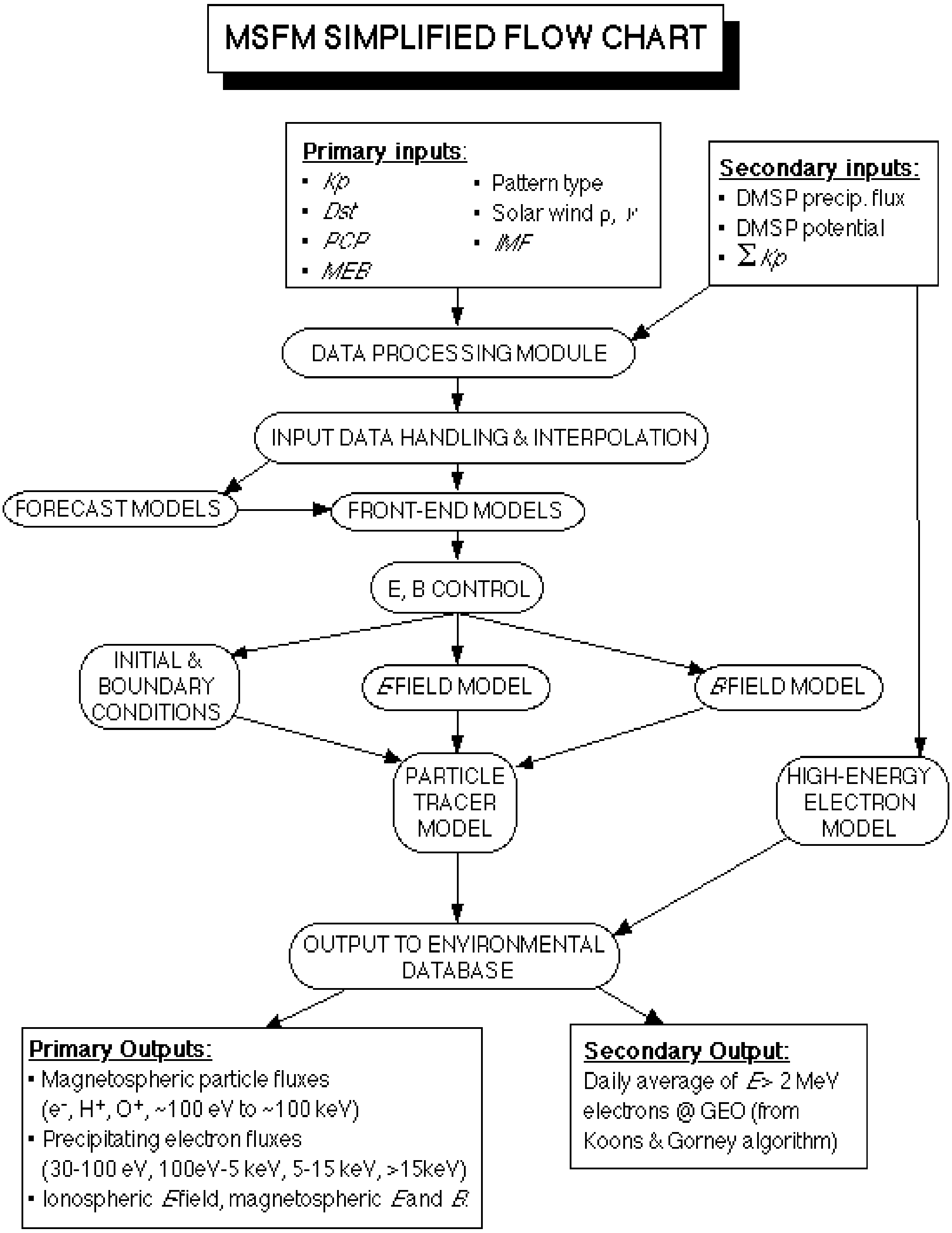

Figure 3.1. Flow chart of MSFM

The MSFM follows particle drifts through the magnetosphere using slowly time-varying electric and magnetic field models while keeping track of energetic particle loss by charge exchange and electron precipitation into the ionosphere. The magnetic field model is based on the model by Hilmer and Voigt (1995). The field values for various conditions are tabulated and the field configuration is updated every 15 minutes. The magnetospheric electric field is determined by specifying the electrostatic potential in the ionosphere (see Heppner and Maynard, 1987; Rich and Maynard, 1989) and mapping this field along magnetic field lines into the magnetosphere. The electric field is also updated every 15 minutes. The model assumes an isotropic particle distribution, which is maintained by pitch-angle scattering mechanisms that do not change particle energy. Data-based algorithms are used to specify the initial particle fluxes and the fluxes at the model boundaries. A simplified flow-chart of the model is given in Figure 3.1.

Extensive tests have shown that the MSFM successfully represents most major electron flux enhancements observed at geosynchronous orbit. Flux dropouts, often preceding the flux enhancements, are predicted with less confidence, especially the dropouts near dawn meridian are often missed.

3.4.2. Salammbô

In Europe there is no effort comparable to MSFM. Many elements of it have been used in scientific analysis also by European scientists, such as the Heppner-Maynard convection models. Instead of Hilmer-Voigt magnetic field model, European scientists seem to favour the empirical models developed by N. A. Tsyganenko (section 3.3.1.). However, the way from a specific scientific study to a model which has potential of being general enough for description of inner magnetospheric particles is quite long.

We comment here one important European model, Salammbô being developed at CERT-ONERA in France (Bourdarie et al., 1996, 1997). The model solves the diffusion and convection equations in the inner magnetosphere assuming a dipole magnetic field and simple convection and corotation electric fields (Volland, 1973). The most recent model (Bourdarie et al., 1997) allows for an eccentric dipole and thus has three spatial dimensions, and energy as the fourth dimension. The model computes the particle fluxes from convection-diffusion equations.

The Salammbô model has some attractive features: (1) It calculates the particles from realistic diffusion equations, including the most important diffusion mechanisms: wave-particle and neutral atmosphere interactions. Because the model equations are physics-based, it is straightforward to include the diffusion coefficients according to the best available physics understanding. (2) The model is well-documented in open scientific literature, which makes it easier to assess than, e.g., MSFM. (3) The model has different level of versions (3D, 4D); in some engineering applications the magnetic local time dimension may not be needed and the model can be run much faster.

More problematic from the operational viewpoint is that in order to produce realistic results the model requires input from several other models in addition to the background electric and magnetic fields, especially, the correct description of the upper ionosphere and atmosphere is essential. Furthermore, the outer boundary conditions as well as more complex background fields require further investigation. However, it would be interesting to do a point-by-point comparison of the respective pros and cons between MSFM and Salammbô. The two models apply to different energy ranges, making Salammbô better suited to radiation effects (10 keV – MeVs) and MSFM to electrostatic effects (100 eV–100 keV). Salammbô could be the starting point for a European inner magnetosphere model which could be able compete with the MSFM.

3.4.3. Radiation belt models

The details of energisation of the very high-energy radiation belt particles in conjunction with large magnetospheric disturbances are as yet poorly understood. Statistically, it is known that the energetic particles appear as a response to high-speed solar wind streams and CMEs, but the acceleration mechanisms are not yet known. Thus, further work is required before the onset of these particle flux enhancements can be modelled and predicted.

The static NASA radiation belt models (AE8 for electrons, AP8 for protons; see Vette, 1991) which were developed mainly in the 1960s have been extensively used in the past spacecraft design and post-event analysis. These models are public domain and available from the NSSDC. Recent measurements have, however, shown that the radiation belts are extremely dynamic, and vary significantly over relatively short periods of time. In addition, there are important interactions between the inner belt and the atmosphere, leading to slow changes. Therefore, several efforts toward more dynamic radiation belt models and standards are presently underway. In Europe, this effort is lead by the Belgian Institute of Space Aeronomy (BIRA/IASB) in Brussels. To co-ordinate the international efforts, COSPAR has accepted a resolution calling for the creation of a new task group to develop new standards for radiation belt models.

BIRA/IASB has lead a series of ESTEC Contracts on Trapped Radiation Environment Model Development (TREND, TREND-2, see Lemaire et al., 1995, and TREND-3). These studies have utilised the AE8 and AP8 models 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/) 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.

As part of the US Air Force Space Radiation Effects Program, the CRRES satellite examined the inner magnetosphere radiation belts for 14 months in 1990–1991 (Gussenhoven et al., 1996). The models created with the CRRES data are attempts to define the dynamical variations that occurred over the satellite lifetime, and are averages of data over time periods considered appropriate to the variations. All these models are pertinent to the solar maximum conditions. Five different models have been compiled: CRRESRAD calculates expected satellite dose accumulation behind aluminium hemispherical shielding for different thicknesses, orbits, and geomagnetic conditions; CRRESPRO calculates proton omnidirectional fluences; PROSPEC gives proton differential fluxes; CRRESELE provides the outer zone electron omnidirectional fluence; and CHIME calculates the differential energy flux for all stable elements over the energy range relevant for major cosmic ray sources. These empirical models handle time-dependence in a purely statistical way since the processes governing short-term variations are non-adiabatic.

3.5. Ionospheric models

The International Reference Ionosphere (IRI) is an empirical standard model of the ionosphere. It has been produced and updated as an international project sponsored by COSPAR and URSI since the late 1960s. It is based on all available data sources. For given location, time and date, IRI describes electron density, electron temperature, ion temperature, and ion composition in the altitude range from about 50 km to about 2000 km; and also the electron content. It provides monthly averages in the low-latitude

ionosphere for magnetically quiet conditions. The major data sources are the world-wide network of ionosondes, the powerful incoherent scatter radars, the past ISIS and Alouette topside sounders, and in situ instruments on several satellites and rockets. IRI is updated yearly during special IRI Workshops. Several extensions are planned, including models for the ion drift, description of the auroral and polar ionosphere, and consideration of magnetic storm effects. The model is available at NSSDC:
http://nssdc.gsfc.nasa.gov/space/model/ionos/iri.html

Modelling of the dynamics of the auroral region and polar cap ionosphere is a more complicated task. Several models have been developed that use multiple source ground-based and space-based observations of the ionospheric dynamics to produce global maps of the ionospheric parameters.

At present the most widely used statistical model of ionospheric plasma convection, based on Dynamics Explorer 2 observations, is that of Heppner and Maynard (1987). It organises the ionospheric convection as a function of Kp and IMF direction. It is available for collaborative scientific purposes and does not require large computational resources. The Heppner-Maynar convection patterns are used as input in the MSFM.

More detailed models utilising more data systems have been produced for scientific purposes. One of them is the AMIE (Assimilative Magnetosphere Ionosphere Electro-dynamics) model that uses data from ground-based magnetometers, radars, as well as particle and electric field measurements and auroral images from low earth-orbiting satellites (for a recent reference, see, Lu et al. 1996). These data are assimilated to produce maps of the ionospheric potential patterns, global magnetic disturbances, and global conductivity patterns. AMIE is a scientific tool that requires a considerable amount of effort for any single event analysis, both for data collection and experimenting with computations. As such the model appears to be too heavy for operational space weather applications.

Using wide enough ionospheric radar network the ionospheric convection pattern is possible to determine in nearly real-time. Applied Physics Laboratory of the Johns Hopkins University has started providing such convection maps in the WWW:
http://sd-www.jhuapl.edu/RADAR/radar/convection/index.html
The convection patterns are derived from the SuperDARN (Dual Auroral Radar Network) system which at present consists of three pairs of coherent HF radars in the northern hemisphere located at Saskatoon (Canada), Kapuskasing (Canada), Goose Bay (Canada), Stokkseyri (Iceland), Pykkvibaer (Iceland), and Hankasalmi (Finland) and three stations in the southern hemisphere. The method how the convection patterns are calculated is presented in Ruohoniemi and Greenwald (1996). Now the network covers about 120˚ of the northern hemisphere polar region and it is planned to expand further.

This WWW server illustrates the power of real-time data transfer to a centre which has resources to compute useful products.

3.6. Atmospheric models

Atmospheric models have several different roles in space weather modelling: (1) They form an important boundary condition for radiation belt and inner magnetosphere models. (2) The increased atmospheric temperature during space weather disturbances is to be considered during launch and re-entry phase of spaceflight. (3) The long-term effects of space weather and space climatology have long-term consequences in the climate of the Earth.

Several national and international organisations have established committees for the development of atmospheric reference models of which the most widely used and well established model is the COSPAR International Reference Atmosphere (CIRA), an effort that started in 1961 with the publication of CIRA-61. The third generation of this model is CIRA-86. In 1970s in situ measurements of atmospheric parameters by mass spectrometers and ground-based incoherent scatter radar observations of thermospheric temperature were combined to establish the Mass Spectrometer Incoherent Scatter (MSIS) models: MSIS-77, -83, -86. The CIRA and MSIS groups joined forces in 1986 and MSIS-86 became the upper part of CIRA-86. The MSISE model describes the neutral temperature and densities in the Earth's atmosphere from ground to thermospheric heights. MSISE-90 is essentially a revised MSIS-86 model taking into account data derived from space shuttle flights and more recent incoherent scatter results. Also these models are available at NSSDC through WWW:
http://nssdc.gsfc.nasa.gov/space/model/atmos/

The atmospheric drag on spacecraft depends both on particle precipitation during magnetospheric storm activity but also on the solar cycle dependent UV ionisation. The average neutral density at 400 km increases by about 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 (for discussion, see Hastings and Garrett, 1996).

The energetic particle precipitation during magnetospheric storms and substorms has consequences to the atmospheric physics and chemistry. The particle-induced ionisation leads to dissociation of the tightly bound N_2 molecules and to the formation of the reactive nitrogen compounds NO and NO_2. These compounds are transported downward from the region they were formed especially during the polar night when photodissociation of NO is weak. In the lower mesosphere and upper stratosphere, the particle-produced NO participates in a catalytic cycle leading to destruction of ozone.

This effect belongs more to the realm of climatology than weather and we do not discuss it further in this context.

3.7. Predictions based on non-linear and AI methods

There are a large number of models that are designed to predict some well-defined parameters of the solar-terrestrial system based on various mathematical methods such as non-linear ARMA (auto-regressive moving average, e.g., Vassiliadis et al., 1995) models or neural networks. Two well-studied examples are the auroral electrojet indices (AL or AE) and the storm-time index Dst which is an approximate measure of the strength of the ring current.

These models do not involve first-principle equations governing the solar-terrestrial physics but are based on relations between the observed parameters, which of course displays the underlying physics. This way of predicting can sometimes catch otherwise hidden physical properties of the system and be very efficient from the application point of view (cf. articles in AI Applications in Solar-Terrestrial Physics, ESA WPP-148, 1998). The great advantage of the non-linear filtering and neural network models is that they are fast to compute and for short prediction periods they are today still more accurate than a derivation of the same parameters from the massive simulation models, e.g., non-linear ARMA models driven by solar wind input can forecast the AL index. As described by Vassiliadis et al. (1995) the AL index can be predicted from the solar wind input very accurately afterwards for up to several hours. Here the term "prediction" is sometimes misinterpreted as advance prediction, whereas it really means the ability to reproduce the index from a given initial value and continuous solar wind input for several hours. For this prediction of the AL-index from the WIND spacecraft data or from a single-point polar cap index and see the WWW-page:
http://lepgst.gsfc.nasa.gov/people/vassiliadis/htmls/alprediction.html

There are, however, strong limitations for long-term in advance prediction. For example, the AE index starts to respond to the changes in the solar wind within about half an hour. Takalo et al. (1994) showed that there is an inherent time-scale in the AE index of about 2 hours after which the self-affinity properties of the index change. This change is related to the autocorrelation time of AE. This may be interpreted so that the index loses its memory in about two hours and there is not much hope to forecast AE further than 2 hours from any external input without actually simulating the physics of the currents giving rise to the index.

Because the Dst index describes a physical system whose temporal variation is slower, its autocorrelation time is also longer allowing for longer prediction times. Using neural network techniques Wu and Lundstedt (1997) have successfully predicted the Dst index some 3-5 hours ahead from solar wind data. However, when the forecasting time exceeds 1-2 hours the method cannot any more reproduce the initial phase of a magnetic storm because it appears soon after the shock hitting the magnetosphere, however the main phase, i.e., the main negative excursion of the Dst index can be forecasted reasonably well up to several hours in advance. Thus if real-time input solar wind and IMF data are readily available, techniques for reliable forecasting of magnetic storms already exist.

3.8. Transforming research models to operational products

Except for certain statistical models (e.g., JPL-91, AE8, AP8) the models discussed above have been designed primarily for scientific purposes. This implies that in many cases the models have features that are not desirable for operational space weather products, e.g.

- the model may require unreasonable computing resources (time, power)
- only few specialists may be able to run the model and/or interpret its output
- the codes may be poorly documented (if at all)
- only basic equations are published but not the details, e.g., how to avoid numerical problems
- needed input data are only rarely available or require long time to collect
- the model may emphasise general physical features at the expense of detail accuracy
- an operational model must be able to run using what input is available whereas scientific modelling is often based on choosing “best events”, based, e.g., on particularly favourable satellite configuration and/or exceptionally interesting case.

Some of the models now in process of becoming operational space weather models are developed under classified contracts, e.g., the MSFM which is being developed for the U.S. Air Force. Their basic principles have been published but the details are not generally available. Every physics-based numerical model contains complicated procedures to deal with numerical problems or to improve computing efficiency which have required considerable amount of work by the modellers. This makes the conversion of these models to user-friendly tools quite difficult.

Before it is possible to estimate how much effort a development of a good modelling tool (see Mälkki et al., 1998) would require several questions are to be answered. For example

- Should the model be able to propagate the state of the system or just assimilate certain amount of data to produce a static pattern?
- What will be the requirements for computing resources and modelling speed?

- Does the model require best possible optimisation?
- How complicated boundary conditions are to be used (e.g., radiation belt-atmosphere interaction)?
- Must the model be portable (perhaps even to massively parallel environment, e.g., in the case of MHD-models)?
- Is high-level real-time visualisation required?

According to modelling specialists it is relatively easy to write even a very complicated model, e.g., a global 3D MHD simulation. The problems arise when the model has to be made efficient, stable and reliable. For example, in development of MHD codes, most effort goes to finding efficient and stable solutions for numerical problems, administrating variable grid sizes, using variable time steps, etc. The easiest way of solving many such problems would be to make the grid finer, but as noted above, decreasing the grid spacing in 3D by a factor of ten, requires 10 times more time steps as well, resulting in 10000 times increased demand for computing, i.e., difference between 1 s and 3 h.

Not all space weather research models are suitable for transformation to operational use. Before the effort is started the candidate models must be carefully studied addressing not only their scientific merits but also such features that may affect their use in practice. For example, will the required input data be available and can the model be coded in an effective way? The Rapid Prototyping Center of NOAA/SEC is an attempt to solve these questions. Whatever the future European approach to space weather modelling will be, continuous model evaluation activity should be a part of it. This would not only save time from unnecessary attempts to take bad models into use but also increase the expertise among those who will be responsible for the work.

The problem of responsbility to do the conversion of research models to operational was addressed at one of the NOAA/SEC user meetings in January 1997. A representative from the US Air Force had a clear opinion that the scientists should NOT do it but the task should be given to computer professionals. The same opinion was stressed by one of the respondents to our questionnaire discussed in section 7.1. below. On the other hand, it has been claimed by representatives of groups developing MHD codes that the task is too difficult to be given to anybody else than that small number of modelling specialists. We do not want to make any clear suggestion here but this is an important question to remember when discussing the implementation of future European space weather activities.

4. User aspects of space weather modelling

The problems of user definition were already discussed in section 1.6. Here we discuss quality and user interface.

4.1. Quality

Probably the most important item that has to be improved in space weather forecasting is the quality of the products. At present there are no generally accepted standards (metrics) for the quality control of the warnings and forecasts, and it is quite difficult to define them given the present level of physical understanding. In the Implementation Plan of the US NSWP an analysis of current capabilities vs. requirements was presented (Table 4.1.)

	Warning	Nowcast	Forecast	Post-analysis
Solar/Interplanetary	fair/poor	fair/poor	fair/poor	fair
Magnetosphere	poor	fair/poor	poor	fair/poor
Ionosphere	poor	fair/poor	poor	fair
Neutral Atmosphere	poor	fair/poor	poor	fair/poor

Table 4.1. Current capabilities for various levels of space weather service according to the US NSWP. The grading scale is poor, fair, good.

The analysis is based on requirements formulated by the US Air Force and the pessimistic result of the analysis may partly be due to specific military requirements, or to the need to stress the urgency of increased resources for the model development and related basic research. However, before a telecommunication operator will decide to switch-off a transmission through the satellite based on a warning, the warning must be very reliable, indeed. Lower reliability can be accepted for decisions to avoid difficult manoeuvres during predicted hazardous conditions.

NOAA/SEC monitors the level of their next-day forecasts for M and X flares, solar proton events, 10.7 cm radio flux, a local (Fredericksburg) A-index, and the planetary Ap index (see, http://www.sel.noaa.gov/forecast_verification/). A useful quality parameter is the so-called skill as a comparison of the actual forecast with respect to a given reference method of the events: If the skill is positive, the forecast is better than the reference estimate, if it is negative the forecast is worse. During last few years the skill of the above mentioned predictions, as compared to climatology, has varied from a quarter to another, but not infrequently most of the parameters show negative skill (e.g., July-September 1997). It is an obvious requirement that one-day forecasts based on actual observations should do better than climatological statistics.

Another interesting statistical result provided by NOAA/SEC is the success of pseudo Ap storm forecasts, defined by the Ap level higher than 30, over the Solar Cycle 22 (July 1986-March 1997). Out of 432 Ap storms only 164 were correctly forecasted and there were 234 false alarms.

For up-to-date information of NOAA forecast evaluation see the WWW home page of SEC.

4.2. User interface

The interface requirements depend on the needs of the different users. A spacecraft operator, whose primary task is to protect the satellite by making, sometimes rapidly, decisions on, e.g., whether some orbit manoeuvring should be avoided, or some critical systems be temporarily switched off due to severe space weather conditions, needs a simple real-time output, perhaps with some means of cross-checking the information. In such a case the information is expected to be on-line at a workstation at the operation centre. For spacecraft engineers and those involved in post-analysis of space weather events the interface requirements are quite different and, again, variable. They usually need products which must, most likely, be specifically designed for the each particular user.

Certain aspects of user requirements for a modelling tool were separately analysed as a part of the present ESTEC Contract (Mälkki et al., 1998)

5. Physics Requirements

Space weather modelling and forecasting cannot be better than our ability to understand the underlying physics. To some extent the modern artificial intelligence (or pattern recognition) methods such as neural networks seem to make miracles. However, that is not quite so. That a neural network produces a correct prediction for the Dst index a few hours in advance is just an expression of the empirical fact that the solar wind drives the magnetospheric activity. The mathematical tool is much more efficient to rigorously identify and categorise details in the solar wind driver and to correlate them with the magnetospheric output than a human being but there is no miracle here. However, limits in forecasting due to the underlying physical system still apply. The analysis by Takalo et al. (1994) indicates that the limit for the AE index from any direct solar wind driver would be about 2 hours. For the Dst index the possible advance prediction time is somewhat longer, but does not extend to days.

5.1. Limits of the AI approach

The non-linear filtering methods and neural networks can still be refined to a much higher level of sophistication than today, especially in the field of specification. A recent overview of the various applications of artificial intelligence in the field of space weather can be found in AI Applications in Solar-Terrestrial Physics, ESA WPP-148, 1998 (proceedings of the Lund AI conference, 1997).

Forecasting AE or Dst alone is not sufficient for many practical space weather applications but the predicted indices may be very useful input to dynamical models. For example, Dst is an input parameter to the MSFM. Calculation of the actual Dst requires magnetometer data and finite time. Thus it is useful to get a reliably predicted Dst in advance to speed up the actual dynamic modelling.

One of the important aspects of the studies of the global magnetospheric dynamics based on the structural properties of the activity indices has been the possibility that the magnetosphere is a low-dimensional chaotic system. Whether it really is such, is still an issue of open debate. If it is, the system is sensitive for small errors in initial data which is not good for long-term prediction but at the same time the low-dimensionality means that the system can be described by a relatively small number of free parameters which is good for development of physically meaningful models that may in future lead to reduced dynamical model execution times.

5.2. Limits of dynamical modelling

All plasma physics-based models of the solar-terrestrial system are approximations to the actual physical environment. Space weather taking place in (nearly) collisionless plasma systems is fundamentally different from the ordinary weather in collision-dominated Maxwellian gases. Both systems have their physical challenges, but they are for a large part different. In dilute non-collisional plasma the dominating interaction is determined by the long-range but weak Coulomb and Lorentz forces. It is impossible to make global modelling based on this level of description and we have to go through a long chain of approximations to end up with fluid descriptions like MHD. Even then we arrive at numerical computation schemes where the numerics is still a more severe problem than the hidden approximations behind the dynamical equations. Going beyond the MHD approach is needed at various levels. For example, the present 3D global magnetospheric MHD models include a non-MHD ionosphere in the calculation scheme. The interface to the inner magnetosphere, on the other hand, is as yet an unsolved problem. In the future the diffusion coefficients at magnetospheric boundaries may be computed using more detailed plasma description in those regions.

Models such as MSFM and Salammbô represent a quite different approach to the global modelling with different physics limitations. They are based on various different pieces of physics knowledge of the magnetospheric system. They rely heavily on empirical models of the magnetospheric magnetic field, the polar region electric potential pattern, and interfacing upper atmospheric models. Several critical assumptions are made and the goodness of the models depends on the goodness of these assumptions. For a magnetospheric scientist it is clear that our understanding of the system is not quite sufficient yet but this understanding cannot be required from a operational space weather forecaster.

5.3. Required advances in physics understanding

We lack sufficient physics understanding on two important fronts. There are large voids in our knowledge of critical physics phenomena concerning, e.g., the solar origins of space weather, details of solar-wind magnetosphere interactions, or particle acceleration in the magnetosphere. Our physical models often give satisfactory answers to average and moderately disturbed conditions. In space weather we are typically much more interested in extreme phenomena, in hurricanes instead of weak afternoon showers, to use an atmospheric weather analogue. The second class of difficulties is related to the complexities in mathematical and numerical problems. It would be a mistake just to wait for better and faster computers to solve the problems. They will help but advances are also required in mathematical and numerical aspects of space plasma physics.

Instead of going too deep into the details we list some of the physics requirements essential for improved space weather modelling:

- understanding the release of CMEs and onset of X-ray flares on the surface of the Sun with associated SEPE production
- determination of the solar wind structure within 1 AU from limited data
- extreme solar wind-magnetosphere interaction, especially associated to CMEs
- details of storm development and storm-substorm relationships
- acceleration to high energies in the magnetosphere

These and related problems are challenges to the STP community illustrating the viewpoint that space weather can be a great motivation for continuous efforts in basic research. These are problems that must be attacked by the scientists being aware of the long-term possibilities for applications, but not too constrained by short-term requirements to be able to provide full-tested models immediately.

6. Practical aspects for improvement of space weather modelling

6.1. Testing

Regardless whether we want to improve the physics-based, empirical, or artificial intelligence methods of space weather modelling we encounter several practical problems to be solved. It is not sufficient to look just for more sophisticated physical models or ingenious mathematical and numerical schemes to solve the physical model equations but the models are to be continuously put to rigorous tests against observations. Furthermore, the models need the best possible observational input. For post-analysis and model development it is acceptable that collecting of observational data takes time but for any real-time specification, warning, or forecasting activity the data inflow must be continuous and reliable.

The current ISTP programme period with its great armada of spacecraft extending from L1 to various parts of the magnetosphere is producing an unprecedented complex of data to be used in tests of space weather models, or scientific models that could be developed to space weather applications. The STP community is already doing this work, but more interaction with the S/C engineering and user communities is necessary. There hardly will soon be another period when the total state of the magnetosphere at the time of satellite anomalies can be determined as completely as now.

6.2. Data acquisition and transfer

Data acquisition is one of the areas where the space weather activities are clearly inferior to the atmospheric weather services, and may remain so. The weather centres continuously receive real-time observations of several parameters world-wide, including continuous global satellite coverage. For space weather the input comes from a small number of space-borne and ground-based observatories and only a fraction of all collected data is in such a format that it can be readily fed into the models. The developing methods of detecting energetic neutral atoms (ENA) from the radiation belt region (Williams et al., 1992) may in future provide global images useful for space weather services.

The rapid development of the internet has improved considerably the access to various data sets. More and more groups are making their data products available in this way. For scientific analysis this is one of the most important steps forward, in some sense comparable to the advent of digital computers. For operational space weather needs this positive development may hide the fact that these data sets are not always in well-defined formats, the availability may vary depending on how much resources the principal investigator happens to have available for this service, etc. Operational space weather services need guaranteed and rapid transfer of the key data they use. To improve this is an obvious task to organisations like ESA. Binding commitments between the data provider and the service centre are necessary, as are rapid data transfer procedures.

6.3. Human resources

As is clear from previous sections, the physical system to be mastered in space weather modelling is very complicated and as yet poorly understood. The research in solar-terrestrial physics progresses continuously toward a better understanding and its results are consequently transferable to the space weather modelling applications. Documentation of models and early conversion to practical applications can be made by scientists but the final products must be produced by professional programmers. Thus, in order to improve the space weather modelling at higher pace than the improvements coming as side-products of the basic research, significant investments in the human resources are necessary. These investments must be made both in the field of fundamental STP research and in the space weather service community for practical model development. The present situation where many STP scientists turn their attention to space weather in order to avoid threatening cuts in basic research is not satisfactory. Without a living STP community there is little hope for practical improvements in space weather either.

6.4. Modelling tools

Although many parts of the space weather modelling can be facilitated using modern work stations, it is important to realise that any significant space weather service requires substantial computer resources both for data acquisition and storage, and running the physics-based models. The front-line magnetospheric MHD models require efficient supercomputers, and yet they cannot use ideal grid sizes and time steps for resolving the dynamics to meet the quality requirements of time constraints of forecasting or real time specification. Dedicated space weather centres must have access to state-of-the-art supercomputers; it is quite another question how many such centres are needed world-wide. More than one is a conservative estimate to allow for competition and flexibility.

6.5. Recommendation

Whatever the near-future European approach to space weather will be it should address the needs for

- testing and verification of models
- improvements in data acquisition, archiving, and transfer
- task division and stronger between the scientists and application model developers
- coordination of information gathering of space weather effects and efficient use of this knowledge
- computer resources

7. Where to go?

7.1. Assessment of specific European capabilities for space weather activities

To collect information about European space weather capabilities and opinions of some leading experts in the field, a questionnaire was sent on October 13, 1997, as an electronic mail distribution to selected 23 persons in various ESA countries and Canada. Nine replies were received. This process was not meant to be a representative opinion poll but merely a collection of ideas about what space weather is and what the European approach to this matter could be. The number of 9 answers may seem a weak response but considering that the persons asked have several other important duties, 40% is actually not a bad number at all. However, we can envision a selection of 9 others to whom the questionnaire was sent and who would respond in a quite different way.

In the following we summarise the answers after each question. Of verbal comments we have selected the most significant and those which we find helpful for the further progress.

Question 1
We have found that the opinions on the concept of Space Weather are strongly variable. Which one of the following do you agree most?

a) Most of Solar-Terrestrial Physics (STP) is Space Weather. Space Weather is a unifying concept for the field and main part of the STP research should be formulated in terms of Space Weather;

b) There is, or should be, a clear distinction between STP and Space Weather. STP is basic research, the results of which may be converted to Space Weather products and services. Space Weather is an application-oriented activity which can stimulate and challenge STP but should not direct the STP research;

c) Space Weather is an opportunistic catchword which has little practical promise and may be detrimental for fundamental space research.

8 clear votes for b)
None voted for a)
One unclear answer, interpreted as b)

Important comments:

- Developments in space weather monitoring and prediction capability MUST be driven by the USERS not the producers.
- Spacecraft constructors want solutions not a ten year research programme.
- Whilst STP provides essential input into space weather, the space weather problem is probably too complicated to be simulated physically. Numerical techniques appear to be a useful way to attack the problem but do not aid STP research directly.

- Scientists are bound to do basic research. The conversion into Space Weather products has to be done by others, i.e. those who are paid for this particular job which is NOT a scientific one.
- The reality is that individuals and groups will make of 'Space Weather' whatever best suits their needs.

Question 2
Have you or your group/institute been involved in any project with specific space weather applications? If yes, please describe briefly. Could you list any other European projects with space weather applications?

This was answered very unevenly.

Specific answers:

- Predicting atmospheric drag on the EURECA and the ERS series of satellites.
- Geomagnetic field monitoring for directional drilling industry in the North Sea.
- Studying the effects of geomagnetic storms on the power distribution network in the British Isles.
- MSSL:

  Applied space plasma physics since 1978 funded by a number of sources on such topics as surface charging, deep dielectric charging, METEOSAT anomalies, charging simulations for space station, radiation belt dynamics and modelling, diagnostic instruments for ion thrusters.
- There have been several other groups working in the same general area, such as NDRE Norway, AEA Culham, DERA Farnborough, DERTS Toulouse, IASB Belgium.
- TREND and SPENVIS projects supported by ESTEC.
- IRF-Lund:

  a) prediction of satellite anomalies

  b) prediction of space weather effects on electrical power systems

  c) prediction of space weather effects on natural gas pipelines

  d) prediction of space weather effects on Aircraft Avionics
- DERA's Command and Information Systems sector has been investigating the possibility of developing non-linear models of geophysical parameters. The technique chosen for model development has been Radial Basis Function Neural Networks. The ionospheric F2 layer critical frequency and geostationary electron radiation fluxes have been the main parameters modelled. The work has involved DERA staff in Farnborough and Malvern and a collaboration with the Department of Mathematics, UMIST, Manchester.
- STRV-1 carried experiments which were relevant to some aspects of space weather - mainly energetic electron and internal charging effects. DERA are also working on a project addressing non-linear analysis of solar-geophysical disturbances. X-ray images from Yohkoh have been used to monitor the coronal hole sources of energetic electrons.
- LASCO on SOHO detects a lot of CMEs, some of them heading at the Earth. The NOAA SEC now regularly checks SOHO quick-look data.

Question 3:
How would you comment on the present European capabilities in the field of Space Weather?

a) Strengths

All comments point essentially to the same conclusions which can be summarised as:

There is a strong scientific community in Europe which is among the world leaders in the relevant disciplines, e.g. solar physics, interplanetary physics, magnetospheric physics etc. Solar and auroral observations started early in Europe. Many important discoveries in solar-terrestrial physics have been made in Europe.

b) Weaknesses

The weaknesses were identified in a more variable way:

- No measurements of high energy particles like GOES, LANL or GPS, no X Ray detectors or imagers on board long-life programs.
- No clear structure on which to base co-operation. There are too many organisations with their own "empires" to defend. There is not a clear understanding of the user requirements.
- Quantitative numerical models seem to be inferior to the US efforts.
- The Space Weather hype has attracted many others who see it as a means to support a research programme in STP, not as an activity for providing answers to specific questions.
- The small number of European scientist who are deeply committed in Space weather studies; and who believe it is important. The efforts are fragmented and lacking focus. There is a gulf between engineering and science.
- Lack of systematic data gathering. No central programme guiding space weather research. Weaker pressure from clients than in the US.

Question 4.
What do you understand by a Space Weather product?

The answers to this were somewhat surprising. Product was rather generally understood as a model, not its output. Partially this reflects the background of the people who responded. However, this further stresses the importance to identify the potential users and convert them to real users.

Selected answers:

- Nowcasting (to interpolate and/or know the environment, especially for satellites) and forecasting, to publish warnings at least for astronautics and Extra Vehicular Activities.
- A space weather product is a product which enables the operators of technology which may be affected by space weather to understand how their system may be affected and how they may manage their system to minimise the effects of space weather. Note that the user does not need to be an expert in STP, and the space weather product providers do not need to be expert in the affected technology, although it helps if there is some overlap in knowledge.
- A tool that can be used for prediction of geophysical parameters based on a combination of (a few) basic input parameters.
- Empirical and [physical] models of all kinds, about all kinds of measurable/physical parameters of the magnetosphere, solar wind and Sun.

- A product that uses information about the space weather to avoid an effect. It could be a trained neural chip which tells the satellite to make a correction.
- A product must predict the state of a useful geophysical parameter with acceptable accuracy, giving sufficient time for appropriate action to be taken.
- One respondent described his only and ultimate Space Weather product as a computer code

  – which at any moment delivers an updated prediction of geomagnetic conditions on various time scales,

  – which is based on continually updated observations of the sun (photospheric magnetic field, active regions, filaments, prominences, CMEs etc.),

  – which must extrapolate the shape and location of the heliospheric current sheet, high speed streams, propagation of shocks and magnetic clouds etc.,

  – which must predict the Bz behaviour at the magnetopause,

  – which must take into account the status of the magnetosphere as it has evolved up to any moment, in terms of "loading", previous substorms etc.,

  – must finally predict geomagnetic conditions as desired by the "customers".

  This code must be permanently updated whenever new data come in and must also take into account its own history and should be able to "learn" from previous experience.

Question 5.
We have identified two main approaches to Space Weather modelling. Do you have an opinion about their importance in future?

a) Space Weather modelling is needed to find engineering solutions to the problems caused by Space Weather phenomena, i.e., the goal is to build space-weather-proof technological systems;

b) In the long term the goal should be in reliable real-time monitoring, forecasting, and warning systems.

Most replies pointed out that both are needed. Blind modelling will not find engineering solutions, but modelling is still necessary. Nowcasting and specification are needed for analysis of problems that have been encountered. Warning may be more important than real forecasting.

Question 6,
Today's Space Weather activities are clearly dominated by the US space community, especially by the Solar-Terrestrial Environment Center (SEC) at NOAA, Boulder. What degree of autonomy should Europe aim at?

The replies extend from a full autonomy to a comment that there is no such thing like autonomy for Europe. Most answers favour close co-operation with the US efforts although some disappointment with the strong US centred flavour of NSWP was voiced.

Question 7.
The following list contains some possible European approaches to Space Weather activity. Which of them do you think would be the most useful or feasible (they are, of course, not mutually exclusive, so please rate them from 10 (highest) to 0, if possible)?

Very uneven distribution of answers (below). Perhaps the only significant conclusion is that there is rather limited support for a full-scale European forecasting and warning centre. A European unit for consultation as well as a European data centre were rather positively assessed. There was also a comment that several European centres were the appropriate route to go but, on the other hand, it was asked why duplicate SEC? Europe should instead ensure that it co-operates as well as possible with SEC.

a) Co-ordination of fundamental STP research keeping Space Weather applications in mind;
5, 3, 10, 0, 2, 7, 2, 10, 10 Sum: 49 3x10, 1x0

b) Establishment of a European data centre (centralised or distributed), including a useful model and/or tool library (e.g, type of NGDC, SEE.MSFC.NASA);
3, 4, 3, 10, 7, 3, 10, 3, 7 Sum: 50 2x10

c) Establishment of a European unit acting as consultants on space weather systems and applications;
3, 9, 3, 5, 9, 10, 8, 8, 2 Sum: 57 1x10

d) Establishment of a full-scale European forecasting and warning centre;
10, 4, 3, 0, 6, 4, 2, 8, 0 Sum: 37 1x10, 2x0

e) Establishment of an interagency co-ordinating activity;
8, 8, 5, 0, 1, 6, 10, 3, 8 Sum: 49 1x10, 1x0

f) Other, please specify.

Establishment of a European Space Weather Idea Group (9)

Greater provision of data, on a routine basis, for space weather activities e.g. by routinely flying radiation and plasma monitors. Such data will be needed on a near real-time basis for predictions to be useful.

Question 8.
If a long-term Space Weather activity would be initiated in Europe (taking into account that current activities are spread over small teams each studying only a small part of the geospace dynamics) where do you think most of the effort should be put?

a) Numerical simulation of global geospace dynamics;
b) Empirical modelling of global geospace dynamics;
c) In-flight experiments and monitors, observation;
d) Databases and data dissemination;
e) Service provision (including models and effects);
f) Other, please specify

Again a very uneven distribution of answers. Some persons wanted to separate a) and b) as purely scientific enterprise, but in total a) was the least and b) the most favoured choice.

Question 9.
What is your opinion on the most promising market for Space Weather products and services in future?

a) S/C engineering, design, and development;
b) Satellite operators;
    b1) geostationary orbit;
    b2) low-altitude telecom networks (type of Iridium);
c) GPS applications;
d) Ground-based technological systems;
e) Commercial air-flight (high-altitude/polar);
f) Manned space-flight;
g) Others, please specify.

This gave also an interesting result. In summary, the respondents expect that the manned space-flight (f) would be the most promising market, thereafter b) and c). Quite surprisingly, a) and d) were found as the least promising!

Question 10.
Any other comments

There were lots of comments to the actual questions. However, under this item an experienced person concluded:

The main problem lies in establishing a 'market'. A few years ago [our organisation] set up an ionospheric weather service for HF comms. During the research and development phase there were many 'users' but they almost all disappeared when they were asked to pay for the service up-front.

These answers illustrate some important facts about the European space weather scene that have been voiced in various contexts. There is a general belief in the high quality of European STP science which shows also in the fact that the first ESA cornerstone mission was the combination of SOHO and Cluster. European scientists participate actively in several NASA and other missions within the ISTP Programme. It is unfortunate for space weather that the ESA Science Programme cannot accommodate more STP missions in its present form. Space research funds are in many countries tied to the ESA programme which may limit future European possibilities to develop a strong and coherent European space weather activity.

The weakest point in Europe are the scattered resources and interests. Several groups have relevant competence, models, and data from their own interest areas. Sometimes this leads to a somewhat narrow perspective to space weather. Also the almost total lack of dialogue between spacecraft engineering and the scientific community is a serious drawback. As illustrated by this ESA contract and more generally by the TOS-EMA R&D activity (http://www.estec.esa.nl/wmwww/wma/) there are some individuals who move across this border and their experience should be utilised much more efficiently than today. This problem also shows in the small number efforts to transfer the results into products and services in Europe.

For up-to-date information about European space weather groups, see the WWW-server developed as a part of the present ESA-Contract: http://www.geo.fmi.fi/spee/

7.2. Recommendations for rationalised development of space weather activity in Europe

This item should probably be analysed starting from the question what to do. However, we live in Europe where interests and resources are scattered, and the question who should take the lead to formulate a rationalised approach to space weather becomes urgent. This actually happened also in the US where the formulation of the NSWP took first several years of inter-agency negotiations and “politicking” before an overall strategy was possible to formulate.

7.2.1. Who should take the lead?

When asking this question we have received three main answers: ESA, EU, a consortium of national institutions. We have also been asked the reverse: Do we have to engage to this at all, would it be enough that we co-operate with Americans? This is of course a legitimate question, but irrelevant to the goals of this study.

A fact is that the European Union is not a natural body to coordinate practical space activities. EU can support, e.g., networks of national groups in space weather-related research. This actually is a recommendable route to take for groups seeking funding in space weather research.

The national institutions interested in space weather form, in any case, the basis of any European space weather activity. None of them, nor any ESA country alone, is expected to be able to support an independent full-scale space weather activity. More limited, localised space weather centres are, on the other hand, quite possible, and would be very valuable as parts of an international space weather system. There are embryos of such, e.g., the Solar-Terrestrial Laboratory of the Swedish Institute of Space Physics in Lund and the ISES Regional Warning Centres, of which the Western Europe RWC is located in Meudon. Furthermore, groups such as MSSL, BIRA/IASB, DERA, ONERA-CERT, IRF, FMI, TOS-EMA, and many others, already have activities which could contribute significantly to a European space weather network.

However, as one respondent to our questionnaire answered: “Europeans have difficulties to agree upon anything.” Thus it may well be that the only way of organising a rationalised European space weather activity is to have an authoritative organisation to supervise the development. For this we have ESA and space weather can be argued to be a classic example of Agency responsibility. At present ESA's engagement in space weather is in the technological front. They have good expertise on the design of spacecraft and single event effects. TOS-EMA at ESTEC has resources for internal activities and controls some amount of funds within TRP for limited studies, such as this particular contract, TREND, SPENVIS, or SEDAT. The present space weather funding is a vanishingly small part of the total annual R&D budget of ESA.

To speed up the process of creating an European space weather agenda the STP community could help much. In the US the NSWP was realised very much by the pressure from the science community and it seems that this pressure is increasing in Europe as well. Note, however, that in the US space sciences and engineering have a tradition of cross-fertilisation which is much weaker in Europe. In Europe a particularly authoritative body is the ESA Science Programme. Thus the most important recommendations of this study are:

1. ESA Science Programme should take space weather on its agenda.

2. Form a formal Science/Technology Interdisciplinary Space Weather Programme which reports to SPC/SSWG and IPC.

At the beginning this does not require large funds and could be realised, e.g, by some increase of TRP funding and matching the activity with Science Programme. The scientific supervision could be defined as a part of the SSWG, or a small ad-hoc working group could be formed to define the ESA Space Weather activities. This group should involve the present expertise at ESTEC and the future activities should be closely co-ordinated with the more technologically oriented projects of ESTEC. It is of crucial importance, however, that ESA will make a long-term commitment to its involvement in space weather: ESA is dependent on space weather as long as ESA remains a space mission agency.

7.2.2. Possible level of concerted European approach

We furthermore suggest that three different levels of European space weather activity should be carefully considered.
1) European Data and Model Centre (EDMC)
2) European Data, Model and Specification Centre (EDMSC)
3) European Space Weather Centre (ESWC)
For simplicity, we call these units here “Centres” although the final solution may be a decentralised structure.

This is a hierarchical sequence: Levels 2) and 3) cannot do without having data and models, and if a centre is able to forecast, it can provide environment specifications and nowcasting as well. Thus the rapid flow of reliable data is basis of everything. At present this is the worst bottle-neck.

1) European Data and Model Centre (EDMC)

The mission of EDMC should be twofold. It should create links to all relevant data for space weather services and be able to provide up-to-date data services to engineers, operators, and scientists. It should also collect available models and have sufficient expertise to work for conversion of these models toward operational applications, resembling the "rapid prototyping" of NOAA/SEC. It is likely that models having significant operational capability will be protected by patents. A natural task for the EDMC would be to take care of the necessary agreements concerning the user rights and in this way also guard the interests of the patent holders.

This operation could be started with a staff of 10-20 persons equally divided between data and model specialists. For evaluation of the models sufficient scientific expertise is necessary.

The centre would not need to be centralised. It needs a head-quarter but it could be distributed provided that the nodes of a distributed system are strong enough for efficient operation. Both centralised and distributed systems have their advantages and problems. A distributed system could more easily get local support and the whole system could be more extensive. On the other hand, this approach requires binding commitments from all parties to guarantee efficient communication and most likely causes increased interface costs. A recommendable compromise would be a central EDMC with local affiliations responsible for products within their local expertise. This solution would probably provide the best outcome for least initial cost to the organisation(s) supporting EDMC.

It should be noted that TOS-EMA already now has activities toward this direction through some of their own activities and contracts such as TREND, SPENVIS, SPEE, and SEDAT (cf. http://www.estec.esa.nl/wmwww/wma/).

2) European Data, Model, and Specification Centre (EDMSC)

This centre should do everything EDMC would and, in addition, provide post-analysis and nowcasting services to customers. EDMSC needs everything there is in an EDMC and scientific and technical staff for analysis and nowcasting. Here a centralised core where the most critical work is performed is likely to be the most efficient. Also the staff must be sufficient, at least 20-30 persons.

3) European Space Weather Centre (ESWC)

This would be a logical third stage based on items 1) and 2) above. It may not be a realistic near-time goal in Europe and will require a thorough market and cost-benefit analysis. Even without such analysis it looks reasonable that it should be realised in close collaboration with other organisations, particularly NOAA/SEC and ISES. In addition to approach 2) the ESWC needs 24-hour operations, fast communication lines, and extensive supercomputer resources. A minimum staff of 50 persons is required.

Our third recommendation is that:

3. ESA should initiate work to establish a European Space Weather Data and Model Centre (either centralised or distributed with a central core). This Centre should have as its goal to become a European Data, Model, and Specification Centre, and it should look for a workable solution for a full-scale European Space Weather Centre.

7.3. Suggestions for space weather studies making use of European S/C data

At the end of this report we list here a number of suggestions where ESA could and should be active without necessarily having to invest large funds.

1. Use of SOHO in studies of the origins of space weather on the Sun should be strongly encouraged. This applies particularly to instruments observing the solar disc and the corona. Especially, development of models to forecast the CMEs and SEPEs should have a high priority.

2. A concrete study to be initiated is investigation how to determine whether a CME will be geoeffective and lead to specific hazardous conditions, or not.

3. Establish a space weather interdisciplinary position in the SOHO team.

4. Space weather issues should be introduced to the agenda of the Cluster mission. While Cluster will not provide direct observations of particles harming spacecraft, it is expected to make significant contributions to the understanding of energy and mass transfer from the solar wind to the magnetosphere. Also here either an interdisciplinary scientist or working group should be established.

5. A goal to include radiation environment monitors (REM, or more advanced devices) in nearly all European spacecraft, commercial and scientific alike, should be pursued.

6. Data from the radiation environment monitors developed at ESTEC must be efficiently exploited.

7. Attempts to make more satellite anomaly data available for studies should be made.

8. Make maximum use of the ISTP programme period to understand satellite anomalies and charging events.

Furthermore, in the future ESA should seek means for helping to secure continuous solar wind monitoring in the future. The STP fraction of the SSWG has tried to persuade this, e.g., in the context of medium scale missions. However, this kind of routine monitoring missions cannot in practise compete with more glorious missions being proposed.

8. List of acronyms

Names of institutes or companies are not included, nor well-known organisations like ESA, EU, NASA, etc. Section where the acronym appears for the first time is given in parenthesis

AE	Auroral Electrojet index (contains AL) (3.1.1)
AE8	Trapped electron model (2.3.1)
AGU	American Geophysical Union (3.1.2)
AL	see AE (3.7)
AMIE	Assimilative Magnetosphere Ionosphere Electrodynamics model (3.5)
AMPTE/CCE	NASA magnetospheric spacecraft (3.3.2)
AMPTE/IRM	German magnetospheric spacecraft (3.3.2)
Ap	Planetary magnetic activity (A) index (4.1)
AP8	Trapped proton model (2.3.1)
ARMA	Auto-Regressive Moving Average (3.7)
AU	Astronomical Unit (about 150 000 000 km) (3.1.2)
CHIME	Radiation belt model (3.4.3)
CIRA	COSPAR International Reference Atmosphere (3.6)
CME	Coronal Mass Ejection (2.2.3)
COSPAR	Committee for Space Research (3.4.3)
CRRES	US Air Force charging technoloty satellite (3.4.3)
CRRESPRO	Radiation belt model (3.4.3)
CRRESRAD	Radiation belt model (3.4.3)
CRRESELE	Radiation belt model (3.4.3)
DMSP	US defence meteorological satellite series (3.4.1)
Dst	Magnetic storm-time index (2.2.3)
EDMC	European Data and Model Centre (7.2.2)
EDMSC	European Data, Model, and Specification Centre (7.2.2)
ESWC	European Space Weather Centre (7.2.2)
EURECA	ESA retrievable spacecraft (7.1)
ERS	ESA Earth observation spacecraft (2.1.3)
ESD	Electrostatic discharge (2.1.3)
ENA	Energetic neutral atom (6.2)
EVA	Extra vehicular activity (2.3.7)
FAGS	Federation of Astronomical and Geophysical Data Services (1.3)
GEOTAIL	Japanese magnetospheric spacecraft (3.3.2)
GIC	Geomagnetically induced current (2)
GOES	NOAA meteorological satellite series (7.1)
GPS	Global Positioning System (1.6)
IAGA	International Association for Geomagnetism and Aeronomy (1.3)
IAU	International Astronomical Union (1.3)
IGRF	International Geomagnetic Reference Field model (3.1.1)
IMF	Interplanetary Magnetic Field (2.2.2)
IMP-8	Solar wind satellite (3.2)
IPC	Industrial Policy Committee (ESA) (Abstract)
IRI	International Reference Ionosphere (3.5)
ISIS	Ionospheric satellite (1970s) (3.5)
ISES	International Space Environment Service (1.3)
ISO	ESA spacecraft (2.1.3)
ISTP	International Solar-Terrestrial Physics programme (6.1)
ITT	Invitation to tender (3.1.1)

IUGG	International Union for Geomagnetism and Geodesy (1.3)
JPL-91	US SEPE fluence model (3.1.1)
Kp	Planetary magnetic activity (K) index (3.1.1)
L	Parameter characterising a shell of particles drifting around the Earth (3.4.3)
L1	First Lagrange point (location of SOHO) (3.2)
LASCO	Coronal instrument on SOHO (7.1)
LET	Linear energy transfer (3.4.3)
METEOSAT	European meteorological satellite (2.1.3)
MHD	Magnetohydrodynamics (Abstract)
MSFM	Magnetospheric Specification and Forecast Model (3.1.1; 3.4.1)
MSIS	Mass Spectrometer Incoherent Scatter model (3.6)
MSM	Magnetospheric Specification Model (3.4.1)
NSSDC	National Space Science Data Center (US) (3.4.3)
NSWP	National Space Weather Program (US) (1.3)
PROSPEC	Radiation belt model (3.4.3)
R_E	Radius of the Earth (about 6370 km) (3.3.1)
REM	Radiation Environment Monitor (7.3)
RWC	Regional Warning Centre (ISES) (1.3)
Salammbô	French dynamic radiation belt model (3.4.2)
S/C	Spacecraft
SSC	Storm Sudden Commencement (1.3)
SEC	Space Environment Center (of NOAA) (1.3)
SEDAT	Space Environment and Data Analysis Tools (3.1.1)
SEPE	Solar Energetic Particle Event (2.3.4)
SEU	Single event upset (2.1.3)
SOHO	Solar and Heliospheric Observatory (Abstract)
SPC	Science Programme Committee (ESA) (Abstract)
SPENVIS	Space Environment Information System (3.4.3)
SSWG	Solar System Working Group (ESA) (Abstract)
STP	Solar Terrestrial Physics (1.1)
STRV	UK spacecraft series (7.1)
SuperDARN	Ionospheric radar system (3.5)
TELE-X	Swedish telecommunication satellite (2.1.3)
TOS-EMA	Space Environments and Effects Analysis Section (of ESTEC) (Title page)
TREND	Trapped Radiation Environment Model Development (3.4.3)
TRP	Technology Research Programme (ESA) (7.2.1)
UNIRAD	ESTEC radiation software (3.4.3)
URSI	International Union of Radio Science (1.3)
UT	Universal time (2.1.2)
WIND	NASA spacecraft (3.3.2)
WWW	World Wide Web (1.1)

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