6. GLOBAL SPACE WEATHER MODELLING

6.1. What is space weather modelling?

Improved modelling is essential 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 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.

6.2. 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 of models to address various aspects 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 Chapter 3.

6.2.1. 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 these aspects 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.

6.2.1.1. 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).

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 that would yield useful predictions. 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 interest for spacecraft engineering.

A new ESTEC contract, called SEDAT, was initiated in 1998. One of its goals is a further development of the solar proton models.

6.2.1.2. 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 it was commonly held that the flares are the most geoeffective form of the solar activity. 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 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.

It is, in fact, possible to make meaningful forecasts and warnings of CME-driven effects in geospace without understanding the origin of CMEs themselves. For practical purposes it will be sufficient to detect an approaching CME after it has left the Sun and base the predictions on this information. Predictions of the effects are still quite uncertain because only a fraction of CMEs hit the Earth and only about 1 of 6 CMEs hitting the Earth produce major geomagnetic storms (e.g., Gosling, 1997).

It is clear 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.

In 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 point is to increase the awareness of space weather among the solar physics community. If this awareness had been at a higher level in mid 1980s, SOHO would carry at least a simple plasma and magnetic field monitoring package to probe the local IMF and plasma conditions.

6.2.2. 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. A particularly useful solar wind monitoring point is the L1 that 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 mapping 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). 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.

6.2.3. 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. This section deals with empirical models describing the magnetopause and the magnetospheric magnetic field and the large-scale MHD approach to magnetospheric dynamics. Section 6.2.4. discusses models whose goal is to model the inner magnetosphere including radiation belts and geostationary orbit.

6.2.3.1. 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 (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, parameterised 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, the Hilmer-Voigt model is used in the MSFM (see section 6.2.4.1. 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 account for 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 the present 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 they can be further developed to produce real-time global maps if implemented together with real-time magnetospheric observations.

6.2.3.2. 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 which people usually refer to in space weather context. In Europe there is only one advanced model at the Finnish Meteorological Institute (Janhunen, 1996) but also it is developed for scientific use only. Furthermore, the group at CETP, France, is doing basic research on MHD simulations. In summary, the field is in a state of continuous evolution and the state of art is not a static concept. 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 understood 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 the difference between 1 s and 3 hr 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 routine in the most advanced models (P. Janhunen, private communication, 1998).

6.2.4. Models for the inner magnetosphere

Models describing particle fluxes in the inner magnetosphere, say inside 10 R_E, are of specific interest to spacecraft engineers and operators. Because the global MHD simulations often are computationally too heavy to determine the electric and magnetic fields needed to calculate the energetic particle trajectories and they cannot yet treat the inner magnetosphere properly, 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 is 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.

6.2.4.1. Magnetospheric Specification and Forecast Model (MSFM)

Of the large-scale physical models, the MSFM is and advanced approach toward 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.

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.

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 (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 6.1.

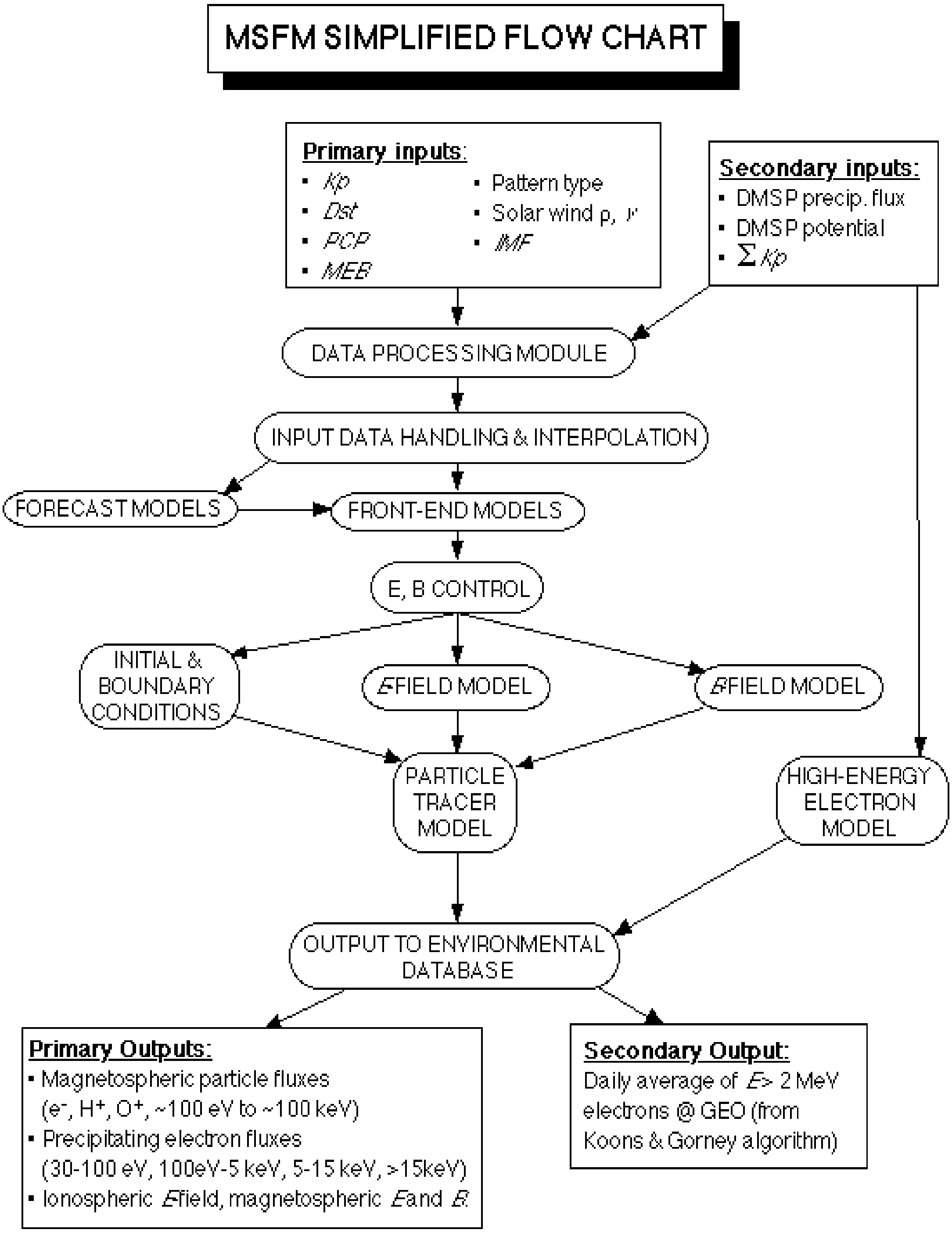

Figure 6.1. Flow chart of MSFM

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

6.2.4.2. 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.

We comment here one important European model, Salammbô of 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). Its recent version (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 discuss 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 Salammbô 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. Salammbô could be the starting point for a European inner magnetosphere model that might be able to compete with the MSFM.

6.2.4.3. 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, 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 and 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, especially the Belgian Institute of Space Aeronomy (BIRA/IASB) in Brussels has been active in this field. 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 led 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 UNIRAD software developed at ESTEC. 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.

6.2.5. 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 50 km to 2000 km, and also the electron content. It provides monthly averages in the non-auroral ionosphere for magnetically quiet conditions. The major data sources are the world-wide network of ionosondes, the powerful incoherent scatter radars, the 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 difficult task. Several models have been developed that use multiple 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 DE 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-Maynard 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 Electrodynamics) 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, the global magnetic disturbances, and the global conductivity patterns. AMIE is a scientific tool that requires a considerable effort for any single event analysis. As such the model appears to be too heavy for operational space weather applications.

Using a 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 that has resources to compute useful products.

6.2.6. 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 model is the COSPAR International Reference Atmosphere (CIRA), an effort that started in 1961 with the publication of CIRA-61. Its third generation is CIRA-86. In 1970s in situ measurements of atmospheric parameters by mass spectrometers and ground-based incoherent scatter radars 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.

6.2.7. 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 that is an approximate measure of the strength of the ring current.

These models do not involve dynamical equations governing the solar-terrestrial physics but are based on the repetitive structure of the observed parameters, which of course displays the underlying physics. This way of predicting is sometimes considered inferior and less physical but from the application point of view the only thing that matters is whether a reliable prediction is available in time to react. 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 and 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.

6.2.8. 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 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 to be developed to operational space weather models are developed under classified contracts (e.g., MSFM). 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 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 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 simply 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.

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 unsuitable models into use but also increase the expertise among those who will be responsible for this work.

6.3. 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 true. 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 involved.

6.3.1. 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. However, there are natural limits in their applicability to forecasting. It is not possible to make reliable predictions further in advance than the underlying physical system permits. 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.

Forecasting AE or Dst alone may not be sufficient for 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.

6.3.2. 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 an operational space weather forecaster.

6.3.3. 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 much more interested in extreme phenomena, in hurricanes instead of 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. 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 an 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 too quickly.

6.4 Practical aspects for improvement of space weather modelling

6.4.1. 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 real-time specification, warning, or forecasting activities 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 models that might be made to space weather models. 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.

6.4.2. 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 will 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 rapid development of the internet has considerably improved 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 a 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.

6.4.3. 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.

6.4.4. 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 worldwide. More than one is a conservative estimate to allow for competition and flexibility.

6.5. Requirements for modelling tools

This section describes a hypothetical space weather modelling tool. Up to now, no such modelling tool has been developed in Europe. There are several physical research models for different parts of the solar-terrestrial system, which are in scientific use. Integration of these to an operational modelling tool, with near-real-time input from space, has been done under a U.S. Air Force contract at Rice University (the MSFM model), but that model is not available for outside users.

6.5.1. Assumptions for the software

The software will use observational data from the Sun, the solar wind, and different regions of the magnetosphere as input. It will use an integrated set of numerical models to give user-dependent relevant parameters at a given time and place in pre-defined regions of the magnetosphere.

The primary uses of the software are in
(1) (post-)analysing spacecraft anomalies after they have been identified.
(2) predicting conditions hazardous for spacecraft

The software can also be used in the design phase of new spacecraft for predicting statistical occurrence of different conditions during spacecraft lifetime, and thus setting constraints for spacecraft design.

The benefits of such a modelling tool are many. At present, spacecraft anomalies cannot be predicted better than as probabilities over an extended period of time. These estimates are either based on data from previous missions, or statistical behaviour of the solar-terrestrial system. With a modelling tool, physical conditions along spacecraft orbit during its lifetime can be estimated with better accuracy.

For operational spacecraft, the modelling tool allows for forecasts of hazardous conditions. By avoiding critical operations when hazardous conditions are predicted, this may save from anomalous effects harming the spacecraft, and at best save the spacecraft from being lost.

When an anomaly has occurred, the modelling tool allows for a detailed post-analysis of the event. At present, there are no models that would give the external physical conditions at the time of an anomaly, and one has to rely on on-board measurements of external conditions. Since the on-board instrumentation for measuring external conditions typically gives few parameters only, if such instruments exist at all, one cannot conclude with confidence what has caused the observed anomaly. With the modelling tool, the post-analysis can be based on more data, which helps in the design of future spacecraft.

The modelling tool also allows for estimating occurrence probabilities of the most hazardous ("worst case") conditions, e.g., in terms of radiation from different sources, and thus vulnerable parts of hardware can be designed according to either maximum, mean, or optimum conditions, whichever is considered most appropriate.

Different users have different needs for the output in terms of access times, required parameters, and user interface. Even if only specifying the two different uses mentioned above, the User and Software Requirements differ. Thus we shall deal with these two uses separately.

The final product shall include, for both user groups,

1. a distributed system for collecting data from observation sites in space as well as on the ground,
2. software for converting these input into a form to be used by the modelling tool,
3. the (physics-based) state-of-the-art simulation model, used for the interpolation/ extrapolation of, and forecasting from, the observational data, and
4. a dedicated user interface for each user group, giving output with an accuracy and in a format best suitable for different uses.

Item 1) is an essential requirement for making the modelling tool. However, it is not an integral part of the system. Instead, organisations responsible for collecting the data shall also be responsible for delivering verified data as input to the modelling tool. Item 2) shall include interpolation routines, both in space and time, to adjust the input data in the format used by the modelling tool. This software shall be called the modelling tool data front end hereinafter. Item 3) includes the most critical software of the modelling tool. It will be called the modelling tool core in this document. Item 4) is the user interface software.

6.5.2. General description of the model

6.5.2.1. Product perspective

Predictive models, using linear/non-linear ARMA or neural network approaches, are able to forecast geomagnetic activity parameters both in the short-term and asymptotically. These models might thus be used for operational forecasting of increased probability of hazardous events. However, they do not fulfil the requirements of prediction of physical conditions at a given place, or of the possibility for post-analysis. For these requirements, a physics-based model is needed.

Essential parts of the physics-based modelling tool include:

- *Solar and solar wind monitors*. The model accuracy relies on continuous monitoring of the conditions in the Sun and the solar wind. Without adequate coverage of observations, no model will have the desired accuracy. Solar and/or solar wind monitors are also needed for predictive models.
- *Model for solar wind behaviour*. Disturbances originated in the Sun propagate to the magnetosphere with the solar wind, and thus a model of the solar wind is necessary. For modelling of solar energetic particle events, this is extremely important, since the particles enter the near-Earth environment in a time scale of the order of 20 minutes, after they have been ejected from the surface of the Sun.
- *Model for solar wind - magnetosphere interaction*. The magnetosphere is a complicated system of different temporal and spatial scales, demanding careful connection of different models, such as
    - model for the large scale behaviour of the magnetosphere,

- empirical models for magnetospheric configuration,
- models for the trapped energetic particle environment,
- ionospheric models, and
- atmospheric models.

The present state of the availability and maturity of different models for operational use was discussed in section 6.2. above.

6.5.2.2. Quality requirements

Probably the most important item that has to improve 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 the current capabilities vs. requirements were presented as Table 6.1:

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

This 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 the need to stress the urgency of increased resources for the model development and related basic research.

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 sample 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). Of 432 of Ap storms only 164 were correctly forecasted and there were 234 false alarms.

6.5.2.3. User characteristics

Two different groups of users of the software have been identified. These are:

1. Study engineers or scientists, and design engineers
2. Satellite operators

These groups have somewhat different needs for the software, and will thus be dealt with separately.

Study engineers and/or scientist work on post-analysis of observed anomalies on spacecraft, that shall be called events in this document. This group will use the Modelling Tool to reconstruct the conditions in the space environment in the vicinity of the spacecraft at the time of an observed anomaly. These users have scientific education, often at doctoral level. Thus the actual physical conditions in the environment of the spacecraft, at the time of the anomaly, are of interest. It is assumed to be up to the users to make their conclusions from the physical data given by the modelling tool. These kind of studies usually take up to a few weeks, and thus the accuracy of the modelling is more critical than a fast response time. Since these users use the tool only occasionally, the interface shall be user-friendly and self-explaining.

Design engineers may use the modelling tool for predicting statistical occurrence of different conditions (e.g., certain levels of radiation) along spacecraft orbit during its lifetime. Precise conditions at a given time and location are not necessarily required, since statistical ('typical') data are to be used as input. Design engineers are professionals in spacecraft design, but not necessarily in space physics. The results of the modelling tool thus have to be translated into occurrence probabilities of radiation doses and other relevant parameters to be defined with the users. The design groups do not use the tool routinely after constraints have been fixed, and thus the user interface has to be user-friendly and easy to familiarise with.

Satellite operators are people working on daily on-line operation of spacecraft, including orbit control, communications and maintenance of the satellite. These users work in a real-time environment. They must make decisions of action immediately, and thus need a reliable software tool with a user-friendly, satellite-specific user interface. These people are responsible for taking care of any action for recovery after an anomaly on the spacecraft has been observed. The people in this group usually have a technical background for operating the spacecraft. Users in this group are not assumed to know the cause and effect relationships between different conditions and the spacecraft in detail, but to be concerned about the kind of anomaly that could be expected.

6.5.2.4. General constraints

In general, the modelling tool has to be

1. Fault-tolerant in terms of input data and run-time instabilities in the physics-based model.

   Bad or missing input data shall not cause the running of the modelling tool to stop, nor shall ill-posed physical conditions cause program error. However, these situations have to be clearly indicated to the user, so that the user knows that the results have to be interpreted with proper care.

2. Flexible in terms of input.
   Input data available from any part of the magnetosphere, on ground, or from the solar wind, shall be possible to include in the input data set used by the tool. An obvious example is data from spacecraft, whose instrumentation and positions are variable. If conflicts between data from different sources exist, the modelling tool shall indicate such occasions. Also, any input data *not* available shall be allowed to be omitted. The modelling tool shall adapt to existing data, and not be critically dependent on single observation.
3. User-friendly.
   The modelling tool shall have a dedicated user interface for each identified group of users, and, for operational use, for each satellite.
4. Reliable in terms of quality of output.
   As already stated in item (2) above, missing or probably erroneous input data shall be indicated as lowering the quality of the output, so that no false conclusions of the cause of an anomaly are made, and no over-design or too small margins will result for design of future spacecraft (user group 1), and no false recommendations for actions to be taken are made (user group 2). Obviously the quality of the output depends on the quality of the data, and a measure of the reliability of the output data shall be given for all users.

Partly these requirements are for the physical models, partly for the modelling tool and its implementation on a computer system. Again, the two are intimately interrelated.

6.5.2.5. Assumptions and dependencies

It is assumed that when the modelling tool is developed, there exist

1. sufficient amount of observational sites in the critical regions of the solar-terrestrial system to provide necessary input data for the modelling tool, and a coordinated system for collection of that data for modelling
2. sufficiently accurate physics models of the solar-terrestrial interaction
3. powerful enough computers to perform the desired calculations in the required response time (group 1), or in the lead time needed for forecasting (group 2).

6.5.2.6. Operational environment

The modelling tool will run in a distributed net of computers, with different tasks in different phases of the modelling in the most appropriate hardware and location. The observations are verified and pre-processed at the organisation responsible for the observation in (near) real-time. The data is then transferred through a network (e.g. internet or a dedicated link) to the modelling centre.

The physics-based model, used for post-analysis, requires (today) super computer class hardware, and thus has to be run in a computer centre having that facility. For ensuring the smooth operation of the modelling tool, dedicated professionals both for computer operation and result verification and interpretation are needed.

For predictive models that can be run on fast workstations, the actual modelling software can be run either at the modelling centre, or at the end user’s organisation. In each case, the verification, selection and integration of input data for the modelling tool is to be done at the modelling centre. When predictive models become real physics-based forecasting models, they will pose more severe environmental constraints, such as massive parallel processing (MSP). However, such models are beyond the scope of this discussion.

The parameters and format of the output depend on the needs of the end user, and the User Interface part of the modelling tool will be run locally in the workstation of the end user. The results from the physical (or predictive) model are distributed through a data network to the users for post-processing.

The modelling tool core shall include the different physics models discussed in section 6.5.2.1, and thus the most natural choice is to distribute the responsibility of development work of the modelling tool to institutions where expertise and resources are available. However, for practical reasons, the final product (core modelling tool) shall be integrated to one place.

6.5.3. On modelling tool software requirements

The model is assumed above to be built on various model elements that have been developed more or less independently. In the development of the modelling tool, the integration of different models to the tool has to be studied and negotiated with each group separately. The fact is that some of the building blocks and, especially, their interrelationships pose such physics and numerical mathematics problems that are difficult to completely hand over to professional programmers.

The software ('modelling tool') serves as a tool to predict space environment conditions that are hazardous for operational spacecraft. It consists of functional blocks, responsible for acquisition, verification and preparation of data ('data front end'), 'core modelling tool' software, including the physics based models that calculate the required output parameters from the input parameters, and the user interface software, dedicated for each user group.

The modelling tool is a system of independent, interacting software, and of manual phases of work (data verification) in a distributed environment. The data collection and verification are done by the organisation responsible for operating the instrumentation. The input data are fed to the data front end of the modelling tool. This software converts the data to a format understood by the modelling tool, and performs, e.g., necessary interpolation routines.

After verification and preparation the data are fed to the core modelling tool. The selection of the structure of the modelling tool is a trade-off between possibility to upgrade with more recent (advanced) partial models and computational efficiency. A completely modular program cannot be optimised to the same level as a model where the computational algorithms are selected according to the functional forms of the models used.

Specifically, the following requirements apply to the modules of the core modelling tool:

- The modelling tool shall include a (dynamic) magnetic field model, run with (near-real-time) physical parameters.
- The modelling tool shall include an electric field model, including electric fields emerging from time-variation of the magnetic fields, to be combined with the output of the magnetic field model, for particle drift calculations.
- The modelling tool shall include models for particle sources (either model or data base) and loss of particles.

The modelling tool core passes its output to the dedicated output software. Output software shall depend on the User group, and whether interactive or batch processing is used.

The block diagram of the modelling tool is shown in Figure 6.2, and a more detailed description of the magnetosphere-ionosphere (core) model in Figure 6.3.

6.5.4. Building blocks of the tool

Magnetic field model

Alternatives for choosing a magnetic field model for the modelling tool are numerous. The most simple models are the *dipole and eccentric dipole models*. These are static models, describing the non-variable component of the Earth's internal field. The advantage of these models is that they have a clear analytic form. As a consequence, analytic manipulation of the equations governing particle behaviour in combined magnetic and electric fields may substantially speed up numerical calculations. The major disadvantage is the small region of applicability of the (eccentric) dipole magnetic field. The magnetospheric magnetic field deviates from the dipole field already at the distance of the geostationary orbit, especially close to the noon-midnight meridian. Thus these models do not describe the true magnetic field very well. Also closer to the Earth, to correctly describe high energy particle precipitation to low altitudes above the South Atlantic Anomaly, a more advanced model has to be used.

The next in order of increasing complexity is the International Geomagnetic Reference Field (IGRF). This model includes higher harmonics of the internal field, and it is also updated regularly, thus following the slow variations of the internal field. However, as the (eccentric) dipole field model, the applicability of this model is also limited to close distances from the Earth, up to roughly 5 Earth Radii on the equator.

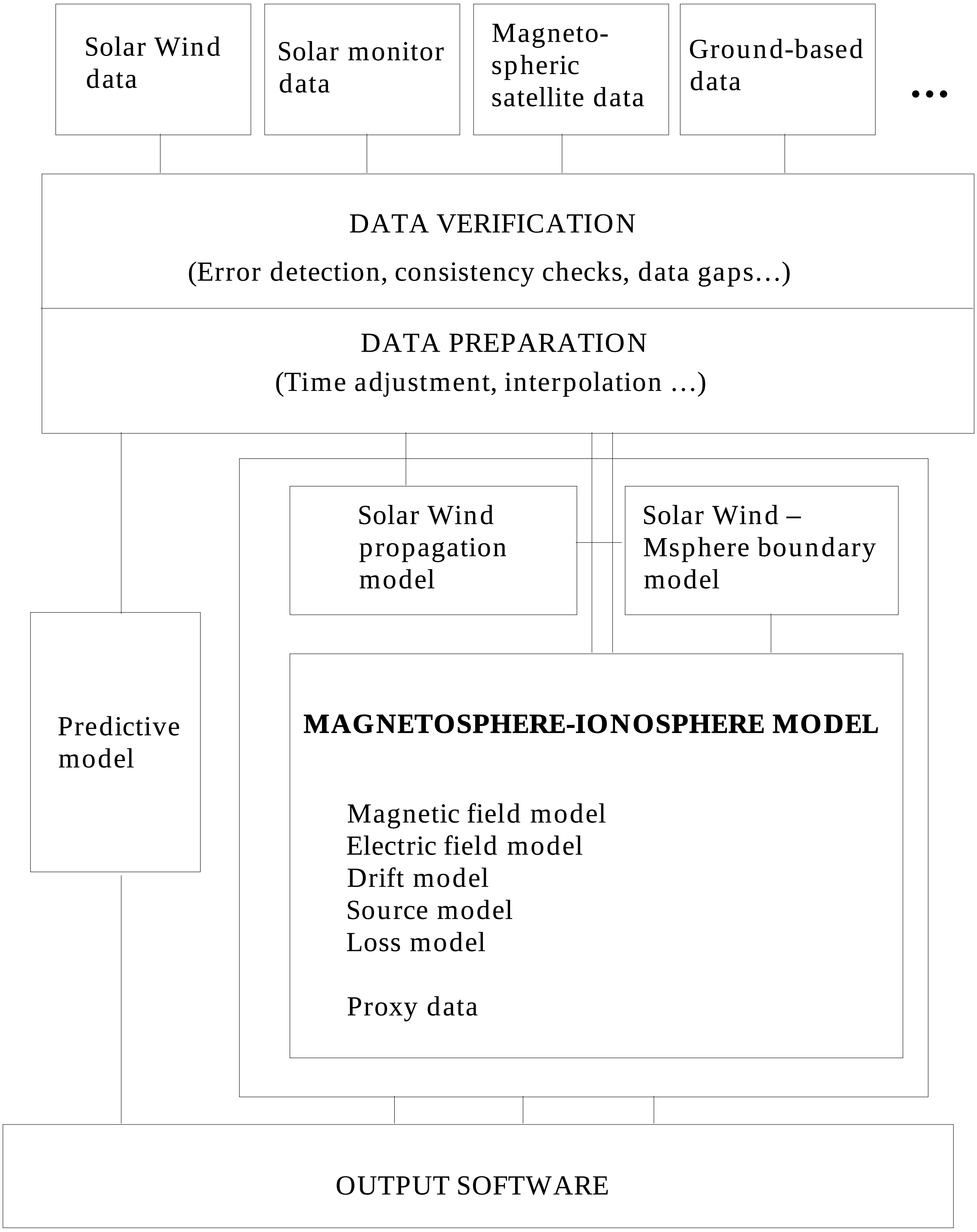

Figure 6.2. Block diagram of the modelling tool.

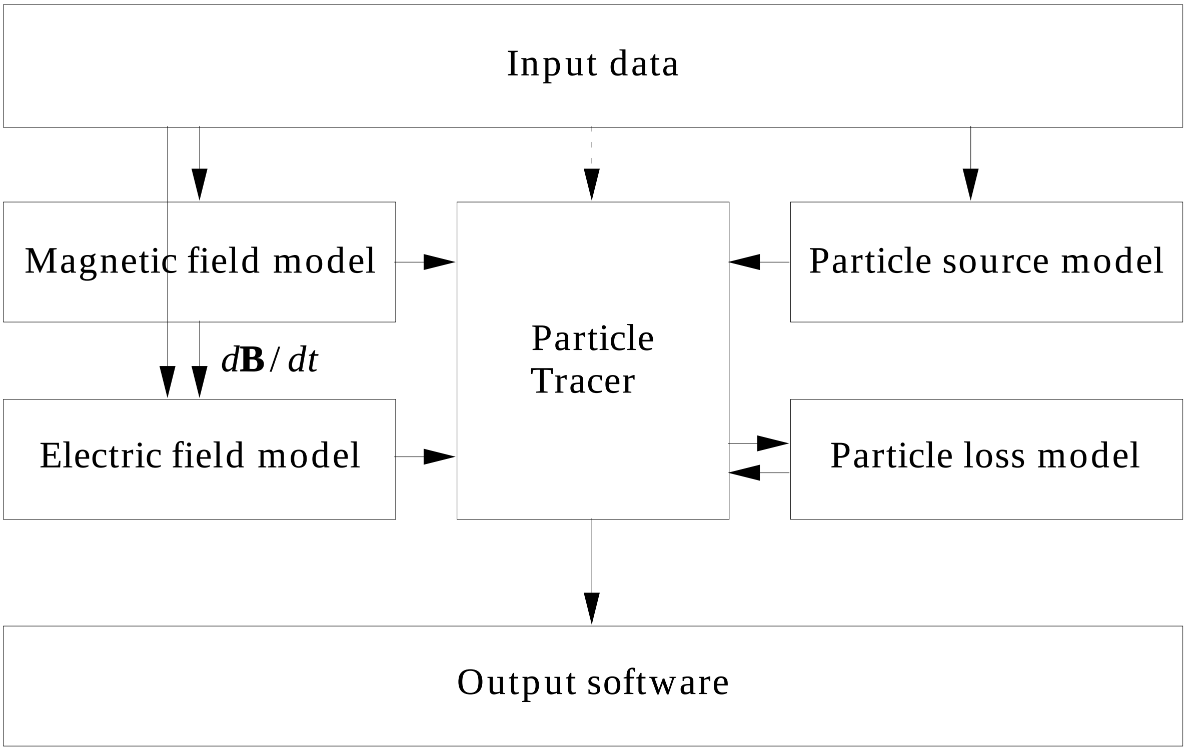

Figure 6.3. Block diagram of the magnetosphere-ionosphere model (modelling tool core) of Figure 6.2.

The magnetic field model by Hilmer and Voigt (Hilmer and Voigt, 1995), which is used in MSFM, combines the dipole magnetic field of the Earth with magnetospheric field components caused by electric currents in different parts of the magnetosphere: the equatorial ring current, the cross-tail current, and the Chapman-Ferraro current at the magnetopause. Using these source fields, the model computes the total field configuration. The input parameters of the model to set the magnitude, location, and extent of the source current systems are:

1 *The dipole tilt angle*, i.e., the angle between the axis perpendicular to the Sun-Earth direction, pointing to the north. Positive values correspond to the northern hemisphere being tilted towards the Sun.

2 *The magnetopause stand-off distance*. This parameter is used to set the size of the magnetosphere by adjusting the strength of the Chapman-Ferraro currents. The magnetopause stand-off distance can be approximated by calculating the pressure balance between the solar wind dynamic pressure and the magnetic pressure of the terrestrial dipole field. Alternatively, a more advanced model, such as Shue et al. (1997) can be used for calculating the stand-off distance from solar wind parameters.

3 *The geomagnetic index Dst*, describing the magnitude of the ring current.

4 *The midnight equatorward boundary of the diffuse aurora*. This parameter is used to indicate the degree of stretching of the magnetotail magnetic field. The midnight equatorward boundary is a rough indicator of the radius of the auroral oval, which is a measure of magnetic flux in the magnetotail. In practice, this parameter is used to define where the tail current sheet must be positioned so

that the inner edge footpoint maps to the right latitude in the ionosphere. This parameter is to be inferred either from ground-based observations, or satellite measurements of precipitating particles in the midnight sector.

In the practical implementation of the MSFM, the model magnetic field values have been pre-calculated and tabulated in the computational grid of the model, for a range of parameters, to save computing time.

The main advantage of the Hilmer-Voigt model is that the input parameters are directly measurable, and thus adjust the magnetic field to the prevailing conditions, with several parameters that can be verified. The region where the model can be used, well covers the inner magnetosphere, up to nearly subsolar point towards the Sun, and down to approximately 30 R_E towards the tail.

The different versions of the Tsyganenko magnetic field models (Tsyganenko, 1987; 1989; 1995; 1997) are widely in use among the scientific community. They are all available on the WWW, and due to the large number of users, they have been thoroughly tested, and the strengths and weaknesses of the models are well known.

For a modelling tool, the main weakness of the Tsyganenko models is that they only use global parameter(s), typically magnetic activity, and in the later versions also solar wind parameters to adjust the magnetic field configuration. Also, like all statistical models, the models have been averaged over large amount of events, and thus extreme configurations are not reproduced.

The basic principle of the Tsyganenko models is very similar to the Hilmer-Voigt model: the magnetic field in the magnetosphere is calculated from electric currents inside and at the boundaries of the magnetosphere. The approach in the Tsyganenko models is to use vector potentials to describe the currents and magnetic fields. This approach ensures that the magnetic field remains divergence-free.

The input parameters for the two most recent versions are, in addition to the point in space where the magnetic field is to be calculated:

- Tsyganenko 1989: Magnetic activity index Kp, and either geodipole tilt angle or date and time
- Tsyganenko 199X: Magnetic activity index Dst, Solar Wind pressure, IMF By and Bz, and either geodipole tilt angle, or date and time.

The user may also choose whether to use the dipole or IGRF internal magnetic field model. The output of the models is a three component magnetic field vector

Electric field model

For the selection of the electric field model for the modelling tool there are essentially two alternative approaches:

(1) Specifying the electric field in the equatorial plane of the magnetosphere, and using mapping along magnetic field lines for the rest of the modelling region, or

(2) specifying the electric field in the high-latitude ionosphere, and using mapping towards the equatorial plane for calculating the electric field in other parts of the model.

Approach (1) has been used in the Salammbô model (6.2.4.2), whereas the latter option (2) has been used in the MSFM model. Both approaches exclude the effects of inductive electric fields, which are important in the dynamics of particles.

The choice is not obvious. The motivation for using the equatorial electric field in Salammbô is that the model used (Volland-Stern-model, Volland, 1973; Stern, 1975) has a simple analytical form that can easily be implemented in the code, and analytic manipulation is straightforward. On the other hand, the Volland-Stern model is very much simplified, and does not correctly account for small-scale structures of equatorial electric field, nor the region between the corotation-dominated electric field (up to 5 R_E) and the convection-dominated electric field (tailward of 10 R_E).

In the MSFM model, the Heppner-Maynard model (Heppner and Maynard, 1987; Rich and Maynard, 1989) is used. It specifies the ionospheric potential pattern at latitude above 60 degrees (thus excluding innermost part of the magnetosphere, inside 4 R_E). The Heppner-Maynard-Rich (HMR) model uses spherical harmonics in magnetic local time and latitude, to describe the variation of the potential pattern, as a function of IMF. For southward IMF, also explicit variability with geomagnetic activity is included. In the MSFM model, the HMR model was modified to accept the Polar Cap potential drop as an extra input parameter. The HMR model is available from its authors.

Neither of the approaches discussed above include time variation of the electric field, nor inductive electric fields due to magnetic field variation. The modelling tool shall be able to model transient effects like Storm Sudden Commencements (SSC), that cause rapid heating of plasmaspheric plasma to keV and even MeV energies, and auroral substorms, that cause flux dropouts and energetic particle injections at geostationary orbit. Both phenomena are, according to present knowledge, due to inductive electric fields (electric fields caused by time variation of the magnetic field, $\partial \mathbf{B}/\partial t$). Those variations are not included in the present magnetic field models (with the exception of some research models).

Particle energisation in the inner magnetosphere due to an SSC was successfully modelled by Hudson et al. (1997), who used magnetic and electric fields obtained from a 3D MHD simulation of an SSC event. The applied azimuthal electric field produces first inward and then outward acceleration of particles, causing acceleration and deceleration, respectively, due to conservation of the first magnetic invariant in an increasing and then decreasing magnetic field.

The Salammbô model originally used the dipole magnetic field and the Volland-Stern electric field model. In later versions, the Volland-Stern electric field model has been modified to also include time variation of the convection electric field (Bourdarie et al., 1997). With this modification, and adding a new low-energy (8 keV) particle source at the near-Earth magnetotail (9 R_E), injection features during strong magnetic activity were modelled. The latest version (Bourdarie et al., 1998) also uses a ring current term (Tsyganenko and Usmanov, 1982) and Mead-Williams (Mead, 1964; Williams and Mead, 1965) model for magnetotail currents. With time-varying magnetotail current location flux dropouts observed at geostationary orbit during substorm expansion phase were modelled. In this model, the injection front of Bourdarie et al. (1997; see above) was not included.

On the other hand, to reproduce the flux dropouts, only minor modifications to the magnetic field are needed, since the geostationary orbit is located in a region, where particle orbits are sensitive to even small changes in the magnetic field (P. Toivanen, private communication, 1998). The recent studies by Toivanen et al. (1999) also show that even moderate changes in the magnetic field, when translated to induced electric field, cause substantial variations in particle distributions during substorm cycles. Thus a model neglecting these terms clearly is not sufficient, if high accuracy is desired.

Particle drift model

Particles in combined magnetic and electric fields drift across the magnetic field, in addition to their rapid gyration around the magnetic field line and their motion along the magnetic field (e.g., Northrop, 1963). These drifts depend on the strength, temporal variation, and spatial gradients of the fields. In addition to these relatively slow drift motions, the particles may also experience acceleration by electric fields parallel to the magnetic field, as well as acceleration by wave electric fields.

In large-scale modelling the fast gyromotion around magnetic field direction is neglected resulting in equations governing the motion of the particle gyrocenter (i.e., the large-scale drifts). The lowest-order drift is the electric drift $\mathbf{E} \times \mathbf{B} / B^2$ which is the same for all charged particles. Slow time variation of the electric field introduces a polarisation drift term that separates electrons and positive charges leading to a polarisation current. Spatial gradients in the magnetic field introduce gradient and curvature drifts. In the nearly dipolar field around the Earth, the gradient and curvature drifts of electrons are eastward and of ions westward. The net current is thus westward.

Particle tracer

There are practically two ways of performing the drift calculations. One is to use the Hamiltonian formalism, as in Salammbô. One does not solve the equations of motion (given above) explicitly, but uses instead the adiabatic invariants in the Hamiltonian equations of motion, and solves the Fokker-Planck (diffusion) equation for the time evolution of the distribution function. Knowing the relation between the distribution function and particle flux, one can then calculate the corresponding measurable parameters from the distribution function.

This approach is effective when the magnetic and electric field configurations have (simple) analytic forms (like a dipolar magnetic field, and Volland-Stern electric field), leading to well-defined and well-behaved adiabatic invariants. In more complicated magnetic field geometries (like any non-dipolar magnetospheric field), the same analytic expressions are not valid, and the calculations become very time-consuming.

Another approach is to use a set of "test particles", which may represent an ensemble of particles with given energies and pitch angles at a given place, and follow their drift paths with integration of the equations of motion in time. At the same time the electric and magnetic fields are updated according to their time evolution (measured or modelled) during the event. This approach is used in the MSFM model, and, e.g., in the drift modelling by Toivanen et al. (1999). Special care has to be taken to ensure that the integration scheme conserves the constants of motion: In the case of a model that is not self-consistent, this has to be regularly checked.

In the Toivanen et al. model particle orbits averaged over one bounce period (time which it takes for a particle to travel from the equator to one mirror point above the ionosphere, to the other mirror point, and back to equator). Thus the smallest time step is the highest energy electron bounce period. The ions drift a substantial distance in the azimuthal direction during one bounce period, and this approach is not accurate to compute ion drifts. Also, the bounce-averaged formalism does not allow for exact energisation of particles (due to electric drifts) during the bounce period: only upper and lower limits are available. Diffusion due to wave electric fields and/or pitch angle scattering are straightforward to implement.

Particle heating due to plasma waves

In addition to drifting in the magnetic and electric field, particles also gain energy by being heated by interactions with plasma waves. Good models for the existence or heating efficiency of plasma waves in different parts of the magnetosphere do not exist. The results shown by the Salammbô group are calculated using a diffusion coefficient, based on simple assumptions of azimuthally constant heating region at the outer edge of the plasmasphere. The values for the diffusion coefficient were calculated using results from Lyons et al. (1972) and Thorne et al. (1973). The results show general agreement with data, but these values are only applicable for this very limited region, and for other parts of the magnetosphere similar models do not exist.

Boundary conditions: Particle sources

There are a number of statistical models for the particle environment in different parts of the magnetosphere. Probably the best modelled regions are the radiation belts, for which the NASA radiation belt models (AE8 for electrons and AP8 for protons, see Vette, 1991), models developed under ESTEC Contracts (TREND, TREND-2, see Lemaire et al., 1995, and TREND-3), and data from the CRRES spacecraft (Gussenhoven et al., 1996) are available.

For other important source regions of plasma in the magnetosphere, the availability of models is not as good. An important reservoir of plasma is the plasmasphere. Plasmaspheric models have been developed, and the average properties at the equator are relatively well known (e.g., Carpenter and Anderson, 1992: an empirical model for equatorial electron density). Lambour et al. (1997) used a modified version of MSFM to model the behaviour of the plasmasphere following storm sudden commencements, with the Carpenter and Anderson model as an initial condition.

The plasma sheet is an important source of particles, especially during magnetically active periods. However, there are no useful models for the plasma sheet. The most coherent set studies of plasma sheet properties, based on measurement on board the AMPTE/IRM spacecraft, was summarised by Baumjohann (1993).

The ionosphere is another important source of magnetospheric plasma. However, its role is more of filling the reservoirs of the plasma sheet and plasmasphere, of lesser importance for this study.

It is important to keep in mind that variations of, e.g., energetic electron flux, from statistical values can be as high as several orders of magnitude during disturbed conditions. Thus, as a conclusion, the only really reliable boundary condition in a source region is an in situ measurement.

Boundary conditions: Particle loss model

In the first order approximation, particles are lost either through precipitation to the ionosphere/ neutral atmosphere, charge exchange, or by drifting to dayside and lost to non-closed orbits.

The precipitation to ionosphere can, in the simplest approach, be modelled through removing particles that have their magnetic mirror points below a given altitude. This is equivalent to assuming a completely absorbing ionosphere. A more accurate model, using an exosphere neutral gas model, and friction model to describe the interaction of energetic particles with neutrals, has been successfully implemented in the Salammbô model (see Beutier et al., 1995)

The efficiency of charge exchange as a loss process depends on neutral (hydrogen) density, and the details of the charge exchange process. Energetic Neutral Atom (ENA) production through charge exchange is generally accepted to be an important mechanism for ring current energy dissipation, and modelling of ENA production during magnetic storms has been presented (e.g., Roelof et al., 1985; Roelof, 1987). However, even if steps towards modelling the microscale interactions and their relation to ENA production have been taken, the models are not mature to be used in an operational model.

Energetic particle loss by drift is automatically included in a complete drift model: When particles drift to non-closed orbits, they are lost from the model.

6.5.5. Resource estimates

Computer resources

The modelling tool, if based on a particle drift model approach, sets high requirements on computing power. Memory resources are not extensive (on a 3D particle drift code one has 12 variables / test particle), but the computations take a long time. The Toivanen et al. (1999) particle drift code used the Tsyganenko 1989 magnetic field, with modifications corresponding to the time-varying magnetic field during substorms, and inductive electric fields calculated from the variation of magnetic field. For modelling of one orbital period of the CRRES satellite (approximately 11 hours of real time) by backward calculation of particle drifts from the substorm onset to the measurement during previous orbit, takes approximately 16 hours of computer time on a fast workstation/server machine (P. K. Toivanen, private communication, 1998).

Most of the time is spent on the tracing of the magnetic field lines of the model, and the more complicated the model is, the slower calculation. It is estimated that tracing the field lines of the Tsyganenko 1996 model takes approximately 10 times more time than tracing the T89 model (N. A. Tsyganenko, private communication, 1998). The tracing part of the code cannot be vectorised, and thus not much better performance is expected on a vector processor.

Manpower resources

Present research models have been developed gradually, as research projects, during several years, and are in continuous development. In general, approximately one third of the development project consists of planning, one third actual programming, and one third tests and, finally, "production" runs. For research models, each "production" run of the model can be considered as one more test.

The effort needed for developing a physics-based model of the dynamics of the magnetosphere is extremely difficult to estimate. However, to give an idea of the order of magnitude of the work needed, we give three sample cases:

The development of the 3D MHD model by Janhunen (1996) was started in 1995, and the model (now in third generation) is still in continuous development. The model today consists of about 35000 lines of code (in C++), including visualisation. Recently almost 95 % of the development work of the code has been directed towards computational efficiency.

Another example, the drift model by Toivanen (1995) was originally developed in one year by one person. That version of the model did not include the time-varying magnetic field, nor the inductive part of the electric field, which both are essential for a complete description of the dynamics. Finding a workable solution for the implementation of these two physical phenomena into an efficient computer code, coding, and testing, took then almost two years (Toivanen et al., 1999).

The first results of the Salammbô model were published in 1995 (Beutier et al., 1995). Since then, the model has been gradually developed, and still, after 3 years from the first results, modifications are made to make the accuracy better (in terms of both qualitative and quantitative agreement with observations). Updating the model with some of the Tsyganenko magnetic fields has also been considered, but not implemented.

The research modelling projects typically are, or at least include, work directed towards doctoral thesis, and thus one could argue that the persons working on the model development perhaps are not the most skilled professionals, neither in physics, nor in computational mathematics. We would not, however, draw this conclusion. Fact is, that there are no better specialists on those fields, and the support by the research groups is enough to guarantee continuation of work. Of course, one can benefit a lot if there is support from specialists available, when needed, but we do not think that would speed up the progress by a factor of two.

Thus one could think that writing a simulation model software is a work of a year or two for a small group of engineers and physicists. It *is* in principle quite straightforward to translate the basic physics equations to a numerical computer code, but to make the model give physical (and even quantitatively correct) results in an acceptable computing time, quite a lot of technical problems have to be solved. This is analogous to building an instrument for space measurements: The basic design is quite straightforward, but to take into account the limitations of mass, power, and telemetry, and still get useful results, one has to work a long time. Usually the problems are solved in an iterative manner (by trial and error) and finding the right solutions to the problems requires a lot of thinking. In conclusion: A computer engineer, even if highly skilled, cannot translate the physics equations to an efficient working model without help from physicists, who know the problem, and maybe skilled mathematicians, specialised in computational mathematics. In an ideal situation, of course, some of these properties are combined in one person.

6.6. Space weather information server

As a part of this project a public WWW server has been developed. It contains
- Links to other space weather servers
- Description of the existing European space weather resources on WWW
- Access to data bases necessary for estimation of satellite anomaly risks
- Technical notes and other documentation of the present study

The address of the server is: http://www.geo.fmi.fi/spee

6.6.1. Links to space weather servers

There are hundreds of space weather-related WWW-servers world-wide. The focus of this server is on operational pages, i.e., modelling and forecasting aspects are underlined. Concerning "purely" scientific servers on ionospheric and magnetospheric physics, we have focused emphasis on European sites, which are also described in more detail within the server itself. The level of space weather pages varies significantly. Some sites provide exact and detailed information, while others are quite short. We have excluded links that contain only little relevant material, or which only reproduce information given on original servers.

The SPEE link lists cover the following topics:
- Case studies

  Most of the events selected here are contributed by several research teams. These presentations are mainly of quick-look type, i.e. contain data and some modelling results. Detailed (and refereed) results should still be read from traditional journals.
- Data

  These are pages with near real time data of the Sun, solar wind, magnetosphere, ionosphere, and geomagnetic field. Additionally, some links to large data archives of older data are included. There are also a huge number of smaller data collections of various projects available on WWW. They are not listed here, but they can be searched for by starting from the link collection page.

- Forecasts
  Space weather forecasts mainly concern with the geomagnetic activity of the next few days. Many of them also contain near real time data.
- General information
  A collection of servers providing space weather information on diverse levels mainly for professionals, but some educational servers are specially written for the large audience. Many of these sites are also included in other topic lists.
- Ground effects
  Some servers contain descriptions on space weather effects on ground technology (mainly power systems) or climate.
- Link collections
  These links points to servers containing extensive lists of solar-terrestrial information. This page is a starting point to find links that are not included on the SPEE server.
- Model development
  Most modelling work presented here deals with the magnetosphere without a direct aim to space weather forecasting. However, these are necessary models for understanding basic physics. Many of them could be developed or already are useful for forecasting or post-analysis too.
- Radio propagation
  A number of links are available which are specifically tailored for radio amateurs. Information is based on solar-terrestrial data obtained from data servers.
- Software
  Some space weather related programs or program packages are described on WWW. So far, interactive use is quite limited.
- Spacecraft environment
  These pages deal mostly with spacecraft charging.

For a convenient access to near real time solar-terrestrial quick-look data plots and forecasts, there are two separate shortcut link collections. Additionally, there is a simple form for key word searches from an ASCII list of space weather servers.

6.6.2. Spacecraft charging databases

The server contains the data base analysed under the present project and discussed further in Chapter 4 above.

6.6.3. Technical remarks

The structure of the server has been kept simple to allow for a convenient and fast use by all widely known browsers. HTML files are compatible with the 3.0 version.

The link list pages are created by a Perl script reading as input an ASCII file, which lists space weather servers and associated key words in a simple format. This allows for an easy and flexible maintenance of the server list. The same ASCII file is used by the search tool, also written in Perl. Access to the internal pages has been restricted by the standard method of .htaccess files.

The space weather WWW servers are as uncontrolled as anything in the WWW. New relevant pages appear regularly, others change their URL, and some of the pages are left there although their content becomes obsolete. Thus there is need for continuous updating of the pages. This requires a regular checking of links (e.g. once a month), as well as active searching for new sites.

6.7. Assessment of specific European capabilities for space weather activities

It is not straightforward to give a full picture of European capabilities in the field of space weather. The meaning of the very concept of space weather is still rather unclear and different interest groups use it differently to seek support to their own activities. Most of the space weather modelling discussed above has started before the whole term was coined. The spacecraft engineers may prefer to talk about space environment modelling and there has been some reluctance to accept the American term by the European STP community as well. During the present project the meaning of space weather was brought up in several discussions and a small questionnaire was sent to some key European players. We briefly summarise here the main results of this questionnaire.

6.7.1. Relationship between space weather and STP science.

While some of the proponent of the US NSWP have voiced an opinion that STP and space weather are (nearly) the same thing, in Europe the claim that there is, or should be, a distinction between STP and space weather seems to be more popular: STP is basic research, the results of which may be converted to space weather products and services whereas space weather is more application-oriented concept which can stimulate and challenge STP but should not direct the STP research. It is important to realise that development in space weather monitoring and prediction capabilities must be driven by users, not by the model developers. It is not possible to develop successful products by creating artificial needs. For example spacecraft constructors want solutions to their immediate problems, not ten-year research programme. Thus it is essential to have a vital basic STP research living in harmony with the application-oriented space weather

6.7.2. Volume of European space weather activities.

The European resources are scattered. ESTEC possesses considerable experience with various aspects of space environment modelling. The recent contract studies in space environment modelling (TREND-1, -2, -3, SPENVIS, SPEE, SEDAT) have been successful in fostering further contacts between groups having relevant competence. Of active groups we can mention RAL, MSSL, AEA Culham, and DERA in the UK, CERT-ONERA in France, IASB in Belgium, NDRE in Norway, IRF (Kiruna, Uppsala, Lund) in Sweden and FMI in Finland.

6.7.3. Strengths and weaknesses in Europe.

There seems to be wide consensus that the European STP science is on a very high level. With SOHO ESA has gained a leadership in one of the key areas of space weather, the Sun.

When it comes to weaknesses in Europe it is useful to compare with the US space weather community. First, the European resources are scattered and there is no clear structure on which to base co-operation. Second, in Europe there is much less cross-fertilisation between the science and application communities than there is in the US. This lack of communication is a particularly serious problem in the field such as space weather where the problems deal with complicated and very expensive technological systems whereas the origin of the problems is in very complicated physics.

6.7.4. Awareness of products

Understanding of a space weather product varies from the science community to the spacecraft engineers. While the science community often sees the models as products they can provide to the applications community, the user of space weather may be interested in the output of the models only. This also reflects the missing dialogue between science and engineering mentioned above.

For the product development the question, who are the users, is a problem. In order to develop products their users should be identified and in order to find users there should be products to offer to them.

6.7.5. Engineering solutions vs. forecasting

It has been asked whether space weather activities should lead to engineering solutions to get rid of the problems once for all, or should we go toward ordinary weather service-type of activity with forecasting and warning. The most reasonable answer is that both are needed. The immediate engineering solutions are necessary but solving the space weather-related problems totally by mission design may become too expensive. There are also hazards that cannot be avoided by engineering, e.g., launch conditions, re-entry to the atmosphere, EVA.

The STP community sees the forecasting development perhaps more challenging than provision of average radiation doses based on long-term statistics to the spacecraft engineers. Also the spacecraft operators would like to know when they should avoid complicated manoeuvres of their spacecraft, especially when the spacecraft become old and more susceptible for anomalies. In the middle between design analysis and forecasting is the specification (nowcasting) which is particularly helpful when something has happened and it is important to know why. As a conclusion there is a continuous need to develop better models for spacecraft engineers but also the forecasting and warning need to be improved.

6.7.6. European autonomy

One of the main motivation for founding of ESA was the establishment of autonomous European space programme. This is an important overall political goal but the degree of autonomy may still vary in various fields of space activities. Concerning the autonomy in space weather the European opinions on autonomy vary from the request for full autonomy to comments that there is no more such a thing as European autonomy. It is clear that space weather is something very global and, for example, proper monitoring of space weather cannot be done by Europeans alone. The strongest space weather activity is in the US and the NSWP will further strengthen their position. Good co-operation with the Americans is probably the most reasonable way to proceed. However, without strong own activity Europe cannot be a credible collaborator.

6.7.7. How Europe should organise the space weather activity?

To this question all kinds of answers are given, extending from "do nothing" to "establish a full-scale European space weather centre". Three alternative levels of engagements are discussed in section 6.8.2. below.

6.7.8. Where to put the European efforts?

Also here the opinions vary much and reflect the background of each individual. Those who work with data bases, see them as the most urgent task, models are the most precious to the modellers. It is clear that engineers need engineering models whereas forecasters need simulation models and input data. A balanced programme should respond to all these interests.

6.7.9. Where are the future markets?

Perhaps the greatest surprise of our investigation of European opinions was that the manned space flight was expected to be the most important market of space weather products in future. This is understandable in the sense that if an astronaut will be killed or seriously harmed by a space weather event, this will get much stronger media response than the loss of Telstar 401 in 1997. However, it is likely that for long time to come the most active users will be the spacecraft engineers and spacecraft operators, including the launch and re-entry operations.

6.8. 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 the coherent strategy was possible to formulate.

6.8.1. Who should take the lead?

When asking this question we have received three main answers: ESA, EU, and 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 very active in practical space activities. It is very difficult to see how EU could take the lead in this rapidly growing and very up-to-date area. 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 space environment effects (SEE). 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 negligible part of the total annual R&D budget of ESA (≈ 40 MECU).

To speed up the process of creating an European space weather agenda the STP community can be very helpful. In the US the NSWP was very much a response to 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, and furthermore, the military sector is much more active in the US. In Europe a particularly authoritative body is the ESA Science Programme. We thus recommend that:

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

2. Form a formal Science/Technology Interdisciplinary Space Weather Programme that 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 coordinated 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.

6.8.2. Possible level of concerted European approach

We also 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 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, and SPEE.

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 solution. 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.

6.9. 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 is 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 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.

7. CONCLUSIONS

Need to understand space environment effects has existed since the first space flights some 40 years ago and even longer if we include the effects on the ground. These 40 years have contributed a wealth of knowledge on the space environment effects and we have learned much how the harmful consequences can be avoided, or at least minimised. However, the space environment remains hazardous. The society is more and more dependent on space technology, the human presence in space is expected to increase, and at the same time there is a tendency toward smaller and more vulnerable electronic components. All these facts underline the need for intensified efforts toward better understanding of the space environment and its effects on technological systems, and toward better warning and forecasting methods.

During last few years the new concept of Space Weather has entered into the scene of space environmental effects and solar-terrestrial physics. While the concept can be argued to be just a new package of old goods, it has had a positive influence making more people aware of the unifying views of the different disciplines. For example, in Europe the communication between the space science community and spacecraft engineering and operations has not been very good. Under the realm of space weather we have a new forum for science and applications communities to meet each other. Space weather is an application-oriented discipline which, at the same time, provides great intellectual challenges to the scientists. On the other hand, the future space weather products need significant scientific expertise to be developed, especially when we come to the question of real forecasting of space weather conditions.

The project summarised in this document was conducted by scientists having expertise in solar-terrestrial physics, spacecraft charging, neural networks, modelling, simulations, etc. However, we certainly hope that the results of this project are useful also for the applications community.

7.1. Charging of Freja

The basic principles of spacecraft charging are well-known but the actual occurrence and severeness of charging events are not known in detail. In this particular study the low-altitude charging events were investigated using the data base of the Freja satellite. While the spacecraft was successfully designed to be electromagnetically clean and highly conductive, it, nevertheless, experienced charging when it crossed a region of intense auroral electron precipitation. To become charged the spacecraft required very low ambient plasma density of 2×10^9 m^{-3} which was about five times smaller than the corresponding threshold for the DMSP satellite. But when the spacecraft became charged, it sometimes reached very large negative potentials, more than –2000 V, under the most intense electron precipitation in the 10-keV energy range. Most, but not all, charging events took place in eclipse and all charging events took place during winter months. From the observed data it can be considered as proven that the auroral electrons of several keV energies are a source of concern for polar orbiting spacecraft.

Several of the Freja charging events were modelled using the POLAR charging code. Even after a very careful modelling of the spacecraft shape and surface materials as well as the observed electron spectra it was impossible to reach the observed charging levels, especially the highest charging levels showed to be beyond the capability of the model to reproduce. Nevertheless, this study gives useful hints for further development of the POLAR code. It must be noted that POLAR was originally designed for studies of the DMSP series satellites in a lower orbit (about 800 km) and, consequently, higher ambient plasma density.

7.2. Satellite anomaly forecasting

The satellite anomalies on GEO were analysed using anomaly data bases from the European meteorological satellite Meteosat-3 and the Swedish telecommunication satellite Tele-X.

Meteosat-3 carried an instrument for local observations of electrons in the range 43–300 keV. These observations were used to study how well neural networks could be trained to predict observed satellite anomalies. After treating the particle data with principal component analysis the networks were found to train well. Requesting that non-existence of anomalies during next 24 hours had to be predicted at least at 80% accuracy about 50% of anomalies were possible to predict based on the local input data.

Tele-X, as most GEO satellites, did not carry instruments to study the local space weather conditions. Both Meteosat-3 and Tele-X anomalies were studied using non-local data including energetic particles ($E > 2$ MeV) from geostationary GOES-6, GOES-7, and GOES-8 spacecraft and ground-based magnetic activity indices Kp and Dst. In this study several variations of neural networks were tested. It was found that the best predictions were obtained using the Kp index, the best predictions for Meteosat reaching about 80% for both anomalies and non-anomalies. The Dst showed to be a less successful predictor. The non-local electron data was not found as useful, especially due to its less accuracy to predict non-anomalies.

Both local and non-local input data were combined in a study to search for a satellite anomaly index. It was found that by combining the non-local and local observations reasonably good anomaly indices can be constructed. However, the index used by satellite operators could be adjusted for each satellite individually, reflecting the fact that anomalies of each spacecraft are caused by a particular combination of environmental characteristics, which can be highly hardware dependent. In addition to local measurements of high-energy electrons, simple lower-energy detectors in the 0–10-keV range are required.

7.3. Space weather modelling

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.

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. It is suggested that the ESA Science Programme should take space weather on its agenda, a formal Science/Technology Interdisciplinary Space Weather Programme which should report to SPC/SSWG and IPC should be initiated, and 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.

7.4. WWW space weather server

The World Wide Web provides an excellent tool to gather up-to-date information. The web is, however, an uncontrolled organism where the information is continuously updated and it requires some expertise to find the most relevant information sources. The WWW server developed in this project is designed to help in this process. We recommend that the readers use this tool in their studies of space weather its interaction with spacecraft. Once more, the address of the server is:

http://www.geo.fmi.fi/spee

This server contains the public documentation summarised in this report and useful links to space weather servers all over the world.

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