Space Weather and Interactions with Spacecraft

Final Report of

Study of plasma and energetic electron environment and effects

ESTEC/Contract No.11974/96/NL/JG(SC)

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PREFACE

This document is the final report of the ESTEC/Contract No.11974/96/NL/JG(SC) "Study of plasma and energetic electron environment and effects (SPEE)". The document summarises the results of the project in a self-contained manner. In addition to this document the different work packages produced Technical Notes and URD/SRD listed below which are available upon request from ESTEC and at the WWW-server of this project: http://www.geo.fmi.fi/spee/docs/

The goals of the present study were to

- gain better understanding of spacecraft charging phenomena
- investigate the forecasting of satellite anomalies based on anomaly database
- summarise the European capabilities in the fields related to space weather and determine requirements for establishing a European space weather programme.

The study was organised under the leadership of the prime Contractor, the Finnish Meteorological Institute, Geophysical Research (FMI/GEO), with two units of the Swedish Institute of Space Physics, Uppsala (IRF-U) and Kiruna (IRF-K) as Subcontractors. In addition to the overall management, FMI/GEO was responsible for the third of the items above. IRF-U took care of the first item (section 4) and IRF-K the second item. The Technical Officer at ESTEC was A. Hilgers. The Project Manager was H. Koskinen from FMI/GEO and the University of Helsinki.

Relevant documents from individual work packages:

WP-110-TN: Charging events identification and case study of a subset of them
WP-120-TN: Modelling of Freja observations by spacecraft charging codes
WP-130-TN: Analysis of Freja charging events/Statistical occurrence of charging events
WP-210-TN: Spacecraft anomaly forecasting using local environment data
WP-220-TN: Spacecraft anomaly forecasting using non-local environment data
WP-230-TN: Spacecraft anomaly forecasting using heterogeneous environment data
WP-310-TN: State of the art of space weather modelling and proposed ESA strategy
WP-320-URD/SRD: Requirements for modelling tools for space weather programme
WP-330: WWW-server: http://www.geo.fmi.fi/spee

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In this kind of a project it is always difficult to give proper credit to all people and organisations who have contributed to its successful execution.

We are deeply indebted to Dr. D. Cooke (US Air Force Research Laboratory) for the provision of the latest version of the POLAR code as well as for instructions and discussions on its use. Without it one of the most important parts of this study would have suffered considerably. Another crucial contribution was the Tele-X anomaly set provided by the satellite owner (Nordiska Satellitaktiebolaget, NSAB). Jonny Järnmark at the Swedish Space Corporation in Kiruna made this possible. Comments and opinions of two members of the Tele-X operational team G. Töyrä and H. Kling were very much appreciated. The Swedish Space Corporation (SSC) contributed substantially by providing the material information of the Freja satellite, for which we are indebted to P. Rathsman. Of course, SSC's excellent management was essential to make this small satellite project successful.

Great number of scientists has given important input to our project. Among the most important were R. Behnke (NSF), D. Boscher (ONERA-CERT), T. Clark (British Geological Survey), C. R. C. Clauer (NSF and University of Michigan), E. Friis-Christensen (DSRI), A. Johnstone (MSSL), J. Lemaire (IASB), D. Rodgers (DERA), R. Schwenn (MPAe), H. Singer (NOAA/SEC), G. Wrenn (T S Space Systems). Furthermore, we wish to thank all those scientists who have contributed to the several space weather-related sessions at various scientific meetings where our team members have participated.

Several of our colleagues at FMI and IRF have contributed in many ways to this project. We wish to give our special thanks to O. Aulamo, P. Janhunen, H. Laakso, R. Pirjola, P. Toivanen, and W. Schmidt from FMI/GEO; I.Sandahl from IRF-Kiruna; T. Carozzi, E. Dackborn, and L. Wedin from IRF-Uppsala; L. Liszka, from IRF-Umeå; H. Lundstedt and P. Wintoft, from IRF-Lund; R. Moses and J. Waldemark, from Umeå University. We also thank each of these institutes for providing their facilities and infrastructure to our project.

Last but not least we wish to thank the ESA TOS-EMA for initiating this project and their interest throughout its completion. Special thanks belong to the ESTEC Technical Officer Dr. A. Hilgers and to Dr E. Daly whose comments were particularly useful. Furthermore, the preliminary study by U. Svensson who was a stagiare at ESTEC was very useful for us.

ABSTRACT

Space weather is a new concept addressing the electromagnetic and charged particle environments of the Earth and their effects on space-borne and ground-based technological systems. In this investigation spacecraft charging phenomena on high-inclination low Earth orbit (PEO/LEO), satellite anomalies on geostationary orbit (GEO), and global space weather modelling have been investigated.

The PEO charging was studied using the database of the Swedish-German Freja satellite. While the spacecraft was successfully designed to be electromagnetically clean and highly conductive, it, nevertheless, experienced charging events of negative potential when it crossed the auroral electron beam. The largest potentials were estimated to exceed –2000 V. Most, but not all, charging events took place in eclipse. Furthermore, all charging events took place during winter months. Several severe payload operation problems occurred during charging, and the high charging levels are large enough to cause arcing effects. This suggests that auroral induced charging may be of concern for future spacecraft operation and design.

Several of the Freja charging events were modelled using charging codes. Even after careful modelling of the spacecraft shape and surface materials as well as the observed electron spectra it was found that the charging levels could not be modelled well, especially the large charging levels caused by intense 10-keV electron precipitation were not possible to achieve. This study gives useful hints for further development of the charging codes to account for auroral plasma environment.

The satellite anomalies on GEO were analysed using anomaly databases 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 lower 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 combining the non-local and local observations reasonably good anomaly indices can be constructed. However, the index used by satel-

lite operators must be adjusted for each satellite individually. In addition to local measurements of high-energy electrons, simple lower-energy detectors in the 10-keV range are expected to be useful.

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

The European solar-terrestrial physics community has strong scientific competence in the fields relevant to space weather modelling and forecasting. On the technological side Europe has good expertise in modelling of the effects of space environment. However, the cross-fertilisation between scientists and engineers is much weaker in Europe than in the US.

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) has given European scientists 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.

User and software requirements for a physics-based space weather modelling tool capable of specifying the conditions in the inner magnetosphere were investigated in the form of User and Software Requirements Document. The most visible output of the project is an open World Wide Web space weather server installed at the Finnish Meteorological Institute and at ESTEC (http://www.geo.fmi.fi/spee).

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

1) The ESA Science Programme should take space weather on its agenda
2) A formal Science/Technology Interdisciplinary Space Weather Programme that should report to SPC/SSWG and IPC should be initiated
3) ESA should initiate work to establish a European Space Weather Data and Model Centre (either centralised or distributed with a central core). This Centre should have as its goal to become a European Data, Model, and Specification Centre, and it should look for a workable solution for a full-scale European Space Weather Centre.

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1. INTRODUCTION

The plasma environment, especially energetic electrons in the upper atmosphere and in the magnetosphere surrounding the Earth form a hazardous environment to man-made Earth-orbiting satellites. As more and more everyday functions rely on satellite operations, knowledge of the plasma and energetic particle effects on technological systems, including reliable modelling and forecasting methods, has become increasingly important. This has led to a number of initiatives world-wide toward more coherent and goal-oriented programmes often referred to as Space Weather programmes.

For both spacecraft engineering and operations, a key question is when, where, and why satellite charging and other environment-related anomalies occur, and how hazardous these phenomena may be. Although much work has been devoted to the understanding of the charging and other anomalous phenomena, and to protection against them, they still take place, sometimes with serious consequences. The development of smaller and more sensitive electronics and, most likely, the increasing use of spacecraft in the most hazardous orbits crossing high latitudes and radiation belts point out the necessity for intensified effort to understand both the origin and effects of these events.

In the present project the recently acquired database from the Swedish Freja mission has been extensively used for studies of charging phenomena. Although Freja was electromagnetically very clean, it experienced a relatively large amount of charging events. Because the spacecraft was specifically designed to study the electromagnetic environment with a several electric probes and particle detectors, its data set allows for both detailed single event studies and statistical considerations. It is also important that Freja's inclination of 63 degrees brought it above the auroral zone from where we have much less experience of charging effects than from geostationary orbit. This together with the altitude range of the Freja orbit (600–1700 km) make this particular study especially relevant for future high-inclination spacecraft. When the Freja charging events were studied with the help of charging codes NASCAP and POLAR, it was found that the high-latitude charging phenomena pose considerable challenge for understanding and, consequently, further development of modelling tools for charging is needed.

Before global "physics-based" models with satisfactory advance prediction, i.e., forecasting, capability will be usable, and most likely also thereafter, an alternative approach to predict the occurrence probability of satellite anomalies is to use information on past anomalies and conditions under which they took place. The commercial spacecraft operators are often reluctant to release their anomaly data bases, but for this study the Meteosat-3 and Tele-X anomaly data were made available. The anomaly data were related both with the local observations onboard the spacecraft in question and/or with non-local data specifying global solar-terrestrial conditions. In this study these data sets were thoroughly analysed using modern neural network techniques. The results were encouraging showing that it is possible to develop a spacecraft anomaly predictor for such phenomena that depend on the state of the magnetospheric plasma. Unfortunately, a large number of anomalies are related to cosmic rays whose appearance is not predictable in the same way.

However, without extensive further development of tools for global modelling of the geospace dynamics, the only way of avoiding hazards due to space environment effects is to build space weather-proof spacecraft which in many cases would require extensive over-design with associated costs. During past few years the development of useful models has advanced significantly due to rapidly increasing computer resources and improved large-scale models for the interactions between the upper atmosphere, the ionosphere, the magnetosphere, and the solar wind. Especially, in the United States a considerable effort has been focused to the creation of truly global space environmental modelling with forecasting capability within the framework of the National Space Weather Program. Although Europe has good resources in this field both in terms of intellectual capacity and computer facilities, the resources are scattered and there evidently is a need for a more concentrated European effort. European resources and opportunities were studied as a part of the present project.

Last but not least, it is important that the widely scattered space community interested in the information of this study gets an easy access to its results. As a visible outcome of this project, a public World Wide Web (WWW) server has been developed and installed at ESTEC with a mirror server at the Finnish Meteorological Institute. The public parts of the server contain detailed information of European space weather resources, links to the relevant Web servers world-wide, samples of relevant data sets, and means of retrieving data from various data bases. WWW is a continuously evolving structure where links change and become obsolete. This particular is planned to be maintained and updated over several years to come.

2. SPACE WEATHER

2.1. What is space weather?

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

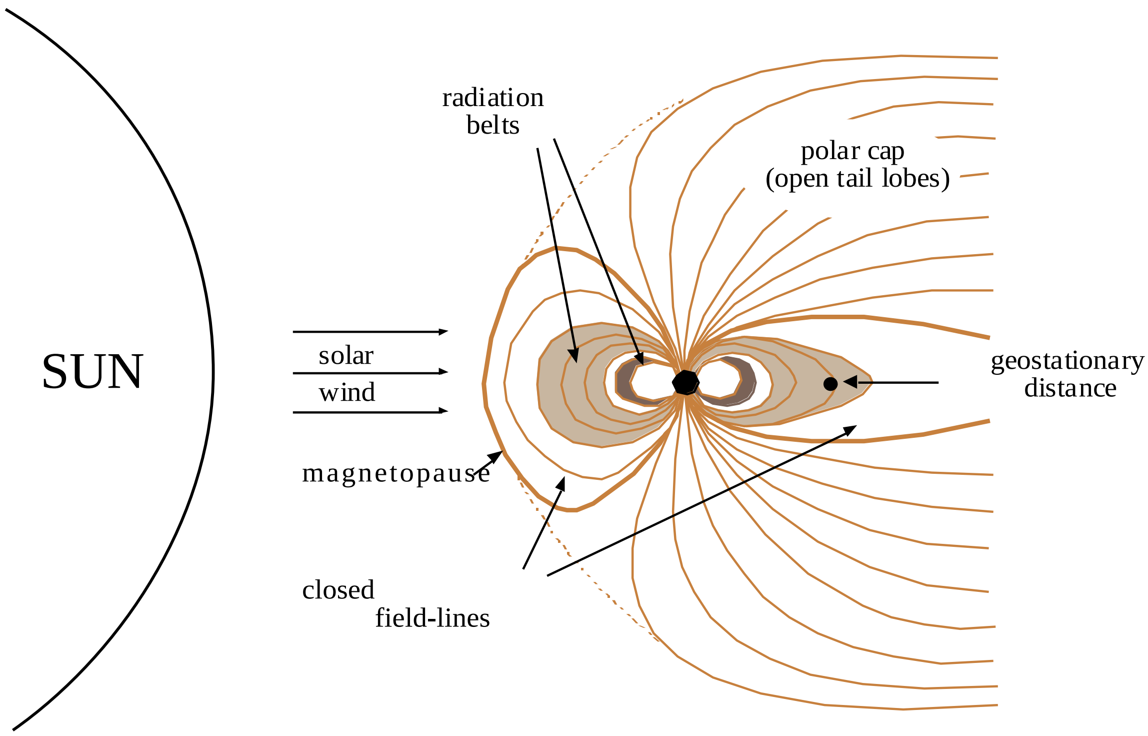

Figure 2.1. Main physical domains of space weather

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

2.2. What are space weather activities?

Space weather has many similarities with atmospheric weather; thus the design of future space weather activities will, to a large extent, utilise the experience from meteorological services. This is already now a fact at Space Environment Center (SEC) of NOAA, and the 55th Space Weather Squadron of the US Air Force, both in Colorado, USA.

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

1) While many meteorological processes are localised and it is possible to make good limited-area weather forecasts, space weather is always global in the planetary scale. This arises from the large spatial scale-sizes of the solar-terrestrial plasma systems and the long correlation times of these plasmas. The most important and most dramatic effects originating from the Sun disturb the Earth's plasma environment, the magnetosphere, which responds to these disturbances globally.
2) Space weather events occur over a wide range of time scales: the entire magnetosphere responds to the solar-originated disturbances within only a few minutes, global reconfiguration takes a few tens of minutes, and sometimes extreme conditions may remain for much longer periods. The fastest signal in the global magnetospheric system is associated to the so-called Storm Sudden Commencement (SSC): ground-based magnetometers react immediately to a significant change in the magnetopause current system when a strong solar wind disturbance hits the magnetosphere. At the slowest end the enhanced fluxes of energetic particles in the radiation belts decay in time scales of days, months, or even years.
3) Our means to monitor the space weather are much more limited than our ability to install weather stations on the Earth's surface: Our prediction schemes must be capable of functioning with input from only a few isolated measurement points in the upstream solar wind conditions and magnetospheric parameters. These aspects are discussed in more detail below in the section dealing with the physics requirements for space weather modelling. As a consequence of these properties, successful space weather activities are performed on a global scale, merging space-borne and ground-based observational capabilities.

There is no doubt that at present the US is further ahead in space weather activities than other countries: They have the largest number of spacecraft, their scientific STP community is the largest, and they already have some operational space weather activities. This is demonstrated by the documentation of the National Space Weather Program (NSWP), which is a result of an initiative from the American space science community in 1993. The Strategic Plan of the NSWP was published in 1995 and the Implementation Plan in 1997.

The European activities and capabilities for an extended European approach are analysed in Chapter 6 below. At present, while Europe has a strong scientific community in the field of STP, there are only few attempts toward space weather, and the resources are scattered to relatively small groups in different countries. Furthermore, Europe is not as independent in space-borne facilities as the US is. The US STP community has always maintained synergies with the applications community. Space physicists often act as consultants on space environment issues for aerospace companies and military organisations. This kind of ties are much weaker in Europe.

As space weather is a global phenomenon, it is not clear that Europe should aim at full autonomy in this field. Actually, although the US NSWP has a strong national flavour, there is a general understanding that the programme must be widened to become international. Most of the present space weather activities are driven by the scientific community and the awareness of the users is only beginning to emerge. When the user awareness increases and more space weather tools and products are developed, the needs to protect national (or e.g., ESA) technological assets and commercial interests move also the space weather modelling away from the scientific openness. This is one reason why ESA should have a clear space weather policy to support the European space weather activities in their integration to the international space weather community.

On the truly international level there actually already exists an organisation that covers most of the world, The International Space Environment Service (ISES) (see: http://www.sel.bldrdoc.gov/ises/ises.html). ISES is a joint service of URSI, IAU and IUGG and a permanent service of the Federation of Astronomical and Geophysical Data Services (FAGS). There are ten Regional Warning Centres (RWC) scattered around the globe. These centres are located in Beijing (China), Boulder (USA), Moscow (Russia), Paris (France), New Delhi (India), Ottawa (Canada), Prague (Czech Republic), Tokyo (Japan), Sydney (Australia), and Warsaw (Poland). A data exchange schedule operates with each centre providing and relaying data to the other centres. The centre in Boulder plays a special role as "World Warning Agency", acting as a hub for data exchange and forecasts. For some reason the awareness of ISES among the present day space weather activists has remained smaller than expected, regardless of the fact that ISES has organised well-attended Solar Prediction Workshops, the latest one in Japan 1996.

Of the European ISES Centres the centre in Paris is the most active in space-based applications, in particular providing services for spacecraft orbits, altimetry, as well as launch and re-entry calculations (see: http://previ.obsem.fr/previ).

2.3. What is a space weather product?

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

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

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

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

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

2.4. Who are the users?

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

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

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

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

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

3. IMPACT OF SPACE WEATHER EFFECTS ON TECHNOLOGICAL SYSTEMS IN SPACE AND ON GROUND

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

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

3.1. Examples of hazardous space weather events

3.1.1. Historical examples

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

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

3.1.2. Recent satellite failures

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

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

A coronal mass ejection emerging from the Sun formed a magnetic cloud, which impacted the Earth on January 10, 1997. On early morning of January 11, 1997, AT&T lost contact with its Telstar 401 satellite. Telstar 401, one of the two Skynet satellites, was fully functioning before the incident. The other, Telstar 402R, took re-routed network signals right away following 401's difficulties. Satellites like the Telstars transpond TV programmes, telephone calls, and computer data. The magnetic cloud caused an exceptionally strong enhancement of relativistic electron fluxes in the Earth's magnetosphere detected both by geostationary and low-altitude polar-orbiting satellites. These electrons remained within the radiation belts for over a week after the incident. Evidence suggests that the increased levels in the radiation environment were connected to the malfunction of the AT&T Telstar satellite although it has remained unclear what the immediate cause of the failure was.
(see http://www-istp.gsfc.nasa.gov/istp/cloud_jan97/event.html)

3.1.3. Other effects on spacecraft

Interference and other hazards (SEUs, problems with star tracking, etc.) are much more common than the most publicised examples discussed above. Examples of space weather related problems on European satellites include radiometer stops of Meteosat, SEUs on most satellites (ISO, Hipparcos, ERS, SOHO, etc.), ISO experienced problems in its star tracker, and so on. Exact information on anomalies is difficult to get. The commercial companies consider this information confidential but even inside space organisations there is reluctance to admit problems. Another problem is that there are no standards how to collect anomaly information. At the beginning of a spacecraft mission the operators report on all anomalies but when more experience of the spacecraft behaviour has been gained, the less harmful anomalies are not always recorded. However, when anomaly information has been available, various effects have been traced directly to space weather events, thus it would be useful to organise homogeneous procedures to gather and report on all anomalies. In Chapter 5 below we discuss the determination of empirical anomaly indices based on extensive anomaly databases from two operational spacecraft Meteosat-3 and Tele-X. Another useful reference is Wrenn and Smith (1996) that includes a table of reported anomalies due to electrostatic discharges (ESD) from 47 spacecraft.

3.2. Spacecraft charging and satellite anomalies

Spacecraft charging and satellite anomalies are closely linked to each other. While spacecraft charging is a general physical phenomenon that cannot be totally avoided, it does not necessarily lead to anomalous behaviour of the spacecraft. On the other hand, damaging anomalies can be due to excessive charging.

Satellite anomaly is here defined as a change in spacecraft behaviour for which the spacecraft was not designed and which is not caused by an operational error. This can be anything from a bit flip to a total malfunction of the spacecraft. In the early days of space activities, some anomalies on geostationary (GEO) spacecraft were linked to the photoemission of the sunlit surfaces. With this knowledge new design recommendations for spacecraft were made. In plasmas where the local Debye length is larger than the spacecraft dimensions (such as in GEO) the main recommendations are proper grounding of the satellite and use of conductive surface materials. These recommendations can minimise or prevent accumulation of charges, which can generate a potential difference between the sunlit and the shaded side of the spacecraft (Frezet et al., 1989).

3.2.1. Spacecraft charging

The accumulation of charges on a spacecraft depends on the charge transport (currents) to and from a surface (including charge transport in the structure). Low energy particles from the plasma are stopped on the surface (photo emission, ionospheric plasma), high energy particles penetrate the surface and can create secondary particles that can deposit charges somewhere else in the spacecraft system. Internal charging takes place when high energy particles penetrate the spacecraft and deposit charges inside the spacecraft. Dielectric charging occurs when a potential has been built up in a dielectric material. Surface charging refers to the surface of the spacecraft and interacts with the surrounding plasma. If one wants to monitor the low energy plasma surrounding the spacecraft these measurements are affected by surface charging which can lead to either shielding off or acceleration into the spacecraft of the low-energy charged particles.

Motion of a body across a magnetic field induces an electric field $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$ (where $\mathbf{V}$ is the velocity and $\mathbf{B}$ is the magnetic field). If the body has low conductivity, this can create a potential difference between two positions on the spacecraft. This effect implies that large objects in strong magnetic field never can have the same potential at all points on the spacecraft without active potential control.

When the accumulation of charges at a location is more rapid than its diffusion, discharges can occur. This can take place between two points on the spacecraft or between spacecraft and space. At a threshold where the discharges occur charges will move between the two points giving rise to a current, followed by an electromagnetic disturbance. The acceleration of particles (a current peak during a short time interval) can cause an anomaly that may damage the spacecraft. Light flashes, such as arcs on solar arrays (between interconnections and space) are commonly observed discharge phenomena. Small discharges cannot be detected when the spacecraft is in space but during the Meteosat-1 ground tests small discharges on the spacecraft surface were observed as frequently as one discharge per second (Hoge, 1980). One problem with the discharges is that they may drain current from the spacecraft system and cause current spikes on the electronics bus. The discharges do not only damage the electronics in different ways but they also damage parts by sputtering the surface material to space and thus change the material properties. Discharges can also lead to degradation, to loss of solar strings, to loss of electronic components, and to changed thermal properties. Discharges may stop after a while in space due to changes in the material caused by the discharges.

Energetic radiation also affects the spacecraft material in different ways, depending on energy and material properties. Radiation on a material causes ageing, changes in thermal and resistive properties, darkening of glass etc. The effects shorten the mission lifetime depending on the total dose the spacecraft is exposed to. These environmental effects on the material have to be taken into account in spacecraft design.

3.2.2. Satellite anomalies

In the months immediately following the launch of a new spacecraft numerous anomalies are usually reported. Later, as knowledge on the spacecraft behaviour improves, the number of reported anomalies drops dramatically (Wrenn, 1995), leaving a significant number of spacecraft anomalies associated with charged particles in the magnetosphere. Possible regions and environmental effects, which may affect spacecraft, are: the neutral thermosphere drag, plasma particles, meteoroids and spacecraft debris, solar radiation, cosmic rays and geomagnetic phenomena. These are often related to each other and determining the cause of a given event is often difficult (James et al., 1994). Spacecraft charging, high-energy particles and debris are the three main causes of anomalies.

When an anomaly occurs it is important to determine if it is caused by a command from the ground or by interference aboard the spacecraft. Sometimes failures occur when two parts of a system interact in a way that cannot be seen when they are operated separately. During 1993-95 twenty environmentally induced anomalies onboard NASA Goddard spacecraft were reported (Goddard Space Flight Center, 1994; Remez and McLeod, 1996; Walter, 1995). While many more anomalies occur during the first few months of spacecraft operation, the more ”interesting” (for this type of study), and possibly more damaging, cases occur once the educational process is completed and the spacecraft is in normal operation. For the Goddard spacecraft more than 400 anomalies occurred in the 3 years of operation but most of these could be identified either as part of the process of learning to control and use the spacecraft or as single event upsets (SEUs) from single high energy particles. Sometimes anomalies can occur due to the RF environment (Leach and Alexander, 1995). For example, NOAA-11 had phantom commands due to a noisy VHF-communication with the spacecraft. On NOAA-12 phantom commands occurred when the vehicle flew over commercial VHF-disturbances in Europe.

NASA maintains a spacecraft anomaly data base (Wilkinson, 1994). NASA’s environment data can be accessed through GOIN and NASDA. On internet anomaly data can be found at http://envnet.gsfc.nasa.gov/. IASB in Belgium provides information about environmental effects on spacecraft as a part of an ESTEC Contract (http://www.spenvis.oma.be).

3.2.3. Causes of spacecraft anomalies

Spacecraft anomalies can have different origins. A short description of some of them is given below.

The vacuum environment

When a spacecraft is launched significant outgassing is taking place that can give rise to anomalies. UV-degradation of different materials can also take place above the atmosphere. We do not further deal with these effects.

The neutral environment (chemical and drag)

The neutral environment extends far outside the Earth's magnetosphere. However, the effects of chemical (mainly atomic oxygen) interaction with spacecraft material and drag forces occur mainly at low heights (below 150 km), where the particle densities are high enough. The neutral environment is not considered in this study.

Plasma interactions

Charges accumulated on spacecraft surfaces (e.g., Garrett, 1981; Garrett and Whittlesey, 1996) can cause potential differences that can impact spacecraft systems through arcing. A discharge can occur between the surface and the surrounding space plasma, between different parts on the surface, or inside materials of the satellite. A current spike, during discharge, can generate electromagnetic radiation that can penetrate the spacecraft and/or damage the surface and electronics directly. Discharges at the edges of solar cells are common (Tribble, 1995).

Potentials can be generated by the **V** x **B** effect, depending on the spacecraft size and the local plasma density and temperature. Other sources for are currents to and from the spacecraft such as photoelectron emission, auroral electron beams, hot plasma injections during magnetic storms or substorms. Charges mainly accumulate at sharp edges and the amount of chargind depends on the surface properties.

On low-altitude orbits outside the auroral region the level of surface charging is usually small and voltages between different surfaces on a spacecraft are usually less than 10 V (See Chapter 4). On auroral field lines the charging may become 100 V or more and voltages above 1000 V may occur (Garrett and Whittlesey, 1996) due to, e.g., the auroral electron beams (Stevens and Jones, 1995; Chapter 4, below).

There is a strong seasonal variation in spacecraft charging. This may be associated to the orientation Earth's magnetotail with respect to the plane of the geostationary orbit, or to the known seasonal dependence of substorm activity, or both. One of the phenomena associated with spacecraft discharges are phantom commands. In the GOES spacecraft practically all phantom commands occurred between 23:00 and 08:00 local time. They peaked in spring and autumn.

Radiation (internal)

High-energy particles can penetrate the surface, interact with the material, and deposit their energy in the interior of the spacecraft. How the energy is deposited and what kind of interactions that takes place depends on the radiation type (photon, electron, ion, or neutral particle), the energy of particles and the material where the energy is deposited. The energy lost by the particle per unit length is referred to as its stop power or its linear energy transfer (LET) (Robinson et al., 1994). The LET depends on the number of interactions the penetrating particle makes with the target material. Secondary particles can cause lattice damages. The charged secondary particles can increase the charge on different surfaces and inside materials.

If charges are built up inside capacitors, which have a slow decay time, radiation induced dielectric charging can occur (Frederickson, 1980). High energy radiation can charge dielectric material to the electric field breakdown level.

Radiation through semiconductors causes electron and hole pairs along the path of the penetrating particle. The extra charges in the semiconductor can cause the component to fail. The generic name for events following a single high-energy particle impact is single event phenomenon (SEP) or single event effect (SEE). There are three classes of SEPs: single event upset (SEU), single event latch-up and single event burnout (SEB) (Hastings, 1995). A single event upset is a change in state of a digital circuit due to a high energy particle. A single event latch-up occurs when, instead of a bit flip, the circuit hangs and a reset has to be made. A single event burnout occurs when the circuit fails permanently due to the high energy particle.

Single event upsets (SEUs) on LEO satellites often occur in or near the South Atlantic Anomaly (SAA). SEUs are anti-correlated with solar activity except for strong solar events, but some of the more intense solar events generate high energy particles, making it more complicating to predict SEUs. The SEU probability is also related to the sensitive area (Lauriente and Vampola, 1996) and to the types of electronic devices.

The high-energy particles from cosmic rays can be predicted statistically but individual impacts are random (later seen as SEUs). Solar outburst effects can be predicted a few hours or days ahead, if adequate data and modelling are available which also can cause SEUs.

Dust and debris interaction

At geostationary distances the main debris are of natural origin. In low-earth orbit the population of man-made micrometer debris are comparable to natural particles. Depending on density, relative velocity and size debris can contaminate spacecraft, puncture insulators or even completely demolish satellites. Small debris can puncture the surface without directly damaging the spacecraft. Small-sized particles impacting on surfaces charged by plasma interactions can initiate a discharge.

Meteor showers can cause problem to satellite operation. Not necessarily a meteoroid making a hole in the satellite, but rather, from the creation of a plasma, or free electric charge on the spacecraft. The discharge can cause damage to sensitive electronic circuits on board the spacecraft, and ultimately cause the spacecraft to fail. The first assumed case of a satellite being lost by a meteoroid came in 1993. The Olympus communications satellite was reported being damaged by a meteor strike (1993 Perseid meteor shower) and was lost as a result of an electrical failure. The ESA press release from 26 August tells. "As indicated in the [earlier] press release of 17 August, 1993, service from the Agency's experimental OLYMPUS satellite was interrupted during the night of 11/12 August when, for reasons which are not yet understood, the satellite lost earth pointing attitude and began spinning. This event, and the subsequent recovery actions, used the last few kilograms of fuel remaining on the satellite. An assessment of the situation indicated that it would be impossible to re-establish service. It has therefore been decided that the Olympus mission should be terminated and the satellite removed from the geostationary orbital ring."

3.2.4. Anomalies and orbits

The types of anomalies vary with orbit (Vampola, 1994), but because the space is not in a steady state, the environment may also change considerably on the same orbit as a function of time, or in different places along the orbit. For example a solar proton event can create a radiation belt at 2 R_E lasting for several months (Daly et al., 1994). During the high solar activity during the coming years we may expect several of these proton events which will effect all spacecraft.

On geostationary orbits surface charging occurs near midnight whereas thick dielectric charging occurs often in early afternoon. SEUs mainly occur if a solar proton event is in progress and due to cosmic rays. The transition between shadow and sunlight can cause surface charging due to photoemission.

On low-altitude polar orbits the most pronounced SEUs occur in the auroral oval and at the South Atlantic Anomaly. Surface charging is usually associated with the auroral oval.

Anomalies are not only reported from satellites orbiting the Earth. For the Voyager spacecraft, during close passes of Jupiter, internal electrostatic discharges occurred. These discharges appear to have resulted from high-energy electron flux with a rather good correlation with electrons of greater than 10 MeV energy. The Pioneer spacecraft encountered severe space weather conditions in the Jovian radiation belts, which nearly destroyed some on-board systems.

Independent of orbit, solar proton events can degrade the solar panels of satellites simultaneously causing reduction in the power output. Intense events can cause sensor failure or loss of the satellite control.

Examples of anomalies that have occurred on spacecraft at different locations and times are given in Table 3.1. The anomalies range from harmless SEU to total loss of spacecraft. The orbits of the satellites range from low-earth orbit to geostationary, but also interplanetary missions are included.

3.2.5. Spacecraft Design

Most spacecraft are designed to have the interior shielded from the surrounding plasma and a wide variety of protections against anomalies. These include shunt diodes for protecting solar cells, filters and diodes to prevent discharges from influencing internal and components and circuits which are SEU and discharge resistant (Kalweit, 1981) and/or constructed with error corrections and latch-up protection.

To avoid potential differences conducting materials are used. If dielectric materials are on the outside they are usually coated with e.g., indium tin oxide (Garrett, 1981). In some scientific experiments active control of potential is established using ion or electron gun.

Spacecraft have been launched with a smaller spacecraft attached by a fibre. These tethered spacecraft are designed to interact with the plasma environment for current generation or thrust, in some cases simply to probe the properties of the plasma.

Spacecraft	Time	Comment	Reference
DSP		Anomalies associated with >1.2 MeV electrons	Vampola, 1994
SCATHA		Internal discharges associated with outer radiation belt	Garrett and Whittlesey, 1996
ATS 5 and ATS 6		Charged to 10 kV in eclipse at GEO	SMASS Report
NOAA spacecraft	from 1971	Contains 2779 events from 1971to 1988	Wilkinson, 1994
Goddard space-craft	1993-1995	More than 400 anomalies	Remez and McLeod, 1996; Walter, 1995
Voyager 1		Power-on resets	Leung et al., 1986
Pioneer		Severe space weather near Jupiter	SMASS Report
GPS		Clock shift, false commands	James et al., 1994
Intelsat 3 and 4		Spin up	James et al., 1994
GOES 2			Lauriente et al., , 1996, 1998
GOES 3		Upsets	
GOES 4	Nov 26, 1982	Instrument failed on arrival of 110-500 MeV protons	Vampola 1994
Intelsat K	Jan 20 1994	Loss of attitude control in GEO	Baker et al. 1994
ANIK E1 and ANIK E2	Jan 20-21 1994	Loss of attitude control due to high energy electrons	Baker et al. 1996
ANIK E1	Mar 26 1996	Array of solar power panels disconnected	ISTP Newsletter, Vol 6, no 2, 1996.
DRA-delta		Phantom commands	Wrenn and Sims, 1996
CTS		Short circuit	James et al., 1994
DSCS II		Spin up, amplifier gain	James et al., 1994
DMSP 7		Charged to 300 V in less than a second- associated with a sharp drop in ion density	Stevens and Jones, 1995
GOES 5	July 22 1984	Failure during high energetic electron fluxes	Baker
DMSP F13		Problems while passing through an aurora	Anderson and Koons, 1996
Hispasat 1A and 1B	Sep 1992 and July 1993		Selding, 1998
Telstar 401	Jan 11 1997	Failure probably due to coronal mass ejection	Anselmo, 1997
Telstar 402		Spacecraft charging	Lanzerotti et al., 1996
Topex/Poseidon		Failures due to electrostatic discharges and SEUs caused by high energy protons	Lauriente and Vampola 1996
Intelsat 511	Oct 7 1995	Lost Earth lock	http://www.astro.lu.se/~henrik/spacew4b.html
GOES 8	Feb 14 1995	Attitude control difficulty	http://www.astro.lu.se/~henrik/spacew4b.html
TDRSS 1	1988-1991	SEUs anticorrelated with solar cycle	Wilkinson 1994
CRRES	1990	674 reported anomalies	Violet & Frederickson 1993
Tempo 2	11 Apr 1997	Temporary power fluctuations.	http://www.seds.org/spaceviews/970515/tech.html
Olympus	11/12 Aug 1993	Affected by the 1993 Perseid meteor shower?	See 2.1.5 above

Table 3.1. Some reported spacecraft anomalies

3.3. Space physics background of charging and anomalies

3.3.1. Trapped radiation belt particles

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

The most obvious effect on Earth-orbiting spacecraft is the radiation dose on satellites traversing the trapped radiation belts. The almost stable inner radiation zones have been extensively modelled in the past (e.g., the NASA AE8 and AP8 models although there are well-known shortcomings in these models). The environment obviously is a major contributor to operational problems, but evaluation of the risk is possible (see, Chapter 5). Although many problems could traditionally be accounted for by radiation hardening of the spacecraft components, there is a drive to use advanced components that are more sensitive to radiation effects. The radiation also causes interference in sensors that cannot always be shielded against radiation. In addition, radiation effects to the growing astronaut population have to be very carefully monitored.

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

3.3.2. Magnetospheric substorms

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

During magnetospheric substorms the plasma density around a geostationary satellite may drop several orders of magnitude. The energetic electrons can then charge insulated surfaces negatively to several kV, especially in eclipse. Negative charging can also become a problem when the spacecraft is immersed within an auroral electron beam, which cannot be compensated by photoelectrons. This is a problem especially in eclipse. The risk for this effect is also strongly enhanced during substorm activity when the electron beams are strongest and most frequent. These kind of charging events are discussed in Chapter 4 below.

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

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

3.3.3. Coronal mass ejections and geomagnetic storms

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

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

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

Geomagnetic storms are most frequent before and after solar cycle maxima, and typically occur much more infrequently during quiet solar conditions.

3.3.4. High-speed solar wind streams and recurrent storms

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

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

The strong driving of the solar wind during storms can cause the magnetospheric boundary to move inside the geostationary orbit. In such cases geostationary satellites on the dayside lose the shielding the magnetosphere provides against solar wind particles as well as the guidance of the magnetic field possibly used by orientation magnetometers. Furthermore, storms include a series of repetitive and often intense substorms, posing similar hazards as discussed above.

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

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

3.3.5. Solar particle events

Coronal mass ejections and flares often accelerate particles to very high energies. If there is a magnetic connection between the disturbance site on the solar surface and the Earth, the energetic solar protons travelling at speeds close to the speed of light can enter the near-Earth space within tens of minutes, and the peak flux can reach the Earth in a few hours. These particles constitute the largest risk for missions outside the magnetosphere, e.g., Moon and the planets. These very energetic protons also have an access to the polar cap regions and the outer magnetosphere where the shielding effect of the geomagnetic field is weakest.

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

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

3.3.6. Galactic cosmic rays

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

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

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

3.4. Outlook for effects

The future society will increasingly rely on space systems. Various positioning applications are already now based on GPS and these applications are continuously expanding. The same happens with communications. Today's geostationary communication systems will be completed by low-altitude polar telecommunications spacecraft networks of which the Iridium of the Motorola company was the first to be deployed with more than 70 satellites. Even larger new type of telecommunications services, based on hundreds of satellites, are expected to take care of wide-band multimedia applications (e.g., Celestri of Motorola and Teledesic of Microsoft). Polar orbiting or high-inclination geosynchronous satellites cross the low-altitude ends of the radiation belts and auroral regions several times every day and thus encounter hazardous conditions more regularly than geostationary spacecraft.

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

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