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Abstract

The effects of space weather on technological systems and humans in space and on the ground are analysed and presented in catalogue form. The discussion of effects in space covers the effects on spacecraft systems, manned space-flight, and launchers. Important effects on spacecraft include spacecraft charging (both surface charging and deep discharges) and single event effects. For humans in space, the same energetic particles that induce single event effects are also of great concern although the protection against harmful effects requires more strict approach. Humans are also exposed to space weather effects on high-altitude / high-latitude air-flight where the cosmic rays penetrating to the atmosphere must be taken into account. The cosmic rays do not pose problems on humans only but also on miniaturised electronic components of the modern aeroplanes. The effects on other technological systems include radio wave propagation both between ground-based sites and in satellite-ground communications, global satellite-based navigation systems, power transmissions systems, telecables, and railway systems. In addition to these systems relationships between space weather and the atmosphere, meteoroids, and space debris are discussed. While the small pieces of debris can have similar effects as naturally occurring particles, they are also influenced by space weather effects as space weather-induced increase in the atmospheric scale height causes orbital decay and finally loss of the particles.

The original goal of this study was to present the causes and effects in a catalogue form. As there are, however, many different viewpoints to space weather it was found more useful to organise the catalogues according to more than one principle. Thus three independent catalogues are presented: Domain-oriented catalogue, Phenomenon-oriented catalogue, and System-oriented catalogue, in order to serve the wide variety of interests in space weather. For the same purpose, quite extensive literature referencing is applied.

Note that the present document is primarily an internal report to feed input to various other parts of the ESWS project, in particular to the Rationale Report built upon this report. All relevant material, including the different catalogues, is included in the final Rationale Report (ESWS-FMI-RP-0002) as well.

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1. Introduction

1.1. Purpose and composition of this document

This Report describes the results of WP 310: "Range of space weather and effects" of the ESA Space Weather Study (ESWS) (ESTEC/Contract No. 14069/99/NL/SB). This is an interim report of WP 300: "Establishment of detailed rationale" whose final deliverable item will be a Report titled "Rationale for European Space Weather Programme".

The present document contains two main parts. In section 2 space weather effects on various systems are briefly discussed and section 3 presents various space weather phenomena and effects in a catalogue form. Information is organised according to three different schemes: Domain-oriented catalogue, Phenomenon-oriented catalogue, and System-oriented catalogue, in order to serve the wide variety of interests in space weather. Note that the primary objective of these catalogues has been to organise the complicated web of natural phenomena and technological consequences to aid further progress of the present project. It is not mentioned either to restrict or reinterpret the actual scope of Space Weather Programme as described in the Statement of Work of this study. As space science and engineering are fields with their own jargon and acronyms, the mostly used acronyms are listed in section 4. An essential part of this catalogue is the reference list in section 5.

1.2. What is space weather?

Quite generally, and according to the Statement of Work of this study, the term "space weather" refers to the time-variable conditions in the space environment that may affect space-borne or ground-based technological systems and, in the worst case, endanger human health or life. The most important social and economic aspects of space weather are related to being aware of and possibly 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. On the climatological time scales there are also potential effects on terrestrial climate.

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

Space weather has many similarities with atmospheric weather; thus the design of future space weather activities may be able to utilise the experience from meteorological services, at least concerning real-time operations, input data management, and nowcast and forecast distribution. The only operational space weather centres, the Space Environment

Center (SEC) of NOAA, and the 55th Space Weather Squadron of the US Air Force, both in Colorado, USA, already operate in this fashion, although in much smaller scale than typical meteorological services.

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

- While many meteorological processes are localised and it is possible to make good limited-area weather forecasts, space weather is always global in the planetary scale. Perturbations originating from the Sun disturb the Earth's plasma environment, the magnetosphere, which responds to these disturbances globally.
- Space weather events occur over a wide range of time scales: the entire magnetosphere responds to the solar-originated disturbances within only a few minutes, global reconfiguration takes a few tens of minutes, and sometimes extreme conditions may remain for much longer periods. Ground-based magnetometers react immediately when an interplanetary shock hits the magnetosphere whereas enhanced fluxes of energetic particles in radiation belts decay in time scales of days, months, or even years.
- Our means to monitor space weather are much more limited than our ability to install weather stations on the Earth's surface: Our prediction schemes must be capable of functioning with input from only a few isolated measurements of the upstream solar wind conditions and magnetospheric parameters. While the present (e.g., magnetic activity indices, interplanetary scintillations) and future (e.g., energetic neutral atom imagery, ionospheric tomography) observations have a global character, they still remain rather far from the present-day rather detailed and continuous coverage of the atmospheric weather. As a consequence, successful space weather activities need to be performed on a global scale, merging a great variety of space-borne and ground-based observational capabilities.

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

1.3. Who are the users of space weather services?

The identification of users of space weather products or space weather modelling is a critical issue 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 of Europe.

The needs of the various users, actual or potential, are very variable, and, for the time being, insufficiently specified. Presently the most important users of space weather products are spacecraft engineering, spacecraft operations, and RF communications dependent on ionospheric properties. The spacecraft development is based on accumulated knowledge of space environment and its effects. Spacecraft operators could use space weather information when planning critical manoeuvres. Spacecraft launchers can make use of exact knowledge of space weather conditions and the re-entry of large vehicles depends on the atmospheric drag conditions. However, the need to assess space weather risks with respect to critical operations is not yet widely agreed. This could lead to ad-hoc decision making when space weather warnings coincide with critical operations. This further demonstrates the need for education and outreach activities; in particular within communities involved in operations with potential space weather risks.

In future the needs of manned spaceflight are expected to become increasingly important when the International Space Station is taken into use. With manned spaceflight "fair-weather" forecasts become important in connection of long extra vehicular activities.

Other users are telecommunication operators, users of the global positioning systems, electric power industry, etc. Commercial airlines must be careful with the radiation doses to their crew and passengers and also consider the potential radiation damages of 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 given by a space weather model.

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

2. Space weather effects

2.1. Effects on spacecraft, manned space-flight, and launchers

2.1.1. The space environment

The natural space environment in the solar system has several components (Hargreaves, 1992, Suess and Tsurutani, 1998):

1) Meteoroids, created in the early solar system. They reach the vicinity of the Sun with nearly a constant flux that, however, is significantly enhanced during known meteor showers (e.g., Leonids).
2) Cosmic rays, charged particles with high energies. They originate from the galaxy as well as from outside the galaxy. Moreover, so-called anomalous cosmic rays are produced by the interaction between the cosmic rays and heliosphere.

3) Solar energetic particles, escaping sporadically from the Sun. Nearly all elements are found but with a composition and charge different from the cosmic rays.
4) Neutrons ejected by the Sun. These neutrons decay rapidly in the interplanetary medium and only a few of them remain in the vicinity of the Earth (but they can be much more abundant near the Sun).
5) Photons, from the γ rays to the radio frequency, coming essentially from the Sun. The maximum of the spectrum is in the visible, but the UV rays have a great influence on the near ground environment of planets and moons.
6) The solar wind, consisting of plasma and magnetic field, the origin of which is in the Sun. At low heliospheric latitudes, its density is of the order of 1 to 10 cm^{-3} but its mean velocity is around 400 km/s with sporadic effects of coronal mass ejections; at high latitudes, as it comes from coronal holes, its velocity is higher (800 km/s) and the density is typically lower.

Moreover, in the vicinity of planets and moons, there are other components:

7) Dust, created by the interaction of meteoroids and small moons. Normally this dust is attracted by the moon that created it, but it can form rings like at Saturn or Jupiter.
8) Neutral atoms and molecules forming atmospheres, the size and composition of which depend on the size of the planet and its proximity to the Sun.
9) Interaction between cosmic rays/solar energetic particles and the atmosphere creates a lot of secondaries, including pions, muons and neutrons. Some of these neutrons can escape the planet and decay in its vicinity, producing protons and electrons.
10) Reflection of the solar spectrum by planets (ground + atmosphere) and moons is known as the albedo. Moreover, as the planets (and moons) are heated by the Sun, they emit in the infrared part of the spectrum.
11) Interaction between UV rays and atmosphere-created ionospheres, plasma made of ions from planetary origin and electrons. The temperature is very low as compared to the solar wind, for example.
12) The planets and moons can have a magnetosphere, which is formed by the interaction of the solar wind with the quasi dipolar internal magnetic field of the body. The magnetosphere of the Earth has a complicated structure and variety of dynamic processes that produce, e.g., the radiation belts, energetic particles trapped by the magnetic field, whose origins are the solar wind or the neutrons escaping from the atmospheres, including the so-called cosmic ray albedo neutron decay (CRAND) mechanism.

Everywhere there is

13) An electromagnetic environment, i.e., the temporally and spatially variable electric and magnetic fields. The magnetospheres (12 above) are important manifestations of this. The dynamics of the magnetosphere is a key space weather phenomenon transferring the interplanetary perturbations to the radiation belts, to the ionosphere and to the ground.

We also identify two man-made environments

14) Man-made electromagnetic environment. The man-made VLF transmitters have interacted with particles in the radiation belts continuously from times before spaceflight. Thus we have never observed the radiation belts without this perturbation.
15) Debris is an increasing space-environmental problem and discussed separately in section 2.6.

2.1.2. Effects of the space environment

Most of the components listed above can have an impact on satellites and launchers. The effect essentially depends on the energy of the component (Bourrieau et al., 1996). Low-energy components interacting with the surfaces of the satellites (thermal coatings, solar cells, antennas) are:

- photons, from UV to radio,
- the solar wind,
- the atmosphere and its different atoms and molecules (oxygen atoms are very corrosive due to chemical reactions),
- the ionosphere,
- plasma in the magnetosphere,
- light dust, micrometeoroids and microdebris.

The interaction depends on the location of the satellite/launcher in space. Low-altitude satellites and launchers are impacted by all these components (except solar wind), while interplanetary mission can interact with the meteoroids, photons, solar wind, solar and galactic cosmic rays, and different magnetospheres.

As the energy increases, particles and photons can penetrate in the satellite body. In this category there are:

- heavy dust, light meteoroids and debris (millimetric and submillimetric),
- energetic particles of cosmic ray, solar or radiation belt origin, including neutrons,
- high energy photons, from γ rays to X rays.

They interact also with astronauts, in particular during extra vehicular activities (EVA).

The worst are meteoroids and heavy debris whose impact can definitely damage the satellite, launcher or human, though the probability of impact is very small (however, the French satellite CERISE was subject to such an impact, see Jane's space directory, 1997). However, from the statistical point of view the most important effect on spacecraft is spacecraft charging due to energetic particles. A recent extensive study (Koons et al., 1999) based on 326 anomaly records containing thousands of individual events concluded that spacecraft charging has caused by far the most environmentally related anomalies and the most serious ones are due to surface charging.

As far as effects on satellites are concerned two different approaches may be considered. The first one deals with the determination of the lifetime of the satellite. For this, long-term effects must be well modelled and predicted. They are related to statistical properties of the space environment; cumulated dose effects belong to this category. For such an approach, models already exist although they have to be improved, e.g., by better accounting for the space environment dynamics (for example the radiation belt models, see Daly et al., 1996). The second approach deals with satellite operations and requires real-time space environmental data. The effects are operational anomalies that can threaten the satellite mission, or at least require a reaction from satellite operators or onboard computers.

For each of space weather effects, the nature of the cause and also the magnitude of the effects must be determined. So we will first review the effects induced by these various components.

Neutral particles from the atmosphere have two main effects on spacecraft. They induce drag on spacecraft and they can induce chemical reactions, as there are oxidising molecules and atoms in space, in particular O, but also NO, NO_3, O_3, HO,…. The drag decreases the apogee of a spacecraft and consequently also the perigee (Tribble, 1995; Koelle, 1961). Manoeuvres are needed to put the spacecraft back on its nominal orbit. The drag is important also in the calculation of braking and aerocapture of planetary probes as well as of the re-entry of large vehicles. It is also an important effect to take into account in the opening of the launcher protecting shroud (Boscher et al., 1998). The heating of high altitude neutrals is modified by UV, which in turn depends on the solar flare activity. The atmosphere can be modified within a few hours. Oxidisation is a more cumulative effect. It induces erosion of the surface, but also contamination of the near satellite environment, and the glowing of that environment by interaction with ambient plasmas (Paillous, 1986).

The first effect of *photons* emitted by the Sun is the heating of illuminated surfaces of the satellites. As un-lit surfaces are not heated, this effect produces temperature gradients in the satellite, which are diminished using highly reflective thermal coatings. Thermal control of spacecraft is a major problem in space, but as the total solar energy flux is nearly constant, we do not consider it as a space weather effect.

At the two edges of the spectrum (UV and radio) the photon flux is more variable. As the UV photons are more energetic, they influence the surface materials of the spacecraft (thermal control coatings, antennas, optics, and contaminants). They induce coloured centres and chemical reactions which modify the visible reflectivity of the materials and therefore the thermal properties of the satellite (Jaffe and Rittenhouse, 1972; Purvis, 1989). This is a long-term effect that is important to the ageing of satellites, but apart from solar cycle influence, this effect is not so important in space weather applications.

Plasmas from solar wind or ionospheric origin are composed of ions and electrons with temperatures up to hundreds of keV. With their relatively low energy, the particles cannot penetrate the satellite more than a few microns but they can produce similar surface effects as the UV radiation. As the plasma particles are charged, they induce charging effects, especially on dielectrics or insulated conductors (Bourrieau et al, 1996). Moreover, as they interact with different materials, differential potentials are set up and discharges can appear. Charging is always present on a satellite, but normally the electric fields are not strong enough to create discharges (apart across very insulating materials). Spacecraft surface potentials are relatively more negative in the wake of low-altitude satellites, during periods of precipitating electrons, or near GEO in the midnight region, during substorm injection (Koskinen et al., 1999). Statistically more negative charging events occur during magnetically active periods.

Energetic particles produce a lot of effects as they induce:

- ageing of electronics, optics and materials,
- single event effects,

- internal charging and electrostatic discharges,
- background noise of electronics and Cerenkov effects.

When radiation interacts with a sensitive volume of electronic components, their electronic characteristics are modified. This is a cumulative effect whose potential damage may take long time to realise.

Energetic ions can also produce Single Event Effects (SEEs) in electronics (single hard errors, single event upsets, latchups, burnouts, gate and dielectric ruptures) (Dyer and Rodgers, 1999; Bourrieau et al., 1996). These effects are normally due to heavy ions, but particles as light as protons or neutrons can produce the same effects as heavy ions through nuclear reactions with silicon inside the electronics (in the future, due to increasing miniaturisation, protons may be able to directly induce SEEs; Inguimbert, 1999). These effects, as they are sporadic, are of major concern for space weather. Some of them are permanent, either directly (e.g., latchup, burnout) or indirectly (e.g., changes in permanent program memory). Launchers are also concerned by SEEs as solar proton events create neutrons at low altitudes, and can directly interact at higher altitudes, especially for GTO and interplanetary launches with the Ariane V launcher (Boscher et al., 1998).

The radiation effects on human beings are similar to the effects on electronics (McNully, 1996). Dose effects affect all cells, especially those, which are not renewed or at least not rapidly renewed. Single energetic particles can also break the DNA chain in the cell nucleus, producing chromosome aberrations, translocations and tumour induction. They can induce also cell mutation that can have effects on the genetics (Lemaignen, 1988).

Energetic ions and electrons locally increase dark currents in detectors (Daly et al., 1994). This effect is clearly visible from imagers on board Earth or Sun observatories. Energetic ions and electrons also produce atom displacements in solar cells, decreasing the output power (Allen and Wilkinson, 1993). Energetic electrons as they penetrate inside the spacecraft produce internal charging and electrostatic discharges. The effect of discharges can be direct destruction but normally they create electromagnetic pulses which produce signals interpreted as false commands by onboard computers (Catani, 1996).

Debris or meteoroids as they impact parts of the satellite can be very destructive. The effect depends essentially on the mass of the object. Light particles induce cumulative effects but as the mass increases, an impact becomes less probable but more dangerous. Heavy particles can even induce problems in attitude control. In any case, the impacts produce secondaries, which can themselves impact some other parts of the satellite. Space weather in this field deals with meteoroid clouds like Leonids, and the orbits of debris relative to satellite during atmospheric heating. For spacecraft control, it is important to watch large pieces of debris, e.g., by means of radars. Debris and meteoroids are discussed more thoroughly in section 2.6.

The space weather events, e.g., magnetic storms, may produce large changes in the local *magnetic field* configuration. This leads to attitude determination problems with spacecraft that use magnetic guidance. The effect can be particularly large for spacecraft that are designed for relatively large magnetic field, e.g., geostationary satellites that may enter the solar wind when extreme solar wind pressure compresses the dayside magnetospheric boundary (normally at 10 R_E) inside GEO.

These components and their effects on spacecraft are presented in tabular form in Table 1. Note that the components are practically never alone in the space environment and combined effects appear. The combination of UV radiation, particles and atomic oxygen gives less degradation than applied separately as oxidation and sputtering strips the surface which then is clean and pure (Koontz et al., 1990). Other synergetic effects are worse, e.g., debris and plasmas. Meteoroids or debris impacting the surface increases its roughness and produces sharpened edges, which helps the discharges to be triggered (plasmas can also be ejected during the impact, increasing the discharge probability) (Levy et al., 1997).

Components of the space environment	Effects	System affected	Other problems
Neutrals	Drag Oxidisation Contamination	Orbit control Temperature control Shields	Glow
Photons	Heating Photo-emission Surface ageing Backgr. noise increase Positive voltage	Temperature control Sensors	Contamination
Plasmas	Surface ageing Current closure Surface charging ESDs EM noise	High-voltage systems Temperature control RF systems	Contamination
Particle radiation	Ageing Atom displacements Internal charging ESDs Backgr. noise increase SEEs DNA damage Cell destruction	Temperature control Electronic components Solar cells Star trackers Detector background Living organisms	Genetics, Cancer Death
Meteoroids	Impact Induced neutral and plasma environment	Partial destruction Attitude control Coating erosion	ESDs Contamination
Debris	Impact Induced neutral and plasma environment	Partial destruction Attitude control Coating erosion	ESDs Contamination
Magnetic field	Local change	Magnetic attitude control	

Table 1: The components of the space environment and their effects on spacecraft.

2.1.3. Effects on spacecraft systems

The drag that directly affects satellites as well as debris and meteoroids is in the first approximation a simple phenomenon. The parameters which determine the drag are the mass-area ratio (the cross-sectional frontal area over the mass of the object), the velocity of the object relative to the fluid, the local fluid density, and a drag coefficient which is difficult to determine but does not vary too much (Koelle, 1961). This coefficient includes all other second order terms related to the flow properties, the parameters of the spacecraft body, the fluid and surface. Globally this coefficient can vary by some 25%, depending on the altitude and the spacecraft material. The most important parameter is the atmospheric density that is difficult to determine because it depends on several variables: the day of year, the latitude, the local time and the solar and magnetic activities. The effect is instantaneous, but the atmospheric density has an inertia that is of the order of hours. The main problems due to drag effects are related to attitude control, orbit decay, and tracking of debris.

The rapid ageing of solar cells as seen on GOES during the large storm in March 1991 (see Allen and Wilkinson, 1993) is due to atom displacements inside the cell caused by high energy particles. Due to the cover glass which is superimposed on the cell, the particles must have an energy sufficient to pass through the coating (but not too high to pass through the whole cell) leaving a part of their energy in it and inducing permanent damage. Atom displacements can also be induced by low-energy particles near the surface. The effect is instantaneous.

In photon detectors an increase in background noise can be due to various particles, e.g., direct impact of protons or heavy ions on the detector. It can also be related to bremsstrahlung, which results from the interaction between incident electrons and surrounding materials, and other secondary processes (Bourrieau et al., 1996). The radiation can interact either directly with the sensor or through other parts of the system (glasses, pre-amplifiers, etc.). It is also an instantaneous space weather effect.

Charging effects are complex phenomena. The total charge is a global effect where electrons and ions can act together and the charge can be deposited inside the material. The surface tends to reach an equilibrium potential such that the total (electrons, ions, secondary emission, photoelectric emission, structural) current is zero (Levy, 1996). However, the different currents given by the protons and electrons vary in time (spatial or temporal variations) and the absolute potential is never steady. Moreover, differential potential may occur on satellites when surfaces are non-conductive because different surface materials are used (thermal coatings, antennas, solar cells) and the exposure to the space environment is different for different surfaces (shadow, non-isotropic particle fluxes), especially when surfaces are made of dielectric materials. The time scale for differential charging can be long, so the equilibrium is usually not reached. Finally, the energy of electrons (and ions) is an important parameter as when they penetrate inside the material, they are gradually decelerated and stopped at a certain depth below the surface, leaving the charge there. The capability of these charges to migrate to the surface depends on the conductivity between the two points. We note that the conductivity of a material is modified by dose effects, so it changes during the satellite life. Contamination by different particles or by thruster plumes also affects the surface material properties, and especially the surface conductivity and the secondary electron emission properties.

The external layer thickness of a satellite being usually around 500 microns, electrons with energies below 300 keV and protons below 8 MeV will generally be stopped in the protecting material. For surface charging, the time scales depend on the material or structure and the differential current. Typical time constants are of the order of minutes for dielectric surface charging, and the order of hours for internal charging. These effects do not affect launchers, due to the short time within the charging environment. Furthermore, these effects may be difficult to model in polar orbit due to rapid passages through auroral arcs.

For SEEs in electronics or computer devices, the particles responsible must pass through the shielding of the satellite (thermal coating and structural materials) and the cover and insulating materials of the electronics, so they must have a sufficiently high energy. The required energy is at least of the order of 10 MeV for protons and more for heavier ions. As single event effects are due to single particles, they are space weather effects, and they are instantaneous. With the present-day technology, protons are not able to directly induce SEEs. Nuclear interactions between protons and silicon produce recoiling nuclei of required energy and this may be the main mechanism for the observed effects. The effects are seen also on launchers. Due to the spreading of microtechnologies, they may even become important on the ground.

For complementary information on space environment, see the ECSS standard on space environment (ECSS–E–10–04).

2.1.4. Effects on launchers

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

Single Event Upsets were recorded during an Ariane V launch without any solar energetic particle event in progress (Boscher et al., 1998). The number of SEUs can increase during such an event. Nevertheless, the redundancy of computers on board this launcher makes fatal error unlikely.

2.1.5. Effects on humans in space

Humans in space are normally well protected by large shielding in space stations (around 5 mm). However, flashes in the astronauts' eyes have been “seen” inside the Shuttle during Solar Energetic Particle Events (SEPEs) (Allen and Wilkinson, 1993).

During Extra Vehicular Activities (EVAs), nearly all effects similar to spacecraft are possible, the suit being similar to the satellite and the shielding being smaller (around 0.5 mm) (Lemaignen, 1988). In particular, astronauts must pay attention to meteoroids and debris, charging effects and energetic particles (protons from the radiation belts and ions from the cosmic rays or SEPEs) on low-altitude stations (like MIR, ISS). Precautions are normally taken, astronauts being normally in the wake of the vehicle to avoid impacts with debris. However, charging effects can appear especially when astronauts cross the boundary between sunlight and shadow. Particular attention must be paid to SEPEs. When a SEPE is in progress, astronauts cannot leave the station and when a SEPE is beginning, they must come back inside the station, lethal risks being too high.

During the potential future interplanetary missions, or missions to the Moon, astronauts are not protected by the magnetospheric shielding and the fluxes are much higher (Bourrieau, 1993). In particular, Moon walks made by US astronauts during the Apollo missions were risky, in spite of the fact that these missions took place during solar minimum (the August 1972 SEPE took place between the Apollo 16 and 17 missions). If astronauts had been walking on the Moon at the beginning of the event, the time to come back to the Apollo Command and Service Module (the only module being enough shielded) would have been too long, and they would have suffered effects of this space weather event. For interplanetary missions, we must think to very large shielding like sarcophagi for astronauts during such events. For lunar or Martian activities, underground or well-protected shelters must be thought in order to avoid these problems.

The effects discussed above in sections 2.1.3.–2.1.5. are summarised in Table 2 below.

Space weather effect	Space weather parameters	Material/object parameters
Drag	Total density Temperature Fluid velocity	Cross-sectional frontal area Mass Relative velocity Shape
Atom displacement	Particle flux	Shielding, material, geometry
Dark current increase	Particle flux Photon flux (UV, X, γ)	Shielding Absorption
Surface charging	Electron flux (< 300 keV) Proton flux (< 8 MeV) UV flux	Secondary emission Photoelectric emission Geometry
Internal charging	Electron flux (> 300 keV)	Shielding, material, geometry
SEEs	Ion flux (> 100 MeV) Proton flux (> 10 MeV)	Technology (CMOS,…)
Human effects	Ion flux (> 100MeV) Proton flux (> 10 MeV)	Cell nature (eyes, gonads, bone marrow)
Orbital elements	Atmospheric scale height	Cross-sectional area, optical properties, shape
Electrostatic discharges	Meteoroids and debris UV radiation, plasma	Relative velocity, size, type of surface
Collision	Meteoroids and debris	Technology, type of materials

Table 2: The space weather effects and their relations to the space environment

2.2. Effects on aircraft, aircrew, and avionics

With the increasing use of microelectronics of ever diminishing feature size, systems are becoming increasingly susceptible to single event effects (SEE) arising from the highly ionising interactions of individual cosmic rays and solar particles. Such single event effects include soft errors, involving both single and multiple bits, and hard errors due to latch-up or burn-out. For space systems an increasing body of evidence has accumulated over the last twenty years, systems have been lost and expensive ground control procedures have had to be invoked (see, e.g., Dyer and Rodgers, 1998). Although cosmic-ray effects are now a normal part of the specification, expensive mistakes are still made.

While the Earth's atmosphere shields out most of the primary cosmic rays at conventional altitudes (30000 to 40000 feet, i.e., 10–12 km), there is a build up of secondary particles (neutrons, mesons and electrons) which reach a maximum at around 60000 feet (18 km) and are only a factor of three diminished at 30000 feet (9 km). By sea level there is a further factor 300 diminution. As a result of this mechanism the radiation hazard at aircraft altitudes is as severe as in certain low-earth orbits. During the past ten years there has been increasing evidence of single event effects on aircraft electronics as well as in sea-level systems (Dyer et al, 1990; Dyer et al, 1992; Olsen et al, 1993; Taber and Normand, 1993; Sims et al, 1994; Ziegler et al, 1996; Normand, 1996).

At altitudes up to about 60000 feet (18 km), neutrons provide the dominant environment component for effects in current and near future electronics. These produce indirect ionisation by nuclear reactions in electronic material (Letaw, 1987; Normand et al, 1994; Dyer et al, 1999). Above this altitude penetrating ions and secondary fragments become increasingly important and these interact by direct ionisation (Tsao et al, 1984). The problem is expected to increase as more low-power, small feature size electronics are deployed in advanced technology aircraft (Kerness and Taber, 1997). Increasing numbers of aircraft functions will be driven electrically in the future (the so called More Electric Aircraft) leading to increased vulnerability (for a review of the subject see Dyer and Truscott, 1999).

At the same time there is new legislation on the allied problem of the effects of radiation on aircrew and frequent flyers. Ionising events in cells lead to free radicals and DNA rupture and increase the risk of cancers. Probabilities are related both to the ionising energy deposited per unit mass (i.e. dose in J/kg or grays) and to the density of ionisation as measured by LET (linear energy transfer or energy deposited per unit pathlength). This is approximated by multiplying the dose by a *Quality Factor*, which is a function of LET, to give *the Dose Equivalent (in Sieverts)*. The Quality Factor is unity for lightly ionising particles, such as electrons and photons, but can be as large as 20 for heavy ions and fast neutrons. Increasing awareness of health risks has led to the European Union Council Directive 96/29/EURATOM, which took effect in May 2000. Article 42 demands that aircraft operators must take account of exposure of air crew who are liable to be exposed to more than 1 mSv (milliSievert) per year. Exposure must be assessed and reduced by rostering where appropriate and workers must be educated on the health risks. Pregnant women must not be exposed to more than 1mSv during pregnancy and crew exceeding 6 mSv per year must be carefully monitored and given health checks. At altitudes up to about 60000 feet (18 km) there are approximately equal contributions from directly ionising particles (protons, electrons, muons) and indirectly ionising neutrons. Above 60000 feet (18 km) ions have to be considered. For aircraft flying above 49000 feet (15 km), where there is a significant probability of increased dose rates resulting from solar particle events, Air Navigation Orders demand that an active warning monitor should be carried. If such a monitor is non-operational, flights may take place only if favourable space weather forecasts are obtained. For comprehensive sets of papers on aircrew effects, see Reitz et al. (1993) and Kelly et al. (1999).

The atmospheric secondary radiation is modulated in anti-phase with the 11-year sunspot cycle. However the amplitude is diminished compared with the free space cosmic ray level due to geomagnetic shielding of the lower energy particles and the greater secondary production efficiency of the higher energy cosmic rays. For example a factor 1.3 modulation at the Climax Mountain neutron monitor may be compared with a factor 3 modulation observed outside the magnetosphere. There is a significant latitude effect with high latitude effects a factor 2 higher compared with the equator. Again this is much reduced compared with the latitude effect of free space cosmic rays which show a factor 10 variation at solar minimum. Short term decreases in cosmic rays and their secondaries (Forbush decreases) result from fast solar wind and/or coronal mass ejections. At aircraft altitudes these can lead to up to 20% reductions in intensity for a few days. Large solar particle events with hard spectra can produce significant enhancements in atmospheric secondaries. Events, which are significant at aircraft altitudes are also observable on the ground and are commonly referred to as Ground Level Events (GLE). Such events typically occur only once or twice per solar cycle. During September and October 1989 a series of events led to enhancements of up to a factor 6 at Concorde altitudes (Dyer et al, 1990), while at mountain altitudes neutrons were increased by a factor 3. Dose-rates would have been of order 100 microSieverts per hour at Concorde and 20 microSieverts per hour at conventional altitudes. The largest ground level event was on 23 February 1956 when a factor 50 increase occurred at high latitudes (1 GV rigidity cut-off). The latitude dependence during solar particle events is much steeper than for quiet-time (Quenby and Webber, 1959). During the 1956 event the enhancement factor was 10 at 3 GV and 2 at 5 GV. It is believed that there were no aircraft observations and the event preceded spaceflight. It is estimated that aircraft dose rates could have been as high as 30 milliSieverts (mSv) per hour at Concorde altitudes and 10 mSv per hour at conventional altitudes (Foelsche, 1974) so that very serious doses could have been received. During a single flight on 23 February 1956, passengers and crew at conventional altitudes could well have exceeded the currently recommended annual exposure limit for radiation workers (20 mSv).

Now that airlines are required to estimate crew dose, the 40% solar cycle modulation represents a significant effect. Accurate prediction of such modulation would assist in crew rostering, particularly around solar minimum. However the most significant space weather issue is clearly the ability to predict the rare, very large solar particle events with hard spectra which lead to Ground Level Events. This is further complicated by the need to consider the reduction in geomagnetic shielding which can occur if there is an associated geomagnetic storm, as occurred during the October 1989 event. Concorde is required to take avoiding action when the onboard monitor shows 0.5 mSv per hour. The 1956 event would have exceeded these rates at conventional altitudes and it is debatable whether anyone should be flying at such a time. Similarly a three orders of magnitude increase in single event upset rates would occur if susceptible electronics were being flown during such an event and this must be of concern for flight safety.

Prediction of cosmic-ray modulation may be made using a variety of methods (e.g. persistence, recurrence, neural networks, radial basis functions) and usually uses sunspot number for predictions several months ahead. Of concern here is the availability of data on high-energy cosmic rays of relevance to aircraft altitudes. Most spacecraft data are for relatively low energy thresholds (e.g. up to 100 MeV on GOES). It is important to provide higher energy channels (e.g. 360 MeV provided by Cerenkov telescopes). Ground level neutron monitors are a good proxy but are dwindling in number. Currently the National Geophysical Data Center site (http://spidr.ngdc.noaa.gov) gives data from only one monitor (Climax Colorado) in 1998 compared with forty-four monitors in 1989. The University of Chicago site (http://ulysees.chicago.edu/NeutronMonitor) gives data from Climax (3 GV) and Haleakala (12.9 GV). It is imperative to keep the current monitors operational and there is a need for a high latitude monitor (< 1GV cut-off rigidity).

The prediction of solar particle events is a major challenge for a space weather system. The most intense events often accompany coronal mass ejections and prediction would benefit from improved understanding and observations of these events. Another technique showing some promise is the hardening of the X-ray flare spectrum, which occurs about a day in advance of the arrival of the peak particle flux at earth. Some large events originate on the far side of the sun and so observations will have to be extended to the full range of heliolongitudes. Adequate monitoring is required and besides the ground-level neutron monitors it would appear essential to have active monitors distributed amongst the vast volume of air traffic. This would afford the possibility of taking avoiding action in extreme events as well as improving essential understanding for the more common, smaller events. Otherwise another event comparable to February 1956 will be much more poorly monitored than the original.

2.3. Effects on RF propagation

2.3.1. Introduction

The ionosphere, an area of the atmosphere which extends from ~80 to ~1000 km, can significantly affect the propagation of radio frequency (RF) signals which pass through it or are reflected by it (Cannon, 1994a; Cannon, 1994b). The effects are varied but include absorption, refraction, retardation and scintillation. At frequencies above ~1 MHz, the lower *D* region causes absorption and the higher *E* and *F* regions cause a variety of other effects. These effects, which include refraction, signal group delay, signal phase advance, pulse broadening and Faraday rotation of the polarisation vector, all follow an inverse power law and are significant only up to a frequency of ~2 GHz. Below ~1 MHz radio systems bounce their signals from the tenuous *D* region; consequently although the height of the layer is important for system operation absorption is not an issue.

The diverse set of affected systems include ground-ground high frequency (HF) communications, ground-space communications, GPS (Global Positioning System) - particularly single frequency- navigation systems, HF over-the-horizon radars, satellite altimeters and space-based radars (Goodman and Aarons, 1990). HF communications and radar systems rely on the ionosphere for their operation but also have to contend with its effects. Most other systems are degraded by the ionosphere but for certain specialist systems detailed knowledge can be of great benefit. Loss of phase lock and range errors in GPS are examples of such deleterious effects.

If the environment were isotropic and stable in time, it would be relatively easy to determine its effects on the propagation of RF waves. Unfortunately, this is not the case. The spatial scales vary from thousands of kilometres to turbulence with scale sizes of a less than a metre. Likewise the temporal scales vary over many orders of magnitude from many years (solar cycle effects on ionospheric propagation) to hours or even minutes (the scale of weather phenomena).

As a consequence of this variability, timely and reliable strategies are required to both specify and accurately forecast the environment and to assess the attendant impact on the operational performance of the systems. These strategies can be used to automatically apply corrections to the system operating parameters or, via a decision aid, advise the user on a course of action that will improve the functionality (Cannon et al., 1997).

2.3.2. Naturally occurring variability

Natural variability can be categorised into that due to bulk effects and that due to irregularities. The bulk effects, including variations in the refraction and time delay of signals propagating through the ionosphere, cause varying areas of coverage in HF systems. At UHF they introduce errors in radar, altimetry, geolocation and space-based navigation systems (~30m). Single frequency GPS transmits model coefficients to mitigate these errors but it is unable to compensate for the day-to-day and hour-to-hour variations. Dual-frequency military GPS can use the different delays in the two transmitted frequencies to calculate the total electron content (TEC) and make an almost exact correction.

Irregularities in the plasma density cause signal scintillation (Aarons, 1982), i.e. random variations in amplitude and phase. These are generally quantified in terms of the standard deviation of phase, σ_ϕ, and the standard deviation of the signal power, normalised to the average received power, S_4. Scintillation can cause data loss in communications via data errors, loss of coherence in radar applications and loss of signal lock in GPS navigation. Fade depths of 30 dB are possible at 400 MHz and 20 dB fades are possible at L-band. Phase changes also limit the ability of synthetic aperture radar (SAR) systems to form a phase coherent aperture and so reduce resolution.

2.3.3. Artificially induced variability

The ionosphere is a naturally occurring plasma environment, which can be artificially modified by four techniques. The first is the modification of the ionosphere by the release of large volumes of chemically reactive gases. This possibility was first recognised by the discovery that rocket exhausts deplete the local charged particle density. The second technique makes use of charged particle accelerators both to modify ionospheric properties and create artificial auroras. The third technique uses VLF radiation generated on the ground to stimulate instabilities in the magnetospheric plasma that in turn generate hydromagnetic emissions and cause particle precipitation. This technique arose from the discovery that ground based power transmission lines could affect the particle distribution in the magnetosphere. The fourth technique uses high power ground based transmitters at LF or higher frequencies both to modify the ionosphere and to generate secondary radio emissions. For purpose built facilities the EIRP can be as high as 80-90 dBW but the EIRP is lower when unintentional modification takes place. Some of the first results from the US HAARP facility are reported in Rodriquez et al. (1998). An example of unintended artificial modification of the ionosphere is reported in Cannon (1982).

2.4. Effects on ground-based systems

2.4.1. Introduction

Large electric currents are continuously flowing in the magnetosphere and ionosphere. When hitting the magnetosphere, a disturbance in the solar wind produces a change in the current system, in which the magnetospheric-ionospheric coupling plays an important role. The geomagnetic field brings the disturbance in particular to high latitudes resulting in visible auroras and in an intense ionospheric current system.

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

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

2.4.2. Power systems

From the viewpoint of a 50 or 60 Hz power system GIC are (quasi-)dc currents having a frequency typically in the 0.1-0.001 Hz range. The magnitudes of GIC in a power system during a geomagnetic storm depend on the geoelectric field affected by the ionospheric current system and by the Earth's conductivity structure. In general, the proximity of the high-latitude auroral zone increases the geoelectric field. A high Earth resistivity makes the geoelectric field values larger. Also, areas near an ocean-continent boundary tend to experience higher geoelectric fields.

It is not only the geoelectric field that dictates the GIC magnitudes in a power system but also the geometrical and structural details have a significant influence (Molinski, 2000). Since GIC are dc currents the resistances of the power network are important and GIC cannot flow at all in lines having series capacitors. Usually GIC greatly vary from site to site in a power system, and model calculations may easily reveal the sites that are probably prone to the largest GIC magnitudes (Viljanen and Pirjola, 1994). In general, transformers located at corners of a power system suffer from large GIC values. Also, long transmission lines carry larger GIC.

In a three-phase power system, GIC is divided equally among the phases. The problems caused to a power grid are due to a half-cycle saturation of transformers resulting from GIC (Kappenman and Albertson, 1990). This means that a transformer which normally operates with a very small exciting current starts to draw an even hundred times larger current, i.e. it operates beyond the design limits. The consequences depend on the transformer type (Elovaara et al., 1992) but, in general, all types are affected by GIC.

A saturated transformer consumes large amounts of reactive power, whose magnitude is roughly proportional to GIC. An increased reactive power consumption decreases the capability of the ac transmission of the system, and the voltage tends to get lower. In particular at times of a heavy loading, this may result in serious system voltage drops and finally in an extensive blackout. The return to normal conditions from the blackout may take several hours as happened in Québec, Canada, in March 1989 (Larose, 1989; Chech et al., 1992; Blais and Metsa, 1993; Kappenman, 1996).

A saturated transformer generates a lot of harmonics in the electricity, which means that the waveforms are distorted from pure 50 or 60 Hz oscillations. These phenomena may lead to false relay trippings of the protective devices and also to additional losses in various equipments (Bozoki et al., 1996). The magnetic flux is increased in a saturated transformer, and it may take paths not designed to carry a magnetic flux (Khan et al, 1993). This causes excess heating in the transformer, and localised hot spots may appear. In the worst case the final consequence can be a permanent damage of the transformer (Balma, 1992).

The flow of GIC can be blocked by using series capacitors in transmission lines or in earthing wires of transformers (IEEE Working group on Geomagnetic Disturbances, 1993). After the March 1989 event, Hydro-Québec has, as a part of an extensive study and mitigation procedure (Bolduc et al., 1998), installed several series capacitors in their system. However, the use of series capacitors is expensive and also technically not straightforward. Therefore, the discussion of GIC countermeasures is still going on.

A different approach is provided by the possibility of forecasting geomagnetic storms, and it would be even better, if GIC magnitudes at different sites of a power system may be forecast. However, exact GIC predictions are not available in practice yet but research work on the topic is intensive (Viljanen et al., 1999). The forecasting of geomagnetic storms is based on observations of the Sun and on satellite measurements in the Earth's near-space. When power utilities are warned about an approaching geomagnetic storm they can take different actions. These include the reduction of the loading in the system, which gives a larger margin, the switching-off of some equipment, the ensuring that the possible series capacitors are operating properly, and being prepared for possible problems. All actions are costly, so unnecessary predictions should not exist. This emphasises the importance of a continuous research on forecasting methods.

2.4.3. Pipelines

Buried oil and gas pipelines are prone to corrosion, which may occur at points where an electric current flows from the metal into the surrounding earth. Therefore pipelines are covered by an insulating coating. The insulation is, however, not perfect, and particularly problematic are possible holes in the coating. To avoid corrosion, pipelines are equipped with a cathodic protection system (Von Baeckamn et al., 1997) which tries to keep the pipeline in a negative potential of roughly 1 V with respect to the soil. Different harmful processes may take place if the negative potential becomes too large, so the adjustment of the potential has to be careful.

GIC flowing along pipelines are accompanied by voltages between the pipeline and the Earth (Boteler, 2000; Brasse and Junge, 1984; Campbell, 1980). GIC are not hazardous regarding corrosion issues but the pipe-to-soil voltage variations related to GIC can easily exceed the cathodic potential making the protection thus invalid (Gummow, 1999). Today's coatings have orders of magnitude higher resistance than those used earlier. This results in larger pipe-to-soil potentials, thus significantly increasing the risk of corrosion at defects in the coating. How much pipe-to-soil voltages induced by space weather effects really increase the corrosion rate of a pipeline is still a somewhat open question, and estimates about times before the wall of a pipeline is seriously damaged vary in a wide range (Martin, 1993; Campbell, 1978; Henriksen et al., 1978; Gideon, 1971). Besides a direct contribution to corrosion, geomagnetically induced pipe-to-soil voltages are a nuisance when measuring cathodic protection parameters and making control surveys (Barker and Skinner, 1980). The measurement results may be completely incorrect and thus lead to erroneous conclusions.

Similarly to a power system, the magnitudes of GIC along a pipeline network and of pipe-to-soil voltages depend both on the geophysical situation and on the details of the network. Model calculations supported by measurements of geomagnetic variations can be performed to reveal the most problematic regions in a pipeline network (Boteler and Seager, 1998). In general, the pipe-to-soil voltages are larger at inhomogeneities of the system, such as ends, bends and branches of the pipeline, changes in the material or size of the pipeline, or variations in the Earth's conductivity. The adjustment distance that expresses the length of the area in which the inhomogeneity affects is typically in the order of tens of kilometres. Long pipelines experience larger geomagnetically induced pipe-to-soil voltages than shorter ones. Therefore, pipelines are sometimes electrically interrupted by installing insulating flanges in series with metallic pipeline parts (Camitz et al., 1997). Such a procedure may really decrease the largest voltages appearing but at the same time increases the number of inhomogeneities. Therefore, all effects of insulating flanges have to be carefully analysed, and the final solution is a compromise.

To avoid the problems caused by geomagnetic storms to buried pipelines, the industry has to be aware of the risk produced by GIC and induced pipe-to-soil voltages. A possibility of forecasting geomagnetic storms will help avoid making control measurements during times of a high probability of disturbances. A forecast of a magnetic storm also gives a reason to check that the corrosion protection systems are in full operation.

In general, space weather risk has not been investigated as much in pipelines as in power systems. Recent investigations (Pirjola et al., 1999) containing improved tools for model calculations are improving the situation, and at present an international "pipeline-GIC" study with eight companies involved is being finished.

2.4.4. Other

The first observations of space weather effects on technological systems were made in telegraph equipment more than 150 years ago (Barlow, 1849). Many times since then, telesystems have suffered from overvoltages, interruptions in the operation and even fires caused by GIC flowing through the equipment (Boteler et al., 1998). Such problems have been reported at least in North Europe as well as in North America (Karsberg et al., 1959; Anderson et al., 1974). It is also a good reason to believe that some disruptions in telesystems whose cause has remained "unknown" have in fact been produced by GIC. Therefore it would be worth comparing recordings of teledisturbances with geomagnetic activity statistics.

The principle of the creation of GIC in telecables is exactly the same as in the case of power grids and pipelines. Records of disturbances also offer a possibility of estimating the magnitude of the geoelectric field by knowing the maximum overvoltage the equipment can stand. In this way, it was concluded that the geoelectric field values had been about 45 to 55 volts per kilometre in northern Norway during a magnetic storm in March 1940 (Harang, 1941), which are clearly the largest values ever mentioned in the literature.

It is probable that today's telecable systems are less prone to carry large and harmful GIC than the old ones, and that the associated equipment are not very sensitive to GIC effects. On the other hand, the systems including different electronic components are getting more and more complicated, so the possibility of GIC problems should never be ignored. Optical fibre cables generally used in telecommunication nowadays do not carry GIC at all. However, their use does not totally remove the problem because the voltage to amplifiers is fed by a metallic cable that may suffer from GIC.

Submarine phone cables lying at ocean floors form a special category of telesystems affected by geomagnetic disturbances (Root, 1979). Their length implies that the voltages induced on such cables during geomagnetic storms are easily hundreds, even thousands, of volts leading to possible problems (Lanzerotti et al., 1995). The voltages, which are also affected by the flow of seawater, are monitored on trans-Atlantic and trans-Pacific cables and on some shorter ocean cables as well.

On railways geomagnetic induction may cause unexpected voltages resulting in misoperations of equipment. During a magnetic storm in July 1982, such a voltage made traffic lights turn red without any train coming in Sweden (Wallerius, 1982). This was explained by observing that the geomagnetic voltage had annulled the normal voltage, which should only be short-circuited when a train is approaching leading to a relay tripping. As in telesystems, it may be believed that some of past "unknown" railway disturbances have in fact been caused by GIC.

In exploration geophysics, magnetic surveys are conducted to obtain information about subsurface rocks. Measurements include temporal changes of the field, so there is a problem of separating these variations from the desired spatial variations (Lanzerotti, 1979). A typical example is an airborne magnetometer survey, which may cover a region of tens of thousands square kilometres. To eliminate temporal effects, a ground-based magnetometer network can be used as a reference, and only times with variations below a given threshold are accepted. Such a method may encounter serious difficulties at high latitudes where the field changes very irregularly. Scheduling surveys for periods when disturbances are forecast to be small could be a solution.

2.5. Effects on middle and lower atmosphere

One of the most interesting, but still controversial, areas in space and geophysical sciences is the possible connection of space weather with terrestrial weather and climate. Evidently there is a coupling between these phenomena but the link is not simple. It is also not understood yet how large the space weather contribution might be compared to other factors, such as direct solar radiation, determining atmospheric weather. One of the clearest evidence of a coupling is obtained from observations on lightning discharges that propagate from the tops of thunderclouds upwards to the ionosphere (Sentman, 1998) which is strongly affected by space weather. Lightnings heat the atmosphere and produces ionisation and thus cause changes in the global electric circuit and terrestrial weather.

During times of geomagnetic storms, a greater number of energetic particles enter the atmosphere. By depositing their energy at altitudes of some tens of kilometres, these particles may contribute to chemical reactions creating nitrogen oxide compounds which in turn may enhance ozone concentrations at lower heights (Jackman et al., 1995). There is some evidence that energetic particles may produce small holes in the cirrus clouds and polar ozone layer, and thus affect to the evolution of atmospheric weather system (Pudovkin and Babushkina, 1992).

Galactic cosmic rays contain particles having relativistic energies which are sufficient to make them penetrate to cloud altitudes, i.e. a few kilometres above the Earth's surface. In the atmosphere, cosmic rays produce ionisation of particles, which can have an effect on the nucleation of water droplets to form clouds (Tinsley, 1996). How these processes really operate and what significance the phenomena have, are not known yet and require plenty of future research. It should be noted that a decreased solar activity implies an increased intensity of galactic cosmic rays entering the Earth's atmosphere. This is due to the more free propagation path of the rays in the less intense solar wind. Therefore the effects on cloud formation might statistically be the largest at times of sunspot minima (Svensmark and Friis-Christensen, 1997).

Quite recently a new type of indirect coupling between space climate and terrestrial climate has been found as a result studies of long-term variability of the "solar constant". It has been known for some time there is a small variation in the solar constant over the solar cycle but now it has been established that during the last 100 years solar-cycle average has also increased. (Lockwood and Stamper, 1999; Lockwood et al., 1999; Solanki and Fligge, 1999). The magnitude of its impact on terrestrial climate is not yet clear. In terms of space climate this effect is related to the magnitude of the solar and solar wind magnetic fields. Whether this effect has any relevance to space weather is also unknown but during the presently stronger magnetic conditions also the overall activity of the Sun is higher as shown by the average sunspot numbers.

2.6. Relationship of space weather with debris and meteoroids

2.6.1. Introduction

Our solar system consist not only of the Sun and nine planets (and their own satellites) but also of thousands of small bodies which occasionally becomes more spectacular than the brightest planet: brilliant comets, asteroids wandering in the vicinity of Earth orbit, meteor flashing across the sky, and meteorites striking the Earth. Collisions amongst them and evolution of their surface have created large population of small particles known as meteoroids or interplanetary dust particles (ranging in diameter from sub-micron to tens of centimetres). More recently, human activity in space has injected in our close environment more than 25000 large objects. Degradation and fragmentation of these have produced a large amount of small debris. This debris, at some altitude and for a given size range, outcomes already the number of natural particles (Anon. 1995; DeWitt, 1993; Johnson and McKnight, 1987).

Spacecraft are affected in many ways by the impacts at very high velocity (between an average of 7 km/s for the orbital debris to more than 30 km/s for the meteoroids) of these meteoroids and orbital debris: large particles can cause catastrophic failures or structural damages, small particles produce generally a degradation of optical and thermal properties of material exposed, by a progressive erosion of the surface (solar arrays, paints, thermal control devices, instruments) (LDEF-69, 1991; LDEF-69, 1993; Tribble, 1995). In addition, electrostatic discharges can be triggered by impacts of hypervelocity particles (especially in GEO orbits) (SEETC, 1992; Levy et al., 1991; Levy et al., 1997; Purvis et al., 1984). Space weather effects have indirectly an influence on this peculiar environment, mainly by a modification of the upper atmosphere of the Earth (Kessler et al., 1990; CNES, 1980).

2.6.2. Meteoroids and Debris

Natural meteoroids. Meteoroids and micrometeoroids are the smallest objects leftover by the formation of our solar system. Most of them are particles ejected from collisions between the asteroids or are particles ejected by cometary nuclei upon their closest approach to the Sun. The flux of meteoroids can be divided into three components: (a) Sporadic flux, background omnidirectional, fairly stable component; (b) Streams, temporary periodic increase (by a factor of ten in the average) over the sporadic level associated with the orbits of short period comets (for instance the Perseids stream in August) (Jenniskens, 1994) and (c) Storms, linked to the temporary increase of the activity of a stream (for instance the Leonids storm in November, with a period of 33 years) (Jenniskens, 1995, 1999). Fluctuation in the environment is therefore linked to the presence of meteoroid streams. As the streams are associated with the orbit of past or present comets, the main parameters of the streams are known with a good accuracy (flux density, orbital elements, size distribution of particles within the stream) and the meteoroid models used in the environment engineering tools incorporate these parameters. Enhancement by a factor of ten is common, during a period of a few days or a few hours. However, the models are statistical and do not allow an actual short term forecast (in space and in time) (Anderson et al. 1994; Cour-Palais, 1969; Grün et al. 1985). There is no direct interaction of solar activity with the meteoroid flux. However, a correlation with the forecast of solar events allows a prediction of increased hazard, possibly caused by charging effects on S/C on GEO orbits. Actually, electrostatic discharges could be triggered by the plasma produced upon hypervelocity on spacecraft surfaces (Levy et al., 1997).

Orbital debris. Unlike meteoroids, which pass through and leave the near-earth area, artificial space debris orbit the Earth and may remain in orbit for long periods of time. Since 1957, more than 3500 launches have injected 25000 different objects in near-earth space. Many of them have naturally decayed in the lower atmosphere but at least 8500 larger than 10 cm are still in orbit, along with a large population of tiny, 1 µm sized particles (Anon. 1995; Johnson and McKnight, 1987; Zhang et al., 1997).

Once in orbit, debris is affected by perturbing forces that can alter its trajectory and even remove it completely from orbit. Other than the gravitational attraction of the Earth, the primary forces acting on a space object in lower orbits (below 800 km) are atmospheric drag and gravitational perturbations from the Earth; for space objects in higher orbits, solar and lunar gravitational influences become more important factors. Small pieces of debris can also be affected by solar radiation pressure, plasma drag and electrodynamic forces.

The rate at which a space object loses altitude is a function of its mass, its average cross-sectional area impinging on the atmosphere, and the atmospheric density. Atmospheric density at a given altitude is not constant and can vary significantly (at less 1000km) due to atmospheric heating associated with the 11-year solar cycle. This natural phenomenon has the effect of accelerating the orbital decay of debris during periods of solar maximum (increased sunspot activity and energy emissions). During the last two peaks in the solar cycle, the total catalogued space object population actually declined, because the rate of orbital decay exceeded the rate of space object generation via new launches and fragmentation.

Objects with low ratios of cross sectional area to mass decay much more slowly than objects with high area to mass ratios. Differences in altitude distribution of objects of different size can be explain by this process: Medium-sized debris which often has a higher ratio of cross-sectional-area to mass than larger debris, will often be more strongly affected by atmospheric drag and thus will experience more rapid orbital decay. Objects at low altitude experience more rapid orbital decay than objects at high altitude. Finally, objects decay much more rapidly during periods of solar maximum than during solar minimum.

Solar radiation pressure normally induces a noticeable effect on a space object if the object possesses a large area to mass ratio. These effects can lead to an increase in the eccentricity of the orbit, which in turn leads to more rapid decay if the resulting lower perigee exposes the space object to significantly greater atmospheric density levels. The combination of all these forces has caused approximately 16000 objects catalogued to re-enter the atmosphere since the beginning of the space era. In recent years an average of two or three space objects large enough to be catalogued re-enter the Earth atmosphere each day. For the orbital debris the main variations in their distributions are linked to the change in the exospheric temperature due to the solar output in the UV range and to the charging effects on the particles themselves, caused by solar events (for the smallest particles - $d < 1\mu m$ - when the interaction with the earth magnetic field is not negligible).

One of the key factors to forecast is indeed the variation of the atmospheric density. Current atmospheric models are statistical and do not allow a short-term prediction for a given altitude. Long and medium term predictions of atmospheric density are based upon measurements of geomagnetic activity (Kp index) and of radio flux at 10.7 cm (which is linked to the solar flux in the UV range). Few direct measurements of the UV flux reaching the upper Earth atmosphere (causing the variation of the exospheric temperature) are available (only from in situ satellite measurements) and are not implemented into the models.

2.6.3. Implications for space debris

Mission planning, precisely controlled orbits, long term and short term, re-entry. Orbital elements of orbital debris are directly affected by the variation of the atmospheric density (orbital decay and orbital lifetime). Actual models take into account long term variation of their spatial distribution with the 11-year solar cycle but do not reflect any short term fluctuations possibly caused by solar events and space weather effects.

The long-term predictions of solar and geomagnetic activity are useful for planning satellite orbits in the months and years before launch. For spacecraft which require to be kept in precisely controlled orbits, it is necessary to predict solar and geomagnetic activity in the short to medium-term to plan manoeuvres which keep the spacecraft on track. Software developed under an ESOC contract (PDFLAP) (Mugellesi-Dow et al., 1993) uses Auto regressive integrated moving average (ARIMA) (Box and Jenkins, 1976) models of the solar flux and geomagnetic time series to predict values up to 27 days ahead. The problem is the same for the forecast of the re-entry of risk objects. Modelling alone does not allows an accurate forecast of re-entry time and location, frequent observations are usually necessary.

Collisions of S/C with large orbital debris. Collisions of S/C with tracked large orbital debris (currently 8500 pieces of debris larger than 10 cm) can be, in theory, predicted with a good accuracy within a short period of time. Uncertainty is linked to the accuracy of determination (and publication) of orbital elements, to the accuracy of current atmospheric models and to the physical properties of objects (geometry, determination of drag coefficient and estimate of optical properties) (Tribble, 1995; Koelle, 1961). Small debris models are statistical and thus is the forecasting collisions with operational spacecraft not currently possible.

Debris Catalogue accuracy. Currently, uncertainty in the future location of objects due to atmospheric drag, is the major limitation on catalogue accuracy in LEO. This uncertainty is due to the variability in the density of the upper atmosphere and uncertainty about objects' orbital attitude (and thus cross sectional area they present to the atmosphere) and inaccuracies caused by observation errors and errors in the propagation theory. Atmospheric drag retardation along the orbital track of medium to large space objects in 300 to 600 km altitude orbits can range up to hundreds of km per day. Improvements in propagation accuracy could be achieved by improving understanding of upper atmosphere density fluctuations.

The most optimistic estimate of the accuracy with which atmospheric drag can be determined is 15 %; consequently a prediction error of several km/day is typically accumulated. Keeping the number of false alarms for a LEO collision warning system at a tolerable level thus requires frequent re-observations of debris objects.

Orbit propagation models. Orbit propagation models predict how the orbits of space objects change as a function of time. This information is used for two major purposes: to determine the location of particular space objects in the relatively near-term (typically over a period of a few days or less for purposes of collision avoidance or re-entry predictions) and making long term (typically over a period of years) predictions about the debris environment. Both short- and long-term propagation models must take into account the various forces acting on space objects in earth orbit: atmospheric drag, solar radiation pressure, gravitational perturbations by the Sun and the Moon and irregularities in the gravitational field of the Earth. Since accurate orbit propagation models that include all forces acting on an orbiting object can be very computation intensive, most models take into account only the forces that most strongly affect the space objects in particular orbital region.

Accurate short-term deterministic propagation models require that the forces on an object be known and predictable. The inherent unpredictability in atmospheric drag thus introduces error into the prediction of short-term deterministic propagation models for objects in low LEO orbits (<500 km). Accurate deterministic predictions in this region for tasks such as collision warning, which require a high degree of accuracy and propagation of at least a significant fraction of a day, can be achieved only by making repeated observations with increasing calculation fidelity as the time to impact decreases (Crowther 1992a, 1992b, 1993). The Russian Space Surveillance System (RSSS) uses such an approach to solve actual task in debris related contingencies (e.g. space objects about to re-enter). Its approach employs short-term density prediction models using (in addition to knowledge of solar and geomagnetic activity) data on the current drag experienced by other space objects to specify atmospheric density (Batyr, 1993). The long-term uncertainty in atmospheric drag, however, still limits the fidelity of long-term propagation models in LEO. If solar and geomagnetic activities are known, long-term atmospheric models are accurate to within about 20%. However, atmospheric density can vary by more than a factor of 10 over the 11-year solar cycle and the level of future solar cycles is unpredictable.

Models of space debris flux. Current models of space debris environment (Klinkrad, 1997, Kessler, 1997) take only into account medium to long-term variation of the debris environment using the average solar flux (F10.7 cm) of the previous year as a parameter. More accurate, short-term forecast could be possible if the variability of the solar flux would more precisely monitored.

Charging effects. Correlation of assessment of impact hazard (meteoroids and debris) with solar events (CME, solar flares) is recommended and could be used for the assessment of increased hazard due to charging effects. Moreover, as observed on dust measurements performed in situ on GEO (Drolshagen, 1999) it is likely that small dust particles could be highly charged to negative values: implications the for orbital evolution in the earth magnetic field could be important.

3. Catalogues

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

3.1. Domain-oriented catalogue

Spatial domain	Systems affected	Effects	Measurable parameter
Interplanetary space	Spacecraft	SEE, radiation damage, noise, charging	Charged particle flux & composition, UV, X-rays
		Meteoroid impact	Mass, velocity
		Magnetic control	Magnetic field
	Manned spaceflight	Tissue damage	Dose Equivalent
Magnetosphere	Spacecraft	SEE, radiation damage, noise, charging, current loops, ESD	Particle flux & composition
		Debris/meteoroid impact	Mass, velocity, charge
	Manned spaceflight	Tissue damage	Dose Equivalent
Ionosphere	Spacecraft	Drag, loss of tracking high latitude charging	Density, precipitating particle Flux, UV
	Communications HF & below	Loss of communications	Mainly D-region electron density
		Change in area of coverage	E & F region electron density
		Low signal power	Mainly D-region electron density
		Fading	Mainly E-F region bulk electron density and irregularities
		Error rate change	Mainly E & F-region irregularities
	Communications VHF/UHF	Fading	E&F-region irregularities
		Error rate change	E&F-region irregularities
	Navigation	Dispersion, scintillation, loss of phase-lock	Total electron content Scintillation via S4 & Sigma-phi

3.1. Domain oriented catalogue (continued)

Neutral atmosphere	Aircraft and crew	SEE, Tissue damage	Neutron, ion, electron, meson fuxes and spectra Dose equivalent
	Launchers	SEE	Neutron, ion, electron, meson fluxes
Earth surface	Power transmission systems	Saturation of power transformers	Geomagnetically induced current, (Time derivative of the) ground magnetic field
		Reactive power consumption Harmonics Stray flux Voltage drops Relay trippings Overheating Black-out	Geoelectric field
	Gas and oil pipelines	Pipe-to-soil voltage variations Disturbance to the cathodic protection system Corrosion	Geomagnetically induced current Pipe-to-soil voltage (Time derivative of the) ground magnetic field Geoelectric field
	Telecables	Overvoltages Interference	Geomagnetically induced current Voltage between groundings of the system (Time derivative of the) ground magnetic field Geoelectric field
	Railways	Overvoltages Signalling problems	Geomagnetically induced current (Time derivative of the) ground magnetic field Geoelectric field
	Geophysical surveys	Interference	(Time derivative of the) ground magnetic field Geoelectric field

3.2. Phenomenon-oriented catalogue

Phenomenon	Dynamic Process	Measurable parameter	Predictability
Energetic electron flux	Magnetospheric Storm	Peak flux, fluence, spectrum	Nowcast, prospects of day ahead
Energised plasmasheet	Substorm	Density, temperature	Nowcast, prospects of day ahead
Trapped proton flux in LEO	Atmospheric removal, solar cycle	Flux, spectrum	Days ahead plus solar cycle
Trapped proton flux in slot	SPE + magnetic storm	Flux, spectrum	Not possible
Debris	Evolution, atmospheric drag	Orbit & size distribution	Weeks
Meteoroids	Streams, storms	Size distribution, flux, orientation	Months, weeks
RF disturbances	Mid-latitude ionospheric storm	Electron density, total electron content Scintillation via S4 and sigma4	Nowcast, forecast hours to days
	High-latitude ionospheric variations	All above	Even nowcast is difficult
	Equatorial ionospheric variations	all above	Nowcast, forecast hours to days
Cosmic radiation	Solar cycle, Forbush decreases	Primary flux & composition, Atmospheric secondaries	Year ahead using sunspot number Decreases via CME
Solar Particle Event	Solar flare, Coronal Mass Ejection	Peak flux, fluence, composition	Difficult
GIC	Substorm related ionospheric currents	dB/dt on ground Geoelectric field GIC Pipe-to-soil voltage Voltage between groundings of the system	Difficult
Atmospheric weather	Ionisation by cosmic rays		
Atmospheric drag	Solar UV, particle precipitation	10.7 cm radio flux, Sunspot number	Solar cycle, nowcast

3.3. System-oriented catalogue

System	Phenomenon	Effect	Predictability
Spacecraft	Energetic electrons, protons and ions, plasma	SEE, charging, dose, damage, noise	Cosmic rays good, SPE poor, Electrons 1 day ahead in prospect Trapped protons in LEO good Trapped protons in slot very difficult
	Debris	Damage, stimulated discharge	
	Meteorites	Damage, stimulated discharge	Weeks
	Magnetic field	Induced currents, attitude control	Hours
	Atmosphere	Drag, loss of tracking	Solar cycle
Manned space flight	Energetic ions, protons, electrons from cosmic rays, SPE and trapped radiation	Tissue damage	Cosmic rays good, SPE poor Trapped protons in LEO good
Launchers	neutrons, ions, protons from cosmic rays & SPE	SEE	Cosmic rays good, SPE poor
Aircraft	Neutrons, ions, protons, electrons, SEE & Tissue damage mesons from cosmic rays & SPE		Cosmic rays good, SPE poor

3.3. System-oriented catalogue (continued)

Communications	RF disturbance	HF and below Loss of communications Change in area of coverage Low signal power Fading, error rate change VHF/UHF Fading, error rate change	Nowcasts and forecasts are possible except at high latitudes
Navigation	Scintillation, dispersion	Loss of phase lock, position errors	Nowcasts, forecasts hours to days
Power transmission systems	Geomagnetically induced current	Saturation of power transformers Reactive power consumption Harmonics Stray flux Voltage drops, relay trippings, overheating Black-out	Nowcast
Gas and oil pipelines	Geomagnetically induced current	Pipe-to-soil voltage variations Disturbance to the cathodic protection system Corrosion	Nowcast
Telecables	Geomagnetically induced current	Overvoltages Interference	Nowcast
Railways	Geomagnetically induced current	Overvoltages Signalling problems	Nowcast
Geophysical surveys	Variations of the ground magnetic field	Interference	Nowcast

4. List of acronyms

ARIMA	Auto regression integrated moving average
CERISE	French satellite
CME	Coronal mass ejection
CRRES	US Air Force charging technology satellite
DNA	Deoxyribonucleic acid
D-region	Lower ionosphere below a height of about 90 km
EIRP	Effective isotropic radiated power
E-region	Upper ionosphere between 95km and 140 km
ESOC	European Space Operation Centre
ESD	Electrostatic discharge
EVA	Extra vehicular activities
F10.7 cm	10.7 cm radio emission
F-region	Upper ionosphere between 140 km and 400 km
GEO	Geostationary Earth orbit
GIC	Geomagnetically induced currents
GLE	Ground level event
GOES	NOAA meteorological satellite series
GPS	Global positioning system
GTO	Geostationary transfer orbit
HAARP	High Frequency Active Auroral Research Program
HF	High frequency
IMF	Interplanetary magnetic field
IR	Infrared
ISS	International space station
Kp	Planetary magnetic activity (K) index
LEO	Low Earth orbit
LET	Linear energy transfer
MIR	Russian space station
PEO	Polar Earth orbit
RF	Radio frequency
RSSS	Russian space surveillance system
S4	Standard deviation of the signal power
SEE	Single event effect
SEPE	Solar energetic particle event
SEU	Single event upset
Sigma-phi	Standard deviation of phase
SAR	Synthetic aperture radar
S/C	Spacecraft
SCATHA	NASA spacecraft
SEC	Space environment center
SPE	Solar particle event
SSN	Sunspot number
STP	Solar terrestrial physics
TEC	Total electron content
UHF	Ultra high frequency
UV	Ultraviolet
VHF	Very high frequency
VLF	Very low frequency

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