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Committee on the Peaceful
Uses of Outer Space
Scientific and Technical Subcommittee
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Long-term sustainability of outer space activities

Working report of expert group C: Space weather

I. Summary

Space weather is the collection of changes in Earth's natural environment and space-based and terrestrial infrastructure caused by solar events that alter the solar system space environment. These solar events, which include flares, the sudden eruptions of energetic photons and charged particles from the sun's surface; coronal mass ejections (CMEs), in which the sun typically sheds billions of tons of mass of its atmosphere as magnetized plasma; and solar wind, the continuous outflow of charged particles that race throughout the solar system at around 400-800 km/sec or more. At Earth, these charged particles and high energy photons have impacts on the dynamics if of the near-Earth space environment, specifically the magnetosphere, ionosphere, and even the neutral atmosphere, and affect the operation of terrestrial and space infrastructure. Perhaps their most well-known and more benevolent impact is the generation of the beautiful aurora — the dancing northern and southern lights.

Charged particles can damage or destroy satellite electronics and pose a radiation hazard to astronauts, and can also increase the dose experienced by aircraft crews especially on polar flights. Space weather also causes changes in the ionosphere that disrupt high frequency communications and alter the signals of position, navigation and timing (PNT) systems including Global Positioning System (GPS)/Global Navigation Satellite Systems (GNSS) systems. Additionally, swelling of the atmosphere as a result of space weather can change satellite orbits, degrading space situational awareness information. Finally, space weather can adversely affect some terrestrial infrastructure, including high voltage electrical transmission systems and pipelines.

This expert group considered impacts of solar storms that are most relevant to space sustainability. This expert group also considered space weather impacts on the scope of the work of the other expert groups: for example, changes in the space debris population and orbital dynamics arising from density changes in the upper atmosphere, and spacecraft failure from space weather effects, resulting in additional space debris (expert group B on space debris, space operations and tools to support collaborative space situational awareness); and potential loss of space-based services, particularly environmental monitoring and development planning (expert group A on sustainable space utilization supporting sustainable development on Earth). Because space services are integrated throughout the global economy, it is in the global common interest to avoid or prevent disruption of those services through mitigation of space weather effects.

Governments and civil space providers in both well-established and emerging space powers have a vested interest in satellites that are resilient to space weather effects. In addition, it is vital to space security and stability that satellite operators be able to attribute space weather impacts on satellite systems. Without proper and reliable attribution, governments and commercial operators alike would be constrained in their ability to respond appropriately to the impacts arising from the loss of satellites. Indeed, future mitigation strategies will likely be needed which rely at least partially on a system resilience approach to critical infrastructure protection.

The goal of securing the long-term sustainability of space against the adverse effects of space weather can be best achieved through the active collection and sharing of key information, including user needs, critical space data, space weather event information, satellite anomaly data, space weather models and forecasts, and the dissemination of relevant products and services. In addition, guidelines and best practices for satellite design and operations should be identified and adopted. The recommendations herein specifically address the operational issues relating to the design and operation of space assets comprising orbital satellites and satellite-subsystems, and the actions Member States can take in order to create the appropriate infrastructure for the mitigation of space weather effects. These actions will not only help protect the operation of space systems, and hence maintain space-based services, but also directly reduce the build-up of space debris arising from space weather-induced events.

In its deliberations, expert group C adopted the following guiding principle:

> Member States and their national and international agencies shall take all reasonable measures to protect vulnerable space and ground-based systems, both in order to maintain vulnerable satellite-based and ground-based services upon which human technological systems increasingly rely and to prevent the creation of space debris arising from the adverse effects of space weather.

Expert group C notes that there is an urgent need to adopt a coordinated approach to the collection, collation, and access to key data, meta-data, design guidelines, space weather models and now- and forecasts, and the reporting of the occurrences of space weather effects and related information, such as records of operational satellite anomalies. This should be achieved, wherever possible, through the use of common data formats and data repositories that will both collate data from international space-faring nations and make those data available to entities with interests in space activities in all Member States.

Member States and international organizations should voluntarily take measures, through national mechanisms, or through their own applicable mechanisms, to ensure that the following candidate guidelines in relation to space weather are implemented, to the greatest extent feasible. In the following chapters, expert group C also lists a series of recommended practices associated with each candidate recommendation and which should be adopted by Member States in order to put them into practice. These expert group C recommendations are listed below. In the interests of brevity, the recommended practices associated with each of guidelines are not listed explicitly in this summary, but are provided in full in chapter VI.

> Guideline 1: Space weather entities, and member states and national and international organizations, should support and promote the collection, archiving, sharing, inter-calibration and dissemination of critical space weather data.
>
> Guideline 2: Member States and their national and international agencies should support and promote further coordinated development of advanced space weather models and forecast tools in support of user needs.
>
> Guideline 3: Member States and their national and international agencies should support and promote the coordinated sharing and dissemination of space weather model outputs and forecasts.
>
> Guideline 4: Member States and their national and international agencies should support and promote the collection, sharing, dissemination and access to information relating to best practices for mitigating the effects of space weather on terrestrial and space-based systems and related risk assessments.
>
> Guideline 5: Member States and their national and international agencies should promote the education, training and capacity-building required for a sustainable global space weather capability.

Finally, as per the terms of reference, expert group C also makes two additional candidate recommendations for consideration by the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space.

> Candidate recommendation 1: Member States and their agencies should work through the United Nations Committee on the Peaceful Uses of Outer Space and related international organizations to develop a basis for the coordination of ground and space based research and operational infrastructure to ensure the long term continuity of critical space weather observations.
>
> Candidate recommendation 2: Member States and their national and international agencies should investigate the coordination of space weather information, including observations, analyses and forecasts, to support decision making and risk mitigation related to the operation of satellites, spacecraft, and sub-orbital vehicles including rockets and vehicles serving manned spaceflight including for space tourism.

Expert group C also suggests that that progress towards long-term sustainability of outer space activities goals should be reviewed by the Scientific and Technical Subcommittee every five years. In the case of space weather, the space weather agenda item of the Scientific and Technical Subcommittee provides an important forum for the development of future strategies, and for monitoring progress in relation to the implementation of the recommended practices.

II. Introduction

A. Background

Space weather refers to changes in the space environment in the solar system that due to solar events influence both the natural environment and space-based and terrestrial infrastructure. Solar events are flares, sudden eruptions of energetic photons and charged particles, coronal mass ejections (CMEs), where the sun sheds portions of its atmosphere as magnetized plasma, typically a billion tons in mass in an event, and solar wind, the continuous outflow of charged particles that races throughout the solar system at 400-800 km/sec. The visible manifestation of these phenomena are limited by human senses; with proper telescopes we can see flares as bright regions on the solar “surface” as well as sheets of material erupting from the sun. At the earth we witness auroral displays primarily in the polar regions. However, there are manifold impacts invisible to the eye.

Charged particles can damage or destroy satellite electronics and pose a radiation hazard to astronauts. Energetic photons and charged particles alter the structure of the ionosphere, which causes high-frequency (HF) communications disruptions and loss of signal from Global Navigation Satellite Systems (GNSS). The atmosphere also swells in response to enhanced energetic photon flux, which can change satellite orbits in unpredictable ways and threaten space situational awareness. Commercial flights over the poles must re-route, at considerable expense, to protect crews from radiation exposure and to assure communications capability. CMEs can disrupt the earth’s magnetic field, leading to electrical blackouts potentially on a continental scale. Additionally, global banking and finance rely on timing signals from GNSS; loss of this service due to a solar storm would lead to disruptions of this economic sector with unforeseeable secondary impacts.

There are three main impacts of solar storms considered by this expert group that are most relevant to other expert groups. First, the space debris population and its evolution are tied to the altitude-dependent density of the atmosphere, which is dependent upon solar effects. Second, the ability to predict conjunctions and hence enable collision avoidance also depends on atmospheric density. These items are both within the purview of expert group B on space debris, space operations, and tools to support collaborative space situational awareness. The third impact is in the provision of space-based services, particularly environmental monitoring and development planning. This is within the purview of the expert group A on sustainable space utilization supporting sustainable development on Earth.

Stakeholder perspectives

Space weather encompasses a broad range of interacting physical phenomena, many of which are poorly understood, to the extent that there are fundamental governing equations to be discovered. Hence, this is a field rich in research opportunities. Because of the many societal impacts, some of them severe, there is great interest in operational capabilities, i.e., the ability to predict solar storms and their effects in time to allow for mitigation measures. Operational capabilities will often require the same measurements as the research communities, but at a faster cadence and much lower latency. There is much room for collaboration between these communities internationally.

Governments and civil space providers have a vested interest in satellites that are resilient to space weather effects. This applies equally to emerging and well established space powers. In addition, it is vital to space security and stability that space weather impacts on satellite system be attributable. Without proper and reliable attribution, governments would be constrained in their ability to respond appropriately to the loss of a satellite. Finally, space services are integrated throughout the global economy, e.g. GNSS applications in resource development, agriculture, recreation, financial services, and it is in the common interest to avoid or prevent disruption of those services.

All the communities mentioned thus far have varying interests in space weather monitoring, nowcasting, and forecasting.

The expert group on space weather arose from the Working Group on the Long-term Sustainability of Outer Space Activities, and hence its work is meant to support the broader goals of the Working Group’s efforts. The Working Group’s mandate was broken into four clusters, of which space weather is one, designated expert group C. Member states and intergovernmental organizations with permanent observer status were invited to nominate experts to participate in the expert groups. Member states were also invited to include private sector experts as part of their delegations. The work of expert group C has been done taking into account a number of parallel space weather definition efforts being completed internationally, and some of these are outlined in chapter V of this document. For example, the World Meteorological Organization (WMO) and the Committee on Global Meteorological Satellites have substantial space weather equities. WMO is represented in expert group C.

B. Objective

The first objective of expert group C is to produce a report on global space weather efforts, including a synopsis of the state of the art understanding of space weather phenomena and impacts on space and terrestrial infrastructure. The second objective of expert group C is to provide a list of guidelines and recommended practices that member states could adopt on a voluntary basis and which would mitigate the effects of space weather.

C. Scope

The scope of expert group C is set forth in the Terms of Reference for the Working Group on the Long-term Sustainability of Outer Space Activities. The topics relevant to expert group C are:

1. Collection, sharing, and dissemination of data, models, and forecasts;
2. Capabilities to provide a comprehensive and sustainable network of sources of key data in order to observe and measure phenomena related to space weather in real or near-real time;
3. Open sharing of established practices and guidelines to mitigate the impact of space weather phenomena on operational space systems;
4. Coordination among States on ground-based and space-based space weather observations in order to safeguard space activities.

The expert group decided to include some consideration of terrestrial impacts, primarily because the potential impact of a prolonged widespread electrical power outage is severe in the extreme. However, expert group C did not consider this case in detail and did not consider cascading failures resulting from loss of space or terrestrial systems.

D. Methodology

Expert group C worked by first developing an outline for its report during informal meetings on the margins of the International Astronautical Congress (IAC) in October 2011 and formal meetings during the Scientific and Technical Subcommittee in February 2012. Expert group C adopted a final report outline at the June 2012 meeting on the margins of the fifty-fifth session of the Committee on the Peaceful Uses of Outer Space, and this outline was developed into a preliminary draft report which was reviewed on the margins of IAC in Naples in October 2012. A further developed report was presented at expert group C meetings during the Scientific and Technical Subcommittee in February 2013, and again at the fifty-sixth session of the Committee in June 2013. This final expert group C report is tabled for consideration at the session of the Scientific and Technical Subcommittee in February 2014. Note that the sources for the figures included in this report are listed in an annex to this report.

III. Identification of risks from space weather

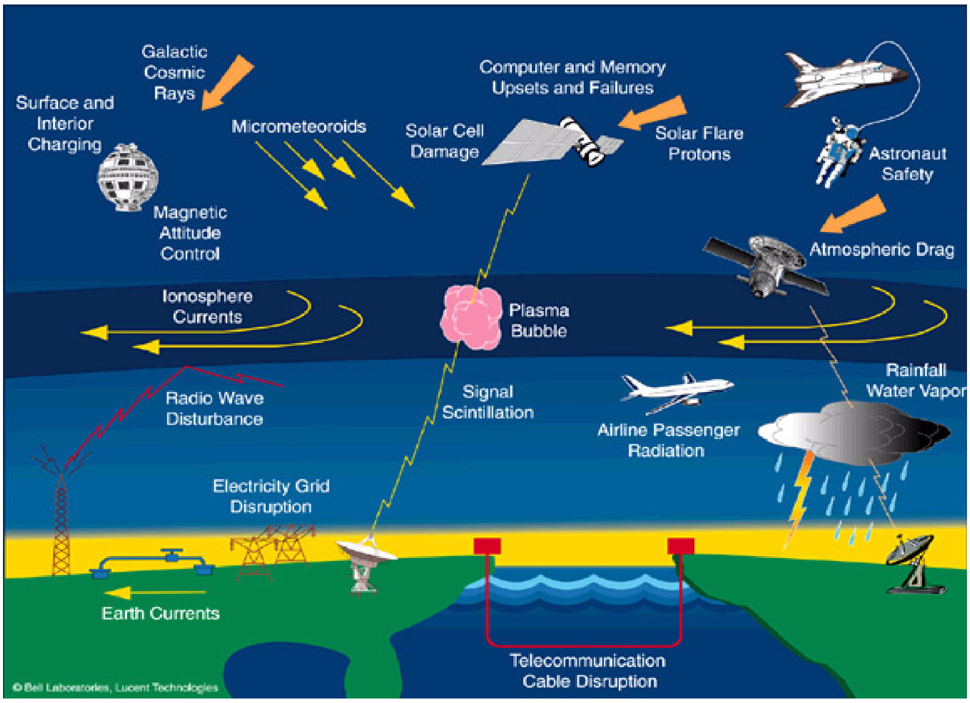
Introduction

The technological progress and development of the ground-based and space technological infrastructure susceptible to the space weather factors make the latter more and more significant. These factors affect the functioning of technological systems and create serious risks to the human activities in space. Taking them into account and mitigating their negative effect must become an essential part of the long-term stable development of space activities. In this section of our report, we shall identify the risks, i.e., describe the dangerous factors of the space weather and the risks involved.

A. Characterization of impacts from storms

The space weather is a source of hazard to the human activity in space producing multiple risks and losses. The solar, galactic, and magnetospheric high-energy particles present a radiation hazard to astronauts and the International Space Station (ISS). Strong auroral currents arising during geomagnetic storms can disrupt and damage modern electric power grids and cause the corrosion of oil and gas pipelines. Ionospheric irregularities caused by magnetic storms interfere with high-frequency radio communications and navigation signals from GPS/GNSS satellites and disturb their operation, the polar cap absorption (PCA) events associated with solar proton flares can degrade and, during severe events, completely blackout high frequency (HF) communications along aviation routes requiring that aircraft be diverted from its course to lower latitudes. The exposure of spacecraft to energetic particles during solar energetic particle events and the radiation belt enhancements can cause temporary operational anomalies, damage critical electronic elements, degrade solar arrays, and blind optical systems such as telescopes and star trackers. An important result of the space weather studies is the identification of direct and indirect risks for space activities and the related societal infrastructures.

Figure 1
Space weather effects on technological systems on the Earth and in space



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The table below summarizes the space weather hazards (risks) and their sources (D — direct impact, I — indirect impact, GCR — Galactic Cosmic Rays, RB — Radiation Belts, SCR — Solar Cosmic Rays, EE — Electromagnetic Emission, SW — Solar Wind, CH — Coronal Holes, CIRs — Corotating Interaction Regions, CMEs - Coronal Mass Ejections).

Hazards and risks ⇓	Factors of space weather				Geomagnetic storms	Geomagnetic substorms
	GCR	RB	SCR	EE		
Radiation hazard for astronauts	D	D	D		I	
SC surface and internal charging		D				I
Degradation of SC solar arrays and materials	D	D	D	D	I	
Single-event effects (SEE)	D	D	D		I	
Blinding optical systems, loss of racking			D		I	
Anomalous drag and loss of altitude				D		
Radio blackouts and disturbance of the normal operation of space radio systems (GPS etc.)			D	D	D	D
Solar sources of the space weather ⇓						
Solar flares			D	D		
Solar wind (CH, CIRs)		D	I		D	D
CMEs	D	D	D		D	D
Periodic solar activity (solar cycle)	D	D	D	D	I	I

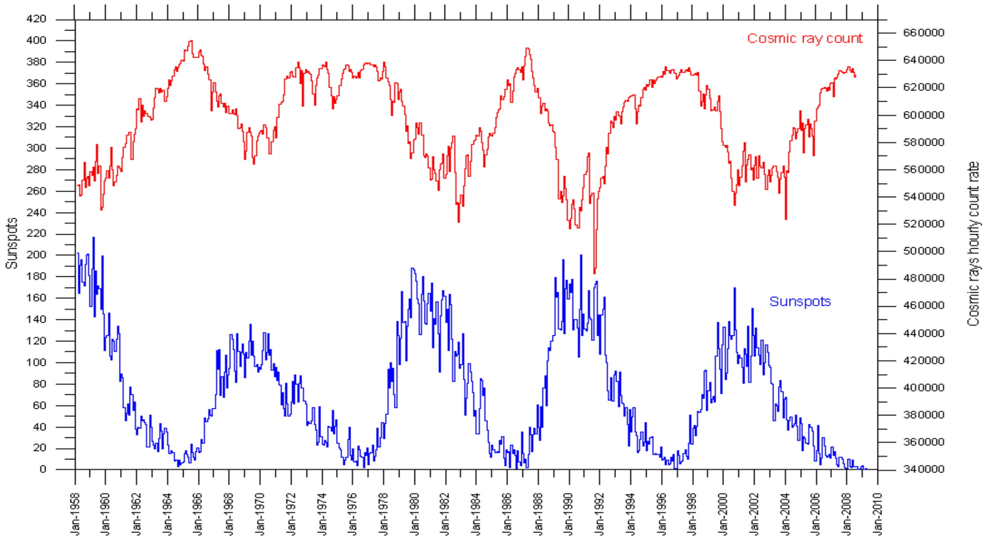
1. Radiation (Electromagnetic Emissions and Energetic Particles)

Corpuscular radiation

(a) Galactic cosmic rays (GCR)

Because of their high energy, galactic cosmic rays are the main source of radiation hazard in space. They determine the radiation doses the astronauts on round-the-Earth and interplanetary orbits and passengers of high-flying aircraft are exposed to. Hitting semiconductor integrated circuits, GCR produce ionization and energy releases, which cause single event effects (SEE) in electronic systems and damage radio electronics. As a result, the satellite may fail to function properly.

Figure 2
The correlation of increased fluxes of galactic cosmic rays with the epochs of minimum solar activity

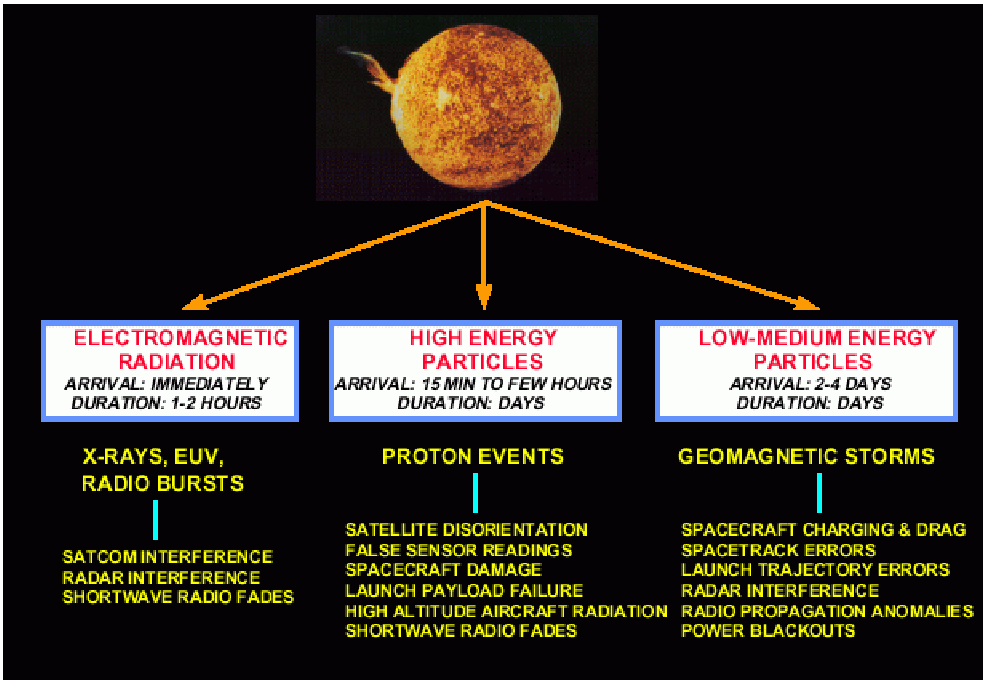


The intensity of GCR in near-Earth space is modulated by solar activity, being the highest at the minimum of the activity cycle and the lowest at the maximum. Correspondingly, the occurrence rate of SEE is the largest at the solar minimum. The dependence of GCR intensity on the solar activity must be taken into account when planning round-the-Earth and interplanetary manned space missions and operation of satellite systems.

(b) Solar corpuscular radiation (SCR)

Solar energetic particles (SEP) (protons) generated in solar proton events — major solar flares — occur sporadically. Their intensity may exceed the background GCR flux by many orders of magnitude, and their energy may reach a few GeV. Penetrating the Earth magnetosphere and atmosphere, SCR augment the radiation hazard to astronauts and high-altitude aviation, increase the number of SEE, disturb the operation of satellite optical and electronic systems, disrupt radio communication, and deplete the ozone layer in the polar zones. SCR events are difficult to forecast. More than a dozen powerful SCR events may occur in the course of a solar activity cycle (11 years).

Figure 3
Electromagnetic and corpuscular solar radiation and its effects



ELECTROMAGNETIC RADIATION
ARRIVAL: IMMEDIATELY
DURATION: 1-2 HOURS

X-RAYS, EUV, RADIO BURSTS

SATCOM INTERFERENCE
RADAR INTERFERENCE
SHORTWAVE RADIO FADES

HIGH ENERGY PARTICLES
ARRIVAL: 15 MIN TO FEW HOURS
DURATION: DAYS

PROTON EVENTS

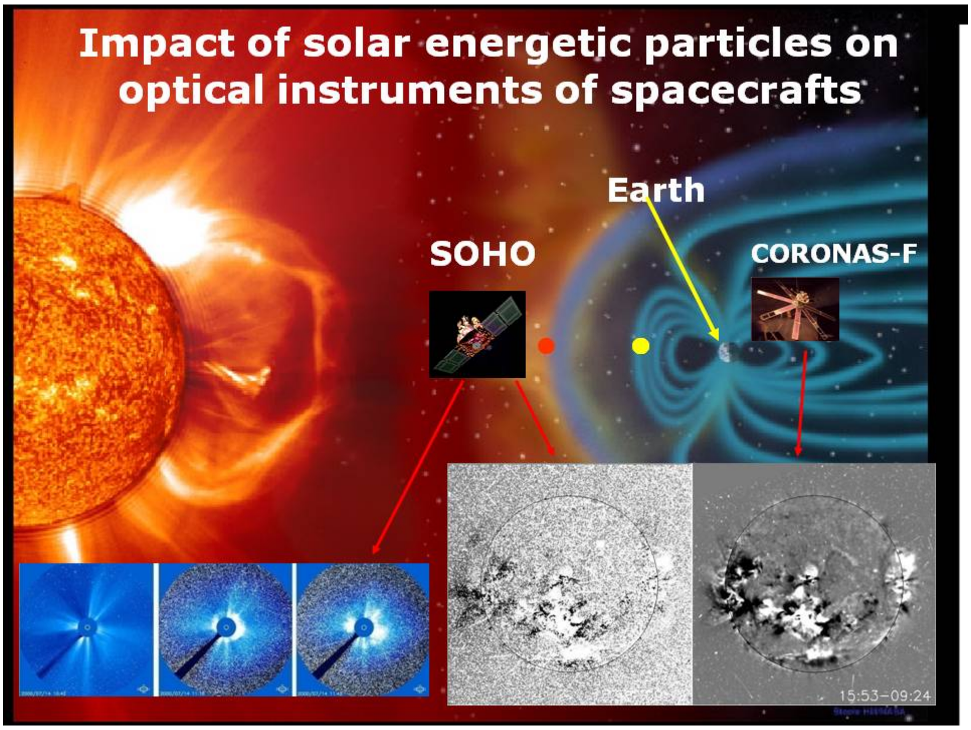
SATELLITE DISORIENTATION
FALSE SENSOR READINGS
SPACECRAFT DAMAGE
LAUNCH PAYLOAD FAILURE
HIGH ALTITUDE AIRCRAFT RADIATION
SHORTWAVE RADIO FADES

LOW-MEDIUM ENERGY PARTICLES
ARRIVAL: 2-4 DAYS
DURATION: DAYS

GEOMAGNETIC STORMS

SPACECRAFT CHARGING & DRAG
SPACETRACK ERRORS
LAUNCH TRAJECTORY ERRORS
RADAR INTERFERENCE
RADIO PROPAGATION ANOMALIES
POWER BLACKOUTS

Figure 4
The effect of high-energy solar protons on the satellite-borne optical instruments



In October 2003, a flux of accelerated protons generated by an outstanding solar event attacked the Euro-American satellite, SOHO, which was moving outside the Earth's magnetosphere not protected by the latter. Energetic particles hit the charge coupled device (CCD) camera blinding the satellite. As a result, the solar images obtained were covered with "snow". At the same time, the Russian-Ukrainian satellite, CORONAS-F, was inside the magnetosphere protected from accelerated solar particles and was able to take high-quality images of that extreme event.

When particles hit CCD they generate electrons which charge up the pixels just like the regular photons, producing images similar to a star. This confuses the attitude control unit and can lead to tumbling.

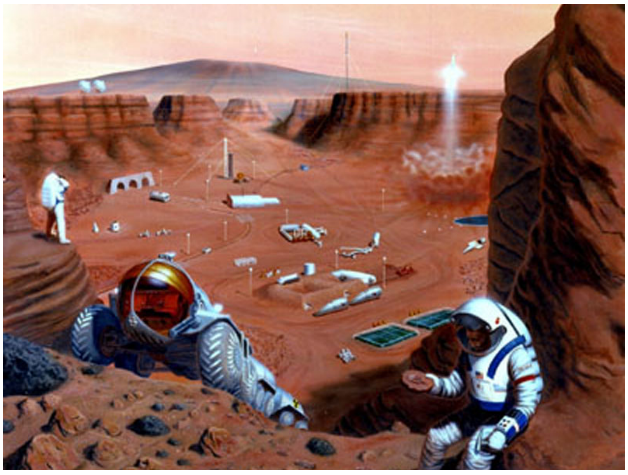
In the periods when major ejections occur in the Sun, generating high-speed solar wind streams, the Earth magnetosphere is compressed, and its boundary point on the day side may move from 10-12 to 5 Earth radii. As a result, geostationary satellites that ensure mobile communications, TV services, etc. find themselves outside the magnetosphere exposed to solar corpuscular radiation, which, under normal conditions, does not penetrate to these orbits. Although the events like that under consideration are rare, they need to be predicted, because they can disable many satellites at a time. The present-day quality of such forecasts is unsatisfactory.

The space missions that involve extra-vehicular activity of astronauts, such as the ISS, and the future manned missions to the Moon and Mars, are susceptible to the risk of radiation exposure of astronauts. Planning such missions requires the knowledge of radiation conditions at the Earth orbit and in interplanetary space that depend on solar activity. Solar cosmic rays can switch off the robotic arm and other facilities on board the ISS and, thus, suspend the work of astronauts.

Figure 5
Solar cosmic rays produce radiation hazard to astronauts in near-Earth and interplanetary space

In future missions to the Moon and Mars, the astronauts unprotected by the Earth magnetosphere will be exposed to larger radiation dozes during longer times than they were in the first flights to the Moon. If the Apollo-16 and Apollo-17 Moon missions had not taken place in April and December 1972, but in August when one of the most intensive solar flares on record emitted large fluxes of high-energy protons, the radiation doses experienced by the astronauts would have been lethal. The radiation protection of astronauts in transit to Mars and on the Mars surface will be one of the main problems of the mission to this planet.

Figure 6
Solar and galactic cosmic rays produce radiation hazard to the crews of space missions to other planets (the Moon, Mars)



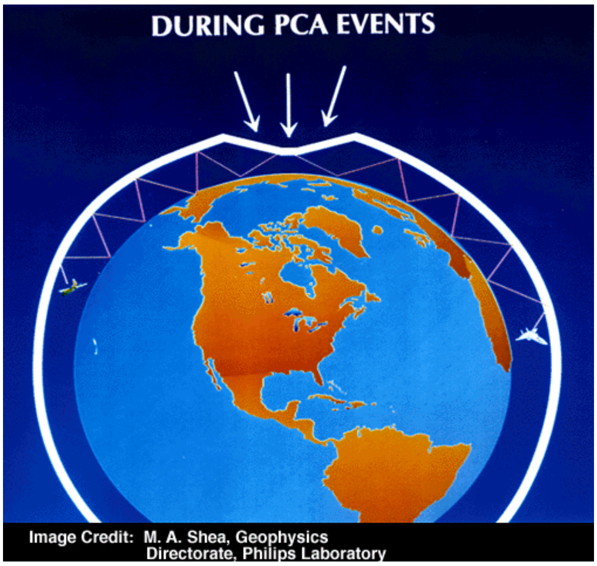
Large SCR fluxes from major solar flares penetrate the Earth magnetosphere and can cause a failure of automatics, in particular, the loss of data in the thruster control system, and affect the launch of space missions. The launch of Kodiak Star was postponed for at least an additional 24 hours. A solar flare of significant magnitude occurred that morning at 7 a.m. ADT (11 a.m. EDT) producing a “proton flux” exceeding the allowable launch criteria for the Athena I. These high levels of charged particles can cause a “data upset” in the launch vehicle guidance system affecting its reliability.

Figure 7
Solar cosmic rays can affect the launch of satellites interfering with the control systems of the launch vehicles

Besides the direct radiation hazard to the passengers of high-flying aircraft, the high-energy protons in the Earth polar regions cause anomalous ionization of the ionosphere, which results in the polar cap absorption events (PCA) — a strong absorption of radio waves and blackout of HF radio communications lasting ten days or longer and affecting the navigation. During several days of disturbed space weather in January 2005, 26 United Airlines flights were diverted to non-polar routes to avoid the risk of HF radio blackouts during PCA events. The increased flight time and extra landings and take-offs required by such route changes increase fuel consumption and raise cost, while the delays disrupt connections to other flights.

Figure 8

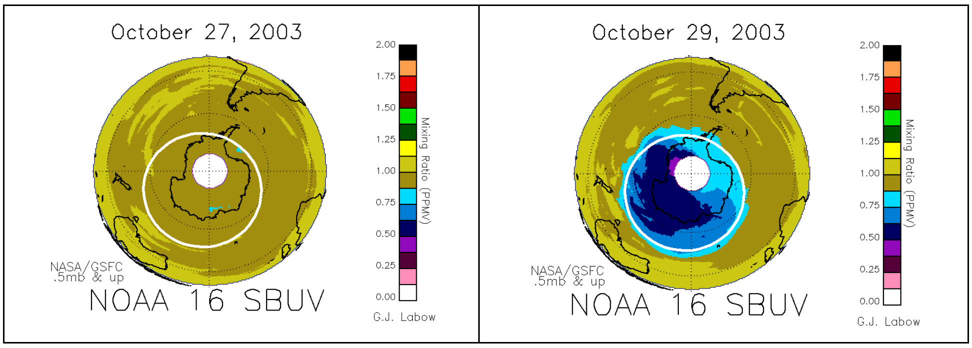
High-energy solar protons moving along the open field lines of the Earth magnetic field in the polar regions penetrate the upper atmosphere and cause radiation enhancements and PCA events — short-wave radio blackouts



SCR penetrate deep into the atmosphere and initiate chemical reactions depleting the ozone layer, which protects the Earth from the damaging effect of ultraviolet radiation. In the middle mesosphere at the height of 55 km, the content of atmospheric ozone can be reduced by 70 per cent. The restoration of the ozone layer may take from a few weeks to a month.

Figure 9

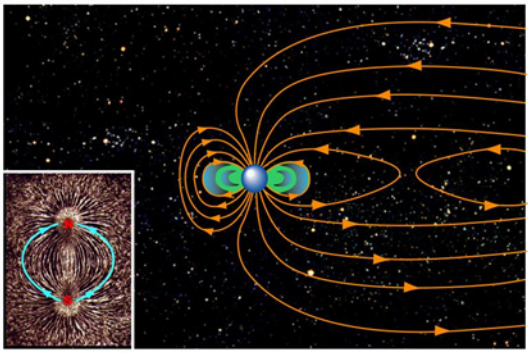
Solar protons cause depletion of the vital ozone layer



(c) The inner magnetospheric radiation — Earth radiation belts (ERB)

Though the ERB particles have, on average, essentially lower energy and, hence, a weaker ionizing effect than SCR, their large fluxes contribute significantly to the radiation doses experienced by astronauts and have a damaging effect on spacecraft, particularly on semiconductor elements of the solar panels (e.g., degradation of the TEMPO, PanAm, ECS, etc. arrays) and on spacecraft electronics.

Figure 10
The increased radiation level in the Earth radiation belts is dangerous to satellites



Energetic protons of the inner radiation belt, like GCR and SCR, hit the satellite electronics producing single event upsets and damaging critical elements, such as on-board memory, semiconductor devices, optical devices, including star trackers, etc. In the South Atlantic Anomaly (SAA) region and at the poles, the background radiation may be tens to hundreds of times higher than elsewhere over the globe making these regions particularly dangerous to satellites. The lower boundary of the inner radiation belt in the SAA region is as low as 250 km.

The low- and medium-energy electrons (keV to tens of keV) knock out electrons from the satellite body and create a large surface charge. This generates electric fields and discharges between different parts of the satellite skin resulting in electromagnetic noise, signal distortions, and operational anomalies. High-energy electrons (from over 100 keV up to MeV and higher) penetrating inside a satellite generate the volume charge, cause dielectric breakdowns, and upset the normal operation of on-board electronics.

These effects are the main cause of outage of satellites in geostationary orbit (GEO). Periodic enhancements of energetic electron fluxes in the magnetosphere are due to the high-speed solar wind streams emanating from coronal holes at the decline of the solar cycle, as well as to acceleration of magnetospheric electrons during magnetic substorms and their injection into the inner magnetosphere that can occur both under relatively quiet conditions and in the disturbed periods.

Two Canadian communication satellites in geostationary orbit were disabled in January 1994. Telesat's Anik E1 was disabled for seven hours as a result of damage to its control electronics by the discharge of electric charge created in the satellite interior by penetrating high-energy electrons. These electrons appeared in the magnetosphere a week earlier as high-speed solar-wind stream swept past the Earth. As a result, news could not be delivered to 100 newspapers and 450 radio stations in Canada. The telephone service to 40 communities was interrupted. Shortly after the E1 operation was restored, its sister satellite Anik E2 went off resulting in the loss of TV and data services to more than 1600 communities. The backup systems of the satellite were also damaged making the $290 million satellite useless. About 100 000 home satellite dishes had to be re-pointed manually to other satellites. It took six months to restore Anik E2 to normal operation. The E2 failure was estimated to cost $50-$70 million including the recovery costs and lost business. Similar anomalies in spacecraft operations due to the space weather effects occurred in January 1997 (Teslar 401) and May 1998 (Equator-S, Polar, and Galaxy-IV).

Figure 11

Hitting microchips of on-board electronics, GCR produce single event effects (SEE). High-energy protons and ions wreck electronic elements and cause single event effects in the operation of satellites. High-energy electrons penetrate the satellite and create the bulk charge, which results in dielectric breakdown and the failure of on-board electronic equipment

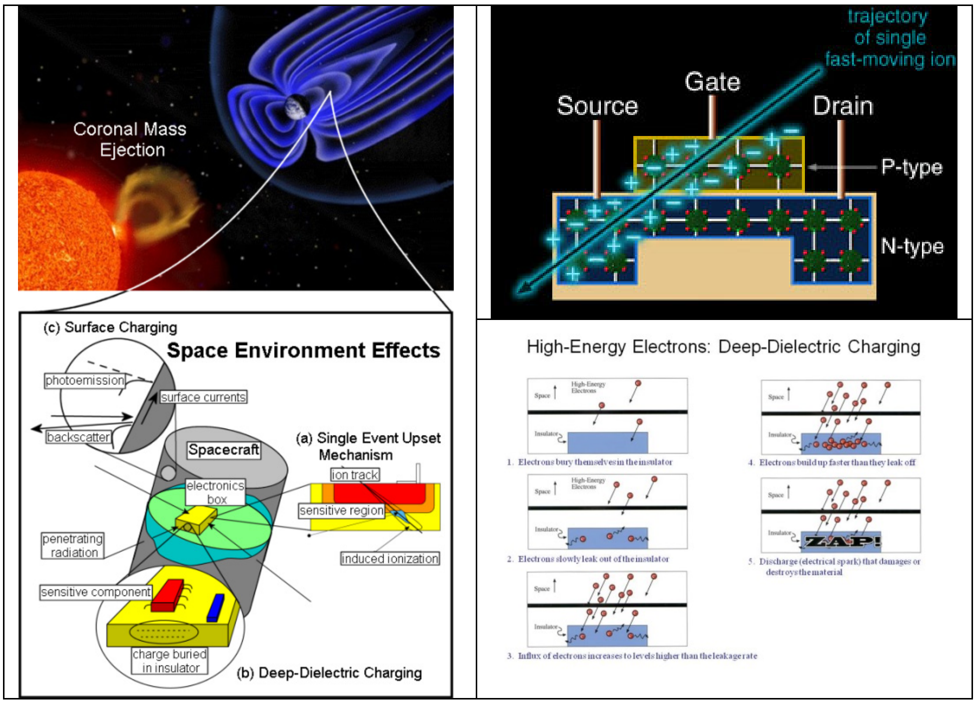
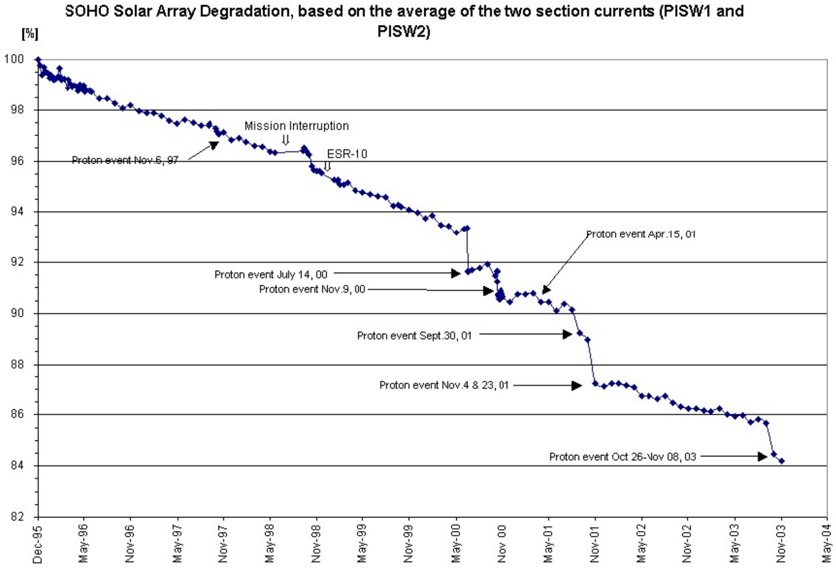


Figure 12

Solar radiation causes a degradation of solar batteries, which may decrease the satellite lifetime by a few years



Some spacecraft have had the efficiency of their solar cells reduced by over 30 per cent in a single large solar particle event. This effectively reduces the lifetime of the spacecraft by several years. The annual losses due to damaging effect of radiation on spacecraft systems amount to hundreds of millions of US dollars. Information about satellite operation anomalies is often concealed because of commercial interests.

(d) Solar electromagnetic emission

Solar flares generate hard electromagnetic emissions from ultraviolet to X-ray and gamma-ray fluxes. These fluxes may exceed the quiet Sun emission in some spectral ranges by hundreds and thousands of times resulting in a noticeable enhancement of ionization in the Earth ionosphere and the associated degradation of radio communications.

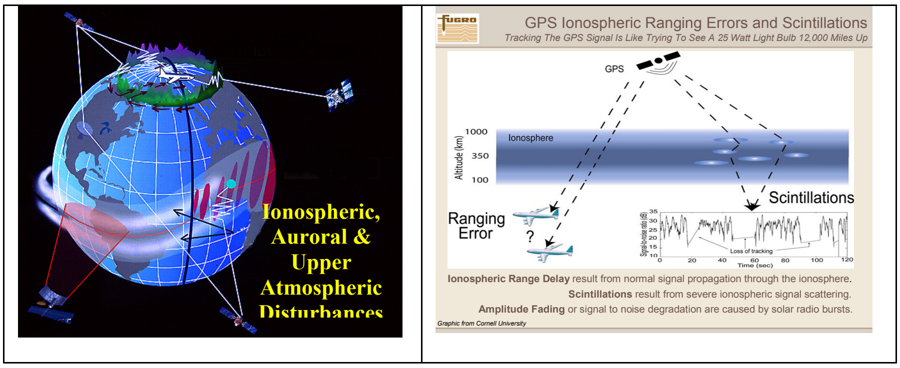
At the maximum of solar activity, hard electromagnetic emission from the Sun enhanced by tens of times compared to the quiet-Sun conditions heats and expands the Earth atmosphere resulting in increased atmospheric drag, which affects low-orbital spacecraft and ISS, decreases the satellite lifetime, and entails additional expenditures on orbit correction. Estimating the orbital lifetime of satellites requires the knowledge of the solar electromagnetic flux throughout the supposed operational period. The neglect of atmospheric expansion by enhanced solar radiation in 1979 resulted in uncontrolled deorbit and fall of the US orbital station, Skylab.

Intense flare-generated X-ray emission can saturate and disable on-board X-ray detectors as it happened when the TRMM X-ray sensors were driven off scale for 11 minutes during a solar flare. Flare-generated radio emission (solar radio bursts) interferes with satellite radio signals and GPS/GNSS navigation signals disrupting services and data transmission (see Section A.2.).

2. Radio systems (including GPS)

Figure 13

Radio signals from all systems are subject to space weather by virtue of variations in the medium they propagate in

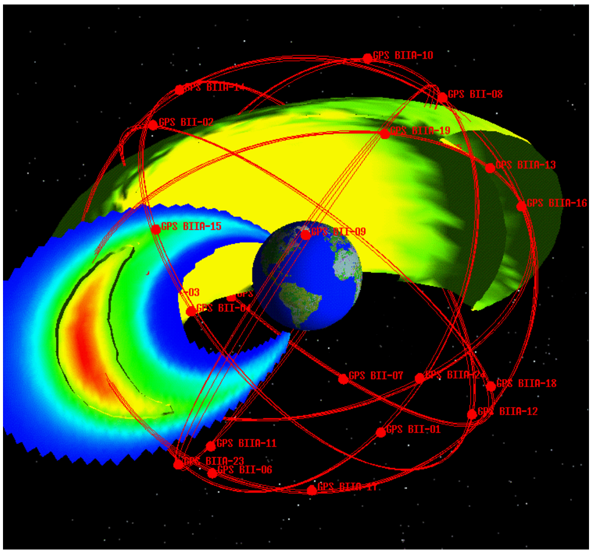


Besides its impact on spacecraft electronics, the space weather also influences the propagation of signals from modern navigation systems (GPS, GLONASS, GALILEO), communication satellites, etc. disrupting satellite navigation and communications and resulting in the loss of satellite data. Propagating through the disturbed ionosphere and atmosphere, the signals scatter and degrade on ionospheric irregularities that occur in the periods of strong geomagnetic disturbances and storms.

The widely used GPS system comprising 24 satellites is vulnerable to space weather, specifically, to ionospheric density irregularities that occur in the equatorial and auroral ionosphere during magnetic storms and affect the propagation of signals from GPS satellites to receivers on the ground. When the ionosphere becomes turbulent and irregular, the GPS signal from one or several satellites may be lost. The single and dual frequency systems may be equally affected. The navigation radio systems using single-frequency receivers are susceptible even to weak ionospheric disturbances. Ionospheric disturbances increase the radio signal propagation time resulting in positioning errors and, thus, decreasing the reliability of GPS. During magnetic storms, the positioning errors increase manifold and may reach a hundred meters or more.

Figure 14

The density irregularities arising in the ionosphere during magnetic storms affect the propagation of signals from GPS satellites

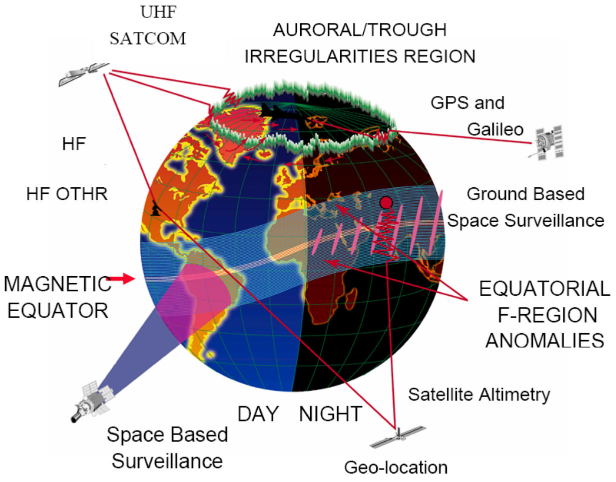


Intense radio emission from solar flares (solar radio bursts) interferes with satellite radio signals and GPS navigation signals disabling services and data transmission. The emission passes through the Earth ionosphere and reflects from the ocean in all directions hitting the satellite sensors and transceivers and resulting in strong noise or off-scale readings. For example, a flare-generated microwave burst saturated the telemetry channels of the TRMM satellite at the frequency of 11 GHz and caused the loss of information transmitted to the ground. Solar radio bursts interfere with GPS signals and lead to their fading and signal-to-noise degradation, which results in deterioration of the positioning accuracy and the loss of the navigation signal on the day side.

Other navigation systems, such as LORAN C and WAAS (Wide Area Augmentation System) are affected in a similar way. Variation in the height of the lower ionosphere by 7-10 km may lead to a positioning error of 1-12 km.

The space weather risks to GPS users involve a suspension of navigation and other services to governmental, civilian, and commercial customers in such vital spheres as transportation (aviation, railways, marine and submarine navigation, etc.), marine construction support, submarine cable surveys, farming, gas and oil production (offshore drilling), geophysics (geophysical surveys), seismology (seismic data collection), oceanology (oceanography), lidar surveys, and Geographic Information System/Data Management (GIS).

Figure 15
Various satellite communication services, such as TV, cellular telecommunications, etc. are subject to negative effects of the space weather



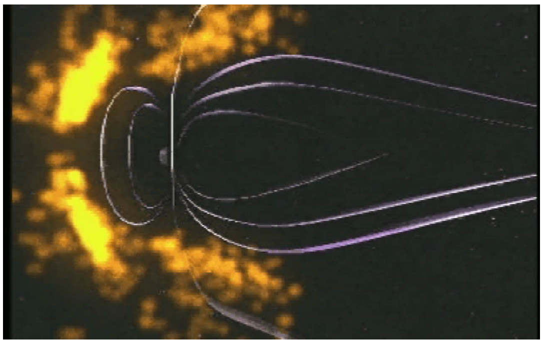
Satellite communication that ensures radio and TV broadcasting, Internet, paging, data transmission, etc. is influenced by the environment in which it operates. This influence involves the effects on satellites (radiation, anomalous drag), effects on the ground segment (power blackouts during magnetic storms), and effects on the signals propagating through the Earth's upper and lower atmosphere.

3. Geomagnetic disturbances

Strong geomagnetic disturbances and geomagnetic storms increase the general level of radiation hazard in the Earth environment (astronauts, spacecraft electronics), cause ionospheric disturbances and generate ionospheric density irregularities (disruption of radio and satellite communications), degrade the satellite navigation, expand the atmosphere resulting in anomalous drag, tumbling of satellites, and launch problems, generate induced currents affecting power lines.

Figure 16

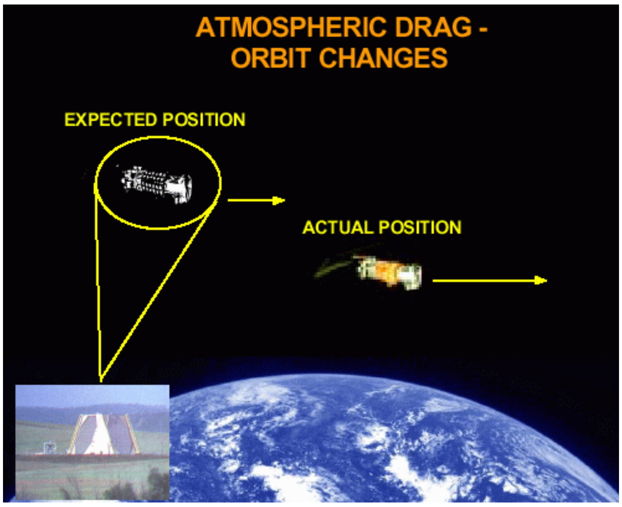
Geomagnetic disturbances and magnetic storms caused by solar mass ejections and high-speed solar wind streams are the most dangerous manifestations of the space weather



The global reconstruction of the Earth magnetic field in the main phase of geomagnetic storm favours the penetration of high-energy GCR and SCR particles into the magnetosphere. As a result, the particle fluxes may increase dramatically. Energetic particles can also be trapped directly from interplanetary space, and a new radiation belt can form inside the magnetosphere and last for a few months. Such situation was observed on 24 March 1991 when a new radiation belt was formed in the Earth's magnetosphere after a magnetic storm and existed until September 1991 increasing several times the radiation dose on board the MIR orbital station. The danger is particularly large when the onset of a magnetic storm coincides with the arrival of SCR flux from an intense proton event in the Sun, as the case was during 6-7 April and 15-16 July 2000. Then, in the period of magnetic storms, large SCR fluxes penetrated the Earth's magnetosphere and atmosphere down to mid-latitudes. Red nightglow caused by the intrusion of energetic protons was observed at Washington. A similar situation occurred in October-November 2003 when a magnetic storm coincided with a series of solar flares, and flare-generated SCR reached the ISS orbit.

Expansion of the atmosphere in the period of magnetic storms makes the ISS lose altitude by about 7-10 km faster than usual. Correcting the orbit and delivering fuel to the ISS take time and increase costs. During the magnetic storm of March 1989, the United States satellite positioning system was paralyzed since many satellites drifted away from their orbits and some of them were lost because of the anomalous atmospheric drag. Atmospheric density variations along a proposed launch trajectory may affect the operation of launching systems as well as the thermal and mechanical interaction of satellite with the atmosphere and, thus, may upset the standard launching procedure.

Figure 17
Uncontrolled variations of satellite orbits due to the swelling of the atmosphere in the periods of magnetic storms cause tracking problems and increase the danger of collision with space debris



The accuracy of GPS and other navigation systems decreases several times during magnetic storms because of ionospheric disturbances. Sometimes, the navigation signal may be lost completely. For example, the United States Wide Area Augmentation System (WAAS) was unable to support vertical navigation services for 30 hours in October 2003 due to ionospheric disturbances associated with a magnetic storm.

Severe magnetic storms generate induced currents in power grids resulting in power blackouts. These currents may also interfere with railway signalling and contribute to the corrosion of oil and gas pipelines. They can affect the power feed for long communication lines. The most dramatic collapse of electric power grids occurred on 13-14 March 1989 in the province of Quebec (see Section III.B.1(c)).

There are also many other effects of geomagnetic storms. They affect surveys for minerals, which use either ground-based or airborne magnetometers to measure the small changes in the Earth's magnetic field associated with deposits of minerals; off-shore drilling in oil and gas production industries, which relies on geomagnetic maps to guide the drill and monitor the well direction; migratory birds and animals (pigeons, dolphins, whales) that have an internal biological compass and find their way by the Earth magnetic field, etc. The most severe magnetic storms ever recorded and described occurred in 1859, 1921, 1989, and 2003 (see Section III.B.1).

4. Satellites and debris orbits

Orbital debris presents danger to spacecraft, especially, to manned space stations. As reported by the United Nations Office for Outer Space Affairs in October 2009, about 300000 pieces of debris are orbiting the Earth.

The distribution of orbital debris is taken into account when planning spacecraft launches. During geomagnetic storms, however, the atmosphere expands, and the atmospheric drag increases affecting the orbits of both satellites and orbital debris. The pieces of low-orbital debris descend and burn in the atmosphere. Such orbital dynamics of debris makes it dangerous to low-orbital satellites, which also change their orbits during geomagnetic storms.

Many cases are known when debris elements collided with space vehicles. For example, a particle less than 1 mm in diameter left a deep crack on the shuttle window in 1983; in July 1996, a French satellite collided at an altitude of about 660 km with a fragment of the third stage of a European launcher, Ariane; in 2001, the ISS narrowly avoided collision with a 7 kg device lost by United States astronauts; on 29 March 2006, the Russian satellite, Express-AM11, was wrecked by collision with orbital debris; on 10 February 2009, a commercial satellite of the American communication company, Iridium, put into orbit in 1997 collided with the Russian military communication satellite, Cosmos-2251, launched in 1993 and taken out of service in 1995.

The collision of spacecraft with orbital debris often creates new debris (Kessler syndrome). In order to avoid uncontrolled increase of the debris density, it is necessary that the monitoring of magnetic storms and associated orbit variations of space objects became an integer part of the program of a long-term sustainability development of space activities.

B. Historical knowledge of the space environment

The historical record reveals that severe space weather events occurred in the past had a catastrophic impact on the Earth and its space environment. Such were the Carrington event of 1 September 1859, the event of 14-15 May 1921, the Quebec event of 13-14 March 1989, and the event of October-November 2003 known as Halloween storm.

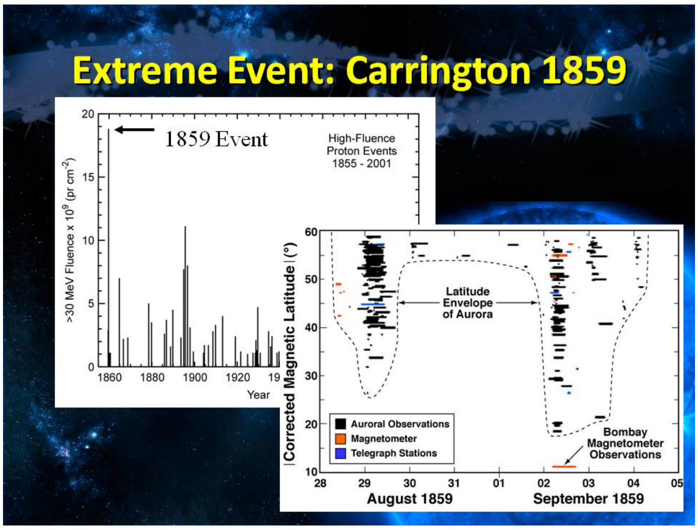
1. Case histories

(a) Carrington event of 1 September 1859

The Carrington event is the most severe space weather event on record. It was named after the British amateur astronomer Richard Carrington, who observed the intense flare of 1 September 1859. The disturbance from the Sun reached the Earth for a record short time of 17.5 hours and caused a severe magnetic storm. Telegraph services in America and Europe were disrupted for several days. Aurora displays were seen at night at unusually low latitudes — in Rome, Havana, Hawaii, and even at the Equator. According to the expert estimates, if an event like that, several times more intense than the Quebec one (13-14 March 1989), occurred today, in the epoch of high technologies, the consequences would be much graver than those of the Quebec blackout. The analysis of ice samples showed that the geomagnetic storm of 1859 was accompanied by enhanced fluxes of solar energetic particle, which exceeded by a factor of 4 the largest fluxes ever recorded during the space era.

Figure 18

During the Carrington event (September 1, 1989), which was the most intensive event ever observed in the Sun-Earth system, strong geomagnetic disturbances were recorded all over the globe from the polar regions to the equator


Extreme Event: Carrington 1859

Though the solar-terrestrial relations were poorly understood at that time, the Carrington event was the first evidence suggesting that solar eruptions are the prime cause of geomagnetic storms.

(b) The event of 14-15 May 1921

Another outstanding geomagnetic storm occurred on 14-15 May 1921. During that storm, the magnetic field change rate was about ten times higher than in the Quebec event. According to a study by the Metatech Corporation, the occurrence today of an event like the 1921 storm would result in large-scale blackouts affecting more than 130 million people only in the United States and would have long-term effect on social and technological infrastructures. Northern Europe would experience a similar impact suffering widespread socioeconomic disruptions.

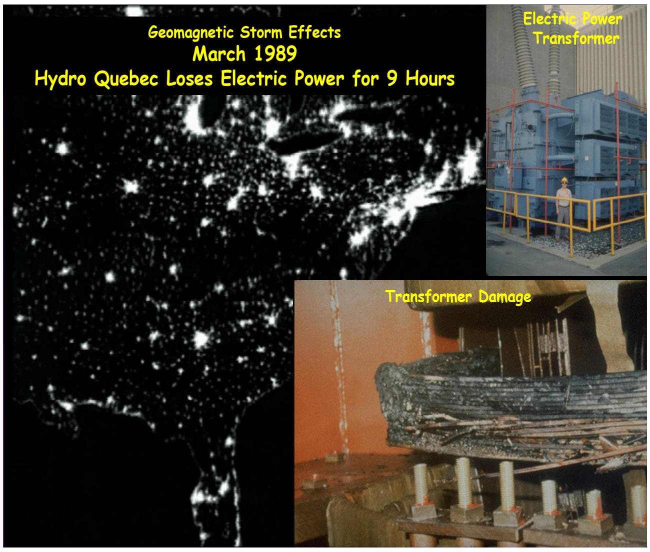
The 1921 magnetic storm was triggered by the activity in a large sunspot at the centre of the disk, which could be seen by naked eye through a smoked glass. That storm caused a series of short-circuit events resulting in fires. It also damaged the submarine cable, electric power lines, and telephone lines on both sides of the Atlantic. An intense aurora event induced large currents in telegraphic circuits and disrupted telegraphic communications in England, Scotland, and Ireland. Strong magnetic storm effects were also experienced by telegraphic and radio communication systems in New Zealand.

(c) Quebec event of 13-14 March 1989

The Quebec event of 13-14 March 1989 was one of the most dramatic impacts that extreme space weather had on the space and ground-based infrastructure of the modern society. It was the first large-scale catastrophe caused by solar activity and magnetic storm whose integral loss was estimated to amount to

$6 billion US dollars. A severe geomagnetic storm triggered by solar ejections disrupted radio communications. The United States space navigation system was paralyzed since many satellites were lost or changed their orbits due to expanding atmosphere and enhanced atmospheric drag. The province of Quebec, was blacked out for approximately nine hours. Electric power grids of the province collapsed owing to induced currents in long transmission lines; the failure of safety devices and transformer damage stalled nonstop production and assembly lines on many industrial enterprises. The failure of transformers and power outages took place not only in Quebec, but also in the United States and Europe (Great Britain). One of the most dangerous incidents was the failure of a large $10 million step-up transformer at the Salem Nuclear Power Plant in New Jersey. Fortunately, it did not result in a major catastrophe, but caused a considerable financial loss and clearly revealed the extent of hazard presented by adverse space weather.

Figure 19
The Quebec event (13-14 March 1989) was the world first large-scale technological catastrophe caused by the space weather



Electric outages at nuclear power plants occurred also in the subsequent years. Geomagnetically induced currents in electric power lines were occasionally recorded in the South America and southern Europe. Thus, in April 1994, five transformers failed in Chicago as a result of enhanced geomagnetic activity. Taking into account the modern technological developments, the space weather effects like those observed in Quebec in 1989 may entail increasingly grave implements and losses. At present, the experts assess losses that may be caused by long-term power outages over a large territory to amount to $1-2 trillion.

The Quebec event was analysed in detail and the resulting report was taken as a basis for up-to-date space weather monitoring and alert systems.

(d) Halloween storm (October-November 2003)

In October-November 2003, a series of major flares and coronal mass ejections occurred on the Sun. They created dangerous radiation conditions in the Earth environment and triggered severe and unusually long-lasting magnetic storms: the geomagnetic field remained disturbed for as long as a week. On October 28, 2003, a large sunspot group produced an intense X-ray flare and a coronal mass ejection that was moving at a high speed. An hour after the ejection, solar energetic particles (SEP) accelerated by the shock wave penetrated the Earth magnetosphere resulting in radio blackouts and degradation of the polar-cap ozone layer. On the following day, as the SEP intrusion into the Earth magnetosphere still continued, a magnetic plasma cloud ejected from the Sun slammed the Earth magnetic field and caused a severe magnetic storm. On October 30, when the geomagnetic field was hardly restored after the first storm, a new plasma cloud from the second coronal mass ejection produced by the same active region, again, hit the Earth and generated another strong magnetic storm. Solar energetic particles accelerated in the second solar event continued intruding the Earth magnetosphere disturbed by the first one until the second storm started, which allowed them to reach the ISS orbit. Fortunately, the station was at that time on the other side of the orbit.

The consequences of the events of October-November 2003 are described in many reports. More than 50 per cent of all satellite operation anomalies recorded in 2003 (46 out of the total number of 79) occurred during that period. A Japanese satellite was lost; a severe HF radio blackout affected many commercial airlines; the United States Federal Aviation Administration (FAA) issued a first-ever alert of excessive radiation exposure for air travellers; the GPS-based Wide Area Augmentation System (WAAS) was disabled for 30 hours; a failure of power supply occurred in the south of Sweden because of the induced-current effects; climbers in Himalaya experienced problems with satellite phones; the United States Coast Guard temporarily shut down the LORAN navigation system.

2. Summary of impacts over time

As evidenced in historical record, human activities, societal institutions, and technologies have always experienced the effect of extreme weather conditions. In the middle of the 19th century, in addition to draughts and floods, ice and snow storms, hurricanes and tornados, the human society in the developed parts of the world became vulnerable to other kinds of extreme weather - severe disturbances in the upper atmosphere and near-Earth space environment associated with solar activity. These disturbances caused disruptions in telegraph networks and later, as new technological facilities developed, they began to affect electric power lines, oil and gas pipelines, telephone and radio communications, space navigation, etc. The vulnerability of modern society and its technological infrastructure to space weather has increased dramatically.

Extreme natural events, such as the Carrington event, the May 1921 event, the Quebec event of 13-14 March 1989, and the 2003 Halloween storms, warn us that the development of technological systems, including space technologies has reached the point when their exposure to adverse factors of space weather may have catastrophic impacts and result in immense losses. A particular feature of the extreme events, such as those observed in 1859 and 1921, is that they may occur during low-amplitude cycles (lower than medium), which makes them difficult to forecast. This means that our space and ground-based technological systems must be designed to operate under adverse space weather conditions and withstand their impact without failing.

C. Evolving technologies and infrastructure

Space technologies find ever-widening application in various spheres of the human life making the modern society increasingly dependent on these technologies and, hence, on space weather. As rapid progress is made in space communications and in positioning industries (GPS, GLONASS, GALILEO), including the development of new navigation systems; the number of countries involved in space activities and flying their own satellites has increased; manned missions are planned to the Moon and Mars, etc.

Severe space weather can induce abnormalities and can damage modern systems, including economic systems, affecting the entire societal infrastructure. Short- or long-term service disruptions may spread from a directly affected system to many other systems due to dependencies and interdependencies among, for example, electric power supply, transportation and communications, information technology, etc. As systems become more complex over time, the social and economic impacts of space weather are likely to increase.

1. Current technologies are more vulnerable

Nowadays, the human society becomes more and more dependent on modern space systems that are vulnerable to the adverse factors of space weather. For example, the rapidly developing communication technologies are based on the use of satellites. These are TV and radio broadcasting, mobile communications, Internet, banking systems, GPS/GNSS navigation services used by over 250 million people, etc. The impact of space weather on modern technologies is described in the previous sections of this report. The knowledge of vulnerabilities of the modern infrastructure to space weather impacts and the development of measures necessary to minimize their negative consequences form a substantial part of the future technological progress.

The appearance of new, highly sensitive, low-weight and low-cost elements make technological systems more and more susceptible to adverse environmental factors, while their wide use increases the vulnerability of modern societal infrastructures to space weather. Potential consequences of the collapse of vitally important technological systems caused by extreme space weather events, such as the Carrington event of 1859 are not yet fully understood.

An example of vulnerability of modern space technologies to space weather is GPS that includes 24 satellites. The system provides various governmental, societal and commercial users (cartographers, farmers, transportation, marine and submarine force, gas and oil offshore drilling companies, etc.) with precise positioning and timing services. Ionospheric disturbances that occur during geomagnetic storms in the equatorial and auroral ionosphere affect the propagation of GPS signal to receivers on the ground resulting in a fading or even temporary loss of the signal and positioning errors. Solar radio bursts interfere with GPS signal affecting its reception on the day side of the Earth.

In future manned missions to the Moon and Mars, astronauts will stay in outer space longer that they did during the first flights to the Moon. This will require additional defensive measures to be taken to protect the crews from adverse factors of space weather.

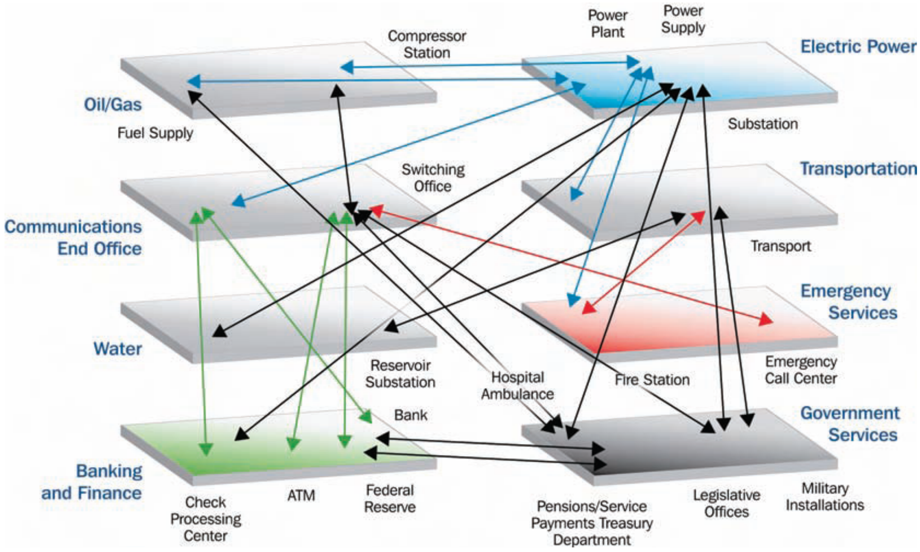
With increasing awareness and understanding of space weather effects on their technological systems, industries begin to apply improved operational procedures and technologies developed to mitigate the threat of extreme space weather to their users. For example, under adverse space weather conditions, launch personnel may delay the launch of a satellite. For the spacecraft industry, however, the primary approach to mitigating the effects of space weather is to design satellites to operate under extreme environmental conditions to the maximum extent possible within cost and resource constraints. GPS modernization through the addition of two new navigation signals and new codes is expected to help mitigate space weather effects, although to what degree is not known.

Our understanding of the vulnerabilities of the modern technological infrastructure to severe space weather and the defensive measures developed to mitigate them are based mainly on the experience gained in the past 20 or 30 years when such outstanding events as the March 1989 and October-November 2003 geomagnetic storms occurred. However space weather events of much greater intensity were recorded in the past, like the Carrington event of 1859 and the great geomagnetic storm of May 1921 — and are likely to occur again sometime in the future — and the society must be ready to withstand the impact.

2. Society is dependent on vulnerable infrastructure

Modern technological society is characterized by complex dependencies and interdependencies between its critical infrastructures. The space and ground-based infrastructures are closely interrelated. So, besides the direct space weather impacts on space activities (such as spacecraft anomalies etc.), we must take into account collateral effects on dependent infrastructures and services. The figure below schematically illustrates the interconnection of critical infrastructures and their dependences and interdependences. As seen from the scheme, a major space-weather-driven outage of any one element of the space infrastructure, such as space communications and navigation, can paralyze other critical infrastructures. For example, many GPS users — transportation companies, oil and gas industries, offshore drilling companies — may experience the space weather effect. Power systems, banking and finance systems, security, government services depend directly or indirectly on space communications and navigation and, hence, on space weather conditions.

Figure 20
A scheme showing the interconnection of critical infrastructures and their qualitative dependencies and interdependencies. As the complexity and interdependence of national infrastructures and services increase, the failure of any single infrastructure will have increasingly widespread grave implications[1]



The critical dependence of modern society on the infrastructure vulnerable to space weather brings to the fore the development of protective measures to mitigate the effects of impending solar disturbances and minimize their social and economic impact.

D. Quantitative estimate of the risk

A complete picture of the socioeconomic impact of severe space weather must include both direct, industry-specific effects (such as power outages and spacecraft anomalies) and the collateral effects of space-weather-driven technology failures on dependent infrastructures and services. If in the middle of the 19th century, the Carrington event resulted only in financial losses to telegraphic and some commercial companies due to the failure of telegraphic services, today an event of equal severity would have more far-reaching impacts. Because of dependencies and interdependencies between systems, the loss of core systems, such as power industry, space communication and navigation would lead to failure in other, dependent systems, and a cascade of system failure would result. For example, the Quebec blackout closed schools and business, kept the Montreal Metro shut down during the morning rush hours, and paralyzes the Montreal Airport. People found themselves stuck in elevators, products were spoiled in defrosted refrigerators.

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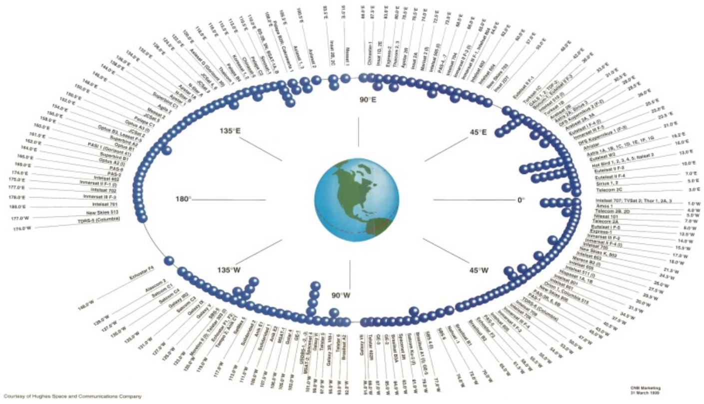
[1] This is Figure from the 8/28/08 Review Draft. Connections and interdependencies across the economy. Schematic showing the interconnected infrastructures and their qualitative dependencies and interdependencies. SOURCE: Department of Homeland Security, National Infrastructure Protection Plan, available at www.dhs.gov/xprevprot/programs/editorial_0827.shtm.

Major space-weather-driven disruptions in the operation of at least one space system — space communications or navigation (GPS/GNSS) — will affect all aspects of social life: transportation, communication, banking, and finance systems, power systems, industry, government services; education, security and emergency services, medication, sanitary, distribution of foods and potable water. The gravity of consequences will depend on many factors, including the duration of the outage.

The description and quantitative assessment of the impact of severe though rare space weather events involves questions concerning the collection of data and assessment methods. Many factors are to be taken into account, including the magnitude, duration and timing of the event, its nature, severity, and extent of the collateral effects cascading through a society characterized by strong dependencies and interdependencies; the robustness and resistance of the affected infrastructures; the risk management strategies and policies that the public and private sectors have in place; and the capability of the responsible federal, state, and local government agencies to respond to the effects of an extreme space weather event. Such a quantitative and comprehensive assessment of socioeconomic impacts of adverse space weather is a truly challenging problem which still is to be solved. Some quantitative assessments of space weather risks are listed below.

Figure 21

The direct and indirect space-weather related risks for the largest group of the high-tech geostationary satellites amount to tens or hundreds of billion dollars



Courtesy of Hughes Space and Communications Company

CNB Marketing
31 March 1999

About 250 geostationary satellites are orbiting the Earth, the cost of each one amounting to approximately $300 million US dollars. This space fleet represents $75 billion investment with annual revenue of about $250 billion ($100 million per satellite per year). The market of commercial satellites increases constantly by about as many as 100 new satellites every year.

The damage to individual systems or complete spacecraft failure due to communication problems and radiation effects may cost $500 million, while the commercial losses may exceed $1 billion. In the worst case, the estimated loss from a severe magnetic storm may amount to $100 billion.

Interruption of surveying and navigation services (GPS/GNSS) will cost from $50,000 to one million US dollars daily for a single company. Due to the increasing volume of GPS-based services ($13 billion in 2003 and $21.5 billion in 2008 to $757 billion in 2017) the risks from the failure of GPS/GNSS systems will increase.

According to a Metatech Corporation estimate, a long-term power blackout over vast territory due to severe space weather could result in damage costing up to $1-2 Trillion during the first year alone with recovery time of 4 to 10 years depending on the extent damage.[2]

IV. Evaluation of current practices and procedures

A. Introduction

In this section ways of mitigation of space environment effects are introduced. Significant improvements in the mitigation of space weather effects can be obtained from a synergistic approach to: the monitoring of space weather in the heliosphere; from modelling space weather dynamics; through the generation of space weather now-casts and forecasts; from studies of the impacts of space weather on technological systems (such as described in Chapter 3 above); and through the development and implementation of technical standards for the design and manufacture of vulnerable terrestrial and space-based infrastructure, including satellites.

B. Observations

In order to perform good space weather forecast, we should need space weather observations, space weather modelling and space weather forecast tools. Observations of space weather from the Sun to the Earth by means ground-based instruments as well as space-based instruments are essential to grasp current status of space weather and to provide sufficient information for space weather forecast.

1. Solar Observation

There are two ways for solar observation, i.e. from the ground and from the space. There are networks to observe the solar phenomena by using Hα light. One of them is CHAIN (Continuous Hα Imaging Network) and CHAIN telescopes are monitoring the Sun continuously, identifying sun spot activity, filament structure, prominence, and solar flare. The solar flare is seen in the active region (sun spot region) through a sudden enhancement of the intensity of the emission.

The sun spot has a strong magnetic field and the magnetic field sometimes contains a large stress. This stress propagates upward, where the solar corona exists. The solar flare occurs when the stress exceeds a threshold. A magnetograph instrument can detect the intensity of the magnetic stress and these are used for the continuous monitoring.

Solar observations from the space have been made. Right now, Hinode, SOHO, Stereo, Trace, SDO and Rhessi are observing the Sun. By utilizing space observation data, physics in the vicinity of the sun spot regions is better understood. Such data are used for the solar flare prediction.

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[2] See “Severe Space Weather Events--Understanding Societal and Economic Impacts: A Workshop Report - Extended Summary”, US National Academy, Space Studies Board (Chair Prof. Daniel Baker) 2009 (www.nap.edu/catalog.php?record_id=12643).

The solar flares are often associated with radio bursts. Observations with a large solar array, called heliograph, have been made to observe a dynamical behaviour of the solar corona. Eruption of corona gas, propagating outward, is detected by the heliograph. Such ejection is called a coronal mass ejection (CME) and has been observed by the telescopes on board the satellites.

One of the big risks arising from the Sun is the solar energetic particle (SEP), which is closely related with the big solar flares. Recent observations revealed that SEPs are produced by the CMEs. The SEPs propagate outward along the magnetic field lines. The SEPs originated in the central and western sectors of the Sun are easily coming to the Earth. Merits of the space observation include the ability to observe the opposite side of the Sun. Right now, Stereo satellites view the far side, which enable observations of both limb regions. These data are useful to detect active regions in advance (east limb) and to alert the production of the SEPs (west limb).

2. Interplanetary space observations

The Sun emits a continuous stream of plasma, called the solar wind, with an average speed of about 400 km/s. Main species are protons and electrons. We can see the solar wind by utilizing radio waves emitting from radio stars. The intensity of radio wave from the star changes in time. This fluctuation is thought to be caused by the scattering of the waves by the small scale irregularities in the solar wind. By tracking these irregular structures we can obtain the solar wind velocity. This observation method is called interplanetary scintillation (IPS) method, which is a good way to see global structure of the solar wind in the interplanetary space.

One of the big disturbances seen in the interplanetary space is CME. When we see CME in the interplanetary space, we call it ICME, meaning interplanetary coronal mass ejection. When ICME hits the Earth, the space environment surrounding the Earth becomes disturbed. We call this a geomagnetic storm. From the information about an ICME, we know the time of the occurrence of the geomagnetic storm in advance.

ICME is also shielding the cosmic rays. Since ICME accommodates a very strong magnetic field inside, the trajectories of cosmic rays are bent to avoid ICME. When the ICME approaches toward the Earth, the intensity of cosmic rays from the solar direction decreases, which suggests the arrival of the ICME. Cosmic ray detectors have been deployed in the world to monitor the cosmic ray intensity from the solar direction, which can help the geomagnetic storm prediction.

The observation of ICME has been done in space. ICME scatters light from the Sun, and we can know the structure of ICME by detecting scatted light. Right now, two STEREO satellites are monitoring ICMEs from both sides with respect to the Sun. NASA is considering continuing STEREO-type observations with more sensitive detectors.

In-situ observation of the solar wind has been done by the ACE satellite, which is located at 1.5 x 106 km in front of the Earth. By using ACE observations, we know the solar wind velocity, density and interplanetary magnetic field (IMF) about one hour in advance. These data are used for space weather forecasting.

Only from space, we know the shape of coronal holes by using X-rays etc. Magnetic field lines originating from the coronal holes are thought to be open, extending into the interplanetary space. High speed solar wind has been observed in the coronal hole region. With a solar rotation, high speed solar wind comes to the Earth almost 2 to 3 days after the coronal hole passage of the central meridian plane of the Sun. The high speed solar wind produces a disturbance in the near Earth space.

3. Magnetosphere observations

The Earth is surrounded by the magnetic field, forming a magnetosphere. The magnetosphere has been studied by using magnetometers on ground. In the 19th century, it was found that 1 per cent of the total magnetic field sometimes decreased. In the 20th century, magnetic field variations in the polar region were found when the aurora appeared. The former decrease is called a magnetic storm with a global signature and the later variation is named substorm with a local characteristics. We will explain magnetosphere, magnetic storm and magnetic substorm, in this order.

The magnetic storm has been investigated with ground-based magnetometers. When the space age came, the magnetic storm was studied by the satellites. Particle detectors found the enhancement of high energy particles surrounding the Earth at around several earth radii (Re) when the magnetic storm commenced. A magnetic field decrease was seen simultaneously with the ring current formation. It was found that the ring current was produced by the strong southward component of the interplanetary magnetic field (IMF).

Methods for observing aurora began with detecting auroral emissions at with several wave lengths. Emissions from oxygen atoms were found by the ground based observations, suggesting precipitating electrons caused the emissions. Satellite observations detected precipitating electrons with energy more than 10 keV above auroral region and brought fruitful information in terms of the auroral disturbances (substorms). One of the strong advantages from the satellite observation is to realize a global observation of aurora. Right now several satellites continuously observe the aurora environment all over the world.

In order to study the origin of auroral particles, extensive observations were done in a far tail region of the magnetosphere. The magnetic fields of the Earth were stretched anti-sunward, forming a magnetotail. In the magnetic equator, where the magnetic field line with opposite direction contact, plenty of plasma with a sheet-like structure was observed. This structure is called the plasma sheet. Energy release in the plasma sheet was found to trigger auroral disturbances (substorms). When the substorm takes place, large amounts of hot plasma are injected to the geostationary orbit altitude from the far tail region. Some of geostationary orbit satellites are monitoring plasma environment.

Efforts to monitor the condition of the magnetosphere from the ground have been made. Energy and plasma were transported from the dayside to the night side across the polar cap region (inside of the auroral oval). This flow is called magnetospheric convection. By using high frequency radar systems, convection has been monitored. From observations, forecasts of auroral substorm become promising.

4. Radiation belts observations

The Earth’s radiation belts with two belts structures were found in 1958 and studies on the radiation belts have continued. Right now, several satellites are observing them. The intensity of the outer belt is increasing during the magnetic storm, causing some troubles in the satellites. Monitoring the outer belt electrons are being made by GPS satellites and geostationary orbit (GEO) satellites. The basic mechanism for the large increase of outer belt electrons is not fully understood. Hence, more observations are planned, especially with observations of seed electrons and low frequency waves.

Main components of the inner radiation belt are protons and electrons. These highly energetic particles are being transported into the inner belt from the outer space. The life time of these particles is quite long, so they continue to stay there for a long time. The loss time scale is getting shorter with radial distance from the Earth. Hence, the peak of the inner belt locates around 1.5Re. An important region is the slot region, where there are little energetic electrons. We don't have any continuous monitor there, but in near future some satellites will be sent there to monitor the slot region.

Efforts to try to get information on the radiation belt from the ground have been made. With a large increase of energetic electrons in the equatorial radiation belt region, some of them precipitate into the atmosphere along the field lines. This precipitation, which is seen in a sub auroral region, leads to produce D layer. This newly formed D layer reflects the radio waves with low frequencies. These low frequency waves are used for monitoring appearance and disappearance of D layer. This method is promising for grovel monitoring of radiation belt changes from the ground.

5. Ionosphere observations

Observation of the ionosphere has a long history of almost one hundred years. An instrument called the ionozonde has been deployed in the world, correcting information of the ionosphere. When the magnetic storm takes place, the plasma density in the ionosphere changes drastically. Ionospheric disturbances with density increase/decrease are called positive/negative storms, respectively. When we use the GPS, a positive storm will give a large error in determining the position. Hence, we need to continue to monitor ionospheric conditions.

The radio waves, emitted downward from the satellite, can reflect back to the satellite. By observing the echo signal of the radio waves, a density profile of the topside ionosphere is obtained. With this instrument (topside sounder) we know the global structure of the ionosphere. In the equatorial region, density enhancement (equatorial anomaly) is seen in the day time and local depletion of density (plasma bubble) is seen in the night. In the polar ionosphere, a large region with less density (polar hole) is found. The information is also helpful to perform high quality communication and obtain good positioning information in the world.

6. Ground-based magnetometer observations

As mentioned previously, observation of magnetic fired variation has a long history. In order to monitor a magnetic storm, magnetometer observations in the equator region are essential. On the other hand, to monitor the auroral disturbances, observations in the polar region are important. With these magnetic field observations, Dst (disturbance) index as well as AE (auroral electro jet) index have been made in Kyoto University. These indexes are used for space weather forecast.

There are several magnetometer observation networks in the world; in Europe, North America, South America, the Far East, and in Africa. By deploying magnetometers longitudinally or latitudinally, information about magnetic field variation is obtained, which covers periods from a few seconds to several hundred seconds. These data have close relation to some important space weather phenomena such as radiation belt variation enhancement, as well as auroral brightening.

C. Space weather models

In this section, we demonstrate some models for space weather phenomena; including Sunspot, solar flare, CME, solar corona, solar wind, interplanetary space, magnetosphere, magnetic storm, auroral substorm, radiation belt, ionosphere, ionospheic storm, polar ionosphere, and atmosphere, in this order.

1. Sunspot model

There are varieties of magnetic structure models covering short- to long-term variations including a rotation of magnetic field. We see different rotation with respect to the latitude; rotation is fastest at the Equator and the rotation speed decreases with an increment of the latitude. Due to this effect, the magnetic field configuration is deformed around the Sun. The magnetic field lines under photosphere elongate horizontally; east to west or vice versa. Recent simulation studies revealed upward movement of the field lines where they appear above the surface of the photosphere. This is promising for predicting sunspot appearance on the solar surface.

A long-term variation of the magnetic field model includes the appearance of Sunspot regions from higher to lower latitudes. Right now many efforts are made to explain both short-term and long-term variations of the solar active regions.

2. Solar flare model

The solar flare is mostly being explained by the reconnection of the magnetic field lines, where the magnetic field line in the sun spot regions shows a loop structure, bridging both Sunspot regions. The loop structure is sometimes stretched, containing lots of magnetic energy. Around the top region of loop structure, the magnetic reconnection takes place, emitting high energy particles both inward and outward. Advanced physical models which accommodate the stress of the magnetic field are under construction to explain details of the solar flare.

3. CME model

A coronal mass ejection (CME) is the phenomenon where by a large amount of solar plasma (solar corona) is emitted into the interplanetary space associated with the solar flare. The CME includes an intense magnetic field with helical structure. Modelling of CMEs has been carried out by using magneto-hydrodynamic (MHD) simulations and several of which successfully connects to the interplanetary CME (ICME), which enabled us to do good forecast of the magnetic storm.

4. Corona model

The solar corona is an atmosphere which extends out to several solar radii. The shape of corona depends on the solar activity and it is more spherical during the solar maximum. The corona includes both closed (loop structure) and open magnetic field lines (coronal holes). An important point of the solar corona model is to calculate the field line. Shapes of the loop structure and the coronal hole are major topics for space weather.

It has been a tough problem why the corona has a very high temperature compared with the chromosphere. Many explanations have been made to explain coronal heating. Temperature in the coronal hole region is rather low, since the plasma may escape easily along the open field lines. When making a corona model it is also important to consider solar wind acceleration. Extensive efforts are being made to have a good model for solar corona.

5. Solar wind model

The Sun continuously loses mass and this loss is called solar wind. The existence of the solar wind was first suggested in the 1950s and was confirmed in the 1960s. According to the theory, solar wind velocity has a close relation with the temperature of the solar corona, but satellite observations revealed that a high speed solar wind comes from the coronal hole. Recent modelling studies on solar wind revealed that some heating processes should take place simultaneous with solar wind propagation.

In making a model of interplanetary space, it is important to have an initial speed of solar wind with good accuracy. Since the Sun is rotating, the structure of the interplanetary magnetic field basically shows a spiral. The strength of bending depends on the solar wind speed and a high speed solar wind can catch a slow speed solar wind, forming a discontinuity. In the interaction region between a high speed and a slow speed solar wind, accumulations of density as well as magnetic field are seen. When the interaction region hits the Earth, disturbance takes place in the near-Earth space.

6. ICME model

Another origin of high speed solar wind is CME. When the CME propagates into the interplanetary space, the initial velocity sometimes reaches 2000 km/s and it maintains 1000 km/s. In front of the CME the shock wave is formed. A cavity region and core region follow it. A core region is identified by measuring scatter lights but shock waves can’t be seen. With a MHD code, ICME models are being constructed. Another important aspect of ICME is the source of the solar energetic particles. Accommodating a shock structure in the MHD scheme, a proton acceleration model is being made to explain SEPs.

7. Magnetosphere model

The Earth’s magnetosphere is formed by the interaction with a solar wind. The magnetic field of Earth’s origin is pushed in the dayside and stretched tailward in the night side. Efforts to reproduce the magnetosphere are being made, accommodating the tilting of the rotational axis. Momentum transfer from the dayside to the night side as well as convection of the magnetic field has been calculated. Depending on the orientation of the interplanetary magnetic field, a configuration of the magnetosphere changes. In advanced models, calculations of test particles are made, which enable us to study penetration of high energy particles into the magnetosphere. On the other hand, empirical models of the magnetic field configuration in the magnetosphere have been constructed.

8. Magnetic storm model

A magnetic storm is the biggest energy release process in the vicinity of the Earth. The cause of the magnet storm is attributed to the formation of the ring current. The ring current is produced by the invasion of hot plasma into the near-Earth region. Important physics of the ring current formation is the transition from open particle trajectories in the plasma sheet region to the closed trajectories in the ring current region. Time variations are needed to properly model ring current variation. Another interesting physics is that of particle acceleration. The main component of the ring current particles is oxygen ions from ionosphere. Some models now accommodate a heating process.

9. Substorm model

Long lasting southward IMF condition results in the accumulation of large energy in the plasma sheet. Along with this process, elongation of plasma sheet occurs. When the stored energy is released, the elongated magnetic field lines reconnect with each other. The outer part forms a plasmoid, a mass of plasma, which propagates to the outer region. On the other hand, in the inner part with respect to reconnection, the plasma starts to flow toward the Earth. This Earthward flow is one of the energy inputs that causes aurora. In order to make aurora, electron beams along the magnetic field lines are needed. Many models which accommodate down-going electron beams are being made. The auroral phenomena are very complicated and better physical models are evolving through time.

10. Radiation belt model

The Earth’s radiation belt consists of two belts; the inner belt and the outer belt. The modelling of the radiation belt has long history of over 50 years. The diffusion model is the major model for the inner radiation belt, which is rather stable showing slow variation. On the contrary, the outer radiation belt is quite variable in time and in space. Hence, efforts to make up new physical models for the outer radiation belt are being made, which include transportation, acceleration, diffusion and loss processes to explain the rapid loss of high energetic electrons at the commencement of the magnetic storm and the large increase of electrons during the storm recovery phase.

Another interesting portion is the slot region. This slot of the electrons belt is made by strong wave-particle scattering and new slot models are under construction. Recent observations demonstrate the variation of the inner radiation belt. Sources of radiation particles in the inner belt are reconsidered.

The South Atlantic anomaly region is a very unique portion in the inner radiation belt. An interesting point is the movement of the anomaly region over forty years. It has shifted westward by 10-15 degrees with respect to the longitude. The development of a new model is important to estimate total radiation flux over the anomaly region.

11. Magnetic field variation model

There are two points of view for magnetic field variation. One is from the storm and substorm, and the other is from the oscillation of the magnetic field lines. Magnetic field oscillation involves lots of information along the field line. Some of them are closely related to the electron acceleration in the outer radiation belt.

12. Polar convection

Convection of the magnetosphere can be easily observed in the high latitude polar region, especially inside the auroral oval. This region is called the polar cap where plasma convection is seen from the dayside to night side across the pole. This is the projection of plasma motion in the lobe region. From this information, we see the energy accumulation in the magnetotail. It is becoming possible to predict the appearance of aurora and the onset of sub-storms.

13. Ionosphere model

The ionosphere modelling has a long history and many researchers are participating in the international reference ionosphere (IRI) project. It includes ionospheric variations, which depend on season, local time, latitude and solar variation. IRI is also trying to include dynamics of the neutral atmosphere to explain both negative and positive storms.

14. TEC model

Total electron content (TEC) has a big influence on positioning. To have accurate information in terms of position, we need to consider TEC at all times to correct errors. In North America, Europe, and the Far East region, TEC measurement systems have been deployed to correct the ionosphere specification. With these data TEC models have been construction.

15. Atmosphere model

One of the main interests of the atmosphere from the space weather point of view is an expansion of the atmosphere due to the heating. This is because the expanded atmosphere makes additional drag on the satellites and causes changes to their orbits. NRLMSIS-2000 and JB2008 are the models that specify the neutral atmosphere; they include solar and magnetic activities.

D. Tools for space weather prediction

Efforts are being made for developing new tools of space weather predictions. Empirical models as well as simulations are used for the space weather prediction using observations as initial condition or boundary condition. They are called data driven models. Items to predict are solar flare, solar energetic particle, CMEs, high speed solar wind, aurora, radiation belt, ionospheric storm, atmospheric expansion, Dst ring current, neutral atmosphere, etc. In the following are brief reviews on some of these issues.

1. Solar flare

Solar flares are classified by the intensity of X-ray emission. Based on the past experiences, solar flare prediction has been made for each class; i.e. C-class, M-class and X-class. The possibility of the occurrence of the solar flare within the coming two days has been predicted by considering a size and rate of growth in solar magnetic energy. The magnetic energy in the active region is evaluated and this energy in the active region is obtained from modern observations. However, the exact threshold which triggers the flare onset is not yet determined.

2. Solar energetic particles

The generation process of solar flare particles is one of the big issues for risks. There are two major theories; one is the generation in the corona near the Sun, the other is their creation in the shock region in front of CME. For each theory, approaches for energetic particle modelling are different. Hence, the way to predict solar energetic particle is not established, requiring more studies.

3. CME

Associated with the solar flare, a mass of plasma is emitted from the Sun. This is called CME. From the several satellite observations with different angles, we see the propagation of CME and can predict the arrival of CME at the Earth. From the CME, low frequency waves are being emitted. By observing the frequency drift, we also can predict the arrival of CME at the Earth.

4. High speed solar wind

Continuous observations of solar corona together with solar wind enable us to predict arrival of high speed solar wind at the Earth. When no temporal variation takes place in the solar surface, we see the same pattern of solar wind velocity every 27 days. But in reality the coronal hole changes in time and in space, the estimated solar wind velocity has some differences. More accurate models are needed for a forecast of high solar wind arrival.

5. Interplanetary magnetic field

Efforts have been made to calculate interplanetary magnetic field which originates in the solar surface. The interplanetary magnetic field has two polarities; i.e. toward (sunward) and away (anti-sunward). The plane in which the magnetic field lines of two different polarities contacts is called sector boundary. The magnetic activity in the magnetosphere increases when the sector boundary passes through the Earth. Especially in spring and autumn seasons, the substorm activity has a close relationship with the passage of the sector boundary. Nowadays the forecast of the sector structure in the interplanetary space is well done with high accuracy.

6. Magnetic storm

Forecast of the magnetic storm is now made with high accuracy when we use solar wind data obtained by the ACE satellite. But this is a short-term forecast with one hour in advance. When we try to make a storm forecast, we need to know the internal structure of CME, which is to come to the Earth. In the CME, helical magnetic field exists.

When a CME passes through the Earth, an intense northward magnetic field is first observed followed by strong southward magnetic field or vice versa, depending the orientation of the helical structure of the magnetic field in the CME. By using the magnetic field observations in the solar surface, the magnetic field structure has been studied but the prediction seems difficult at this stage.

Some magnetic storms are due to the high speed solar wing. The arrival of high speed solar wind is not so difficult but difficult point is to estimate direction of the magnetic field. More difficult point is to estimate duration of the magnetic storm. Some storms last one week. For such long-lived storms a good forecast seems to be difficult now. One idea will be to know the size of coronal hole in the solar surface.

7. Auroral substorm

The occurrence of aurora has been well predicted since we have a solar wind monitor in real time. However, the aurora is a result of energy release in the magnetotail and we have errors in time and in space for the occurrence of aurora. Many models are being developed and they are trying to predict much better. Auroral current estimation is also under construction but the current has also errors depending on models.

8. Radiation belt

Variation of outer belt electron has close relationship with solar wind velocity, while the variation of electrons in the heart of outer radiation belt has close relation with magnetic activity. Empirical forecasts are made by collecting some information together. For the loss of outer radiation belt electrons, some physical explanations are proposed which include losses to the atmosphere and magnetopause. However, a good forecast has not yet been achieved.

9. Ionospheric storm

Forecasts of the ionospheric storms have difficulty in estimating dynamical behaviour of the neutral atmosphere. Input of energy both to polar region and to the equatorial region causes the winds in the neutral atmosphere, resulting in change of composition. More accurate forecasts of the ionospheric storms (positive storm and negative storm) is being developed.

10. Expansion of the atmosphere

Expansion of the atmosphere is caused by the heating of the atmosphere. Estimation of the energy inputs to the upper atmosphere is key point to predict expansion of the atmosphere and forecast models have been developed. JB2008 and NRLMISIS-2000 are examples models.

E. Engineering approach to mitigating space environment effect

By the effects of the space environment, satellites cause anomalies. The following are examples of satellite anomalies:

- Failures caused by electrostatic discharge;
- Memory errors, malfunction of computers, single event upset, single event latch up;
- Total dose effect on semi-conductors;

- Degradation in solar cells, displacement damage of CCD;
- Impact of space debris and meteoroid;
- Orbit change due to variable atmospheric drag;
- Erosion of the surface materials by atomic oxygen.

According to the past statistical studies, 50 per cent of problems come from discharge, 30 per cent from single events and 20 per cent from radiation effect. To avoid risks from the space environment, the following actions have been made.

1. Measures for mitigating charging

Electrons in the magnetosphere cause satellite charging. Electric potential of the satellite becomes negative due to the electrons in the magnetosphere. The satellite potential shows large negative voltage especially in the insulator down to -10 kV or so. When the voltage exceeds a threshold, the discharge takes place, causing damages in the satellite. Strong electric fields affect electric devices, especially in triggering circuit, as well as in switching circuit and logics. The most dangerous local time is post-midnight to morning sector (0-6 LT). Probabilities of the satellite potential with -1 kV and -10kV are 40 per cent and 1-2 per cent at the geostationary orbit (GEO) altitude. Serious anomalies took place when the satellite potential was lower than -10kV.

In order to reduce charging, efforts have been made to remove insulator materials on the surface of the satellite, to make the surface with same electric potential by jointing all parts by electrical lines and to make coating of the cover glasses. Efforts have been made to make a good simulation model to calculate satellite potential at any conditions. With these data, the manufacturing of the satellite is done to avoid a serious situation in terms of charging in space.

Next we discuss measures for internal charging. Highly energetic electrons penetrate satellite walls and invade into the satellite. The electrons accumulate on the insulators and so on. When the accumulation takes place for a long time, the possibility of discharge increases. In order to avoid serious charging, some measures have been used; i.e. shielding with aluminium, avoiding use of Teflon, setting leak pass for charges. Technical standards exist with recommendations to minimize deep dielectric charging risks.

2. Measures for avoiding single events

The single events are in most cases caused by the highly energetic charged particles such as galactic cosmic rays and solar cosmic rays. A way to avoid single event is to use devises with small cross-section. Development of a calculation code of single events has been done to have good interface with cosmic rays observations. Development of an electric circuit which identifies errors and recovers from the anomalies has also been done.

3. Measures for mitigating total dose effect

Accumulation of radiation effects increases leak current and degradation of devices. Spot shielding is essential to mitigate such effects. 4mm or more shielding can be effective, depending on orbit, and some agencies accommodate this engineering issue in their technical standards.

V. Coordination among States on data and services to safeguard space activities

The long-term improvement of space weather services requires coordinated, committed partners from around the world. International cooperation is necessary to create a shared satellite-based observing system for our critical observations, to maintain reliable access to regional data, to advance our service capabilities, and to ensure the global consistency of the end products that are delivered. Fortunately, with the growing interest in space weather, a number of organizations have brought space weather within their spheres of interest or expanded their efforts, and activities are underway that are facilitating interaction among space weather service providers.

In order to advance the partnerships that will improve the quality and the delivery of space weather services, efforts are going on at many levels around the world, from global coordination fostered by organizations in the United Nations, to bilateral cooperation and to interagency agreements within individual countries. The major ongoing international activities today that support space weather are summarized below. These efforts represent a valuable foundation upon which we can maintain awareness of activities around the globe and coordinate these activities.

International Space Environment Service

The International Space Environment Service (ISES) has been the primary organization engaged in the international coordination of space weather services since 1962 (www.ises-spaceweather.org). ISES is a permanent "service" of the Federations of Astronomical and Geophysical Data Analysis Services (FAGS), under the auspices of the International Union of Radio Science (URSI) in association with the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG). It is currently comprised of 14 Regional Warning Centers (RWCs) around the globe and four Associate Warning Centers, one in France and three in China (Figure 22). The European Space Agency (ESA) serves as a Collaborative Expert Center for data and product exchange in Europe. The NOAA Space Weather Prediction Center in the United States serves as the World Warning Agency and acts as a hub for the exchange of forecasts.

The mission of ISES is "to encourage and facilitate near-real-time international monitoring and prediction of the space environment, to assist users reduce the impact of space weather on activities of human interest." The RWCs share data and forecasts among the Centers and provide space weather services to customers in their regions. The RWCs provide a broad range of services, including forecasts, alerts and warnings of solar, magnetospheric, and ionospheric conditions; extensive space environment data, customer-focused event analyses, and long-range predictions of the solar cycle. While each RWC concentrates on its own region, ISES provides a forum to share data, to exchange and compare forecasts, to discuss customer needs, and to identify the highest priorities for improving space weather services.

Figure 22
International Space Environment Service — Regional Warning Centers

The establishment of new ISES Regional Warning Centers is encouraged. As members of ISES, the Regional Warning Centers interact with a wide network of experienced service providers. ISES can be an effective forum for new space weather service providers to become familiar with the host of services available today and can help them integrate their capabilities into the global network. To be eligible to become a Regional Warning Center, an organization must have the endorsement of its national government, coordinate the collection of data in their area, allow free exchange of data and products with other Centers, provide timely forecasts and warnings for local users, and exchange forecasts with the other Centers.

World Meteorological Organization

The World Meteorological Organization (WMO), a specialized organization of the United Nations, has a membership of 189 states and territories. Its primary mission is to coordinate the activities of its Members in the areas of weather, climate, and hydrology, in support of protection of life and property, economic and social well-being, and monitoring and protection of the environment and natural resources. WMO establishes and coordinates global operational observation and telecommunication networks, and operational procedures for weather forecasting, disaster warning and climate monitoring. It fosters standardization and best practices, capacity-building, improved service delivery, research and development.

Following a review of international needs for space weather services (The potential role of WMO in Space Weather, WMO-TD No1482, April 2008) and in response to a request from ISES, WMO has recently included space weather as one of its areas of involvement with a goal to facilitate the international coordination of operational space weather observations, products, and services, working closely with ISES and other organizations. At the 16th World Meteorological Congress in May 2011, the WMO Members noted that a coordinated effort was needed to address the observing and service requirements to protect against the global hazards of space weather.

In May, 2010, the WMO formed the Inter-Programme Coordination Team on Space Weather (ICTSW) with the following Terms of Reference:

1. Standardization and enhancement of space weather data exchange and delivery through the WMO Information System (WIS);

2. Harmonized definition of end products and services, including e.g. quality assurance guidelines and emergency warning procedures, in interaction with aviation and other major application sectors;

3. Integration of space weather observations, through review of space-based and surface-based observations requirements, harmonization of sensor specifications, monitoring plans for space weather observation; and

4. Encouraging the dialogue between the research and operational space weather communities.

The ICTSW now has representatives from 19 countries and 7 international organizations. With the leadership of the WMO Space Programme, the ICTSW activities to date have included the establishment of a Space Weather Product Portal, completion of a first iteration of space weather observing requirements for global services, and an assessment of the current gaps in our observing systems. With this framework in place, space weather is now fully integrated into the WMO processes and plans for the evolution of the observing systems.

The Space Weather Product Portal is intended to enhance the visibility and enable a demonstration of space weather products being created by the service centres around the globe. Many of the products created today have global applicability. By making these products available, new groups around the world with an interest in serving their local customers can gain familiarity with space weather phenomena and impacts, and can use the existing products directly to define or begin delivering their own services. Furthermore, this Product Portal will facilitate the comparison of products and will encourage consistency of information and the adoption of best practices by the global service providers.

The ICTSW is coordinating with the International Civil Aviation Organization (ICAO) on its Concept of Operations for International Space Weather Information for Global Aviation. The importance of space weather for international civil aviation is recognized. Space weather concerns include degradation of radio communication, reduction in the accuracy and availability of Global Navigation Satellite Systems (GNSS), and energetic particle impacts to humans and flight avionics. The space weather services required by ICAO, including the international obligations of ICAO member states and the procedures for delivering warnings and alerts, will be specified in an annex to the ICAO Convention, to be jointly adopted by WMO and ICAO.

Coordination Group for Meteorological Satellites

The Coordination Group for Meteorological Satellites (CGMS) is the coordination body of space agencies operating meteorological, climate monitoring and environment satellites in support of WMO programmes. CGMS is a forum for global planning coordination, technical harmonization, and exchange of information on geostationary, polar orbiting and other satellite systems with a particular focus on ensuring long-term continuity of observation in support of operational applications. The group was formed in 1972 by representatives from the European Space

Research Organization (now ESA), Japan, the United States of America, observers from the WMO and the Joint Planning Staff for the Global Atmosphere Research Program. Its membership includes all the operators of meteorological satellites, the WMO, and space agencies operating research and development satellites that contribute to WMO programs.

The CGMS has an interest in space weather, both from the perspective of the impacts of space weather on satellite systems and for the opportunity to coordinate space weather observations being made from meteorological satellites. A permanent action item has been for Members to report on spacecraft anomalies from solar events at CGMS meetings. In October, 2011, this permanent action item was modified for Members "to report to CGMS meetings on their activities and plans related to space weather including: (i) impacts of solar events, space radiation and protective measures, (ii) space weather observations, and (iii) space weather warning systems". The CGMS also tasked WMO, through the ICTSW, to propose a template to facilitate harmonized reporting on spacecraft anomalies related to space weather.

An important issue for future space weather services is deploying and maintaining the space-based system needed to obtain the required real-time observations. At CGMS-39, the WMO emphasized the need for a high-level coordination of satellite-based and ground-based space weather observing assets to ensure that high-priority gaps are addressed in a cost-effective manner through shared capabilities. The CGMS can be an important organization to assist with this coordination of space assets.

International Space Weather Initiative

The International Space Weather Initiative (ISWI) is a program initiated by the United Nations Committee on Peaceful Uses of Outer Space and supported by the United Nations Office of Outer Space to develop scientific understanding of space weather and to promote education and public outreach. Its main research objective is to develop the scientific understanding that will allow space weather disturbances to be reconstructed and eventually forecast. ISWI activities include the distribution of small monitoring instruments in countries around the globe and the hosting of workshops and schools to promote joint research and training. As a result of this effort, new instrument arrays are being deployed, and programs are being created for space science research and education. Because research institutions often do not have the infrastructure or interest to provide access to continuous, real-time data, many of the data streams from these instruments are not available to support space weather services. A challenge for the future will be to encourage relationships between the service-providing organizations and the research institutions to make the data from the instruments deployed through ISWI available for space weather services.

International Living With a Star

International Living With a Star (ILWS) is an initiative to stimulate, strengthen, and coordinate space research. Contributing organizations include the major space agencies around the world as well as agencies engaged in space science research and space weather services. ILWS objectives include the study of the connected Sun-Earth system, collaboration and coordination of missions and research, and the effective use of data.

European cooperation

Scientific cooperation has been encouraged by the European Union through the process of COST actions (European Cooperation on Science and Technology), such as COST action 296, 724, or 803 which have strengthened the space weather community in Europe.

ESA has launched in 2009 its Space Situational Awareness (SSA) programme that includes three main components, one of them being the Space Weather Element (SWE), which focuses on services for owners/operators of satellites in space and infrastructure on the ground, such as spacecraft design; spacecraft operation; human space flight; launch operation; trans-ionospheric radio communications; SSA surveillance & tracking, or non-space system operation. ESA's SWE services will enable end-users in a wide range of affected sectors to mitigate the effects of space weather on their systems, reducing costs and improving reliability. Thirteen ESA Member States are participating in the programme.

Further coordination activities

Each of the organizations mentioned above have a distinct role to play, in development, in operations, in capacity-building, in regional cooperation, or in space-based observation, although better visibility should be given to these complementary roles.

In spite of these valuable initiatives we do not have as yet an overall strategy to ensure the efficient coordination of our observing systems nor a strategy to focus product-development efforts on the highest priority service needs. A key question going forward is thus how will we build on the foundation for collaboration that has been established, and implement the needed improvements to our observing capabilities and to our services? With the increasing number of partners committed to moving the space weather enterprise forward, we must create a forum to support the definition of common priorities and to identify the actions that will yield the space weather observations and service capabilities needed today and in the future.

VI. Candidate guidelines and recommended practices

A. Preamble

This chapter presents a synopsis of the guidelines and recommended practices defined through the work of expert group C for the long-term sustainability of outer space activities.

B. Guiding principle

Member States and their national and international agencies should take all reasonable measures to protect vulnerable space- and ground-based assets from the adverse effects of space weather in order to maintain the satellite-based services upon which human technological systems increasingly rely, including preventing the creation of related space debris.

C. Guidelines and Recommended practices

The scope of expert group C is set forth in the Terms of Reference (ToR) for the Working Group on the Long-term Sustainability of Outer Space Activities. The topics relevant to expert group C are:

ToR-(c)(i). Collection, sharing, and dissemination of data, models, and forecasts;

ToR-(c)(ii). Capabilities to provide a comprehensive and sustainable network of sources of key data in order to observe and measure phenomena related to space weather in real or near-real time;

ToR-(c)(iii). Open sharing of established practices and guidelines to mitigate the impact of space weather phenomena on operational space systems;

ToR-(c)(iv). Coordination among States on ground-based and space-based space weather observations in order to safeguard space activities.

For each guideline below we have provided traceability to the specific item in the terms of reference to which it refers in parentheses following the guideline text.

Guideline 1: Space weather entities, and member states and national and international organisations, should support and promote the collection, archiving, sharing, inter-calibration and dissemination of critical space weather data. (TOR-(c)(i); TOR-(c)(iv))

Note that throughout this document the term “data” in the candidate guidelines and best practices is used to define the complete collection of information required to work with the measured data, including, but not limited to: the data itself, and any related meta-data including state-of-health and data quality indicators or other relevant information. Ideally this might also include the means to read the data, and where appropriate and feasible could include related tools for reading the data, applying calibration supplied by the instrument teams, and analysis tools, as appropriate. Note also that it is implicit that the guidelines are intended to cover all historical, current and future critical space weather datasets.

Note some of the work relating to Guideline 1 (and in fact Guideline 2) could be done in association with the WMO Inter-Programme Coordination Team on Space Weather (ICTSW). In relation to Guideline 1. space weather entities relates to any organization whose operations relate to space weather. Therefore this includes governmental and non-governmental organisations, as well as commercial entities, who may be designing, launching or operating space assets, including users of space weather data who are developing value-added data products.

Recommended practices:

1.1 Member States and their national and international agencies should engage experts in identifying data sets critical for space weather services and research.

1.2 Member States and their national and international agencies should adopt policies for the free and unrestricted sharing of critical space weather data from their space- and ground- based assets.

1.3 All space actors and government, civilian and commercial space weather data owners are urged to allow the free and unrestricted access to and archival of such data for mutual benefit.

1.4 Member States and their national and international agencies should share real-time and near-real-time critical space weather data and data products.

1.5 Member States and their national and international agencies should:

(i) Cross- and inter-calibrate critical space weather data and data products.

(ii) Openly share critical space weather data and data products in a common format.

(iii) Adopt common access protocols for their critical space weather data and data products.

(iv) Promote the interoperability of space weather data portals promoting ease of data access by users and researchers.

1.6 Member States and their national and international agencies should undertake a coordinated approach to identify measurement gaps in order to meet critical space weather needs.

1.7 Member States and their national and international agencies should undertake a coordinated approach to maintain long-term continuity of space weather observations, and to fill key measurement gaps, in order to meet critical space weather needs.

1.8 Space actors including Member States and their national and international agencies are urged, to fly small and low power integrated payload for space weather science and monitoring whenever and wherever possible (e.g., radiation monitors on Earth-orbiting satellite missions).

Guideline 2: Member States and their national and international agencies should support and promote further coordinated development of advanced space weather models and forecast tools in support of user needs. (TOR-(c)(ii))

Recommended practices:

2.1 Member States and their national and international agencies should engage experts in a coordinated approach to document space weather research, user needs, and operational models as well as forecasting tools currently in use, and assess them in relation to space weather science, service and user needs.

2.2 Member States and their national and international agencies should undertake a coordinated approach to identify gaps in research and operational models and forecasting tools required to meet space weather science, service and user needs.

2.3 Member States and their national and international agencies should undertake a coordinated approach to fill gaps in models and forecasting tools needed to meet space weather needs. Where necessary this should include coordinated efforts to support and promote research and development to further advance space weather models and forecast tools.

Guideline 3: Member States and their national and international agencies should support and promote the coordinated sharing and dissemination of space weather model outputs and forecasts. (TOR-(c)(i))

Note that throughout this document the term “space weather model outputs and forecasts” in the candidate guidelines and best practices is intended to include, but not be limited to: outputs from space weather models and tools, space weather now-casts and forecasts, space weather alerts and warnings, various space weather services and products, which can include visualizations and other relevant information as appropriate.

Recommended practices:

3.1 Member States and their national and international agencies should identify high priority needs for space weather models, space weather model outputs, and space weather forecasts.

3.2 Member States and their national and international agencies should adopt policies for the free and unrestricted sharing of space weather model outputs and forecasts.

3.3 All government, civilian and commercial space weather model developers and forecast providers are urged to allow the free and unrestricted access to and archival of space weather model outputs and forecasts for mutual benefit, which will promote research and development.

3.4 Member States and their national and international agencies should encourage their space weather service providers to:

(i) Undertake comparisons of space weather model and forecast outputs with a goal of assessing their metrics and comparative performance towards the goal of improved model and forecast accuracy.

(ii) Openly share and disseminate historical and future critical space weather model outputs and forecast products in a common format.

(iii) Adopt common access protocols for their space weather model outputs and forecast products to the extent possible, to promote their ease of use by users and researchers including through interoperability of space weather portals.

(iv) Undertake coordinated dissemination of space weather forecasts among space weather service providers and to operational end users.

Guideline 4: Member States and their national and international agencies should support and promote the collection, sharing, dissemination and access to information relating to best practices for mitigating the effects of space weather on terrestrial and space-based systems and related risk assessments. (TOR-(c)(iii))

Recommended practices:

4.1 Member States and their national and international agencies are urged to:

(i) Submit, to a common archive, documentation outlining best design practices, guidelines, and lessons learned relating to the mitigation of the effects of space weather on operational systems.

(ii) Submit, to a common archive, documentation and reports relating to space weather user needs, measurement requirements, gap analyses, cost-benefit analyses, and related space weather assessments.

4.2 Member States and their national and international agencies should provide support to enable their national agencies, satellite operators, and space weather service providers to work towards the development of international standards and best practices applicable for the mitigation of space weather effects on satellite design.

4.3 Member States and their national and international agencies should support and promote co-operation and coordination on ground-based and space-based space weather observations, forecast modelling, satellite anomaly and space weather effects reporting, in order to safeguard space activities.

This could be done in collaboration with ISES and WMO.

4.4 Member States and their national and international agencies should:

(i) Incorporate current, now-cast and fore-cast space weather thresholds into space launch commit criteria.

(ii) Provide support to enable their satellite operators to work together with space weather service providers to identify the information that would be most useful to mitigate anomalies and to derive recommended specific guidelines for best practices for on-orbit operation. For example, if the radiation environment is hazardous, this might include actions to delay the uploading of software, action manoeuvres, etc.

(iii) Incorporate the capability to recover from a debilitating space weather effect, such as including a safe mode, in satellite designs.

(iv) Incorporate space weather effects into satellite designs and mission planning for end-of-life disposal in order to ensure that the spacecraft either reach their intended graveyard orbit or de-orbit appropriately, in accordance with the Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. This should include appropriate margin analysis.

4.5 Member States and their national and international agencies should:

(i) Encourage the collection, collation and sharing of information relating to ground- and space-based space weather related impacts and system anomalies, including spacecraft anomalies

(ii) Encourage using a common format for reporting the information. In relation to the reporting of spacecraft anomalies, the CGMS template provides an excellent candidate approach.

(iii) Encourage policies promoting the sharing of satellite anomaly data such that the satellite anomaly archive is available to all Member States.

Expert group C acknowledges that some data may be subject to legal restrictions and/or protection of proprietary or confidential information. Note that the Coordination Group for Meteorological Satellites (CGMS) requested the WMO to recommend a template for the information to be included in satellite anomaly reports. The WMO space weather team, the Inter-Programme Coordination Team for Space Weather, has now submitted to CGMS a template that was recently recommended by The Aerospace Corp. in the United States. A process of collation of satellite anomaly information and a Satellite Anomaly Mitigation (SAM) portal for the archiving and access to this anomaly data is also in development at the NOAA National Geophysical Data Center (NGDC).

4.6 Member States should undertake an assessment of the risk and socioeconomic impacts of the adverse space weather effects on the technological systems in their respective countries. The results from such studies should be published and made available to all Member States.

Guideline 5: Member States and their national and international agencies should promote the education, training and capacity-building required for a sustainable global space weather capability. (TOR-(c)(iii))

Given the WMO already has extensive training programs in relation to terrestrial weather, expert group C considers expanding this to also include space weather training would be valuable since it would leverage their existing infrastructure and capabilities.

Recommended practices:

5.1 Member states and their international organizations should encourage space weather training in space weather workshops.

Examples of training opportunities include Space Weather Workshop in the United States, European Space Weather Week and Asia-Oceania Space Weather Alliance workshops, International Space Weather Initiative schools, and the Regional Centres for Space Science and Technology Education, affiliated to the United Nations.

D. Candidate recommendations for consideration by the Scientific and Technical Subcommittee

Under the terms of reference of the Working Group on the Long-term Sustainability of Outer Space Activities, areas which have been identified during the course of the work can also be highlighted and brought to the attention of Scientific and Technical Subcommittee. Below, expert group C forwards two candidate recommendations which we believe should be considered by the Subcommittee for potential further study and evaluation. These relate to long-term sustainability issues but which go beyond a purely space weather consideration. We propose that the final report of the Working Group should include such recommendations, as well as the related practices, in the implementation section, for consideration by the Subcommittee.

Candidate recommendation 1: Member States and their agencies should work through the United Nations Committee on the Peaceful Uses of Outer Space and related international organizations to develop a basis for the coordination of ground and space based research and operational infrastructure to ensure the long term continuity of critical space weather observations. (TOR-(c)(ii))

Member States should work through the space weather agenda item of the Scientific and Technical Subcommittee in order to provide a mechanism for the coordination of ground and space based infrastructure to ensure the long term continuity of critical space weather observations.

Member States should work through the Scientific and Technical Subcommittee to implement a process to evaluate the impact and review the progress of the implementation of the guidelines including coordination of ground and space based infrastructure to ensure the long-term continuity of critical space weather observations. Reviews should be completed at least every 5 years.

Candidate recommendation 2: Member States and their national and international agencies should investigate the coordination of space weather information, including observations, analyses and forecasts, to support decision making and risk mitigation related to the operation of satellites, spacecraft, and sub-orbital vehicles including rockets and vehicles serving manned spaceflight including for space tourism. (TOR-(c)(iv))

Note: In coordination with the considerations of the other expert groups, this recommendation could form the basis for a cross-cutting proposition for consideration by the Working Group for the study of the means and feasibility of delivering a space equivalent to ICAO, including a potential role in “Space Traffic Control”.

Annex

List of references for figures included in the report

Figure 1. Space weather effects on technological systems on the Earth and in space. Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 2. The correlation of increased fluxes of galactic cosmic rays with the epochs of minimum solar activity. Source: Cosmic ray intensity and sunspot activity www.climate4you.com/Sun.htm

Figure 3. Electromagnetic and corpuscular solar radiation and its effects. Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 4. The effect of high-energy solar protons on the satellite-borne optical instruments. Source: V. D. Kuznetsov. Solar-terrestrial Physics and its applications. Uspekhi Fizicheskikh Nauk 182(3), 327-336, 2012.

Figure 5. Solar cosmic rays produce radiation hazard to astronauts in near-Earth and interplanetary space. Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 6. Solar and galactic cosmic rays produce radiation hazard to the crews of space missions to other planets (the Moon, Mars). Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 7. Solar cosmic rays can affect the launch of satellites interfering with the control systems of the launch vehicles. Source: D. N. Baker. The Economic and Societal Impacts of Space Weather. Presentation STP-12, Berlin, 2010.

Figure 8. High-energy solar protons moving along the open field lines of the Earth magnetic field in the polar regions penetrate the upper atmosphere and cause radiation enhancements and PCA events — short-wave radio blackouts. Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 9. Solar protons cause depletion of the vital ozone layer. Source: Charles Jackman & Gordon Labow (NASA).

Figure 10. The increased radiation level in the Earth radiation belts is dangerous to satellites. Source: NASA.

Figure 11. Hitting microchips of on-board electronics, GCR produce single event effects (SEE). High-energy protons and ions wreck electronic elements and cause single event effects in the operation of satellites. High-energy electrons penetrate the satellite and create the bulk charge, which results in dielectric breakdown and the failure of on-board electronic equipment. Source (left): D. N. Baker. The Economic and Societal Impacts of Space Weather. Presentation STP-12, Berlin 2010. Source (right): Takahiro Obara. Status report of expert group on Space Weather. 2012. Source: D. N. Baker. The Economic and Societal Impacts of Space Weather. Presentation STP-12, Berlin, 2010.

Figure 12. Solar radiation causes a degradation of solar batteries, which may decrease the satellite lifetime by a few years. Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 13. Radio signals from all systems are subject to space weather by virtue of variations in the medium they propagate in. Source (right): Paul M. Kintner, Jr., Cornell University, "A Beginner's Guide to Space Weather and GPS," February 21, 2008, available at http://gps.ece.cornell.edu/SpaceWeatherIntro_update_2-20-08_ed.pdf. Source (left): Kelly J. Hand, U.S. Air Force, "Space Weather—A DOD User Perspective", presentation to the space weather workshop, May 22, 2008.

Figure 14. The density irregularities arising in the ionosphere during magnetic storms affect the propagation of signals from GPS satellites. Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 15. Various satellite communication services, such as TV, cellular telecommunications, etc. are subject to negative effects of the space weather. Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 16. Geomagnetic disturbances and magnetic storms caused by solar mass ejections and high-speed solar wind streams are the most dangerous manifestations of the space weather. Source: NASA.

Figure 17. Uncontrolled variations of satellite orbits due to the swelling of the atmosphere in the periods of magnetic storms cause tracking problems and increase the danger of collision with space debris. Source: P. Brekke. Space Weather Effects. Presentation, ESTEC, 1 December, 2004.

Figure 18. During the Carrington event (September 1, 1989), which was the most intensive event ever observed in the Sun-Earth system, strong geomagnetic disturbances were recorded all over the globe from the polar regions to the equator. Source: D. N. Baker. The Economic and Societal Impacts of Space Weather. Presentation STP-12, Berlin, 2010.

Figure 19. The Quebec event (13-14 March 1989) was the world first large-scale technological catastrophe caused by the space weather. Source: Rodney Viereck, NOAA Space Environment Center, "Space Weather: What Is It? How Will It Affect You?", available at lasp.colorado.edu/~reu/summer-2007/presentations/SW_Intro_Viereck.ppt.

Figure 20. A scheme illustrating the interrelation and interdependence of the critical infrastructures. As the national infrastructures and services and their interrelations become more and more complicated, a serious fault of one element may have far- reaching impacts. Source: This is Figure 3.1 from the 8/28/08 Review Draft. Connections and interdependencies across the economy. Schematic showing the interconnected infrastructures and their qualitative dependencies and interdependencies. Source: Department of Homeland Security, National Infrastructure Protection Plan, available at www.dhs.gov/xprevprot/programs/editorial_0827.shtm.

Figure 21. The direct and indirect space-weather related risks for the largest group of the high-tech geostationary satellites amount to tens or hundreds of billion dollars. Source: This is Figure 5.13 from the 8/28/08 Review Draft. High energy electron flux history shows some repeatability suggesting short term forecasts with some confidence might be made. Source: David Chenette, Lockheed Martin Space Systems Company, "Aerospace Industry User Perspectives on Space Weather Data Products (and Models)," presentation to the Space Weather Workshop, May 22, 2008.