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Manual on Space Weather Information in Support of International Air Navigation

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and published under his authority

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International Civil Aviation Organization

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Chapter 1

INTRODUCTION

1.1 GENERAL

1.1.1 From an operations perspective, space weather events occur when the Sun causes disruptions to aviation communications, navigation and surveillance systems, and elevates radiation dose levels at flight altitudes. Space weather events may occur on short time scales, with the effects occurring from seemingly instantaneous to a few days hence.

1.1.2 From a broader perspective, the World Meteorological Organization (WMO) defines space weather to be, “The physical and phenomenological state of the natural space environment, including the Sun and the interplanetary and planetary environments.” This more-comprehensive definition cuts a broader swath across the system, to include the slowly varying Galactic Cosmic Rays (GCR) coming from outside the heliosphere as well as the repetitive high-speed solar wind streams from voids in the solar corona. In short, not all space weather stems from eruptions, but also from variations in the flow of charged particles, photons, and magnetic field.

1.1.3 Space weather forecasts for international air navigation, address particular types of disturbances, i.e. solar radiation storms, geomagnetic storms, ionospheric storms, and solar flares. In addition, predictions of the slowly varying elements; i.e. GCR and high-speed-stream-induced geomagnetic storms, are also produced. These forecasts enable operators the opportunity to be situationally aware and to formulate alternative plans should the impending conditions be of a magnitude and a type that could disrupt normal operations.

1.1.4 The goal of this document is to enable operators to make informed decisions when space weather impacts occur. A proper balance between operationally relevant information and scientific completeness is sought. In many areas, more scientific rigor and detail could be brought forward, but that would not enhance this manual’s utility to the aviation community. There is a deeper explanation of the science underpinning the field of space weather science in Appendix 2.

1.2 SPACE WEATHER INDICATORS

1.2.1 The effects of space weather come from processes that are invisible to the human eye. The sole exception are the brilliant auroras, spawned by energetic electrons and ions. Energized auroras indicate the deposition of energy into the upper atmosphere, and may herald the degradation of communications, navigation, and surveillance on aircraft in the vicinity.

1.2.2 For space weather events, the signs of their occurrence and system impacts are very subtle in real time. Given that, the prime value of space weather information is to enhance situational awareness of the proper function of aircraft systems. Anticipating and planning for degraded performance of communications and navigations systems add to the margins of safety. Often degraded performance is unavoidable, but being ready to respond to it with a pre-conceived plan is most desirable.

1.2.3 On the occasions when the effects are apparent, the signs of system impacts may include:

a) Erratic, degraded, or unavailable high frequency (HF) voice communications that worsen very quickly, especially when the aircraft is in the sunlit hemisphere or operating in high latitudes and polar regions;

b) Data and voice dropouts on satellite communications (SATCOM) links, especially for frequencies less than 2 GHz;

c) a variance in positioning between the Actual Navigation Performance (ANP) and the Global Navigation Satellite System (GNSS)-based performance;

d) reduced availability of GNSS augmentation systems; and

e) reboot of on board electronics or display of indications of non-standard performance.

1.2.4 It is not realistic to expect an aircrew to be aware of the slowly occurring variations of space weather, so-called “space climate”, in real-time. Nevertheless, indicators such as the change in GCR flux allow an awareness of the variability. The change in GCR flux over an 11-year solar activity cycle (see Appendix 2, Section 3, for explanation of the 11-year solar cycle) is opposite of the conventional solar cycle – GCR is highest when sunspots are lowest – and may be as much as a factor of two at altitudes where commercial aircraft fly.

1.2.5 Some indicators of this slow GCR flux change may include:

a) more than normal avionics (computer) inconsistencies and reboots; and

b) more than normal interruptions of SATCOM for all frequency bands as satellite-borne electronics experience radiation-induced upsets.

1.3 THE HAZARDS

1.3.1 Space weather impacts occur to communications, navigation, surveillance, radiation-sensitive electronics, and human exposure. Beyond the more generic indicators described in section 1.2, the system impacts may include:

a) unexpected loss of communications;

   — HF voice and HF data link, i.e. Controller Pilot Data Link Communications (CPDLC), on routes where HF is employed;

   — poor or unusable performance of L-band SATCOM;

b) degraded performance of navigation and surveillance that rely on GNSS;

   — Automatic Dependent Surveillance – Broadcast (ADS-B) and/or Automatic Dependent Surveillance – Contract (ADS-C) anomalies;

   — sporadic loss-of-lock of GNSS, especially near the equator, post-sunset;

c) unanticipated non-standard performance of on-board electronics, resulting in reboots and anomalies; and

d) issues related to radiation exposure by aircrew and passengers.

1.3.2 Over the longer term, the slowly varying component of GCR incrementally adds to effective dose over the lifetime of the passengers and aircrew. The radiation can also cause single event upsets to on board electronic systems. An awareness of the changing GCR flux allows post-facto troubleshooting of operational system issues, as well as serving to educate and inform the passengers and aircrew.

1.4 SPACE WEATHER MITIGATION ASPECTS

1.4.1 Space weather events affecting aviation can be sudden and, at times, unpredictable. For example, dayside HF radio blackouts often come with no warning. Solar radiation storms offer some opportunity for prediction, but at times, radio blackouts, are very fast to impact systems and humans.

1.4.2 Geomagnetic storms, by their nature, are the response of Earth's magnetic field to enhanced energy from the Sun, and are the slowest to eventuate. From the fastest of about 18 hours from the solar eruption, to more commonly a few days from the Coronal Mass Ejection (CME) launch, these events offer forecasters the longest lead time. Even longer lead times are possible with the prediction of recurring high-speed solar wind streams that also cause typically less intense geomagnetic storms. These events may be accurately predicted weeks in advance.

1.4.3 The timely availability of reliable and consistent space weather information (observations and forecasts) is essential to mitigate the safety risk of aircraft losing key in-flight functionality. The designated Space Weather Centres (SWXC) have at their disposal information from satellite and ground-based sensors enabling both prompt event detection as well as providing input for predictive models. Physics-based models are now available to operations centres to predict the trajectory of CMEs and there now exists an ability to predict the onset of a geomagnetic storm to about +/- eight hours. Ionospheric storms, to first order, can be predicted in a similar way.

1.5 COORDINATING THE RESPONSE TO A SPACE WEATHER EVENT

1.5.1 There are many contributors to the overall space weather risk mitigation system such as Air Navigation Service Providers (ANSP) including Aeronautical Information Services (AIS), Air Traffic Flow Management (AFTM) units, surveillance and communication providers, operators, States, Civil Aviation Authorities (CAA), and SWXCs. Their cooperation in assessing, coordinating and providing information relevant for pre-flight and in-flight decision making is essential for effective mitigation of any potential impacts from a space weather event.

1.5.2 Information on the procedures of these units in respect to operations in areas forecast to be affected by space weather is available in International Civil Aviation Organization (ICAO) documents including:

a) Annex 3 – *Meteorological Service for International Air Navigation*

b) Annex 10 - *Aeronautical Telecommunications*

c) Annex 15 – *Aeronautical Information Services*

d) Doc 9377 - *Manual on Coordination between Air Traffic Services, Aeronautical Information Services, and Aeronautical Meteorological Services*

e) Doc 8896 - *Manual of Aeronautical Meteorological Practice*

f) Doc 9849 – *Global Navigation Satellite System (GNSS) Manual*.

1.5.3 This manual, in providing advice to States on addressing the role of the aircraft operator and of the corresponding CAA, is complementary to the documents listed above.

Chapter 2

SPACE WEATHER PHENOMENA AND AVIATION OPERATIONS

2.1 GENERAL

2.1.1 Various types of eruptive space weather disturbances whose occurrence vary over the eleven-year solar cycle, can directly impact critical systems used in aviation. In addition, long-term variability in GCR can also enhance the radiation environment in which these systems function. A prudent approach to formulating actions is to understand what types of conditions may occur, and what systems are most likely to be affected during storm times.

2.1.2 In the design and implementation of aviation systems and procedures, space weather impacts are known and appreciated. It behooves aircrew and operations personnel to understand the full extent of these impacts when the environment is highly disturbed and systems are stressed.

2.2 GEOMAGNETIC STORMS

2.2.1 Geomagnetic storms are strong disturbances in the Earth's (geo) magnetic field. These are the response to a heightened energy flux carried by the solar wind. The solar wind is the continuous outflow from the Sun of magnetic field and charged particles. Its speed and composition varies dramatically from the normal ambient state to greatly enhanced levels that fuel geomagnetic storms. This energy may come from a CME, an explosive solar event, or the more-gentle sweep of a high speed solar wind stream as it rotates past Earth.

2.2.2 The strongest geomagnetic storms are caused by CMEs; high-speed solar wind streams are typically less intense. The duration of storms varies from a few hours to as long as a few days.

2.2.3 High latitudes and the polar regions bear the strongest impacts, as evidenced by the brilliant auroras seen in the auroral zone that accompany the storms. Lower latitudes experience auroral surges during very intense activity, but typically are less affected. Equatorial regions see but minor impacts. Communication and navigation system impacts from storms are, however, global in longitude.

2.2.4 The frequency of geomagnetic storms, in general, mimics the 11-year solar activity, or sunspot, cycle. A closer inspection of the historical record shows a bi-modal distribution. The strongest storms cluster near solar maximum, as they are usually caused by CMEs, whereas a second peak in activity happens during the declining phase of the solar activity cycle, due to the stable solar coronal holes emanating high-speed solar wind streams.

2.2.5 The strongest storms occur at the rate of approximately four per 11-year cycle. Lesser-sized but significant storms have been observed to occur approximately 200 times per cycle. It should be noted, though, that geomagnetic storms can occur at any time. Even in the quiet of solar minimum, isolated CMEs do occur and can perturb the Earth's magnetic field.

2.3 IONOSPHERIC STORMS

2.3.1 Ionospheric storms are the result of adding energy to the weakly ionized plasma that is the ionosphere, which extends upward from about 60 km. In most cases, due to the close coupling between the ionosphere and the magnetosphere, they occur in tandem with geomagnetic storms. The intertwined physical relationship between the ionosphere and the magnetosphere causes difficulties when distinguishing which system is affected by a disturbance. For aviation, the physical perturbation in the ionosphere is the primary driver for impacts to HF and GNSS. The boundary of the auroral zone that moves during geomagnetic storms, is significant for radiation effects.

2.3.2 The symptoms of an ionospheric storm are: enhanced electrical currents, magneto hydrodynamic turbulence and wave activity of the plasma. The electrodynamics lead to a non-homogeneous distribution of plasma, particularly in the region about 350 km in altitude. Neutral winds also contribute to the irregular distribution of free electrons and ions.

2.3.3 GNSS signals, originating at the satellite orbiting at about 20,000 km in altitude, pass through this disturbed region and retain their unique characteristics so as to be identified and processed by the GNSS receiver on an aircraft in flight. During ionospheric storms, GNSS amplitude and phase may each be affected making the signals of one or more satellites in view impossible to track. This loss-of-lock may result in reduced positioning accuracy or, at worst case, a denial of GNSS service. In addition, variability in the free electrons along the path of a GNSS signal, so called Total Electron Content (TEC) results in increased range errors, and hence, errors in aircraft positioning. However, it is the gradient of the TEC that may pose the greatest challenges for aviation receivers.

2.3.4 HF propagation is adversely affected, typically during the late phases of ionospheric storms, with the unavailability of the higher end of the HF band. Long distance HF communication is enabled by reflection from the ionosphere. The maximum usable frequency (MUF) for a given communication path is the highest HF radio frequency that can be used for communication via reflection. A depression of the MUF prohibits aircraft from accessing the highest frequencies normally available.

2.3.5 Ionospheric monitoring for HF communication is achieved by monitoring the MUF over a vertical path. MUF depression for a given time of day is defined as the percentage decrease in MUF compared to a 30-day median MUF (for the same local time) in order to account for diurnal, seasonal, and solar cycle variations in ionospheric support of HF.

2.3.6 Given the physically connected relationship between geomagnetic and ionospheric storms, the durations are similar. Some incidents last for days.

2.3.7 The frequency of occurrence of ionospheric storms is also similar to geomagnetic storms with one important exception. The near-equatorial ionosphere – a band extending roughly +/- 20 degrees in latitude on either side of the magnetic (not the geographic) equator – can be very disturbed in the post-sunset hours, even in the absence of a geomagnetic storm. Processes internal to the Earth's system cause a fountain of electrons that rise from nearer the equator and fall on the higher latitude edges. Large depletions in ionospheric electron density may form post-sunset, producing strong spatial gradients in ionospheric distribution. The associated instabilities cause GNSS signals to fluctuate rapidly in amplitude and phase.

2.3.8 Amplitude scintillation can have a serious impact on aircraft using GNSS for Required Navigation Performance (RNP)-based flight navigation. Aircraft lose lock on one or multiple GNSS signals and find GNSS unavailable for short periods.

2.3.9 The strongest ionospheric storms occur at the rate of about four per 11-year cycle (from the geomagnetic storm data). Less impactful storms have been observed to occur approximately 200 times during the same interval. Post-sunset equatorial scintillations interrupting GNSS occur at rates somewhere in the 200 times per cycle range.

2.3.10 Aircraft communications, particularly HF, are degraded or unavailable during geomagnetic storms. Surprisingly, some paths can actually be improved during these times, although those occurrences seem somewhat random and very difficult to foresee. Very high frequency (VHF) and ultra high frequency (UHF) links may also suffer lesser levels of degradation.

2.3.11 SATCOM may be affected during ionospheric storms, but the impacts are minimized the higher the frequency employed. For example, L-band systems may suffer losses similar to GNSS systems, whereas S, C, Ku, and Ka-band systems will rarely be impacted at all by space weather.

2.3.12 Air traffic management in future years plans to make a more extensive use of ADS-B, ADS-C, and SATCOM S, C, Ku and Ka data links. Fundamental to the method, GNSS navigation will enable appropriate positioning for phase of flight, and SATCOM will enable transmission of the information to/from aircraft. In that GNSS is L-band, it will be affected by adverse ionospheric conditions as has been described here. However, for communication frequencies above 2 GHz, impacts will be minimized. And since some L-band SATCOM satellites are in low-earth orbit (LEO), vs. GNSS at medium earth orbit (MEO), the signal will experience less r^{-2} attenuation; furthermore, many communication satellites have higher power transmitters than GNSS.

2.4 SOLAR FLARE RADIO BLACKOUTS

2.4.1 Solar flare radio blackouts are strictly a dayside impact. Solar flares are rapid releases of energy stored in strong, localized magnetic fields on the Sun. When an instability occurs, the speed-of-light flash of X-rays and extreme ultraviolet (EUV) bathe the sunlit side within minutes. The effect is the most acute at the sub-solar point, i.e. local noon near the equator.

2.4.2 These solar flare blackouts can eliminate or degrade HF, both voice and data link, for periods ranging from a few minutes to a few hours. The duration of the impact is much shorter than it is during geomagnetic storms. The affected range of HF frequencies is also quite different. During solar flare radio blackouts, the lower frequencies are lost, similar to the early to mid-phase of a geomagnetic storm. During the latter stages of geomagnetic storms, it is the upper range of HF frequencies that is most affected or completely lost.

2.4.3 Solar flare radio blackouts are most frequent during solar maximum years, and rare during solar minimum years. But during maximum years, there can be as many as 10-20 episodes of solar flare radio blackout on a given, active day.

2.4.4 The worst solar flare radio blackouts occur at a rate of 1 to 2 per 11-year cycle. Less impactful events occur approximately 175 times per 11-year cycle. It should be noted that even low levels of blackout intensity – happening about 2,000 times per cycle – still impede dayside HF communications for a few minutes at a time.

2.4.5 On rare occasions, L-band radio bursts during solar flares are strong enough with the proper polarization to affect GNSS receivers, right hand circularly polarized (RHCP), to overwhelm the reception of GNSS signals for short periods of time (5-10 minutes). This is strictly a dayside impact and primarily seen by non-aviation-type GNSS receivers employing high-precision techniques. The most notable example of this interference occurred in December 2006.

2.4.6 Since aircraft employ a more-robust application of GNSS for navigation, it is highly unlikely this impact would ever be seen in aviation. It has also been noted that dayside HF and UHF radars can be adversely affected by strong solar radio bursts. In 2015 secondary surveillance radars were impacted by solar radio noise.

2.5 SOLAR RADIATION STORMS

2.5.1 Solar radiation storms occur when charged particles, primarily protons, are energized and accelerated in processes occurring near the Sun or beyond. These particles are guided by the interplanetary magnetic field and, under the right conditions, engulf the Earth with additional radiation.

2.5.2 High altitude aircraft flights are susceptible to the ill effects of the added radiation dose, but are protected due to the Earth's atmosphere and magnetic field. Protection increases with lower altitudes (where the atmosphere is more dense) and lower latitudes (where the magnetic field is more horizontal). If an aircraft responds by flying lower in latitude and/or altitude, only events with abnormally high energy (greater than 500 MeV) protons elevate the radiation dose experienced in flight.

2.5.3 Polar and near-polar flights are the most exposed during solar radiation storms. There the geomagnetic field topology allows easy access for the radiation to penetrate through the atmosphere, from the poles to about 60 degrees geomagnetic latitudes. In lower latitudes, the dipole-like magnetic field configuration inhibits the transit through the atmosphere.

2.5.4 Degraded HF during smaller, more commonplace radiation storms, termed Polar Cap Absorption (PCA) can be present for many days at high latitudes., This impact results from energetic proton precipitation into the D-region ionosphere below approximately 100 km.

2.5.5 Solar radiation storms can be long-lived, persisting up to a week, resulting in degraded HF communications at high latitudes for a similar period. Geomagnetic storms also drive the normal boundary (approximately 60 degrees geomagnetic) for increased radiation further equatorward by perhaps an additional 10 degrees in both hemispheres.

2.5.6 Solar radiation storms occur in cadence with the solar cycle with peak occurrence near solar maximum. However, they can occur at any time in the cycle, even very intense ones. The worst solar radiation storms occur roughly just 1-2 times per cycle. Events significantly impacting polar aviation operations may happen 10-15 times.

2.5.7 Solar radiation storms, particularly those with an abundance of high-energy protons, pose concerns for radiation exposure for aircrew and passengers. Aircrews are designated as radiation workers. The United States National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP) have established 45-year exposure limits in NCRP Publication 160, Section 7, and ICRP Publication 132, Section 2.4, respectively.

2.5.8 Semi-conductors in avionics can malfunction during these events in a seemingly random manner. Single event upsets may cause a reset to a computer system. Over the long term, radiation damage may hasten failure of the chip.

2.5.9 Solar radiation storms add to the ever-present GCR-induced radiation dose that, to varying degrees, affects every place on Earth. GCR is addressed in the last section of this chapter. The sum of the two components is the radiation background. It changes with time, place, and level of activity.

2.6 ATTRIBUTES OF ERUPTIVE SPACE WEATHER

2.6.1 Figure 2-1 is a summary of the individual elements described in this chapter. It shows the various types of solar and interplanetary phenomenology, the varying times of propagation to Earth, the domains near the Earth that are affected, and at the far right, potential impacts.

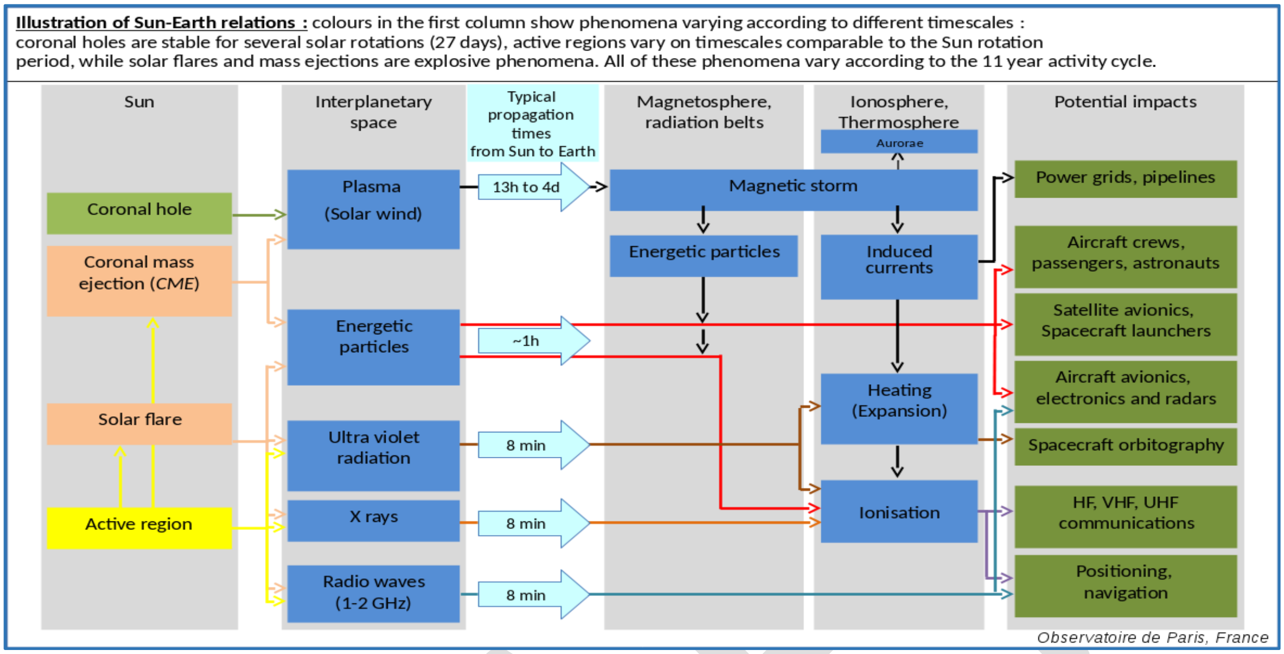


Figure 2-1. Schematic diagram of space weather from Sun to Earth

Note. —All the above phenomena maximize in occurrence and potential impacts to airline operations in the solar maximum epoch.

2.6.2 The sole exception to the focus of activity near solar maximum relationship is GCR. In the following section, properties of GCR are given and an explanation of why it is they are the strongest when the Sun is at its weakest.

2.7 GALACTIC COSMIC RAYS

2.7.1 GCR are the slowest changing element in the suite of variables. Originating in distant supernovae, they are kept to a minimum near the Earth when the Sun is eruptive and producing flares and CMEs, due to the turbulence that activity spawns in the inner heliosphere. As a result, the magnitude of the GCR is inversely correlated (Figure 2-2) with the solar activity cycle.

2.7.2 GCR flux changes over the solar cycle, with its maximum occurring at solar minimum. This variability is a function of energy, location, and altitude of the detector. For typical commercial flight altitudes, the variation is about a factor of two; i.e. the flux is double during solar minimum from solar maximum. However, there are conditions during which the background GCR can quickly abate, due to large-scale shocks, for a few hours at a time. These depletions of GCR are known as “Forbush Decreases.”

2.7.3 Higher GCR cause elevated radiation to be measured on polar and high-latitude flights. GCR rates also increase with altitude, until it maximizes at around 18 000- 19 500 metres (60-65,000 feet), the so-called “Pfotzer Maximum.” Similar to solar radiation storms, the impacts are focused on health-related issues for the aircrew and passengers, as well as proper functionality of avionics.

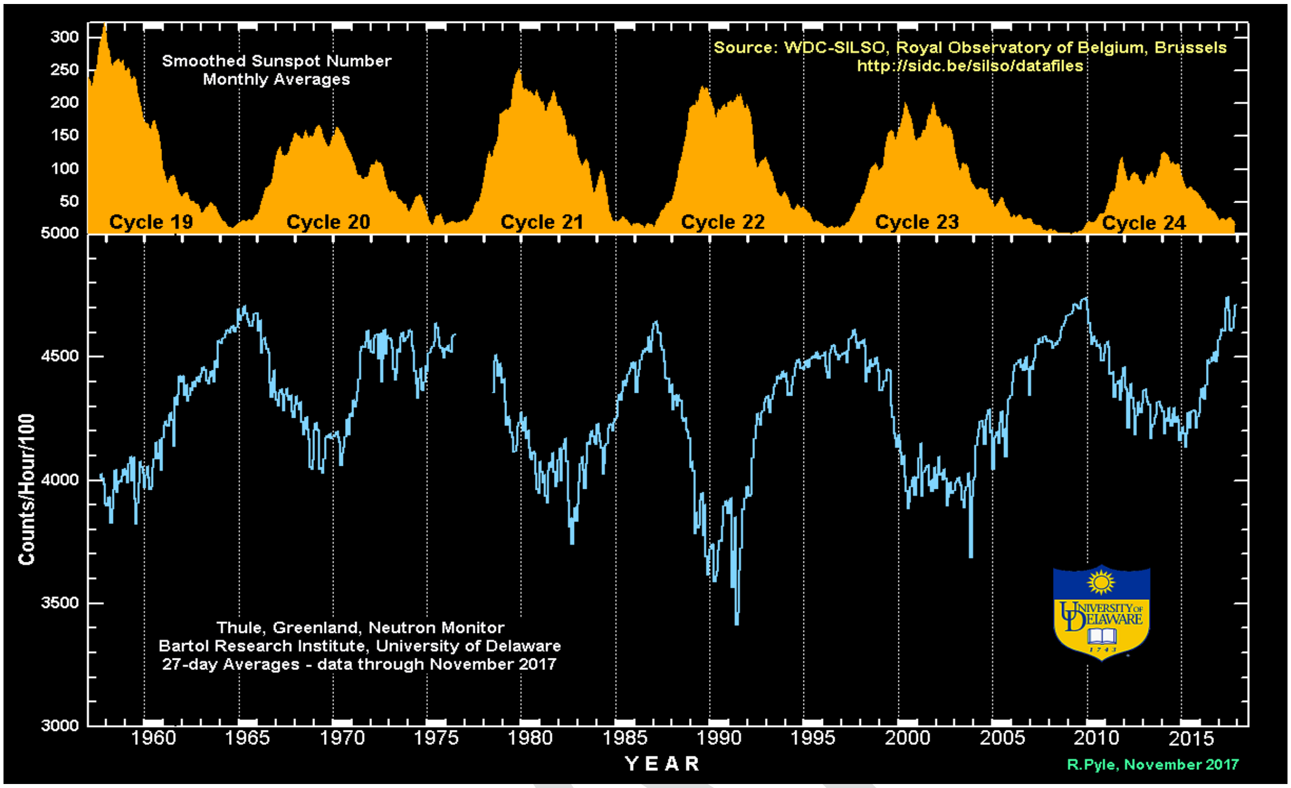


Figure 2-2. Relationship between solar cycles, depicted by sunspots (top panel) and neutrons measured at sea level from GCR (bottom panel); note the anti-correlation between the two quantities.

2.7.4 The goal of this document is to strike a balance between operationally relevant information and scientific completeness. In this chapter, more detail could have been brought forward, but it is considered that it would not have enhanced its utility to the aviation community. Additional details on the sources of space weather are nevertheless provided in Appendix 2.

Chapter 3

PROVISION OF SPACE WEATHER ADVISORY INFORMATION

3.1 GENERAL

The information and services required for safe and efficient aircraft operations will be provided by two designated global centres, assisted by as many as four regional centres passing relevant information to the global centres for dissemination. The working principle for the centres is to provide space weather advisory information that users can employ for decision-making.

3.2 SPACE WEATHER CENTRES (SWXC)

3.2.1 There are basic requirements for the centres, not limited to, but including, reliability, sustainability, and connectivity, to both the users of the services as well as the inflowing data and observations necessary for the products defined by the ICAO Standards and Recommended Practices (SARPs).

3.2.2 Currently, the SWXCs support a broad user base. These users typically include electric power entities, satellite operators, emergency managers, and a myriad of other interested parties. Aviation products must have a high priority in the formulation and distribution of the required space weather advisory information due to the prompt effects on aircraft navigation and communication systems as well as radiation impacts to passengers and aircrew.

3.2.3 The SWXCs are responsible for providing all necessary services in view of issuing space weather advisory information in a timely manner. Specifically, the data and model output must include:

a) ionospheric scintillation (amplitude and phase), and TEC for GNSS;

b) effective dose for radiation; and

c) Kp, PCA, Solar X-ray flux (or equivalent), and MUF for HF.

3.2.4 In some cases, physics-based models are envisioned to support the requirements stipulated by SARPs, in particular, for radiation. The SWXCs must have access to the model and be able to provide output from the model as quickly as possible. It is recognized that input data will have some latency, and performance requirements will evolve to the cadence of the model-based information being disbursed.

3.2.5 The SWXCs must be staffed 24 hours a day/ 7 days a week. Operations personnel are required to keep abreast of the current conditions and disseminate for short-term forecasts as defined in the SARPs.

3.2.6 All SWXCs must develop coordination protocols and procedures to enable clear and unambiguous information disseminated to the aviation industry.

3.3 SPACE WEATHER ADVISORY INFORMATION

3.3.1 Amendment 78 to Annex 3 introduced a requirement to issue space weather advisory information when necessitated by space weather events. The space weather advisory message is similar in structure to advisory messages issued for tropical cyclones and volcanic ash clouds, issued by the tropical cyclone and volcanic ash advisory centres concerned.

3.3.2 SWXCs issue the space weather advisory when impacts to HF communications, communications via satellite, GNSS-based navigation and surveillance systems, or heightened radiation occurs.

3.3.3 The advisory message informs the user of:

a) the type of impact;

b) the expected onset, or that the event is already in progress;

c) the duration of the event;

d) a generalized description of the spatial extent affected for the next 24 hours; and

e) a description of the severity of the impact in moderate (MOD) or severe (SEV) categories.

3.3.4 The space weather advisory uses the spatial ranges and resolutions as shown in Attachment E to Annex 3.

3.4 COMBINATIONS AND USE OF THE COVERAGE DESCRIPTIONS

3.4.1 GEOMAGNETIC STORMS

3.4.1.1 Geomagnetic storms perturb the ionosphere to affect HF communications and GNSS navigation in the high latitude (HNH and HSH) regions and sometimes include middle latitude (MNH and MSH) regions. Equatorial regions (EQN and EQS) may be affected during the worst of storms.

3.4.1.2 If an event were strong enough to produce moderate degradation in the equatorial regions, it would likely be severe in the middle and high regions. In this case, there would be two advisories issued, one for the severe event affecting the high and middle latitudes (HNH, HSH, MNH and MSH), and a second advisory for the moderate event affecting the equatorial latitudes (EQN and EQS).

3.4.1.3 Combinations of latitude bands include:

a) HNH and HSH

b) HNH, HSH, MNH and MSH

c) EQN and EQS

d) MNH, MSH, EQN and EQS

Note.1. — A single band (e.g. HNH) would not be used for geomagnetic storms since both poles are affected.

Note.2. — Altitudes (e.g. ABV FLnnn) are not used.

3.4.1.4 When using the latitude bands, the latitudes are used to indicate the horizontal extent. Normally the entire latitude band is affected, thus E18000 – W18000 was chosen for the example in Annex 3. Thus, E18000 – W18000 will normally follow the pairing of latitude bands.

3.4.2 IONOSPHERIC STORMS

3.4.2.1 Ionospheric disruptions, caused by scintillation, primarily affect the equatorial and high latitude regions but can also extend into the middle latitudes. In any case they may affect GNSS navigation. These perturbations can be more localized than the other space weather events and thus may be best-described using latitude and longitude coordinates. They can also be described using longitude lines and one or more of the latitude bands.

3.4.2.2 Altitudes (e.g., ABV FLnnn) are not used. Combinations include:

a) a four-sided polygon using four latitude and longitude coordinates;

b) one or more latitude bands coupled with two lines of longitude, e.g.:

— EQN Wnnn(nn) or Ennn(nn) – Wnnn(nn) or Ennn(nn)EQS Wnnn(nn) or Ennn(nn) – Wnnn(nn) or Ennn(nn)

— EQN EQS Wnnn(nn) or Ennn(nn) – Wnnn(nn) or Ennn(nn)

— MNH EQN Wnnn(nn) or Ennn(nn) – Wnnn(nn) or Ennn(nn)

— MSH EQS Wnnn(nn) or Ennn(nn) – Wnnn(nn) or Ennn(nn)

3.4.3 SOLAR FLARE RADIO BLACKOUTS

3.4.3.1 Solar flare radio blackouts degrade communications, and on rare occasions GNSS navigation, and are a “daylight side” impact only. These events may last from a few minutes to a few hours and are a much shorter duration than geomagnetic storm impacts. For the forecast portions of the advisory, the remarks section may include the statement that “periodic disruption possible on the daylight side”. Also a note that these events typically are most acute on the lower end of the HF band. When possible include a forecast of the duration of the blackout.

3.4.3.2 Solar flares are usually very impulsive. Advisories denoting the MOD and SEV, if attained, thresholds are likely to be issued in rapid succession.

3.4.4 SOLAR RADIATION STORMS

3.4.4.1 The impacts of solar radiation storms are most intense at high latitudes and are usually confined to the HNH and HSH latitude bands. On rare occasions they could extend into the MNH and MSH. Solar radiation may be severe above a certain altitude, i.e. Flight Level (FL), and moderate below. For example SEV ABV FL340, MOD FL250-340, which will require two advisories.

3.4.4.2 When two advisories are issued for the same area, it is important that the number of the other advisory and the intensity be stated in the remarks section. For example, an advisory for MOD radiation from FL250-340 would include in the remarks “SEE SWX ADVISORY NR 2018/7 FOR SEV RADIATION ABV FL340”.

3.4.4.3 Radiation storms are the only events that will use altitudes, i.e. ABV FLnnn. Combinations include:

a) HNH and HSH E18000 – W18000 ABV FLnnn

b) MNH and MSH E18000 – W18000 ABV FLnnn

c) EQN and EQS E18000 – W18000 ABV FLnnn

d) HNH, HSH, MNH and MSH E18000 – W18000 ABV FLnnn

e) HNH, HSH, MNH, MSH, EQN and EQS E18000 – W18000 ABV FLnnn

f) HNH and HSH E18000 – W18000 FLnnn–nnn

g) MNH and MSH E18000 – W18000 FLnnn–nnn

h) EQN and EQS E18000 – W18000 FLnnn–nnn

i) HNH, HSH, MNH and MSH E18000 – W18000 FLnnn–nnn

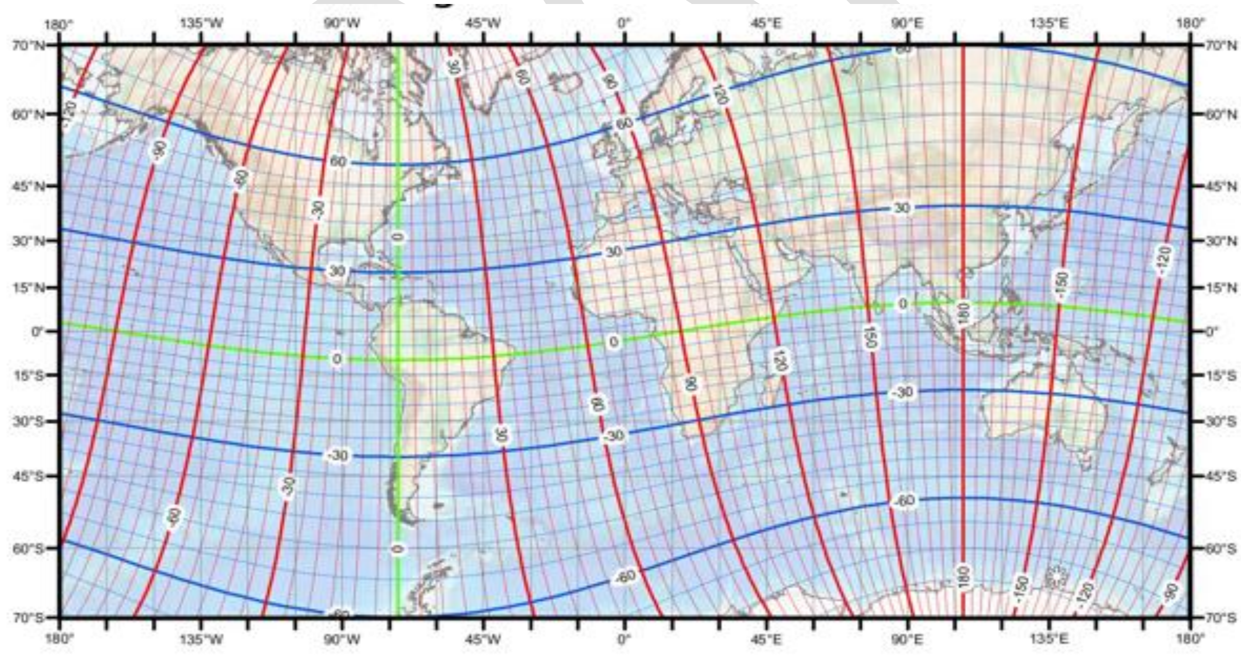
j) HNH, HSH, MNH, MSH, EQN and EQS E18000 – W18000 FLnnn–nnn

3.4.4.4 In accordance with Attachment E to Annex 3, the range for the flight levels is from FL250 to FL600, with a resolution of 30, i.e. 3,000 feet. Usable flight levels for the advisory are: FL250, FL280, FL310, FL340, FL370, FL400, FL430, FL460, FL490, FL520, FL550, and FL580.

3.5 GEOMAGNETIC VS. GEOGRAPHIC LATITUDE

3.5.1 It must be emphasized that with the exception of the “dayside” HF impact which are due to photons, all locations listed in this document are referenced to geographic – not geomagnetic – latitude. It is the Earth’s magnetic field that guides and modulates the charged particles that come from the Sun. The reality of this influence is some regions are exposed (the poles) while other regions are shielded (the equator).

3.5.2 The difference between the two coordinate systems is most pronounced in the American sector, where the magnetic field sags down over North America (Fig 3-1). As an example, Oslo (59.9° N) and Minneapolis (45.0° N) geographic, are at nearly the same magnetic latitude, 56.0° geomagnetic. The net effect of this dipole tilt (maximized near 90° W longitude) is many space weather impacts are most acute over North America. The analog in the Southern Hemisphere is southwest of Australia over the Indian Ocean, a remote sector for airline operations.



Units: degrees
Countour Interval: 5 degrees
Map Projection: Mercator

Figure 3-1. US/UK World Magnetic Chart – Epoch 2010 Geomagnetic Coordinates

3.5.3 This offset has practical consequences for aircraft operators. On polar flights between North America and Asia, the aircraft spends an appreciably longer time in the high geomagnetic latitudes where impacts to HF and GNSS are most likely. More critically, the radiation "zone," i.e. area above 60^{o} N, is stretched southward, meaning longer travel times – and more exposure – through that region.

3.6 ADVISORY THRESHOLDS

3.6.1 Annex 3 refers to thresholds of space weather activity that trigger an advisory. As much as possible, the principle used to define these thresholds is based on impacts to systems rather than phenomenological severity. Unfortunately, the data does not exist for a 1-1 correspondence between system degradation and space weather intensity; therefore estimates are necessary in some cases. This approach makes it necessary for periodic updates to this document, as improvements to the technologies that support critical systems occur.

3.6.2 Table 3-2 is a list of thresholds for the various types of space weather events affecting aviation. Categories are listed as Moderate or Severe, as referenced in the Space Weather Advisory Message in Annex 3.

Table 3-2. Thresholds for space weather advisory

		Moderate	Severe
GNSS			
	Amplitude Scintillation (S4)(dimensionless)	0.5	0.8
	Phase Scintillation (Sigma-Phi)(radians)	0.4	0.7
	Vertical TEC (TEC Units)	125	175
RADIATION			
	Effective Dose (micro-Sieverts/hour)*	30	80
HF			
	Auroral Absorption (Kp)	8	9
	PCA (dB from 30MHz Riometer data)	2	5
	Solar X-rays (0.1 - 0.8 nm)($W\text{-}m^{-2}$)	$1X10^{-4}$ (X1)	$1X10^{-3}$ (X10)
	Post-Storm Depression (MUF)**	30%	50%

** MOD advisories will only be issued when the MOD threshold is reached at FL460 and below. SEV advisories will be issued when the SEV threshold is reached at any flight level.*
*** As compared to a 30-day running median of the critical frequency of the F2 layer (foF2).*

Note. — A more detailed description of how these values were determined can be found in Appendix 1 to this manual.

3.7 EXAMPLES OF SPACE WEATHER ADVISORY MESSAGES

3.7.1 Examples of space weather advisory messages are provided in Annex 3, Appendix 2. Examples A2-3, A2-4 and A2-5 relate to GNSS and HF COM effects; RADIATION effects; and HF COM effects, respectively.

3.7.2 Space weather advisory messages may include multiple categories, e.g. GNSS and HF, HF and RADIATION.

3.8 ACCURACY GOALS FOR SPACE WEATHER ADVISORY INFORMATION

3.8.1 Like all forecasts, space weather advisory information is assessed on its accuracy. Similar to terrestrial weather predictions, forecasts of the extreme events draw the most attention. A key difference between terrestrial and space weather forecasts is the vast volume of space and the sparse data that space weather forecasters are faced with.

3.8.2 Accurate predictions of onset time, duration, and magnitude are of great importance for safety and efficiency to aircraft operators. False alarms and missed events factor into the cost/loss matrices of operators as they try to make the most prudent – yet most economical – operating decisions during an event.

3.8.3 There is a challenge between providing longer lead-time and, at the same time, predicting correct intensity for space weather forecasters. The system that comprises space weather is vast, and data collection is sparse. Improvements in forecast skill do occur, but often depend on new science missions that are infrequent and costly.

3.8.4 Various metrics are used in the validation and verification of space weather advisory information, similar to those used in conventional meteorology. Reliability diagrams, contingency tables, and traditional metrics such as Probability of Detection (POD), False Alarm Rate (FAR), etc., are used.

Chapter 4

USE OF SPACE WEATHER ADVISORY INFORMATION

4.1 GENERAL

Space weather advisory messages must be issued in accordance with the provisions in Annex 3. Some advisories will allow time for a well-considered response plan and no change to an already planned flight. The other extreme will be at the last minute, or enroute, necessitating a recalculation of a preordained flight plan. In many ways, these advisories will be similar to conventional, more familiar products and services documented in Annex 3. But due to the insidious impacts to systems and radiation levels, flight crews and ANSPs may be suddenly faced with situations requiring prompt action.

4.2 PRINCIPLES GUIDING BEST PRACTICES

4.2.1 Solar radiation storms are one type of space weather event that may necessitate a fast response due to the immediacy of its impacts. The lead time for the radiation advisory may be only a few minutes at most at times. In avoidance of radiation, considerations of time, distance and shielding enable decisive actions for mitigation of the threat. Solar radiation storms are the sole space weather type that can be mitigated by shielding.

4.2.2 Shielding from radiation consists of protection by (assuming that the skin of the aircraft provides negligible shielding):

a) the overhead atmosphere. That is, the lower the altitude, the greater protection by the air overhead; and

b) the geomagnetic field. When the field vector is more horizontal than vertical, charged particles are diverted away. The Earth's magnetic field is vertical at the poles and horizontal at the equator, so flying at lower latitudes increases the shielding.

4.2.3 Making use of time and distance flexibility may lessen impacts from other space weather scenarios.

4.3 RESPONDING TO A SPACE WEATHER EVENT

4.3.1 FLIGHT CREW

4.3.1.1 Advisories of imminent or on-going disruptions to HF, GNSS, and occurrence of radiation effects enable alternate route planning, or delayed use of polar routes. Options may include:

a) time – delayed entry into regions specified in the advisory. Radiation and some HF advisories typically have very short (minutes) lead times, whereas the majority of the HF and GNSS advisories may have hours before the threshold is reached;

b) distance – not only avoiding specified regions, but in the case of radiation, flying at a non-optimal but lower altitude for more shielding by the atmosphere. A roughly 2 100-metre (7,000-foot) decrease in altitude decreases the radiation dose by approximately 50%. Polar flights may consider planning lower latitude routes where practicable (the geomagnetic latitude where Earth's magnetic field provides an appreciable boost of shielding is about 60°).

4.3.1.2 GNSS and HF degradations do not offer many mitigation options:

a) time – wait for the disturbance to abate;

b) distance – an element of the disruption is due to the movement overhead of structures in the ionosphere. If those trajectories can be known, then potentially a mitigation strategy could be a change in course. Changing altitude has no effect;

c) other – HF can sometimes improve by using higher frequencies during HF absorption events (solar flares, solar radiation storms) or employing lower frequencies during HF depressions (ionospheric storms). Guidance is found in the remarks section of the space weather advisory.

4.3.2 OPERATOR

4.3.2.1 Operators should develop operational procedures for managing flights in areas impacted by space weather events. Procedures should include the use of risk assessment techniques to determine informed actions based on the provision of space weather advisory information. This includes flight planning tracks using forecasts and tactical nowcasts for inflight situational awareness and re-planning. The best situation is to be able to plan12-24 hours ahead, making allowances for flight reroutes, fuel, and crew schedules. Long-haul flights may be the most problematic as options are constrained by fuel, particularly if the airplane is en route when an unpredicted event occurs.

4.3.2.2 As with ANSPs, situational awareness is very important for safe and efficient flight management. Operators should work with SWXCs to familiarize themselves with the products and services provided, as well as to develop a strong working relationship.

4.3.3 AIR NAVIGATION SERVICE PROVIDERS

4.3.3.1 Situational awareness, in the broader context of managing multiple (numerous) flights, is vital in maintaining safe and efficient operations. The insidious nature of space weather impacts to critical systems necessitates a well-designed advisory that proves useful. Unlike convective weather, there is no visual clue for space weather impacts.

4.3.3.2 ANSPs are well aware of HF issues and have many years of experience working around those. GNSS uncertainties may require greater spacing among aircraft, as a function of phase of flight.

4.3.4 CIVIL AVIATION AUTHORITY

As the statuary authority regulating and overseeing all aspects of civil aviation in each country, the CAA is responsible for properly integrating space weather into the existing docket of aviation considerations. Prescribed actions, centre requirements, and other functional necessities need to be in place to address the deleterious impacts to aviation in the State's purview.

Appendix 1

MODERATE/SEVERE CATEGORY DEFINITIONS

1. GENERAL

As much as possible, these thresholds were based on established system impacts. In some areas, i.e. GNSS, there was more data to make the link between system impacts to space weather activity. In other cases, such as radiation impacts, those data were less available. Additionally, it was much more straightforward to relate GNSS signal fades to receiver loss-of-lock, as opposed to radiation dose to the risk for travellers and flight crew.

2. SPACE WEATHER AFFECTING HF COMMUNICATIONS

2.1 Aircraft cannot avoid the impacts of solar flares as the photons travel at the speed of light and the dayside ionosphere is quickly affected. There is no advance warning for operations on the sunlit side of the earth. The value of the advisory is to alert when they occur, the duration of the impact, and post-facto troubleshooting for equipment performance questions. In regards to HF degradation, MODERATE can be thought of “weak HF communications,” whereas SEVERE to be “”radio blackout or scarcely perceptible HF communications.” Use R3 (X1) (175/cycle) for MOD; R4 (X10) (8/cycle) for SEV.

2.2 Radio blackouts that result during geomagnetic storms also affect HF. Typically these occur at the latter phases of a storm, and depress the HF band, making the high end of the band unusable. Use a depression of MUF against a 30 day baseline, of 50% (SEV) and 30% (MOD).

2.3 The third type of HF radio blackout is the PCA (see next section).

3. SOLAR RADIATION STORMS

3.1 Solar radiation storms can be predicted with some skill. These inhibit HF at high latitudes (PCA), and also enhance radiation on polar and high latitude flights. To predict the intensity and spatial extent of a PCA, an internationally accepted model should be used. PCA criteria, using data from a typical 30 MHz riometer, are 2.0 dB (MOD) and 5.0 dB (SEV).

3.2 Riometers give the best local measurement of the ionosphere and HF conditions. Threshold levels are defined as; MOD, 2.0 dB; and SEV, 5.0 dB. An additional requirement is that these thresholds must be attained for 15 successive minutes. Additionally, consideration by the global centre, is if a solar radiation storm is in progress, should be taken into account in the analysis of occasionally noisy one-minute riometer data. The 15-minute interval is included so as to avoid noise spikes or momentary disruptions triggering unwanted advisories.

3.3 For the health-related impacts of solar radiation storms, the best way to monitor that environment is to measure effective dose rate. Ideally, sensors with known time and position is the optimal situation. Short of that, a modelled output, from an internationally accepted model, is sufficient. Input to the model should include neutron monitor data, magnetic field data and satellite-based proton data. The output of the model will be the sum of the GCR and solar radiation components.

3.4 The thresholds for radiation are the result of consultations with both space and health scientists. SEV is an effective dose rate of 80 micro-Sievert/hour. MOD is an effective dose rate of 30 micro-Sievert/hour. The dose rates and the location and time will be the output of an accepted radiation model. In that this manual is focused on users in commercial aviation, it follows that the altitudes at which the dose rate is computed be FL460 and below.

4. GEOMAGNETIC STORMS

4.1 Geomagnetic storms allow for the longest lead time predictions, usually on the order of a few days ahead. Impacts from geomagnetic storms are: HF – and to a lesser degree, VHF – at high latitudes; GNSS applications, primarily at high latitudes, although can occur nearer the equator. Rarely are impacts seen at middle latitudes, but do occur occasionally, e.g. Halloween Storms, 2003.

4.2 A secondary effect from geomagnetic storms is the polar cap expands, extending to lower-than-normal latitudes (lower latitude auroras attest to this). That extends the area (volume) affected by enhanced radiation. Generally speaking, where the typical boundary for heightened radiation may be 60^o geomagnetic latitude, during a geomagnetic storm that may drop down to 50^o. Airplanes on polar routes will have longer intervals aloft in areas where heightened radiation exposure occurs.

4.3 MOD threshold is Kp = 8 (100 per cycle). SEV threshold is Kp = 9 (4 per cycle).

5. IONOSPHERIC STORMS

5.1 The normal sequence of events that leads to an ionospheric storm begins with a solar eruption that brings additional enormous energy to the Earth's space environment. Usually it is a CME that causes the ionospheric storm, but not always. At times the shower of energetic protons at high latitudes during a solar radiation storm triggers the ionospheric storm near the poles. And paradoxically, equatorial ionospheric disturbances can occur without any stimulus from the Sun; these disturbances come from instabilities within the domain of the magnetosphere/ionosphere.

5.2 There are a number of ways to measure ionospheric disturbances; signal amplitude scintillation, signal phase scintillation, and TEC in a column extending through the overhead ionosphere can be measured by ground-based GNSS receivers and ionosondes can measure the depressions in MUFs. Scintillations cause signal fades and receivers lose lock on signal if the scintillations are sufficiently strong. A 20 dB fade will typically cause loss of lock by the receiver.

5.3 Amplitude scintillations are measured by specialized GNSS receivers and are given by the index S4, the normalized standard deviation in the signal strength. Phase scintillations, also from specialized receivers, are categorized by the parameter sigma-phi. It is the standard deviation in phase. Typically, S4 and sigma-phi are measured over one minute intervals.

5.4 TEC varies over the globe, the highest values typically near the geomagnetic equator. Values vary by season, time of the solar cycle, and can be heightened or diminished by eruptive solar activity. High TEC results in greater range error for single frequency users. TEC of approximately 200 TEC units occurred over the south-eastern United States during the Halloween Storms in 2003. Commercial airplanes use single frequency L1 receivers. It is often the TEC gradients that challenge and inhibit the proper function of receivers on aircraft.

5.5 Large TEC gradients and scintillations can adversely affect SATCOM at times, especially for frequencies less than 2 GHz. Similar to GNSS, some providers use L-band and, as such, are affected with data losses when the ionosphere is disturbed at thresholds defined in table 3.2 for GNSS. For systems using C, Ku, and/or Ka bands (all well above 2 GHz), space weather is not a troublesome issue. Even for L-band SATCOM systems, when compared to GNSS, the signal is much stronger and the satellites are closer to earth (LEO vs. MEO), so the susceptibility to faults is diminished by design.

5.6 Ground-based ionosondes measure characteristics of the ionosphere that impact HF. Their data allow operators to derive estimates of MUFs and identify periods during which those frequencies are depressed. Typically ionospheric depressions occur during the latter phase of a geomagnetic storm, making the high end of the HF frequency band unusable.

5.7 GNSS thresholds are:

a) S4; MOD, 0.5; SEV, 0.8 (dimensionless units);

b) Sigma-phi; MOD, 0.4; SEV, 0.7 (radians); and

c) TEC; MOD, 125 TEC units; SEV, 175 TEC units (1 TEC unit = 10^{16} electrons/m2).

5.8 MUF depressions against a 30-day median of 30% (MOD) and 50% (SEV) drive the issuance of a Space Weather Advisory.

Appendix 2

SPACE WEATHER SCIENTIFIC BACKGROUND INFORMATION

1. THE SUN – PRIME SOURCE OF SPACE WEATHER

1.1 The Sun is the primary source of the conditions commonly described as space weather. The expression "space weather" is used to designate processes occurring on the Sun, in Earth's magnetosphere, ionosphere and thermosphere, which have the potential to affect the near-Earth environment. Its emissions are continuous in nature; i.e. solar luminescence, solar wind, but also can be eruptive. The eruptive aspects consist of CME, and streams of charged particles. In addition, the periodic fast solar wind streams from coronal holes contribute, especially in the declining phase of the solar cycle. The sudden eruptions cause radio blackouts, magnetic storms, ionospheric storms, and radiation storms at Earth.

1.2 Akin to the activity that originates at the Sun, GCR – the charged particles that originate in more distant supernovae – add another ingredient to the space weather mix. Essentially, these charged particles comprise a steady drizzle of radiation at Earth. On top of this background, the Sun increases the radiation levels during radiation storms, with the sum of the two components being the full extent of the potential radiation dose received. The size of the GCR levels varies inversely with the sunspot cycle. That is, when the interplanetary environment near the Earth is laminar and steady – conditions seen near sunspot minimum – the GCR component is large due to its easier access to the near-Earth environment. At sunspot maximum, the turbulence and energetics associated with solar eruptions reduces GCR access to the vicinity of the Earth.

2. THE SUN'S ENERGY OUTPUT AND VARIABILITY

2.1 The Sun is a variable star. What that means is the aggregate of the continuous emissions and the eruptive emissions changes with time. One metric that is commonly used to track this variability is the occurrence of sunspots. Observers have been recording sunspot observations continuously for hundreds, maybe even thousands, of years. There are mentions of Chinese sunspot observations from many centuries ago and, more recently, European observations for the past 400 years. Though the underlying physics is still not well understood, it is established that sunspots come and go, on average, on an 11-year period. The magnitude and duration of individual cycles varies, but typically more eruptive events occur near the height of the cycle – solar maximum – while few are observed near solar minimum. All solar electromagnetic emissions, from radio to X-rays are also stronger during solar maximum and less intense near solar minimum.

2.2 Satellite observations garnered since the 1960s have added more measurements to describe the Sun's variability over the course of the solar cycle. X-ray emissions increase by a factor of 10; EUV by a factor of 4-5; and the solar constant – the sum of all the electromagnetic energy radiated by the Sun – increases by approximately 0.1% as the Sun evolves from its quiet to its active phases.

3. SUNSPOTS AND THE SOLAR CYCLE

3.1 The sunspot cycle and solar activity cycle are loosely synonymous, with sunspots often used as a proxy index for changing space weather conditions. This is because sunspots, by their very nature, exist due to strong local solar magnetic fields, and when these fields erupt, severe space weather can occur. While sunspots are easily seen on the Sun, other factors, such as GCR, CMEs, and increased solar wind associated with coronal holes, actually cause space weather, but in most cases are more difficult to observe from the ground and cannot be described by long historical records of observation as are sunspots.

3.2 The modern record of sunspot observations extends back roughly 400 years. Galileo and other astronomers in Europe noted these "blemishes" on the surface of the Sun, and speculated as to their origin. Over time, sunspots became the standard used to track the solar variability. Figure A2-1 shows a close up of a mature sunspot group.

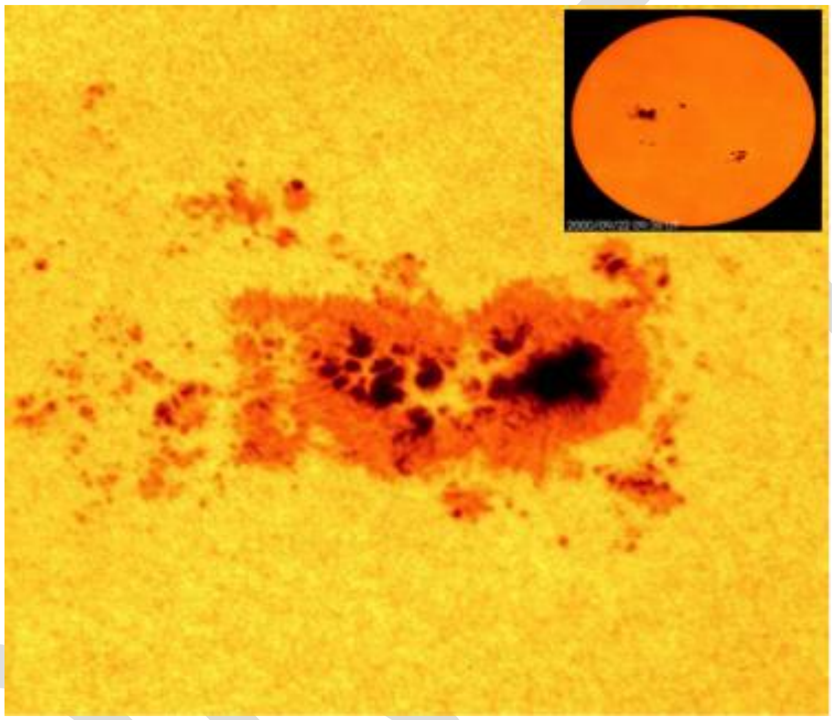


Figure A2-1. A mature sunspot group (inset: the solar disk with this sunspot group center left)

3.3 The solar activity cycle is of consequence to the aviation community as the events that affect communications, navigation, and radiation dose, vary over the 11-year solar cycle (Figure A2-2). In short, explosive solar events that affect aviation are more likely to occur, and be more severe, in the epoch near solar maximum.

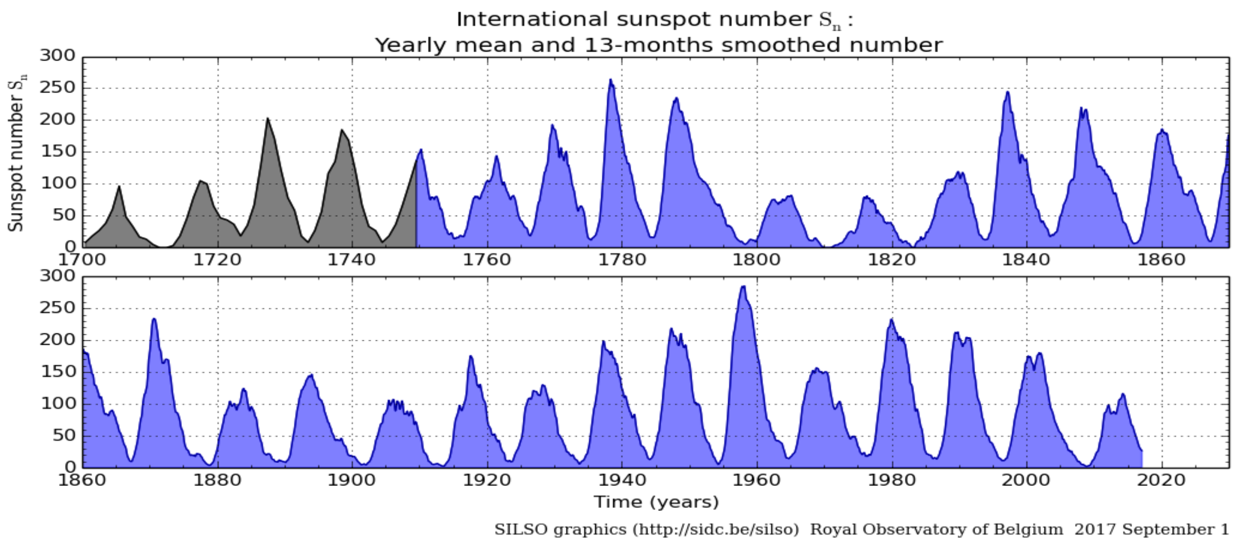


Figure A2-2. Approximately 11 year quasi-periodic variation in the sunspot number

Note. — The polarity pattern of the magnetic field reverses with each cycle. An increase of solar activity, such as solar flares and CMEs, occurs typically during the maximum sunspot period. Cycle 24 is most recent (lower right). Data with greatest uncertainty upper left (gray).

4. SOLAR WIND

4.1 The solar wind is the continuous flow away from the Sun of charged particles and magnetic field, called plasma. It is a consequence of the very high temperature of the solar corona and the resultant expansion of the plasma into space. Electrons and protons with energies of about 1 keV are the dominant constituents.

4.2 The solar wind existence was predicted by Eugene N. Parker in the 1950s who coined the term “solar wind”. This hypothesis was verified by the Soviet satellite Luna 1 in January 1959.

4.3 The solar wind carries the energy from most solar eruptions that affect the near-Earth environment. The sole exception, solar flare photons – light and X-rays– carry the energy released in solar flares. Even in the absence of an eruption, the constant flow of plasma fuels Earth’s magnetic – geomagnetic – field.

4.4 The solar wind may be fast and energetic if an eruption occurs, or can gradually increase due to a coronal hole structure, which allows unimpeded high-speed solar wind to escape from the corona. As seen from the Earth, the Sun rotates on approximately a 27-day period, so well-established coronal hole structures that persist for several months will swing by Earth on schedule, roughly every 27 days when they exist.

4.5 Clearly, knowledge of the conditions existing in the solar wind, (e.g. its speed, density, temperature, magnetic field) is necessary to specify and predict space weather. Understanding normal values for solar wind properties enables realization of typical or atypical conditions.

4.6 Typical values for density are 5 cm-3, and magnetic field, 7 nT. The average speed of the solar wind is approximately 450 km/s, roughly one million miles per hour. In round numbers, that means it takes about four days for a parcel of plasma to travel from the Sun to Earth, a distance of 93 million miles. For severe space weather events, the solar wind speed may be three, four, even five times faster. The latter was observed during the series of extreme space weather events that occurred in October of 2003. The very fast energetic solar wind causes the geomagnetic field to be extremely disturbed.

5. SOLAR ERUPTIVE ACTIVITY

5.1 Most solar eruptions originate in areas that have strong magnetic fields. Almost always with sunspots, these areas are commonly called active regions. Uniquely, the National Oceanic and Atmospheric Administration (NOAA) SWPC in the United States designates, i.e. numbers, active regions for common reference by the space weather community.

5.2 Active regions are numerous and common during solar maximum and scarce during solar minimum. Forecasters scrutinize each active region to discern its potential for eruption. The factors analysed are: the size of the region, its recent dynamic or static nature, the strength and orientation of its magnetic fields, and its recent eruptive activity history.

5.3 Flares and CMEs are two of the major types of solar eruptions. They may occur independently or at the same time. Solar flares have been recognized for more than 100 years, as they can be seen emitting in white light from the ground on rare occasions. Hydrogen-Alpha (656.3 nm wavelength) filter-equipped ground-based telescopes have been used to easily observe flares in recent years.

5.4 Flares are characterized by a very bright flash-phase, which may last for a few minutes, followed by a period of 30-60 minute decay. Flares can emit at all frequencies across the electromagnetic emission spectrum, from gamma rays to radio.

5.5 CMEs, in contrast to solar flares, are difficult to detect, not particularly bright, and may take hours to fully leave the Sun. CMEs literally are an eruption of a large volume of the solar outer atmosphere, the corona, and prior to the satellite era, they were very difficult to observe.

5.6 The energy released in a large solar flare is on par with that released in a CME, but CMEs are far more effective in perturbing the Earth's magnetic field and are known to cause the strongest magnetic storms, due to the strong magnetic fields encapsulated in CMEs.

5.7 A typical travel time for a CME from the Sun to Earth may range from less than one day, to more than four days. The travel time of the electromagnetic emission produced during flares, by comparison travels at the speed of light – eight minutes Sun to Earth – instantaneously affecting the dayside of Earth. Forewarning of its arrival depends on predicting when a flare will occur.

5.8 The frequency of solar flares and CMEs tracks with the solar cycle. Flare rates on the order of 25/day may occur during the maximum phase of the solar cycle, while at solar minimum it may take six months or more for 25 flares to occur. CME frequency varies from about 5/day near solar maximum, to one per week or longer, at solar minimum. However, many CMEs observed lifting off the Sun are not Earth-directed and are therefore of no consequence to near-Earth technology.

6. MAGNETOSPHERE

6.1 Earth's magnetic field, the volume of space that surrounds Earth, extends away from it as a dipole, and forms a cocoon for the planet in the flow of the solar wind. The structure – the cocoon – is called the magnetosphere. If Earth did not have a magnetic field, the solar wind would blow past unimpeded and only be affected by the mass of Earth and its atmosphere, as it adjusted downstream to the impediment it just experienced.

6.2 The magnetosphere typically extends towards the Sun about 10 Earth radii on the dayside and stretches away from the Sun many times more than that on the night side. The shape is similar to a comet tail, it being extended during strong solar wind conditions and less so during more quiet times. On its flanks the magnetosphere extends outwards roughly 20 Earth radii in the dawn and dusk sectors.

6.3 The magnetosphere deflects most of the energy carried by the solar wind while making a fraction of it available to be absorbed by the near-Earth system. When the Sun is active and CMEs interact with Earth, the additional energy disrupts the magnetosphere resulting in a magnetic storm. Then, over time the magnetosphere adjusts, through various processes, and once more returns to normal.

6.4 The most visible manifestation of the energy being absorbed from the solar wind is the aurora, both in the Northern and Southern Hemispheres. Although the auroral glow originates from the ionosphere (see next section), it is a product of the close coupling that exists between the magnetosphere and the ionosphere. Simply put, the more energy in the solar wind, the brighter and more widespread the aurora glow becomes.

7. IONOSPHERE

7.1 Nearer Earth is another region called the ionosphere. The ionosphere is a shell of weakly ionized plasma, where electrons and ions exist embedded in the neutral atmosphere. The ionosphere begins at roughly 60 km in altitude, and extends to many Earth radii at the topside. Figure A2-3 depicts ionospheric electron density distributions at sunspot maximum for day and night times.

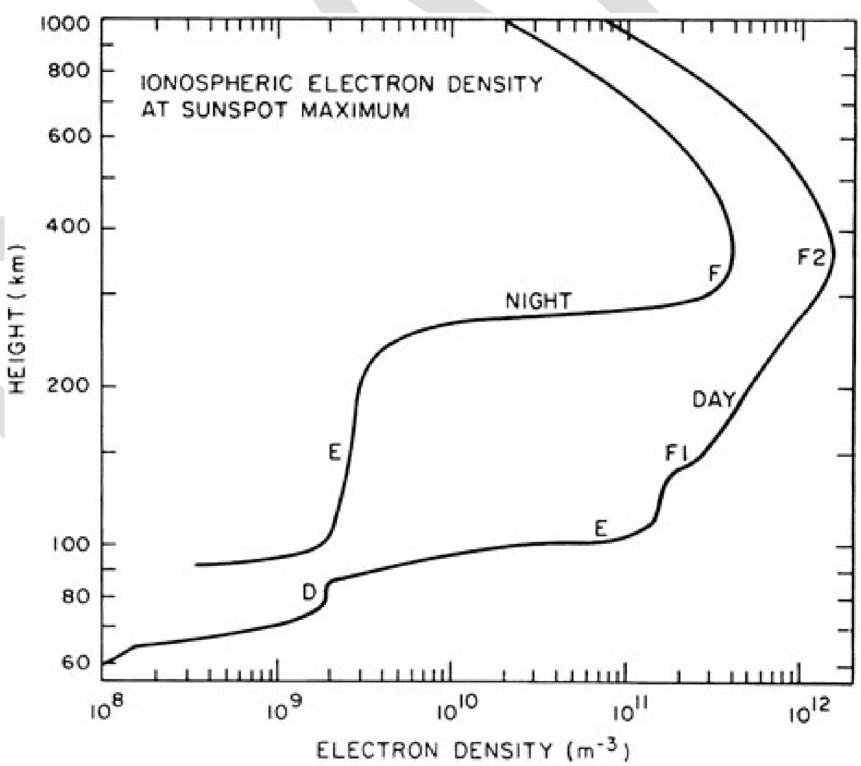


Figure A2-3. Day and night electron density distributions, from 60 to 1,000 km.

7.2 EUV solar emissions create the ionosphere by ionizing the neutral atmosphere. The electrons and ions created by this process then engage in chemical reactions that progress faster in the lower ionosphere, such as the D-Region, than higher up, in the F-Region, the most important ionospheric region. The ionosphere changes significantly from day to night, because when the Sun sets, the slower F-Region chemical processes together with other dynamic processes allows some of the ionization to remain until the new day brings the solar EUV once again. The F-Region of the ionosphere is important because it reflects short-wave radio around the curvature of Earth.

7.3 Below about 90 km some radio energy is lost through the interaction of free electrons and the atmosphere at that height. The amount of energy lost or absorbed increases as the radio wave frequency decreases. Thus the higher the HF radio frequency used, the less it is absorbed.

7.4 It is noted that ionospheric behaviour differs by latitude. At high latitudes, magnetospheric effects are dominant, while neutral atmosphere dynamics dominate low latitudes.

7.5 The ionosphere poses problems for trans-ionospheric propagation, i.e. GNSS, satellite communications, because its waves and density irregularities can distort and damage the information content of transmissions through it. However, the ionosphere is necessary for HF propagation. Therefore, it may be an obstacle or an aid, depending on the application.

7.6 The important point is that the energy that comes from the Sun in the solar wind makes its way to the ionosphere where it alters the ambient conditions either abruptly (storms) or gradually (diurnal variability). This variability may impact HF and GNSS-based activities.

8. GALACTIC COSMIC RADIATION

8.1 Galactic Cosmic Radiation, more commonly known as GCR, is a consequence of distant supernovae raining charged particles – heavy ions, protons, and electrons – onto the inner heliosphere, where the GCR have access to Earth. The abundance of GCR is a function of the solar cycle. When the solar wind flow is turbulent and strong, around solar maximum, the GCR flux is inhibited and therefore low. At solar minimum, the GCR flux increases as a function of energy.

8.2 GCRs are atomic nuclei from which all electrons have been stripped. The energy spectrum goes up to very high energies, i.e. 3×10^{20} eV. The spectrum includes the relevant energy that impacts commercial aviation altitudes. That flux is roughly twice at solar minimum what it is at solar maximum.

8.3 When high energy GCR enter Earth's atmosphere, they create a cascade of interactions resulting in a range of secondary particles – including neutrons – that make their way to Earth's surface. The neutrons are detected by ground-based neutron monitors and are indicative of high-energy particles at high altitudes. These neutrons reflect the changing radiation environment experienced at airline altitudes, and thus are a space weather issue for aviation.

Appendix 3

GLOSSARY AND EXPLANATION OF TERMS

1. GLOSSARY

A

ABV	Above
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
ATFM	Air Traffic Flow Management
AIS	Aeronautical Information Service
Annex 3	Meteorological Service for International Air Navigation
ANP	Actual Navigation Performance
ANSP	Air Navigation Service Provider

C

C-band	4-8 GHz frequency range of radio spectrum
CAA	Civil Aviation Authority
CME	Coronal Mass Ejection
CPDLC	Controller-Pilot Data Link Communications

E

EQN	Equatorial Latitudes Northern Hemisphere
EQS	Equatorial Latitudes Southern Hemisphere
EUV	Extreme Ultraviolet

F

FAR	False Alarm Rate
FL	Flight Level

G

GCR	Galactic Cosmic Rays
GNSS	Global Navigation Satellite System
GPS	Global Positioning System (United States)

H

HF	High Frequency (3-30 MHz)
HNH	High Latitudes Northern Hemisphere
HSH	High Latitudes Southern Hemisphere

I

ICAO	International Civil Aviation Organization
ICRP	International Commission on Radiological Protection

K

Ka-band	26.5 – 40.0 GHz frequency range of the radio spectrum

Kp	A 3 hourly planetary index of geomagnetic activity
Ku-band	12 – 18 GHz frequency range of the radio spectrum

L

L1	GPS frequency at 1575 MHz
L-band	1-2 GHz frequency range of radio spectrum
LEO	Low Earth Orbit

M

MEO	Medium Earth Orbit
MNH	Middle Latitudes Northern Hemisphere
MOD	Moderate
MSH	Middle Latitudes Southern Hemisphere
MUF	Maximum Usable Frequency

N

NCRP	National Council on Radiation Protection and Measurements (United States)
NOAA	National Oceanic and Atmospheric Administration (United States)
nT	nanoTesla – Unit of magnetic field measurement

P

PCA	Polar Cap Absorption
POD	Probability of Detection

R

RHCP	Right Hand Circular Polarization
RNP	Required Navigation Performance

S

S-band	2-4 GHz frequency range of radio spectrum
SARP	Standards and Recommended Practices
SATCOM	Satellite Communication
SEV	Severe
SWPC	Space Weather Prediction Center (United States)
SWXC	Space Weather Centres

T

TEC	Total Electron Content

U

UHF	Ultra High Frequency (300 – 3000 MHz)

V

VHF	Very High Frequency (30 – 300 MHz)

W

WMO	World Meteorological Organization

2. EXPLANATION OF TERMS

***Effective dose*.** A quantity defined by the ICRP that accounts for the type of incoming radiation as well as the nature of the material or organ being irradiated.

***Ionosphere**.* The region of the Earth's upper atmosphere containing free electrons and ions, extending from about 60 to 1,000 km above Earth's surface.

Magnetic latitude. A coordinate system linked to the location of the magnetic poles rather than the geographic poles. It is most relevant for space weather effects as charged particles are modulated by magnetic fields and are insensitive to geographic locations.

***Magnetosphere*.** The volume of space near the Earth, influenced by the interaction between Earth's magnetic field and the solar wind.

***Scintillations*.** In the context of this document, scintillations refer to the variations in amplitude and phase of a GNSS signal located in L-band (1-2 GHz) of the radio spectrum, due to effects from diffraction and refraction.

***Solar maximum*.** A few year period, centered around the point of the 11-year solar cycle, during which solar eruptive activity is at its peak.

Thermosphere. The region of the Earth's upper atmosphere with air density so low that it is commonly referred to as outer space. It extends from roughly 90 to between 500 and 1,000 km.