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Space environment (natural and artificial) — Space weather information for use in space systems operations

Environnement spatial (naturel et artificiel) — Informations météorologiques spatiales pour utilisation dans les opérations des systèmes spatiaux

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document describes the dynamic variability of the environment, i.e. space weather, and identifies the tools and parameters needed for space systems operations. This document is important for satellite operators who are not be familiar with space weather. For example, when Satellite operators arrive on shift, they are often briefed about terrestrial weather, geomagnetic storms, and collision reports. This provides insight into any possible collisions that their system can have with debris or other satellites. In addition, others who participate in space systems operations can benefit from this document. For example, designers, manufacturers, and launchers of space systems require real-time, operational space weather parameters that can be measured, monitored, or built into automated systems. Users of these systems include developers of software systems that provide LEO satellite orbit determination, radio communication availability for scintillation events (GEO-to-ground L- and UHF-bands), GPS uncertainties, and the radiation environment from ground-to-space for commercial space tourism. These groups require recent historical data, current epoch specification, and forecast of space weather phenomena for their automated or manual systems. National government agencies often rely on space weather data provided by their national organizations, such as those represented in the International Space Environment Service (ISES) group of 14 national agencies, and this document identifies key descriptors provided by those agencies.

This document identifies the phenomena of space weather as a dynamic component of the space environment that affects the technology of space systems. Annexes A and B describe expanded material including guidelines on how to use the document, how to obtain specific space weather parameters, and short but detailed descriptions of parameters. Annexes A and B enable easy updates for this document because new advances in scientific and engineering understanding provide new tools for characterizing the domain of space weather. Table 1 gives an overview of existing ISO documents related to the space environment.

Table 1 — Terrestrial and lunar environment documents

	LEO	PEO	MEO	GEO	>GEO
Testing/analysis/ framework	ISO 15856, ISO 17851, ISO 21980, ISO/TS 22295, (AUL)	ISO 15856, ISO 17851, ISO 21980, ISO/TS 22295, (AUL)	ISO 15856, ISO 17851, ISO/TS 22295, (AUL)	ISO 15856, ISO 17851, ISO/TS 22295, (AUL)	ISO 15856, ISO 17851, (AUL)
Cosmic rays	ISO 15390, ISO 17520, ISO/TR 23689	ISO 15390, ISO 17520, ISO/TR 23689	ISO 15390, ISO 17520, ISO/TR 23689	ISO 15390, ISO 17520, ISO/TR 23689	ISO 15390, ISO 17520, ISO/TR 23689
Solar photons	ISO 21348, ISO/TR 23689	ISO 21348, ISO/TR 23689	ISO 21348, ISO/TR 23689	ISO 21348, ISO/TR 23689	ISO 21348, ISO/TR 23689
Solar particles	ISO 16698, ISO 17520, ISO/TR 18147, (solar wind), ISO/TR 23689	ISO 16698, ISO 17520, ISO/TR 18147, (solar wind), ISO/TR 23689	ISO 16698, ISO 17520, ISO/TR 18147, (solar wind), ISO/TR 23689	ISO 12208, ISO 16698, ISO 17520, ISO/TR 18147, (solar wind), ISO/TR 23689	ISO 16698, ISO 17520, ISO/TR 18147, (solar wind), ISO/TR 23689
Solar fields	ISO 16689, (solar wind), ISO/TR 23689	ISO 16689, (solar wind), ISO/TR 23689	ISO 16689, (solar wind), ISO/TR 23689	ISO 16689, (solar wind), ISO/TR 23689	ISO 16689, (solar wind), ISO/TR 23689
Main magnetic field	ISO 16695, ISO 16698, ISO/TR 23689	ISO 16695, ISO 16698, ISO/TR 23689	ISO 16695, ISO 16698, ISO/TR 23689	ISO 16695, ISO 16698, ISO/TR 23689	ISO 16695, ISO 16698, ISO/TR 23689

Key

AUL application utility level

IRENE International Radiation Environment Near Earth

AO atomic oxygen

Table 1 *(continued)*

	LEO	PEO	MEO	GEO	>GEO
Magnetosphere	ISO 16695, ISO 16698, ISO 19923, ISO/TR 23689, (PC-index)	ISO 16695, ISO 16698, ISO 19923, ISO/TR 23689	ISO 16695, ISO 16698, ISO 22009, ISO 19923, ISO/TR 23689	ISO 12208, ISO 16695, ISO 16698, ISO 22009, ISO 19923, ISO/TR 23689	ISO 16695, ISO 16698, ISO 22009, ISO 19923, ISO/TR 23689
Radiation belts	ISO 17761, ISO 17520, ISO/TS 21979, (IRENE, internal charge), ISO/TR 23689	ISO 17761, ISO 17520, ISO/TS 21979, (IRENE, internal charge), ISO/TR 23689	ISO 17520, ISO/TS 21979, (IRENE, internal charge), ISO/TR 23689	ISO 17520, ISO/TS 21979, (IRENE, internal charge), ISO/TR 23689	ISO 17520, ISO/TS 21979, (IRENE, internal charge), ISO/TR 23689
Plasmasphere	ISO 16457, ISO/TR 23689	ISO 16457, ISO 19923, ISO/TR 23689	ISO 16457, ISO 19923, ISO/TR 23689	ISO 16457, ISO 19923, ISO/TR 23689	ISO 16457, ISO 19923, ISO/TR 23689
Ionosphere	ISO 16457, ISO 16698, ISO/TR 23689	ISO 16457, ISO 16698, ISO/TR 23689	(topside)		
Neutral atmosphere	ISO 14222, ISO/TR 11225, ISO 16698, (AO, satellite drag), ISO/TR 23689	ISO 14222, ISO/TR 11225, ISO 16698, (AO, satellite drag), ISO/TR 23689	(He, H)	(He, H)	(He, H)
Micrometeoroids	ISO 14200	ISO 14200	ISO 14200	ISO 14200	ISO 14200
Debris	ISO 14200, (radiation debris)	ISO 14200, (radiation debris)	ISO 14200	ISO 14200	ISO 14200
Lunar					ISO 10788

Key

AUL application utility level

IRENE International Radiation Environment Near Earth

AO atomic oxygen

Space environment (natural and artificial) — Space weather information for use in space systems operations

1 Scope

This document contains internationally accepted descriptions of the main phenomena of space weather, including its sources and effects upon space systems.

This document is applicable for a variety of engineering and scientific domains. It is applicable to space system operations include ground-based, on-orbit, and deep space automated satellite operations. It can be applied by developers of software systems for space systems, designers of space systems, and launchers of space systems.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
aerodynamic drag
force derived from the kinetic energy of an orbiting object encountering an *atmosphere* (3.2) as a result of the work done against the object by the atmosphere

3.2
atmosphere
layer of gases surrounding a planet, moon, asteroid, or comet with species composition and temperature often described by altitude

3.3
deep space
region of space beyond the Earth's *atmosphere* (3.2) and magnetosphere and especially beyond the Moon's orbit

3.4
geomagnetically induced current
GIC
induced magnetic field variation caused by geomagnetic disturbances such as CMEs upon the Earth's magnetic field

3.5
geostationary Earth orbit
Earth orbit having zero inclination, zero eccentricity, and an orbital period equal to the Earth's sidereal rotation period

Note 1 to entry: This orbit allows a satellite to remain continuously over approximately the same point on the Earth's surface.

[SOURCE: ISO 24113:2023, 3.11, modified — The abbreviated term “GEO” has been removed; note 1 to entry has been added.]

3.6
geosynchronous Earth orbit
orbit with an orbital period equal to the Earth’s sidereal rotation period

3.7
heliosphere
region surrounding the Sun where the emanating solar wind dominates the interstellar medium

Note 1 to entry: It is the magnetosphere and outermost atmospheric layer of the Sun, taking the shape of a vast, bubble-like region of space, i.e. a plasma cavity formed by the Sun in the surrounding interstellar medium where the strength of the solar, interplanetary magnetic field is greater than that of the local galactic magnetic field.

[SOURCE: ISO 15856:2010, 3.1.8, modified — The word "emanating" has been added; the original note 1 to entry has been replaced by a new one.]

3.8
low Earth orbit
Earth orbit with an apogee altitude that does not exceed 2 000 km

3.9
MEO
medium Earth orbit
mid-Earth’s orbit
Earth orbit with apogee an altitude that is greater than 2 000 km but does not exceed 36 000 km

3.10
space environment
surrounding, aggregated conditions and influences of photons, particles, and fields outside of planetary *atmospheres* (3.2)

3.11
space weather
dynamic variability in the transfer of energy via photons, particles, and fields from the Galaxy and Sun to the *heliosphere* (3.7), including planetary bodies, other objects, and their environs

3.12
suborbital flight
flight at an altitude and velocity that would result in a trajectory incapable of circling the Earth at least once

3.13
sunspot number
R
daily index of sunspot activity defined as k (10 g + s) where s is the number of individual spots, g is the number of sunspot groups, and k is an observatory factor

[SOURCE: ISO 16457:2022, 3.6, modified — Notes to entry have been removed.]

4 Space weather

4.1 Origin of space weather concept

The space weather concept originated in the mid-1990’s within the space physics community and their attempt to understand the temporal, non-climatological variations in the space environment along with the effects at Earth.

4.2 Concept of space weather

Space weather primarily includes energetic processes that originate on the Sun but can include energy transfer from galactic sources outside the heliosphere. Space weather can affect natural environments and human technology starting at and below the surface of the Earth through the outer reaches of the Earth's magnetosphere. It can also affect the environments around other bodies in the solar system.

4.3 Space weather factors

Solar wind plasma, cosmic rays, solar energetic particles and solar electromagnetic and particle ionizing radiation are the main space weather factors. All space factors either originate from the Sun or are modulated by solar activity. Variations of space weather factors influence interplanetary space and planetary (terrestrial) environments.

4.4 Space weather impacts on the near-Earth space

Space weather factors influence space and terrestrial environments. The main space weather manifestations occur following solar flares and coronal mass ejections that produce magnetic storms and magnetospheric substorms, solar proton events, ionospheric disturbances, changes in thermosphere densities, variability in the radiation environment at aircraft altitudes, as well as variations of ground currents at and below the Earth's surface.

4.5 Space weather domains

Solar-terrestrial coupling plays the key role in the development of space weather events. Physical conditions in the Sun, in the heliosphere and in the Earth's magnetosphere are susceptible to space weather factors and impact the terrestrial environment. In various space domains different processes are coupled with solar irradiation, both electromagnetic and particulate, and can influence space weather factors. Solar-terrestrial coupling is produced by the chain of the interconnections between processes in the Sun's environment, in the heliosphere and in near-Earth space. Measurements of the physical conditions in different regions of space can be used to estimate the intensity of space weather factors and their possible impact on planetary environments, including the Earth.

4.6 Space weather information

Space weather information is obtained from satellite, air, and ground-based measurements as well as from space weather models, the combination of which can be used to determine the state of the space environment. Information is collected by governmental, academic, and industrial space weather data centres and processed by operational IT-services that can give a reliable release of space weather conditions.

4.7 Space weather operational models

The models of physical parameters for the space environment depend on measurements and often work automatically in real-time mode. Operational models typically originate from scientific models that are modified to run automatically using observational data input. The process of conversion of scientific models to operational ones is called R2O (research to operations). Operational models testing is called V&M (validation and metrics). The process of using the results of operational models to understand shortcomings for further scientific research is called O2R (operations to research).

4.8 Space weather time frames

Space weather information in different time frames can be used to validate space weather models (e.g. historical data), for verification diagnostics of current space environment conditions (current data), and for space weather predictions (forecast data).

5 Time frames for space weather information

5.1 Historical

A historical time frame for space weather information starts at the current epoch and continues backwards in time.

5.2 Current epoch (Nowcast)

The current epoch for space weather information is the present moment in time and whose interval is user-defined; for example, the current epoch can be the present second, minute, hour, or day.

5.3 Forecast

A forecast time frame for space weather information starts at the current epoch and continues forwards in time. The forecast horizon is the time period when forecast can be adequately used as a decision-aid.

6 Galactic cosmic rays

Galactic cosmic rays (GCRs) are high-energy charged particles penetrating the heliosphere from local interstellar space (ISO 15390). They are comprised of high-energy charged particles consisting of approximately H, He, and small contribution of heavier ions[34] contributing to background radiation and event radiation levels. The ISO 15390 model is used for GCR flux calculations. Originating from outside of the solar system, the GCR flux within the heliosphere is modulated inversely with the solar cycle, i.e. there are higher particle fluxes during solar minimum. Galactic cosmic rays give radiation impact on hardware and on biological objects in space. They are also responsible for single-event effects on electronic devices. Considering GCR effects are especially important for long-term space missions.

7 Solar environment within the heliosphere

7.1 Solar dynamo

7.1.1 Phenomenology

The solar dynamo is the source of the Sun's magnetic field. The solar dynamo refers to the physical process whereby the Sun's magnetic field is created. It contains the elements of rotation of the Sun and the existence of highly ionized plasma in a region below the surface of the Sun above the core and radiative zone, and below the convective zone, called the tachocline. Here, solar temperatures in the range of 2 million K are cool enough for ions to form and, as they move as a result of the Sun's rotation, act in a way such that their kinetic energy is converted into electromagnetic energy.

7.2 Solar environment

7.2.1 Phenomenology

7.2.1.1 Structure of Sun

The internal structure of the Sun is comprised of the core where thermonuclear reactions occur, the radiative zone, the tachocline interface layer, and the convective zone. The photosphere is the visible surface of the Sun where sunspots, faculae, and granules can be observed. The surface of the Sun is also considered the photosphere at a mean altitude of 0 km or 1,0 solar radii.

7.2.1.2 Rotation

The Sun's average rotation period is 27,75 days from Earth's perspective. The rotation period varies with the latitude ranging from 30 days at the poles (90°) to 24,47 days at the equator (0°) also known as the sidereal period.

7.2.1.3 Magnetic fields

The Sun's magnetic dipole reverses and returns to the same polarity approximately every 22 years and is known as the solar magnetic cycle. At the beginning of each 11-year half cycle of the magnetic dipole reversal, new sunspots begin forming in a band between 25 and 30 degrees north and south latitude; they then progress towards the equator and this process is known as the solar sunspot cycle.

7.2.1.4 Heliosphere

The furthest extent of the Sun's magnetic field out into the local galactic medium, whose border is defined as that region where the Sun's magnetic field strength equals the local galactic magnetic field strength, also called the heliopause. Inside that bounded region the Sun's particles, photons, magnetic fields (gravitational and electromagnetic), dominate all energy transfer processes while outside that region the Galaxy dominates. All solar-system planets reside within the heliosphere.

7.2.1.5 The photosphere

This is the lower layer of the Sun's atmosphere, that is about 100 km to 300 km thick. Temperature in this layer varies from 8 000 K to 4 000 K outside. The Sun's visible radiation is formed here. The photosphere provides the most part of the star's radiation.

7.2.1.6 The chromosphere

This is the region of the Sun's atmosphere above the photosphere and below the transition region, which exhibits temperatures between 4 000 K to 8 000 K.

7.2.1.7 The transition region

This is the region of the Sun's atmosphere above the chromosphere and below the corona, which exhibits temperatures between 8 000 K to 500 000 K.

7.2.1.8 The corona

This is the region of the Sun's atmosphere above the transition region and has temperatures starting at 500 000 K.

7.2.1.9 Solar flares

An explosive release of magnetic energy manifested as a solar atmosphere phenomenon and observed as a sudden brightening in the electromagnetic radiation from the hard X-rays through far ultra-violet wavelengths.

Solar flares are classified into two types of events using soft X-ray duration and other characteristics. One type is an impulsive flare whose characteristics are short duration (minutes to an hour), an impulsive time variation in the hard X-rays, and formed from a simple compact loop structure as observed in soft X-rays. The other type is a long duration event (LDE), which shows a large-size or complex structure in the soft X-rays and a gradual time variation in hard X-rays (hours).

Solar flares can be sources of the solar energetic particles that can reach the Earth environment and produce so-called solar particle events, i.e. abrupt enhancements of energetic particle fluxes, mostly protons, in the energy range about 1 MeV to 10 GeV (7.5.1).

7.2.1.10 Coronal mass ejections

A coronal mass ejection (CME) is an explosive release of charged particles into the ambient solar wind; the particles were formerly captured in coronal loops in the solar atmosphere and that are released a result of magnetic shearing process in flaring regions. Solar flares usually occur on solar magnetic field loops while CMEs are the release of charged particles from ruptured magnetic field loops. The transient ejecta from the Sun expands as it travels out from the Sun, initially radially, on the curved interplanetary magnetic field lines. Coronal mass ejection material is also known as magnetic cloud or flux rope ejecta.

7.2.1.11 Coronal holes

Regions that are observed in XUV and EUV solar images as dark areas are manifestations of open magnetic field lines extending outwards from the Sun into the interplanetary medium. These open field lines enable the escape of highly energetic particles, especially electrons, and that are associated with high-speed streams (HSS).

7.2.1.12 Solar wind

A non-uniform supersonic stream of charged particles, mostly electrons and protons, ejected from several source regions on the Sun, including coronal holes, boundaries with regions of magnetic activity, and ejecta during solar flare events. The solar wind velocity ranges from 300 km/s to over 2 000 km/s, depending upon the solar source of the material in the solar wind. The solar wind plasma consists of electrons and protons that are constrained to follow the interplanetary magnetic field (IMF) emanating from the Sun. The plasma is usually inhomogeneous and can contain magnetic field properties different from interplanetary space.

7.2.2 Effects

The Sun's magnetic field created by the solar dynamo is the source of small-scale phenomena such as sunspots, flares, and coronal mass ejections as well as large-scale phenomena such as the interplanetary magnetic field that extends throughout the heliosphere and acts as a guide for charged particles moving out through and into the heliosphere. At Earth, sunspots have the effect of diminishing the TSI. Flare short wavelength photons arriving at Earth can cause ionization in the ionosphere and heating of the neutral thermosphere. Solar energetic particles give rise to significant intensification of ionizing radiation during solar proton events.

Coronal mass ejection material upon arrival at Earth can cause geomagnetic storms as the charged particles in the magnetic cloud or flux rope get injected onto Earth's magnetospheric field lines, which can direct particles inwards towards geosynchronous Earth orbit and then all the way down to the auroral zones at the top of the atmosphere Geomagnetic storms can be also caused by the fast solar wind streams originating from the coronal holes, which are dark large regions on the Sun. Strong magnetic field variations are responsible for particle acceleration. The addition of charged particles can severely disrupt the Earth's electrical field, even in subsurface conducting layers, to cause power surges in terrestrial power transmission lines. These highly energetic events can cause effects on Earth such as radio communication loss, power grid failure, satellite surface charging, increased satellite drag, and even particle precipitation that enhances the radiation environment at commercial aviation altitudes. Wave-particle resonant interaction can accelerate electrons up to relativistic energies and produce satellite deep dielectric charging.

7.3 Sunspots

7.3.1 Phenomenology

Sunspots are regions of cold and tenuous plasma on the solar surface that appear dark. These regions are clearly visible on the surface, or photosphere, of the Sun that evolve through time with expansion and breakup stages. Sunspots contain strong magnetic fields emanating from the interior, or convective zone, of the Sun and often form in groups or pairs with one spot having a negative polarity and the other one having a positive polarity.

7.3.2 History of discovery, long-term record

Records of sunspot observations go back as far as 3 000 years ago in China. The first mentions of sunspots in western culture occurred in Greece around 300 BC. Galileo Galilei began to study and record the spots in 1610 with the first astronomical telescope.

7.3.3 Variability

The number of sunspots grows and reduces in concert with the strength of the Sun's magnetic field half cycle. During the 22-year Hale full cycle the overall solar magnetic field makes one complete polarity reversal, where the north pole has one polarity at the beginning of a cycle, has the opposite polarity at the mid cycle of approximately 11 years and regains the original polarity at the end of the cycle. The approximate 11-year half Hale cycle defines the sunspot solar cycle whereby the number of sunspots visible on the solar disk at the beginning of a sunspot solar cycle are zero; the number of sunspots rapidly rises to a maximum count at the sunspot cycle maximum, and the number slowly declines back to zero at sunspot cycle minimum.

The strong localized magnetic fields emanating from the convective zone vary in strength and duration, manifest as sunspots on the photosphere, and are coincident with active bright regions in higher solar atmosphere layers, include coronal loops. At the start of a solar sunspot cycle these strong magnetic fields manifest at solar mid latitudes (north and south) and, during the cycle, appear at more equatorial latitudes until solar minimum is reached, where they disappear entirely.

7.3.4 Effects

Sunspots consist of an absence of photons on the solar visible surface, or photosphere, and have the effect of reducing the total solar irradiance (TSI) (ISO 21348), sometimes inappropriately called the solar constant. A single large sunspot moving across the solar disk as it is fixed in the solar rotational coordinate system can become up to a 1 % reduction of the TSI when the sunspot is near disk centre.

Although individual sunspots can reduce the total radiative output of the Sun, they are a proxy (ISO 21348) for the overall strength of energy output from the Sun during a solar sunspot cycle. The sunspots are but one aspect of the total energy output, whose source is the increased magnetic field strength. That increased magnetic field strength translates into increased magnetic energy deposited into high atmosphere layers of the Sun, which can then become bright active regions, flares, and coronal mass ejections with up to orders of magnitude more photons being created in the ultraviolet, far ultraviolet, extreme ultraviolet, soft X-ray, and X-ray portions of the radiative electromagnetic spectrum (ISO 21348).

7.4 Solar shorter wavelength electromagnetic radiation

7.4.1 Phenomenology

The solar electromagnetic radiation spans the entire spectrum from gamma-rays to radio wavelengths as blackbody radiation (ISO 21348). Solar photons travel at the speed of light from the Sun to all parts of the solar system, the heliosphere, and out into the Galaxy. Depending upon their wavelength, the photons can cause larger or smaller transfers of energy to other bodies and objects in the solar system.

Solar electromagnetic radiation is a manifestation of all permitted atomic energy level transitions, where the photons are primarily created in solar surface and atmosphere phenomena. The more magnetic energy is injected from below the solar surface, through the surface, and into the atmosphere, the more energy is available for transitions of ions and electrons from one energy state to another. The discrete energy transition relaxations from one atomic energy level to another account for the total of all photons released across all wavelengths. Shorter wavelength electromagnetic radiation originates from the photospheric surface through all solar atmosphere layers.

Shorter wavelength electromagnetic radiation ranges from the gamma-rays to ultraviolet wavelengths.

7.4.2 Ranges of electromagnetic radiation with the shortest wavelength

7.4.2.1 X-rays (0,001 nm to 0,1 nm)

Hard X-ray irradiances are defined as the wavelength range of $(0{,}001 \leq \lambda < 0{,}1)$ nm and come from the solar corona. See ISO 21348:2007, 6.4.1.

7.4.2.2 Soft X-rays or XUV (0,1 nm to 10 nm)

Usually associated with solar coronal phenomena, flares, million-degree temperatures, and atomic dissociation, the corona extends from about 21 000 km to 1 400 000 km above the photosphere. X-ray flares are responsible for enhancements in the D and E regions of the Earth's ionosphere as well as heating below 150 km in the terrestrial neutral atmosphere. See ISO 21348:2007, 6.4.2 and ISO 14222:2022, B.2.2.1.

7.4.2.3 Extreme ultraviolet or EUV (10 nm to 121 nm)

EUV has emission lines that come from the upper chromosphere (near-coronal temperatures), transition region, and lower corona. This spectral band is responsible for ionization and heating in the E and F regions of the terrestrial ionosphere as well as heating above 150 km in the terrestrial neutral atmosphere. See ISO 21348:2007, 6.5.4 and ISO 14222:2022, B.2.2.2.

7.4.2.4 Far ultraviolet or FUV (122 nm to 200 nm)

FUV has emission lines that come from the photosphere. This spectral band is responsible for molecular dissociation and heating in the lower terrestrial thermosphere. See ISO 21348:2007, 6.5.5.

7.4.2.5 Ultraviolet or UV (200 nm to 400 nm)

UV has emission lines that come from the photosphere. This spectral band is responsible for molecular dissociation and heating in the lower terrestrial mesosphere and stratosphere. See ISO 21348:2007, 6.5.1 and ISO 14222:2022, B.2.2.3.

7.4.3 Effects

Shorter (higher energy) wavelength from the ultraviolet to the gamma-ray part of the spectrum can cause molecular dissociation and atomic ionization.

7.5 Solar longer wavelength electromagnetic radiation

7.5.1 Phenomenology

Longer wavelength electromagnetic radiation originates from the photospheric surface through all solar atmosphere layers. It ranges from the visible to radio wavelengths.

7.5.2 Ranges of short-wave electromagnetic radiation in the longer wavelength range

7.5.2.1 Visible

Visible radiation is classified as electromagnetic radiation with wavelengths between 380 nm and 760 nm. The strongest blackbody radiation for the Sun is primarily emitted in the visible spectrum and is the reason that life on Earth adapted to this wavelength. Visible is emitted primarily by the solar photosphere.

7.5.2.2 Infrared

Infrared radiation is classified as electromagnetic radiation with wavelengths between 700 nm and 1 mm (430 THz to 300 GHz). Blackbody radiation is primarily emitted in the infrared spectrum, making infrared a reliable source in thermographic applications. Infrared is emitted primarily by the translation, vibration, and rotation as well as interaction of particles. Any object above absolute zero emits infrared radiation.

7.5.2.3 Microwave

Microwave radiation is classified as electromagnetic radiation with wavelengths between 1 mm and 1 m (300 GHz to 300 MHz). Microwave radiation is primarily used for line-of-sight communication and radar. It additionally has limited range in the atmosphere due to high absorption by moisture in the air. It can be used for point-to-point communication to transmit data, noise, or video. Microwaves can be used in radar systems to detect the location of objects.

7.5.2.4 Radio

Radio frequency (RF) radiation is classified as electromagnetic radiation with wavelengths between 1 m and 10 km (30 kHz to 300 GHz). This range includes microwave radiation. Most low-frequency RF is suitable for long-distance communication using methods such as ionospheric reflection for over-the-horizon communication. It is widely used for communication between spacecraft and ground systems.

7.5.3 Effects

Longer (lower energy) wavelengths from the radio to the visible part of the spectrum can impart kinetic energy changes to molecules such as translation, rotation, and vibration.

7.6 Solar energetic particles

7.6.1 Phenomenology

Solar energetic particles (SEPs) are primarily protons ($Z = 1$) with energies ranging from 1 MeV to 500 MeV ejected from the Sun during explosive events. The other ions can be also ejected from the Sun during flares. Solar energetic particle fluxes can have spectra for species through $Z = 92$.

7.6.2 Solar particle events

Solar energetic particle ejected by flares can escape from the Sun environment into the heliosphere. Particle propagation is controlled by an interplanetary magnetic field. Solar wind structure can be also complicated due to interaction between high speed streams produced by the Sun. In particular, in addition to solar energetic particles, solar flares can also produce coronal mass ejections with the magnetic flux rope inside. Their passage through the ambient solar wind creates a shock front that can additionally accelerate solar particles.

Solar particle events (SPEs) occur when solar energetic particles reach the Earth's environment. Enhanced particle fluxes can be registered during several days.

7.6.3 Effects

SEPs provide a severe ionizing radiation in space environment that can damage electronic of spacecraft and aircraft and is also dangerous for humans on-board.

8 Solar event effects on the near-Earth environment

8.1 Magnetosphere

8.1.1 Phenomenology

Structure of the Earth's magnetosphere depends on magnetospheric magnetic field driven by solar wind parameters (plasma bulk velocity, density) and interplanetary magnetic field strength and direction. High speed streams, coronal mass ejections and IMP reversals all influence geomagnetic disturbances within the Earth's magnetosphere.

8.1.2 Magnetospheric magnetic field

Near-Earth environment is strongly influenced by solar activity. Any solar effects reveal themselves as changes inside the Earth's magnetosphere.

The magnetospheric magnetic field is the region surrounding the Earth or another astronomical body in which its magnetic field is the predominant effective magnetic field. The magnetospheric magnetic field is the superposition of the magnetic fields of planetary internal and external sources. The Earth's internal magnetic field is generated by the currents in the Earth's core (ISO 16698) while external magnetic field is produced by magnetospheric currents (ISO 22009). The internal magnetic field experiences slow changes (about 7 % per century) while the external field is highly dynamical under continuous influence of solar activity.

8.1.3 Trapping

Particles become trapped in the inner magnetosphere throughout phenomenon called magnetic mirroring. In the region with quasi-dipolar magnetic field particles gyrate around the field line, and bounce along it at high speed between mirror points in the northern and southern hemispheres. In this region particle trajectory is spiral around the magnetic field lines. Moreover, most energetic particles are strongly affected by the curvature and gradient drifts, which results in a relatively slow drift around the Earth. If a particle completes its drift around the Earth without being lost to the atmosphere or the magnetopause, such a particle is considered stably trapped. Trapping contributes to the ring current and the particle population of the outer radiation belts.

8.1.4 Geomagnetic storms

Geomagnetic storms are magnetic field disturbances in the near-Earth environment, which are caused by solar wind and interplanetary magnetic field changes that originate from solar events such as coronal mass ejections or coronal holes. The latter produces high speed solar wind streams. Geomagnetic storms are associated with:

a) major disturbances in the magnetic field;

b) strong increase of energetic (tens to hundreds of keV) ions in the (ring current) region;

c) often intense fluxes of relativistic (MeV) electrons and occasional acceleration of electrons to ultra-relativistic (multi-MeV) energies in the outer Van Allen radiation belt.

A geomagnetic storm is a temporary but major disturbance of the Earth's magnetosphere caused by changes in charged particle densities, pressures, magnetic directionality, and velocities in the solar wind. A solar wind shock wave and/or magnetic cloud of particles interacts with the Earth's magnetic field and transfers energy into the near-Earth environment. The strength of a geomagnetic storm is often defined by changes in the proxy of the ring current called the D_{st} index. A geomagnetic storm has three phases: an initial phase, a main phase, and a recovery phase. The initial phase (also referred to as a storm sudden commencement, SSC) is characterized by an increase of D_{st} by 20 nT to 50 nT in tens of minutes. Not all geomagnetic storms have an initial phase and not all sudden increases in D_{st} are followed by a geomagnetic storm. The main phase of a geomagnetic storm is defined by a decrease in D_{st} to less than -50 nT. The selection of -50 nT is arbitrary and some operational systems use -75 nT or -80 nT as thresholds. The minimum value during a storm can be between -50 and approximately -600 nT. The duration of the main phase can extend up to ten of hours. In the recovery phase the D_{st} relaxes from its minimum value to its quiet time value. The recovery phase can last from hours to days.

8.1.5 Magnetospheric substorms

Magnetospheric substorms are caused by the dynamic response of the magnetosphere to varying solar wind conditions. The energy input from the solar wind is governed by the orientation of the interplanetary magnetic field, usually with Bz southward, and, as long as the magnetospheric region remains stable, energy is stored as magnetic energy. At some critical point the magnetotail becomes unstable and the magnetic energy is released via the “substorm expansion phase”, which involves:

a) injection of energetic (tens to hundreds of keV) particles (electrons and ions) to the vicinity of the geostationary Earth orbit;

b) strong electric currents in the auroral region;

c) rapid fluctuations and configuration changes of the magnetospheric magnetic field.

8.1.6 Effects

Earth’s magnetospheric magnetic field deflects most of the solar wind, whose charged particles would otherwise strip away the ozone layer that protects the Earth from harmful ultraviolet radiation. However, substorms and geomagnetic storms can cause precipitation of energetic particles that affect the NO_x-concentration and thereby the ozone in the Earth’s lower atmosphere as well as the cooling rate in the upper atmosphere. Earth’s magnetospheric magnetic field protects the Earth’s environment from cosmic rays and solar energetic particles originated from solar flares.

From the other side, magnetospheric magnetic field variations can provide the geomagnetically induced currents in the polar and subauroral regions and also energetic electron fluxes variations in the outer radiation belt.

8.2 Plasmasphere

8.2.1 Phenomenology

A torus of cold, relatively dense (> ~1 000 cm^3) plasma in the inner magnetosphere is trapped on the Earth's magnetic field lines and co-rotates with the Earth. This cold plasma is considered to have energy of between a few electron volts and a few dozen electron volts. See ISO 16457:2022, 3.2. The plasmasphere can significantly contribute to the total electron content (TEC). It controls wave-particle interaction and thus can influence the ring current and the radiation belts.

The plasmasphere is populated by the outflow of ionospheric plasma along mid- and low-altitude magnetic field lines (i.e. those that map to magnetic latitudes of around 60 degrees and less).

8.2.2 Geo corona

The geocorona is part of Earth's exosphere that reflects UV light and is primarily composed of escaping hydrogen and helium.

8.2.3 Dynamics

Unlike the plasma of the central plasma sheet, which in general convects sunward toward the dayside magnetopause, the cold, dense plasma of the plasmasphere is trapped on magnetic field lines that rotate with the Earth and thus co-rotates with the field lines. It is the competitive interplay between these two flow regimes, i.e. one convecting sunward and the other co-rotating, that, together with the outflow of plasma from the ionosphere, determines the size, shape, and dynamics of the plasmasphere, which varies strongly according to the level of magnetospheric activity.

8.2.4 Effects

Due to high level plasma density in the plasmasphere whistler mode emissions up to tens of kHz can occur. Whistler mode waves occur inside and outside of the plasmasphere and significantly contribute to TEC. The plasmasphere demarcates the region of hiss and chorus waves and is a boundary between an outer region where whistler mode waves provide acceleration and an inner region where waves provide loss of relativistic electrons.

8.3 Van Allen radiation belts

8.3.1 Phenomenology

The Van Allen radiation belts are zones of highly energetic charged particles in the inner magnetosphere that are trapped by Earth's quasi-dipole magnetic field. This population consists of electrons with energies from about 40 keV to dozens of MeV and protons from MeV to several hundreds of MeV. The source of the inner radiation belt is the galactic cosmic rays (GCRs). The sources of the outer radiation belt are the magnetotail particle injections. The sources of the new belt(s) are solar winds and anomalous cosmic rays. Some other sources include solar energetic particles (SEPs) and nuclear explosions.

The first direct measurement of the outer radiation belt particle fluxes was made by Soviet Sputink-2 in November 1957. However, the discovery of these belts is credited to James Van Allen, who observed them and correctly explained the measurements after the launch of Explorer 1 in 1958.

8.3.2 Outer radiation belt

This energetic trapped particle population (electrons and ions) is populated by the particles originating from the solar wind and ionosphere. The outer radiation belt generally extends from approximately 2 to 7 Earth radii. This region contains electrons have energies >100 keV along the outer edge and can drop to normal interplanetary levels within about 100 km (a decrease by a factor of 1 000) because of the solar wind. Unlike the inner belt, the outer belt's particle population changes by up to 3 orders of magnitude or more on times scales ranging from minutes to days and years. Electrons in the outer radiation belt usually have energies below a few MeV but for selected events reach up to 8 MeV. Electron fluxes usually drop during the main phase of the storm due to precipitation into the atmosphere and the outward radial diffusion that is driven by the loss to the magnetopause. In the recovery phase of magnetic storms electron fluxes can rise to higher than pre-storm levels.

Electron fluxes in the outer radiation belt are highly variable due to the interplay between acceleration and loss mechanisms in the inner magnetosphere during geomagnetic disturbances.

8.3.3 Inner radiation belt

This population consists of trapped particles (mostly protons and electrons) populated mostly by the decay of albedo neutrons whose source is galactic cosmic rays. The inner belt is separated from the outer belt by the so-called slot region which is usually devoid of high-energy particles. During geomagnetic storms Neutrons with decay times of <0,6 s break up into a proton, which captures most of the energy, an electron, and a massless neutrino. The inner radiation belt extends from 650 km to 6 300 km, where the greatest intensity is between 1 000 km and 5 000 km. This region forms a ring mostly concentrated in equatorial plane. It consists mostly of very stable protons on the order of 10 MeV to 50 MeV with particle lifetimes of up to 1 000 years. Also contains electrons, low-energy protons, and oxygen atoms with energies of 1 keV to 100 keV.

8.3.4 Ring current

The ring current is another trapped particle population at a distance of 3 R_E to 8 R_E, which produces an electrical current in equatorial plane and circulates clockwise around the Earth when viewed from the north. During solar superstorms ring current can reach 2 R_E. The dawn-ward drifting electrons and the dusk-ward drifting protons in this region produce a current system that induces a magnetic field in opposition to the Earth's magnetic field. When this induced magnetic field occurs, an observer sees a decrease in the Earth's main magnetic field and the negative deflection due to the ring current is measured by the D_{st} index.

8.3.5 Other radiation belt variability

Two more radiation belts that were recently discovered exist around Earth. One of the belts was formed by a Coronal Mass Ejection on March 24, 1991, which trapped electronics and ions in a region outside of the inner radiation belt. Another new belt was also discovered inside of the outer radiation belt, containing heavy nuclei (mainly oxygen). The sources of this radiation belt are anomalous cosmic rays (ACRs), which come from supernovae. Radiation belts have variable levels of charged particles over time. New particles are occasionally injected by solar wind activity and cosmic rays from outside of the solar system. In between events, the charged particles within these radiation belts decay over time. The slot region between the inner and outer belt can be highly variable due to solar wind particles from geomagnetic storms injecting particles, temporarily filling in the gap between belts and then recovering back to equilibrium after some days or weeks. In 2012 right after the launch of the Van Allen Probes, the third radiation belt formed in the slot region. The formed belt later disappeared due to the loss to the atmosphere. Such transient remnant belts periodically occur and are usually observed at ultra-relativistic energies.

8.3.6 South Atlantic Anomaly

The proton-rich inner radiation belt dips nearest to Earth's surface (250 km) near South America and it is called the South Atlantic Anomaly. It is the region above the surface of the Earth with the weakest magnetic field. The increased flux of energetic particles exposes low Earth orbiting (LEO) systems higher levels of radiation. The heart of the region is in the southern hemisphere of the Atlantic Ocean, but the end regions are dependent on the altitude of the spacecraft.

8.3.7 Effects

Radiation in space can cause surface impacting effects on spacecraft and even penetrate deep layers of materials and systems. The surface charging is mostly due to the ring current particles. The deep dielectric charging is mostly produced by the relativistic and ultra-relativistic electrons in the radiation belts. Energetic particles such as solar energetic protons can originate from the Sun and most energetic particles such as galactic cosmic rays originate from outside of the solar system and penetrate the Earth's magnetosphere. Conducting materials can degrade over time from radiation impacts and can lead to premature end-of-life (EOL) of spacecraft. Radiation also decreases the output of solar arrays due to atomic displacement and the formation of colour centres in cover glasses and the underlying solar cells.

The effects of natural space radiation can be broadly categorized as: total ionizing dose, displacement damage, and single event effects.

Total ionizing dose (TID) is a cumulative effect that measures the total amount of ionizing energy (i.e. causing ionization by releasing electrons) deposited in a material. TID can be accumulated over time from both charged particles and photons. The primary source of TID in the natural space environment is trapped electrons in the Van Allen radiation belts. The response differs by material, and the TID refers to the energy deposited per unit mass of silicon formerly designated as Rad (Si). Now, TID is measured in units of gray, Gy [1 Gy = 1 J kg^{-1} (= 100 rad)]. Silicon semiconductors can be sensitive to TID due to the importance of free electrons in how the material is utilized. Following this same principle, inorganics and insulators are also sensitive to total ionizing dose, while metals are characterized by mobile electrons and are thus more easily able to maintain equilibrium when TID sources liberate additional electrons.

Displacement damage (DD) is a form of non-ionizing radiation, meaning no electrons are released. Instead, atoms are knocked out of their position in the lattice structure of a material. This type of damage can be caused by charged particles, photons, or neutrons, typically protons or electrons with greater than 1 MeV. Although trapped protons and electrons are the source of DD in the space environment, testing of materials and electronic components is often conducted with high energy neutrons due to greater availability as compared to protons. Therefore, the units of displacement damage when referring to material and component hardness capabilities are often given in terms of neutron fluence (n/cm^2 of 1 MeV neutrons).

Single event effects (SEE) refers to short lived circuit responses caused by a single charged particle. When heavy charged particles interact with a semiconductor device, they create ionization tracks that result in spurious current in a device. The resulting current can be small enough to have no impact on device operation while more deleterious responses can corrupt stored data or output signals with some currents even having the potential to destroy the device.

8.4 Polar region and high-latitude magnetosphere

8.4.1 Phenomenology

The high-latitude (or outer) magnetosphere is filled with magnetic field lines connected through the high-latitude ionosphere to the geotail and interplanetary space. This is the most dynamic part of near-earth space that actively reacts to changes in the interplanetary environment. Variations in the solar wind and interplanetary magnetic field cause geomagnetic disturbances, which result in moving the boundaries of plasma formations and changes in the spectral characteristics and particle fluxes.

8.4.2 Auroral oval

This region of auroral emissions in the upper atmosphere contains supra-thermal (tens of eV to 20 keV) particles (mostly electrons) precipitation from the geotail plasma sheet along the magnetic field lines.

8.4.3 Polar cap

This region of ionosphere is connected by magnetospheric field lines with interplanetary space. It is open to galactic cosmic rays and solar energetic particles coming from outside the magnetosphere.

8.4.4 Field aligned currents and auroral electrojets

Field aligned currents flow along the magnetic field lines in the inner boundary of high-latitude magnetosphere. They connect ionospheric and magnetospheric currents in the geotail and on the magnetopause. The strongest field-aligned currents (up to 10^6A) arise during magnetic storms and magnetospheric substorms. In these times strong ionospheric currents along the nightside auroral oval called auroral electrojets are developed.

8.4.5 Effects

The high-latitude magnetosphere and ionosphere is of great applied importance for space weather. Inhomogeneities of particle fluxes are transmitted from the magnetosphere to the ionosphere, which creates great interference for radio communications in the Earth's ionosphere due to interference of radio waves on plasma inhomogeneities. Precipitation of particles in the region of high-latitude electrojets changes the conductivity of the ionosphere, which leads to variations in the magnetic field at auroral latitudes and the appearance of geomagnetically induced currents. The interaction of various layers of the ionosphere and magnetosphere is important for tropospheric and stratospheric meteorological and other weather-forming processes.

8.5 Geomagnetic cut-off

8.5.1 Phenomenology

The ability of a geomagnetic field to prevent penetration of energetic particles originating from the Sun or from galactic cosmic rays into the different regions of the magnetosphere.

Charged particle motion in the magnetic field depends on magnetic field induction and particle charge and momentum. Magnetic rigidity is the simple parameter that describes the trajectory of the particles in a magnetic field. Magnetic rigidity $R=pc/Z$, where p is particle momentum component orthogonal to magnetic field, and Z is the charge of the particle (ISO 17520). Particles with the same rigidity have the same trajectories. In the dipole magnetic field there exist regions that can be accessed from outside by charged particles with the given rigidity (allowed trajectories) and that cannot be accessed by these particles (forbidden trajectories).

8.5.2 Cut-off rigidity

Magnetic rigidity is defined as the total amount of energy required for a particle to penetrate the magnetosphere at a given level. The magnetosphere therefore prevents particles with too low energies from interacting with Earth. Cut-off rigidity is the concept that the Earth's magnetic field can stand off charged particles trying to come into the magnetosphere from external sources like galactic cosmic rays or solar energetic particles. It describes the minimum energy required for a charged particle to penetrate at a particular location (ISO 17520). Typically, only highly energetic particles can penetrate to equatorial regions, whereas most particles can penetrate into high latitudes since there are weaker field lines at the poles. It is not effective for neutral particles since they do not travel along field lines.

8.5.3 Effects

Cosmic ray and solar energetic particles penetrate into the polar region, which has relatively low cut-off rigidity, and permit greater radiation impact on hardware and biological objects in space. They are also responsible for single event effects on electronic devices. In the Earth's upper atmosphere, they are interacting with atmospheric particles and produce the secondary charged particles that can influence avionics.

9 Terrestrial environment

9.1 Neutral atmosphere

9.1.1 Phenomenology

The entirety of the Earth's atmosphere primarily consisting of neutral gas molecules. The Earth's atmosphere can be classified into different regions based on temperature, composition, or collision rates among atoms and molecules. For the purposes of the document, the atmosphere is broadly divided into these regimes based on all three properties: the troposphere, the stratosphere, the mesosphere, the thermosphere, and the exosphere.

In practice, the boundaries between these regions, whether determined in altitude or in a pressure co-ordinate system, vary with solar, seasonal, latitudinal and other conditions.

Due to winds and turbulent mixing the homosphere has a nearly uniform composition of about 78,1 % N_2, 20,9 % O_2 and 0,9 % Ar. The temperature profile of the thermosphere increases rapidly above a minimum of ~180 K at the mesopause, then gradually relaxes above ~200 km to an asymptotic value known as the exospheric temperature.

Aerodynamic flight is only possible below around 100 km. Above this point (known as the Karman line), the density of the atmosphere is too low to support winged flight, and space begins. The neutral atmosphere can create a drag force on satellites that can perturb its orbit. Additionally, above 200 km atomic oxygen becomes the main atmospheric constituent in the range of about 200 km to 700 km. It can cause erosion and oxidation on spacecraft surfaces, depending on the material.

9.1.2 Atmospheric layers

Multiple layers including the troposphere from 0 km to 15 km, the stratosphere from 15 km to 50 km, the mesosphere from 50 km to 85 km, the thermosphere from 85 km to 500 km, and the exosphere >500 km. Each layer has different properties as follows.

— In the troposphere, ambient temperature decreases as altitude increases. Convection is the primary thermal process, and turbulent mixing is the primary kinetic process.

— In the stratosphere, ambient temperature increases as altitude increases. Convection is the primary thermal process, and turbulent mixing is the primary kinetic process.

— In the mesosphere, ambient temperature decreases as altitude increases. Radiation is now the primary thermal process, but turbulent mixing is still the primary kinetic process.

— In the thermosphere, ambient temperature increases as altitude increases. Eddy conduction and molecular conduction are now the primary thermal processes, while eddy mixing and molecular diffusion are now the primary kinetic processes.

— In the exosphere, temperature now remains constant as altitude increases. There are no more thermal processes; atom escape is the primary kinetic process.

9.1.3 Effects

9.1.3.1 Atmospheric drag

Atmospheric drag is the force derived from the kinetic energy of an orbiting object encountering an atmosphere as a result of the work done against the object by the atmosphere. Atmospheric constituents impact the spacecraft and produce a net force that is generally opposite the direction of velocity. The acceleration experienced by the spacecraft is dependent on the atmospheric density at that altitude, cross sectional area, mass, and coefficient of drag of the spacecraft, and velocity of the spacecraft relative to the surrounding atmosphere:

$$A_D = 0{,}5 C_D A \rho v^2 m^{-1}$$

where

A is the effective cross-section of the satellite interacting with the atmosphere;

ρ is thermospheric density;

v is the velocity of the satellite relative to the atmosphere;

m is the mass of the satellite;

C_D is the dimensionless aerodynamic drag coefficient.

9.1.3.2 Atomic oxygen

Atomic oxygen (ISO 23129:2021, 3.1.1) is the main constituent of the upper atmosphere (i.e., thermosphere) above 200 km. Atomic oxygen is highly reactive. It can cause erosion and oxidation on spacecraft surfaces, depending on the material. As a spacecraft orbits the Earth at high speed, atomic oxygen can collide with the spacecraft's surface at high speed and degrade the surface material.

9.1.3.3 Vehicle glow

Spacecraft in low Earth orbits (LEO) can emit a glow as the vehicle collides with ambient gas atoms and molecules around the Earth. As these collisions occur, the atoms and molecules can be raised to a higher energy level and thus emit a photon of light through photoionization. A visible “glow” emanating from the forward-facing surface of a spacecraft caused by the impact of atmospheric gas molecules with the spacecraft surface.

9.2 Ionosphere

9.2.1 Phenomenology

The ionosphere is the region of the Earth's atmosphere in the height interval from 50 km to 1 500 km containing weakly ionized cold plasma, both electrons and ions (ISO 16457:2022, 3.1). It is within the mesosphere and thermosphere that has been ionized by solar EUV photoionization, Joule heating, charged particle precipitation, waves, and winds. Since the primary process is solar EUV photoionization, the electron densities increase during the day and collapse at night. There is also an increase in electron densities during high solar activity. Ionospheric effects can contribute to scintillation and satellite surface charging.

9.2.2 Ionospheric layers

The D-region exists from 50 km to 85 km and is dominated by $H2O^+$. The E-region exists from 85 km to 140 km and is dominated by $O2^+$. E-F1 valley is the cross-over between E and F1, which exists from 140 km to 250 km. It is dominated by NO^+ and the maximum electron density in this region exists at 200 km. The F2 region exists from 250 km to 500 km and is dominated by O^+. The maximum electron density exists at 300 km. Topside ionosphere is everything upwards of 500 km and is dominated by O^+. The entire integrated ionosphere from top to bottom is referred to as the total electron content (TEC).

9.2.3 Ionospheric storm

An ionospheric storm lasts about a day and is documented by depressions and/or enhancements of the ionospheric electron density during various phases of the storm. Ionospheric storms are the ultimate result of solar flares or coronal mass ejections, which produce large variations in the particle and electromagnetic radiation that hit Earth's magnetosphere and ionosphere, as well as large-scale changes in the global neutral wind, composition and temperature (ISO 16457).

9.2.4 Effects

9.2.4.1 Scintillation

Gradients in the total electron content (TEC) can be caused by traveling ionospheric disturbances, bubbles, plumes, streams, or sharp borders. Small structures within the ionosphere are frequently associated with large-gradient regions and can cause scintillation. For GPS users, scintillation is observed as amplitude and phase fluctuations in the received signal. Severe scintillation effects in either amplitude or phase can cause a GPS receiver to lose lock.

Large gradients in TEC and scintillation are primarily associated with the equatorial and polar regions. However, large gradients in TEC and scintillation can be observed at mid-latitudes during moderate to severe geomagnetic disturbances. Because most GPS users are located at mid-latitudes, the disturbances caused by large geomagnetic storms can potentially affect the average GPS user.

Knowledge of these TEC gradients is important to various GPS users. When a GPS signal encounters large gradients in TEC, the ionospheric error in the range measurement is difficult to model and remove (required for single-frequency GPS users), or in the case of differential GPS, it cannot be cancelled out. For DGPS or RTK users, differences as small as two TEC units over the baseline (one TEC unit is 1×10^{16} electrons m^{-2}) can make resolution of ambiguities difficult. (A TEC unit is approximately equivalent to 0,162 m of range delay at L1, or 1 m of delay at L1 is equivalent to 6,159 TEC units).

9.2.4.2 Surface and deep dielectric charging

Spacecraft charging is a variation in the electrostatic potential of a spacecraft's surface with respect of the surrounding plasma. Insulators and dielectric materials can differently charge with respect to other spacecraft surfaces. It can occur in the ionosphere, at LEO, MEO and GEO.

Surface charging is a phenomenon in which charged particles in the natural space environment accumulate on the exposed surface of a spacecraft. These charged particles are typically characterized by low energy levels as higher energy particles would penetrate further into the vehicle and would thus be classified as bulk or deep dielectric charging. While the distinction is somewhat arbitrary given that they both refer to the accumulation of charged particles, surface charging is generally considered to refer to surfaces directly exposed to space or those having less than approximately 3 mils of aluminium shielding.

The effects of surface charging can result in the space vehicle suffering an electrostatic discharge (ESD) event if not designed properly. The settling of charged particles, either positive or negative, results in a potential build up. If sufficient charge accumulates to reach the voltage required for arc over, a property of the specific material, then the surface discharges to restore a more favourable energy state. The rush of current caused by the discharge event has the potential to damage circuits if directed into a signal line. The radiated emissions from the discharge has the potential to interfere with space craft receivers. These problematic effects are avoided by providing all surfaces with a low impedance path to ground. Therefore, design practice for mitigating spacecraft charging include grounding all metals and ensuring that all insulation materials have a surface resistivity less than 1E9 Ω per square, as well as utilizing robust circuits with sufficient filtering and protection diodes.

10 Micrometeoroid and debris environment

10.1 Phenomenology

Micrometeoroids are a naturally occurring environmental condition – part of solar system particle and dust environment. Micrometeoroids or interplanetary dust particles tend to be <1 mm. The debris environment is human generated from non-operational objects. Debris is generated by a number of processes including vehicle-released objects, fragmentation, mission operations and manoeuvres.

10.2 Natural

Particles can be of natural origin that result from the disintegration and fragmentation of comets and asteroids, which orbit around the Sun (ISO 14200:2021, 3.11).

10.3 Artificial

Human-made objects can include active spacecraft as well as fragments thereof in Earth's orbit. There are currently more than half a million pieces of space debris orbiting the earth. Forty percent of these objects are larger than 10 cm while the rest are about the size of 1 cm. They all travel at speeds faster than 7,5 km/s and can severely damage a satellite. There have been several incidents that have caused the creation of increased debris fields and, if left unmitigated, can become a larger problem of debris conjunction with active vehicles (ISO 24113:2023, 3.17).

Annex A
(informative)

Space weather indices

A.1 K_p index (planetary K index)

A.1.1 Phenomenology

This is the planetary three-hour semi-logorithmic index of geomagnetic activity characterizing the disturbance in the Earth's magnetic field over three-hour universal time (UT) intervals (ISO 16457:2022, 3.10).

A.1.2 Description

The planetary K index quantifies the disturbance in the horizontal component of Earth's main magnetic field. It is derived from a network of 13 geomagnetic observatories that record the maximum fluctuations from a quiet day curve of horizontal components observed by magnetometers during three-hour intervals. The K_p ranges in 28 steps from 0 (quiet) to 9 (disturbed) with intermediate values denoted by -, o, or +, resulting in 0o, 0+, 1-,1o, 1+, 2-, 2o, 2+, ..., 8-, 8o, 8+, 9-, and 9+. The value of 5 or more indicates a geomagnetic storm. See ISO 16698:2019, 5.4 and Reference [24].

A.1.3 Application utility

The K index defines the level of geomagnetic activity.

A.1.4 Contributors

Meannook, Canada; Sitka, USA; Lerwick, Shetland Is., UK; Ottawa, Canada; Uppsala, Sweden; Eskdalemuir, UK; Brorfelde, Denmark; Fredericksburg, USA; Wingst, Germany; Niemegk, Germany; Hartland, UK; Canberra, Australia; Eyrewell, New Zealand.

A.1.5 Index access

https://www.gfz-potsdam.de/en/kp-index/
https://www.swpc.noaa.gov/products/planetary-k-index

A.2 a_p index

A.2.1 Phenomenology

The planetary daily index of geomagnetic activity characterizes the average disturbance in the Earth's magnetic field over the whole day in UT (ISO 16457:2022, 3.11).

A.2.2 Description

The a_p index is the average of the eight values of the a_p index in a UT day. Where a_p is a three-hour UT amplitude index of geomagnetic variation equivalent to K_p. The a_p index is introduced as it is roughly proportional to the geomagnetic disturbances. One a_p unit corresponds to approximately 2 nT of geomagnetic variations. See Reference [27].

A.2.3 Application utility

The A-index defines the level of geomagnetic activity.

A.2.4 Contributors

Meannook, Canada; Sitka, USA; Lerwick, Shetland Is.,UK; Ottawa, Canada; Uppsala, Sweden; Eskdalemuir, UK; Brorfelde, Denmark; Fredericksburg, USA; Wingst, Germany; Niemegk, Germany; Hartland, UK; Canberra, Australia; Eyrewell, New Zealand.

Union, Washington DC

A.2.5 Index access

https://www.gfz-potsdam.de/en/kp-index/

A.3 D_{st} index (storm time disturbance index)

A.3.1 Phenomenology

The planetary one-hour index of geomagnetic activity that quantitatively characterizes the disturbance of the horizontal component of the magnetospheric magnetic field at the Earth's geomagnetic equator.

A.3.2 Description

The disturbance storm time index (D_{st}) estimates the globally averaged change of the horizontal component of the Earth's magnetic field at the magnetic equator based on measurements from four magnetic observatories. The source of magnetic changes comes from the solar wind's perturbation of the Earth's magnetosphere and, most prominently, the magnetospheric ring current. Severe, global perturbations are generically referred to as magnetic storms while smaller events related to the reconfiguration of the Earth's magnetosphere are called sub-storms.

The D_{st} index is a measure of the axially symmetric part of the H component along geomagnetic equator on the ground, and the main physical source is a combination of the equatorial ring current, the plasma sheet current and the magnetopause current.

The D_{st} index is defined as the average of the disturbance variations of the H component, D_i, at the four observatories (i = 1 to 4), which are listed in Table A.1, divided by the average of the cosines of the dipole latitudes at the observatories for normalization to the dipole equator. D_{st} is computed for each UT hourly interval from the four observatories. See ISO 16698:2019, 5.6 and Reference [29].

A.3.3 Application utility

The D_{st} index defines the storm phase and the level of magnetic storm intensity within the ring current. It is a surrogate for the effect of low-to-medium energy ions that sweep toward the Earth from the magnetotail under the influence of electric fields and enhanced by the merging process. Four observatories contribute to the D_{st} index (Table A.1).

A.3.4 Contributors

Table A.1 — Four observatories contributing to the D_{st} index (ISO 16698:2019, Table 6)

Observatory, Country	Code	GLat (°N)	GLon (°E)	Dipole Lat (°)
Kakioka, Japan	KAK	36,230	140,190	26,0
San Juan, USA	SJG	18,113	293,850	29,6
Honolulu, USA	HON	21,320	201,998	21,1
Hermanus, South Africa	HER	-34,425	19,225	-33,3

A.3.5 Index access

http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/index.html

A.4 Sunspot number (*R*)

A.4.1 Phenomenology

The sunspot number quantitatively defines the level of solar activity.

A.4.2 Description

The sunspot number (R) is alternatively called R_i or R_z. R_{12}(R_{z12}) is the 12-month running mean of the sunspot number R. See ISO 14222:2022, B.2.3.2 and Reference [33].

A.4.3 Application utility

The sunspot number identifies the phase of solar cycle activity.

A.4.4 Contributors

Royal Observatory of Belgium, Brussels

A.4.5 Index access

A.4.5.1 Radio and Space Weather Services

Commonwealth of Australia 2014, Bureau of Meteorology, Radio and Space Weather Services, (ABN 92 637 533 532), https://abr.business.gov.au/ABN/View/92%20637%20533%20532

A.4.5.2 Solar Influences Data Analysis Center

SIDC-team, World Data Center for the Sunspot Index, Royal Observatory of Belgium, *Monthly Report on the International Sunspot Number,* online catalogue of the sunspot index: https://www.sidc.be/sunspot-data/

A.4.5.3 National Geophysical Data Center

A.4.5.4 Solar – Terrestrial Physics Division

https://www.ngdc.noaa.gov/stp/

A.4.5.5 European Space Agency (daily)

https://space-env.esa.int/

A.5 $F_{10.7}$

A.5.1 Description

$F_{10.7}$ (abbreviated F_{10}) is a traditional solar energy proxy. It corresponds to the solar radio flux emitted by the Sun at 2 800 MHz (10,7 cm wavelength). The Sun emits radio energy with a slowly varying intensity. This radio flux, which originates from atmospheric layers high in the Sun's chromosphere and low in its corona changes gradually from day-to-day in response to the number of spot groups on the disk. Solar flux density at a wavelength of 10,7 cm has been recorded routinely by radio telescope near Ottawa since February 14, 1947. Each day, levels are determined at local noon (1700 GMT). Beginning in June 1991, the solar flux density measurement source is Penticton, B.C., Canada. Its observations are available through the DRAO website and all values are also archived at the Space Physics Interactive Data Resource (SPIDR). See Reference [30].

Three sets of fluxes — the observed, the adjusted, and the absolute — are summarized. Of the three, the observed numbers are the least refined since they contain fluctuations as large as 7 % that arise from the changing Sun-Earth distance. In contrast, adjusted fluxes have this variation removed; the numbers in these tables equal the energy flux received by a detector located at the mean distance between the Sun and Earth. Finally, the absolute levels carry the error reduction one step further; here each adjusted value is multiplied by 0,90 to compensate for uncertainties in antenna gain and in waves reflected from the ground.

NOTE The physical units of $F_{10.7}$ are 10-22 W $m^{-2}Hz^{-1}$; the numerical value is used without the multiplier as is customarily done and expressed as solar flux units (sfu), i.e. a 10,7 cm radio emission of 150 × 10^{-22} W $m^{-2}Hz^{-1}$ is simply referred to as $F_{10.7}$ = 150 sfu.

$F_{10.7}$ and the sunspot number, R, are correlated. Averaged (over one month or longer) values can be converted by the following formula:

$$F_{10.7} = 63{,}7 + 0{,}728R + 8{,}9 \times 10^{-4}\ R^2$$

See ISO 14222:2022, Formula (B.2).

A.5.2 Application utility

The daily $F_{10.7}$ solar proxy has a long history of use since 1947 and provides a range of variation with enough resolution to see 27-day solar rotation variability. The 81-day smoothed $F_{10.7}$ proxy highlights the evolution and decay of solar magnetic active regions. The 365-day smoothed $F_{10.7}$ proxy identifies the maximum and minimum of solar magnetic field cycles. It is used in many thermosphere and ionosphere models, including JB2008.

A.5.3 Index access

https://spacewx.com/jb2008/

A.6 $S_{10.7}$

A.6.1 Description

$S_{10.7}$ (abbreviated S_{10}) is a solar energy index of the integrated 26 nm to 34 nm solar extreme ultraviolet (EUV). This EUV flux originates from the solar chromosphere and low corona. It is reported in units of 10^{-22} W m^{-2} Hz^{-1} or sfu. The JB2008 (ISO 14222) thermospheric density model contributes 74,1 % of the energy input into the thermosphere.

As described in Reference [31], the $S_{10.7}$ index is the integrated 26 nm to 34 nm solar irradiance that is measured by the Solar Extreme-ultraviolet Monitor (SEM) instrument on the NASA/ESA Solar and Heliospheric Observatory (SOHO) research satellite. SOHO has an uninterrupted view of the Sun by operating in a halo orbit at the Lagrange Point 1 (L1) on the Earth-Sun line, approximately 1,5 million km from the Earth. SEM was built and is operated by University of Southern California's (USC) Space Science Center (SSC). SOHO was launched on December 2, 1995 and SEM has been making observations since December 16, 1995. The SEM instrument measured the 26 nm to 34 nm solar EUV emission with a 15 s time resolution in this first-order broadband wavelength range. Since SOHO SEM, the NASA TIMED SEE and SDO EVE instruments, along with GOES-13, -14, -15, -16, and -17 EUV and EXIS instruments have been measuring this band.

The $S_{10.7}$ index is created by first normalizing the data and then converting it to sfu via a first-degree polynomial fit with $F_{10.7}$. Normalization is achieved for the 1 AU adjusted epoch values by division of a mean value over a time frame common to multiple datasets. The mean value = 1,995 5 × 10^{10} photons cm^{-2} s^{-1}. The common time frame is December 16, 1995 to June 12, 2005, which is generally equivalent to solar cycle 23. See ISO 14222:2022, B.2.3.5 and Reference [31].

A.6.2 Application utility

The daily $S_{10.7}$ solar index has a history of use since 1997 and provides a range of variation with enough resolution to see 27-day solar rotation variability. The 81-day smoothed $S_{10.7}$ proxy highlights the evolution