Space Weather

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Introduction

As Engineers, we often don't consider how the outside world affects what we design. Weather can affect a design because we can see rain and feel wind or heat. Space weather is another way that a design can be affected. Often this is in the form of interference with radio waves or GPS.

The term space weather is the effects of the space environment from the sun. These take the form of emissions, such as solar flares, coronal mass ejections, or solar energetic particles. Most often, it has an effect on radio propagation, but can also affect critical infrastructure, such as electrical power, the water supply, healthcare, and transportation.

NASA has studied space weather for years and how it can degrade, disrupt, and damage the technology (both wired and wireless) we depend on daily. The most noticeable is radio transmission. It is now coming to the attention of the common engineer and the emergency manager. It can pose a significant risk to national security, so is now included Strategic National Risk Assessment, that outlines threats that pose the greatest risk.

Defining Space Weather

Space weather events occur on a regular basis and has measurable effects on Earth-based infrastructure. Among these affected systems are Global Positioning Systems (GPS), satellite operations, communications, aviation, and the electrical power grid, just to name a few. Large-scale disruptions on the electrical power grid can also affect the water supply, healthcare, and transportation.

The main cause of space weather is activity on the sun. It can cause space weather storms that can affect us on Earth. Solar storms can impact technology we use every day, such as Global Positioning Systems (GPS), satellites, and electric power grids. The official source for alerts and warnings is the National Weather Service Space Weather Prediction Center in Boulder, Colorado.

Space weather is a consequence of behavior of the Sun, our location in the solar system, and the nature of the Earth's magnetic field and atmosphere. Various phenomena that originate from the Sun can result in space weather storms. Among these are Flares and Coronal Mass Ejections (CME) that send space weather storms outward through the solar system. A constant stream of radiation is emitted from the Sun in the form of charged particles. These charged particles make up the plasma of the solar wind.

The Solar Cycle

We will start with the solar cycle. This is due to the fact that most space weather events and storms have a source in the Sun. The solar cycle is an approximately 11-year cycle. During this cycle, there is a periodic variation in sunspot numbers and the polarity of the Sun's magnetic field reverses. During the portion of the cycle with maximum sunspots, there is an increase of solar activity. This includes solar flares and CMEs. The Sun is composed of electrically charged hot gases. These hot gases move and generate a magnetic field. This powerful magnetic field reverses during the solar cycle. This means that the Sun's north and south poles switch places during the cycle.

The Sun is approximately 93 million miles from Earth. The average distance from the Sun to Earth is called the Astronomical Unit (AU). It takes 8 minutes for the light from the Sun to reach Earth.

The Sun is constantly spewing gases and particles radially in every direction. The stream of particles is known as the solar wind. The outer atmosphere of the Sun, known as the corona, originates the gas and particles that the solar wind carries towards Earth at up to a million miles per hour.

The solar cycle affects sunspot activity on the Sun. Sunspots are caused by the Sun's magnetic field, which cause changes in sunspot activity as they change. Sunspots are darker and cooler areas on the Sun's surface and are regional magnetic storms. They contain strong and constantly shifting magnetic fields. They occur when the strong magnetic fields come to the solar surface and allow the area to slightly cool from approximately 6000 degrees Celsius down to 4200 degrees Celsius. These cooler areas appear as dark spots on the surface of the Sun. They appear to move from right to left as the Sun rotates on its axis. The Sun takes 27 days to complete one revolution on its axis.

There is an increase and decrease in the number of sunspots on the surface of the Sun during the eleven-year solar cycle. The years when the number of sunspots is lowest are referred to as Solar Minimum. The years when the number of sunspots is highest are referred to as Solar Maximum, where there are numerous sunspots. The Sun is usually very active when sunspot counts are high. Severe solar storms, however, can happen at any time in the solar cycle. The sunspots indicate locations where the Sun's magnetic field energy is building up and can release solar flares and CMEs. During solar maximum, the Sun also gives off more radiation that creates changes in the ionosphere (Earth's upper atmosphere).

Earth's Magnetic Field and Ionosphere

Earth is surrounded by a magnetic field known as the magnetosphere. It is generated by forces at the Earth's core. The magnetosphere protects the Earth from the solar wind, particle radiation, and cosmic rays that come from deep space. The magnetosphere traps this excess energy from space at a safe distance from the Earth's surface. Variations in the solar wind can disturb the Earth's magnetic field. This allows charged particles to get past the Earth's shield created by the magnetosphere. This occurs at higher latitudes and when these particles hit the atmosphere, a glowing light occurs. This light is known as an aurora.

The ionosphere is an ionized layer of the Earth's atmosphere that is roughly 80 kilometers above the Earth's surface and extending to 1000 kilometers. In the ionosphere solar radiation ionizes both molecules and atoms, separating electrons from their parent particles by creating free electrons and positive ions. This solar radiation is in the form of extreme ultraviolet and X-rays. The ionosphere can conduct an electric charge and it is affected by magnetic fields. The ionization is more extensive in the daytime.

Regions (layers) of the ionosphere include the D, E, and F regions. Each of these regions have their own characteristics and implications to space weather. The D-region is the lowest layer of the ionosphere. It ranges from 50 to 85 kilometers in altitude. Electron production in the D-region is from solar radiation and high-energy electrons and protons from the Sun and magnetosphere. In this region, ionization is primarily from ionization of nitric oxide (NO) as well as molecular oxygen and nitrogen (N_2 and O_2). Lower HF and Medium Frequency radio waves are attenuated in the D-region ionosphere. Recombination rates are high in the D-region, so the D-region exists mostly in the daytime hours.

The E-region of the ionosphere is in the range of 85 to 150 kilometers. The normal E-region consists of mostly oxygen and nitric oxide ions. Ionization in this region is due to x-ray ultraviolet and ultraviolet solar radiation. The E-region affects all radio waves by refraction, absorption, and range delay. Typically, the E-region can only reflect radio waves with frequencies below 10 MHz and this region is important for daytime propagation of HF (for distances less than 1,000 miles). The E-region weakens and decays rapidly at night. After sunset the peak height rises, which causes an increase in the range that HF radio waves can travel due to reflection and the primary source of ionization (solar radiation) no longer being present.

There are occasionally thin layers of very high levels of ionization in the lower E-region (Es-layer). These embedded layers are known as sporadic E. This layer is mostly composed of metallic ions from meteorites. The ionization in these layers can be up to five times more than normally achieved at the peak of the sunspot cycle. The Es-layer can reflect frequencies up to 50 MHz and higher during intense events.

The F-region of the ionosphere extends from 150 to 500 kilometers altitude. The F-region is where the highest electron density can be observed in the ionosphere. It is the most important region for long distance HF radio communications. All radio waves propagating in the F-region are impacted, by both a range delay and refractive bending.

The ionosphere is a communications medium for the propagation of radio waves. An example is a telecommunications satellite using frequencies that rely on the interaction between free electrons and the ionosphere. Solar radiation increases can cause instabilities in the ionosphere and can have a major effect on the satellite signal.

The ionosphere can be used by radio operators to extend the range of transmissions. Radio waves usually travel in straight lines so the curvature of the Earth limits the range of radio transmissions. This is referred to as “Line of sight”. Certain frequencies of radio waves are reflected off the electrically charged particles and travel long distances around the globe, known as a “skip”.

The ionosphere can also absorb or dampen radio signals and can bend radio waves, as well as reflect the signals. The exact behavior will depend on the characteristics of the ionosphere as well as the frequency of the radio signal. GPS satellites use radio signals to determine locations. The accuracy of the GPS can be seriously reduced when the signals bend as they pass through the ionosphere. Radio communications can be dampened or absorbed entirely, giving a weakened or lost signal.

Above the ionosphere is the outer layer of the neutral atmosphere, known as the thermosphere. The thermosphere extends from 90 to 600 kilometers above the Earth’s surface.

Space Weather Phenomena

Space weather has both internal and external drivers. External drivers include solar, solar wind, and cosmic rays.

Solar Wind

The solar wind is a stream of magnetic flux and hot charged particles in the form of plasma (consisting of protons and electrons), that flows continuously outward from the sun. The solar magnetic field is embedded in the plasma flowing outward with the solar wind. Some of these charged particles originate in the photosphere and some in the corona. The velocity and temperature of each component is different. The coronal component generally has a velocity of 400 km/sec and a temperature of 1.5 Mega Kelvin. The photospheric component tends to be cooler (0.8 Mega Kelvin) and faster (750 km/sec).

Also, different regions on the Sun produce solar winds of different velocities and densities. Coronal holes (cooler and less dense plasma) produce high velocity solar wind of 500 to 800 kilometers per second. The north and south poles of the Sun have large coronal holes that produce high velocity solar wind (higher latitudes). In the equatorial plane, where the planets orbit, the most common state of the solar wind is the slow speed solar wind (400 kilometers per second). This portion is the equatorial current sheet portion of the solar wind.

High speed solar winds can bring geomagnetic storms. Slow speed solar winds are associated with calm space weather.

Sunspots

Sunspots are the dark areas of the Sun that are apparent in the photosphere. These are the result of an intense magnetic flux that is pushing up from the interior of the Sun. The active regions have cooler areas (7000 deg F) that are darker and less dense. The surrounding photosphere is 10,000 deg F. The darker areas are seen as sunspots. The rapid changes in the magnetic fields among these areas are the likely sources of space weather events such as solar flares, CMEs, radiation storms, and radio bursts.

Sunspots continuously change and can last a few hours or days. Sunspots can appear in many shapes and forms. They also tend to appear in groups. The darkest area of the sunspot is known as the umbrae. The less dark, outlying fibril-like area that develops around the umbrae, is known as the penumbra. Figure 1 is a NASA image that shows an example of a sunspot with its size relative to Earth. They can grow in size and number.

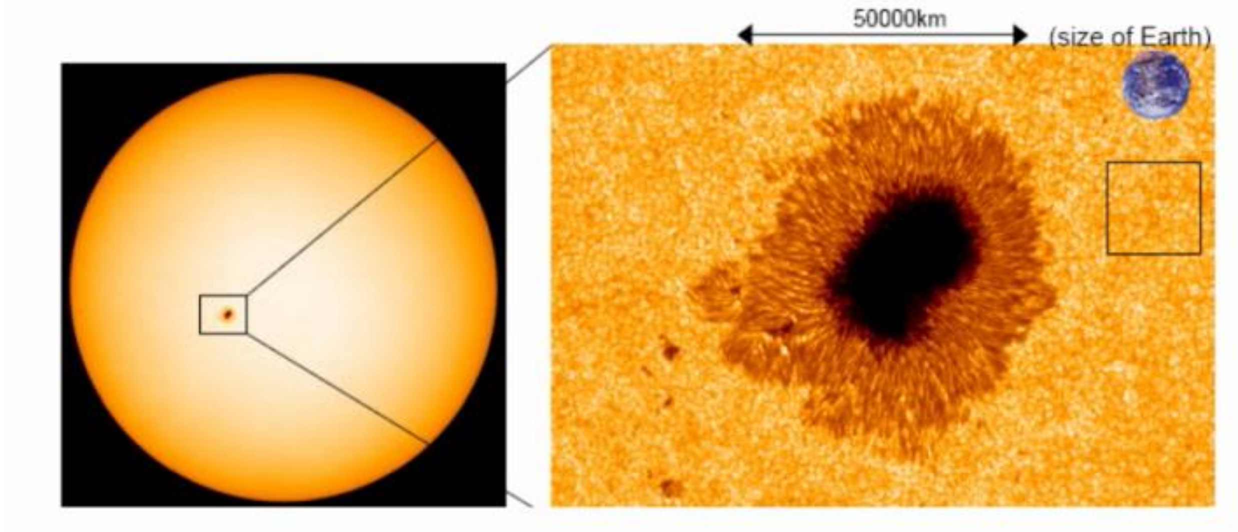


Figure 1. NASA image of a sunspot shown with the relative size of Earth.

Sunspots and sunspot groups are tracked by the Space Weather Prediction Center. Groups that are clearly visible are assigned a four-digit region number to be officially tracked and recorded. The sunspot groups are characterized based on their size and complexity, using the modified Zurich classification scale and the Mount Wilson magnetic classification system.

Sunspots can last for months in the more intense groups. The 11-year solar cycles began in 1755 with solar cycle 1. We are presently in solar cycle 25 that began in December 2019.

Solar Flares

A Solar Flare is a huge eruption of electromagnetic radiation on the Sun that is an external driver of space weather. Solar flares are the sudden brightening of coronal loops over a broad range of the electromagnetic spectrum caused by the impulsive heating of coronal plasmas. These flares occur in the photosphere and corona above the active regions that are associated with sunspots. It appears as a sudden and intense brightening area on the Sun and lasts from a few minutes to a few hours. The heating in the solar corona can produce temperatures that reach 10 to 20 million K. They span several areas of the electromagnetic spectrum, appearing as bright areas in the visible wavelengths and as bursts of noise in radio wavelengths. The primary energy source for these flares is the tearing and reconnecting of strong magnetic fields. The electromagnetic emissions produced takes approximately 8 minutes to reach Earth and travels at the speed of light. Flares associated with CMEs and SPEs are energetically comparable to CMEs.

There is an increased level of x-ray and extreme ultraviolet radiation that results in ionization in the ionosphere on the side of the Earth facing the Sun. During strong solar flares, ionization is produced in the lower layers of the atmosphere (D-layer). The lower layers of the atmosphere are denser. Radio waves in the HF band (3 to 30 MHz) lose energy as they interact with electrons and can be degraded or absorbed. This affects both HF radio and navigation.

Solar flares usually take place in the areas of the Sun with a strong presence of magnetic fields. These are usually associated with sunspot groups. These fields can reach a point of being unstable, and release energy in the form of electromagnetic radiation observed as solar flares. Figure 2 shows a NASA image of a solar flare on the Sun.

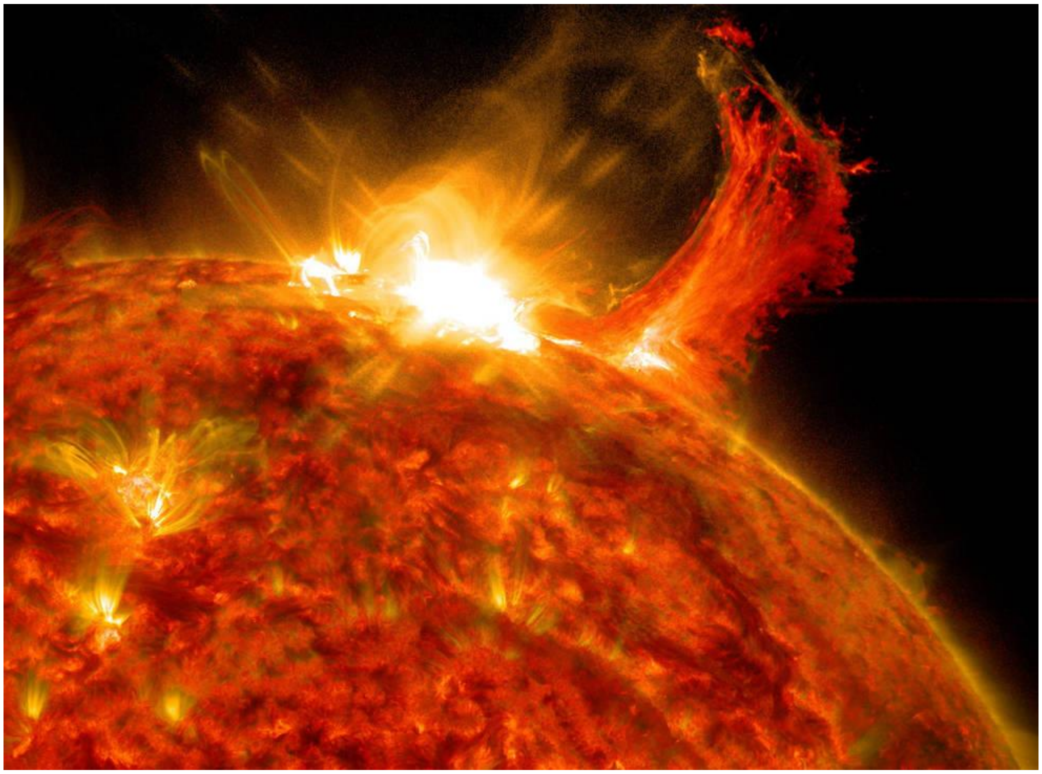
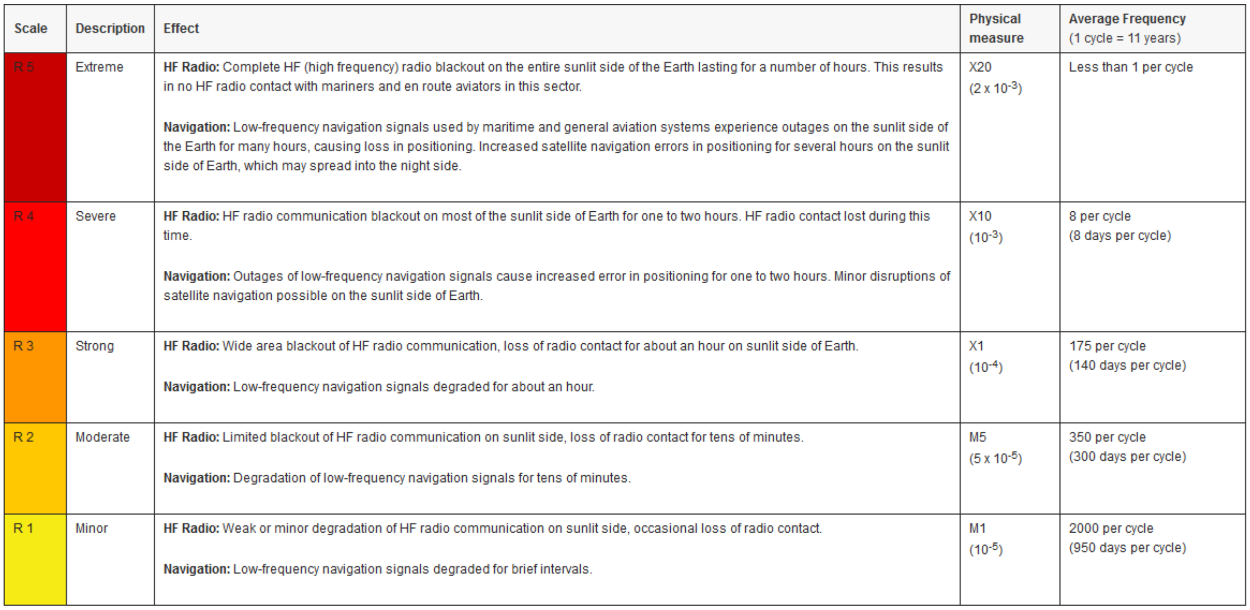


Figure 2. NASA image of a solar flare.

Radio blackouts are classified by NOAA using a five-level Space Weather Scale. The scale is directly related to the flares maximum peak in soft x-rays. The Space Weather Prediction Center forecasts the probability of C, M, and X flares.



Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2 x 10^{-3})	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5 x 10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

Figure 3. Blackout scales used by the Space Weather Prediction Center.

Solar Particle Events (SPE)

Solar Particles Events (SPE) are a release of large number of high-energy charged particles that are an external driver of space weather. Most of these are particles are protons and electrons, that are accelerated at a large fraction of the speed of light. These particles arrive at Earth between 30 minutes to several hours (light reaches in approximately 8 minutes). They are associated with solar eruptions resulting in high fluxes of energetic protons (1-500 MeV), electrons (up to MeV), and heavier elements (tens of MeV per nucleon) that flood interplanetary space at a wide range of longitudes. SPEs greater than 10MeV can penetrate space suits. Energies greater than 100 MeV can penetrate spacecraft. This makes an SPE event a risk for crew health and safety. Electronics aboard a spacecraft can be affected by an SPE by degradation, data corruption, noise, system shutdowns, and circuit damage. A Ground Level Enhancement (GLE) can also be produced, although less common, when nuclear interactions in the atmosphere at energies above 500 MeV produce neutron fluxes readily measurable at ground level.

At Earth's level, an SPE can be trapped in the geomagnetic field. During intense geomagnetic storms, they can gain access to lower radial distances in the magnetosphere. SPEs are a significant radiation hazard in the heliosphere and geospace. Since the Earth's magnetic field has a dipole nature, the impacts are most pronounced at the poles. Due to this, airlines flying polar routes during an SPE event have higher risk the health and safety of the crew and passengers, as well as the aircraft systems and components, due to the radiation dose.

Coronal Mass Ejections (CME)

A Coronal Mass Ejection (CME) is an explosive outburst of magnetized plasma from the Sun's outer atmosphere (Corona) into the heliosphere. The normal CME will begin as streamers that brighten approximately a day before erupting as massive releases that carry intense magnetic fields. A CME is an external driver of space weather. A CME will typically carry approximately a billion tons of material outward from the Sun. This material is carried at speeds of hundreds of kilometers per second, up to 3,400 kilometers per second (typical 250-3,000 kilometers per second). A CME contains particle radiation (protons and electrons) and powerful magnetic fields. They are not bright like solar flares are. They take approximately 1 to 4 days to travel to Earth, but some have arrived in as little as 18 hours. The slowest can take several days to arrive.

CMEs expand in size as the propagate away from the Sun. CMEs and the shocks associated with them can accelerate particles to relativistic energies. Approximately fifty percent of CMEs can drive shocks at the Earth's level. The shock wave is generated when the CME is traveling faster than the background solar wind. These shock waves can accelerate charged particles that are ahead of them. This causes and increased radiation storm potential or intensity. Sunspots can grow from the individual (unipolar) spot into more organized (bipolar) spot groups, and can even become complex sunspot groups (mixed polarities). These can be many times the size of the Earth and the number varies with the solar cycle. Figure 4 shows a NASA illustration of a CME blast and how it impacts Earth.

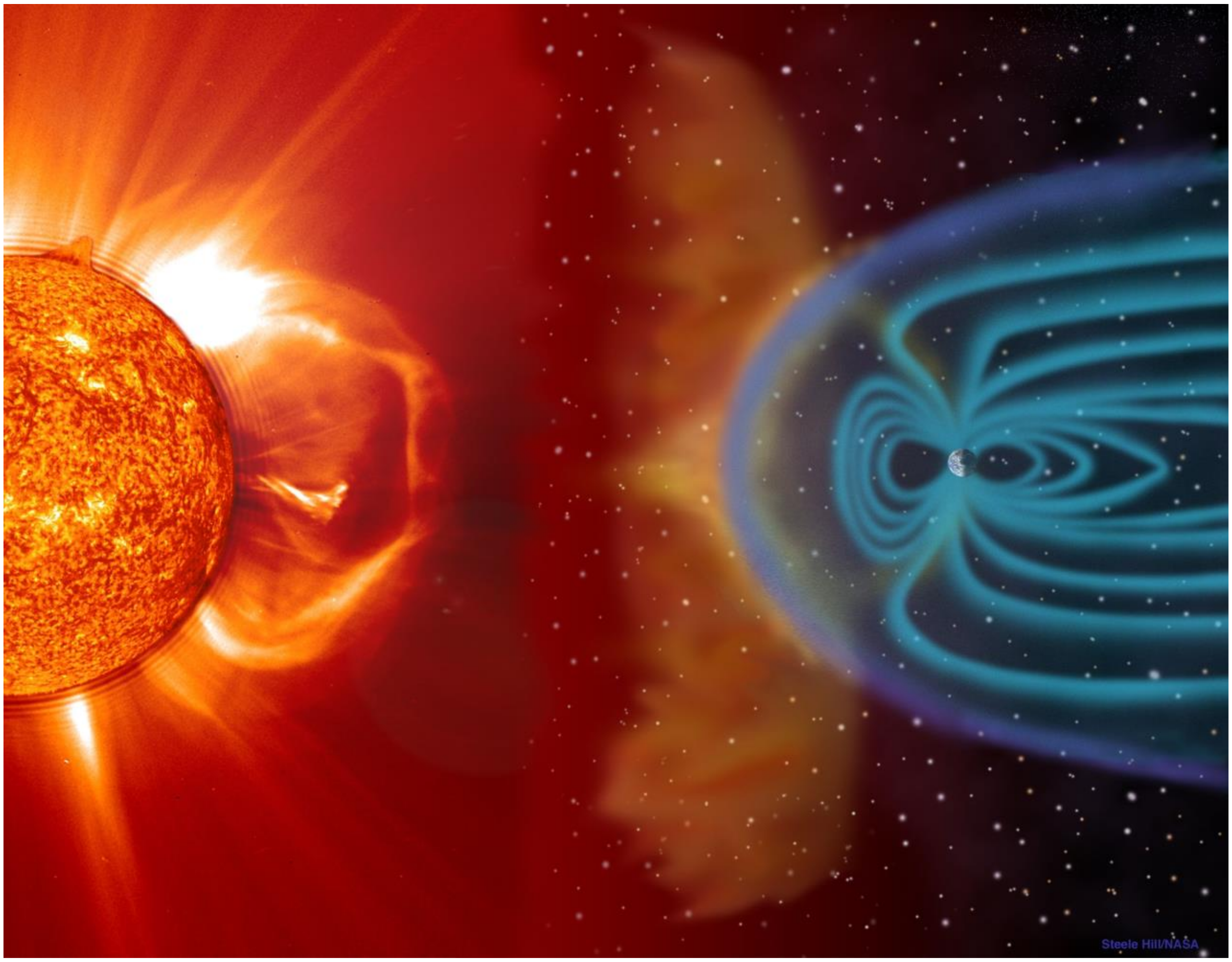


Figure 4. NASA illustration of a CME blast and its impact on Earth.

The more explosive CMEs typically start when highly twisted magnetic field structures (flux ropes) in the lower corona become too stressed and realign into a less tense configuration. This reconfiguration is called magnetic reconnection and can result in a sudden release of electromagnetic energy in the form of a solar flare. A solar flare typically accompanies the explosive accelleration of plasma away from the Sun. This type of CME usually occurs in areas of the Sun with localized fields of strong and stressed magneic flux. For example, active regions associated with sunspot groups. The most dangerous CME are dense and fast, and with magnetic fields parallel to and moving in the opposite direction (antiparallel) to the Earth's magnetic field. The anti-parallel magnetic fields reconnect with field lines in the bow wave, carrying them towards the tail. This allows CME plasma to propogate into the magnetosphere. Regardless of the orientation of the CME's magnetic field, the fast and dense CME produces an electromagnetic disturbance at the surface by compression of the magnetosphere's bow wave. If a CME is directed towards the Earth, it can interact with the Earth's magnetic field and cause geomagnetic storms.

CMEs are analyzed based on their size, velocity, and direction. SWPC forecasters attempt to determine the likelihood the CME will impact Earth, using these properties. They are inferred from orbital satellites' coronagraph imagery by SWPC forecasters. The imminent arrival of a CME is observed by the Deep Space Climate Observatory (DSCOVR) satellite in the L1 orbit area.

Radio Blackouts

Radio blackouts can be caused by solar flares and is one of the most common space weather events to affect the Earth. Solar flares emit bursts of X-ray and extreme ultraviolet radiation. The HF band (3-30 MHz) is the range typically affected. Fading and diminished reception may spill over to the VHF band (30-300 MHz) and higher frequencies. These storms are due to enhanced electron densities that are caused by the emission of solar flares. The solar flare emissions ionize the sunlit side of Earth, which increases the amount of energy lost as radio waves pass through this ionized region.

Minor radio blackout events occur approximately 2000 times each solar cycle. Blackouts are the fastest to impact our planet since the X-rays creating radio blackouts travel at the speed of light (approximately 8 minutes Sun to Earth). The Space Weather Prediction Center measures the intensity of solar flares and predicts their duration. Radio blackouts last from minutes to hours.

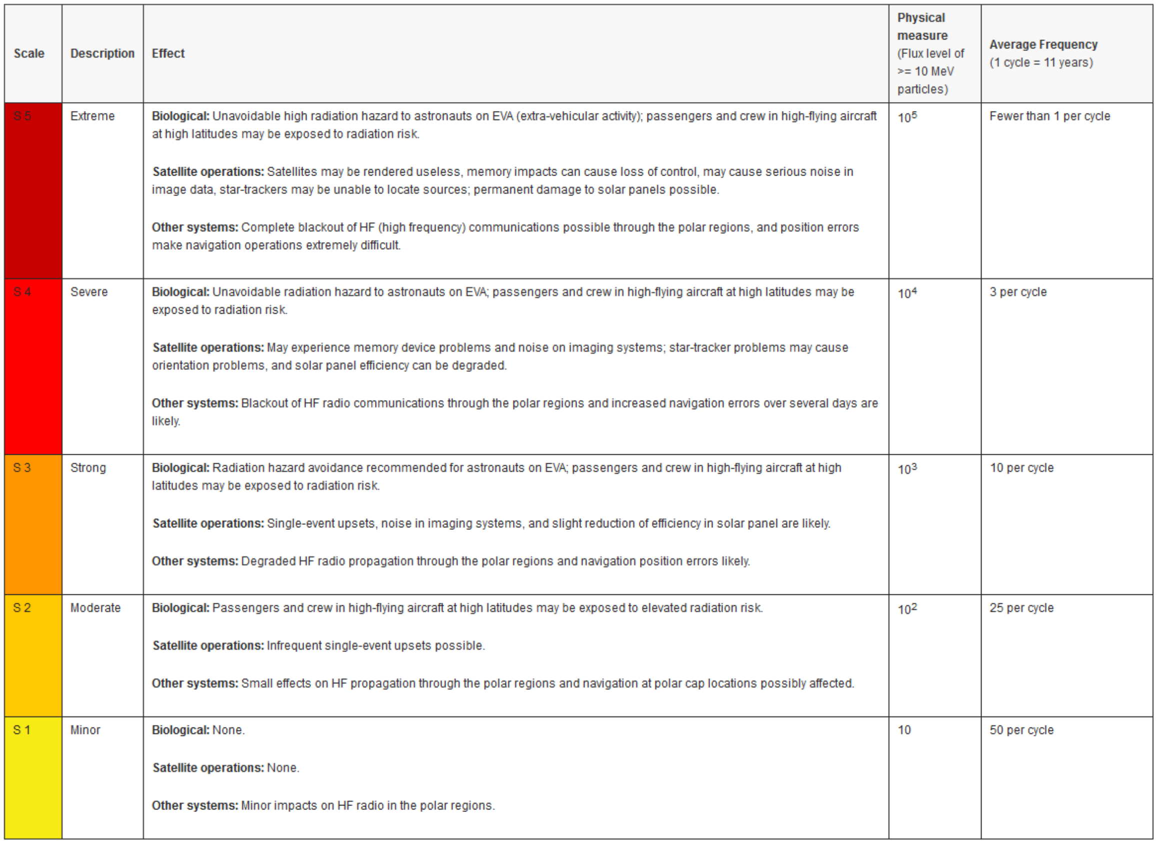
Industries that rely on HF and low frequency radio signals will feel the impacts of radio blackouts. These are primarily the aviation and marine industries that use these bands.

Solar Radiation Storms

Solar radiation storms happen due to the acceleration of large quantities of charged particles (protons and electrons) at or near the Sun. When these processes occur near the Sun, the near-Earth satellite environment is bathed with high-energy particles. A little protection from this radiation is offered by Earth's atmosphere and magnetic field. The amount of protection, however, is a function of altitude, latitude, and magnetic field strength. The most affected regions by energetic particles are the polar regions. This is because the magnetic field lines at the poles, extend downward vertically allowing the particles to spiral down the field lines and penetrate the atmosphere. This increases ionization.

Energetic protons arrive at Earth between 30 minutes to several hours after the solar eruption (light reaches in approximately 8 minutes), just like a solar particle event. The travel time will depend on the magnitude of the eruption. Solar radiation storms tend to be most common around the solar maximum, but can occur at any time in the solar cycle.

The impacts of solar radiation storms include the loss of HF radio communications through the Polar Regions. It also includes navigational position errors, and elevated radiation exposure to the crew and passengers in aircraft flying at high altitudes and latitudes. Damage to satellite systems can also occur. Solar radiation storms are rated by the Space Weather Prediction Center. Figure 5 shows the scales used and the effect of solar radiation storms as used by the Space Weather Prediction Center.



Scale	Description	Effect	**Physical measure** (Flux level of >= 10 MeV particles)	**Average Frequency** (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

Figure 5. Scales used by the Space Weather Prediction Center (SWPC) for radiation storms.

Geomagnetic Storms

Geomagnetic storms are strong disturbances to Earth's magnetic field. They create problems for technological systems as well as critical infrastructure. The magnetic field of Earth changes during a storm as the near-Earth system attempts to adjust to the energy from the Sun carried by the solar wind. Variations in the solar wind produce major changes in the plasmas, currents, and magnetic fields in the Earth's magnetosphere that help produce these storms.

The condition in the solar wind that best creates geomagnetic storms include sustained periods of high-velocity solar wind and a southward directed solar wind magnetic field (opposite direction of Earth's magnetic field) on the Sun facing side of the magnetosphere. This is the condition most effective in transferring energy to the Earth's magnetosphere from the solar wind.

Coronal Mass Ejections are the most energetic phenomena in the solar system and can disturb the geomagnetic field for several days at a time. The largest geomagnetic storms are associated with CMEs, where plasma from the Sun and its embedded magnetic field arrives at Earth.

The most visible signal of a geomagnetic storm is the aurora. It becomes brighter and moves closer to the equator. An example of an aurora is shown in Figure 5. It shows aurora australis taken from the International Space Station (ISS). Geomagnetic storms can last for a few hours to a few days with the strongest lasting for a week. A string of CMEs can cause a prolonged period with additional energy being pumped into the Earth's magnetic field. The frequency of geomagnetic storms depends on the solar cycle, with most storms occurring near solar maximum. They are also common in the declining phase because of high-speed solar wind streams.

Figure 6. The Aurora Australis in a NASA picture taken from the International Space Station.

In space, a ring of westerly current moving around Earth produces magnetic disturbances in the ground. A measure of this current, known as the disturbance storm time (Dst) index, has been historically a method to size a geomagnetic storm. It is a measure of the hourly average horizontal field strength measured by four magnetometers located near the equator around the globe. Dst is expressed in nano Teslas.

Horizontal magnetic field variations are measured by Kp. It is the 3-hour average of the field variation average at thirteen magnetometers. It is expressed as an integer between zero (0) and nine (9). When Kp=7, is when power companies begin monitoring these changes.

Geomagnetic storms can create aurora. These include the Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights). Figure 6 shows a NASA photo of the Aurora Australis taken from the International Space Station (ISS). Aurora is the result of electrons colliding with the upper Earth atmosphere.

Geomagnetic storms can also disrupt navigation systems, such as the Global Navigation Satellite System (GNSS). Geomagnetically induced currents (GIC) can be harmful to pipelines as well as the power grid. GIC can linger for hours with short burst of intense flow.

The Space Weather Prediction Center rates the strength of geomagnetic storms as shown in Figure 7. Geomagnetic storms can be responsible for generating or enhancing many space weather hazards. These hazards include GIC, radiation hazards, thermospheric expansion, and ionospheric disturbances. Geomagnetic storms typically occur frequently (several per month) during solar maximum and one or two per month around solar minimum.

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

Figure 7. The strength of geomagnetic storms as shown by the Space Weather Prediction Center.

Solar Irradiance

Another external driver of space weather is solar irradiance at ultraviolet and shorter wavelengths. It is important in the Earth's atmosphere and the ionosphere where those wavelengths are absorbed. Most energy in the Sun's irradiance is in the optical or near infrared wavelengths (greater than 300 nm) that either pass through or are reflected from the atmosphere and have no significant impact on space weather. Wavelengths shorter than 300 nm are absorbed by the upper atmosphere. Solar emissions between 120 nm and 300 nm reach to the 100 km height (E-layer) and are absorbed by oxygen and ozone.

The shorter wavelengths act as a major driver of space weather phenomena in the Earth's atmosphere, even though they transport much less energy. The shorter wavelengths are able to photoionize atomic and molecular particles to disturb the ionosphere. Less than 100 nm is dominated by lines from the hot plasma in the chromosphere, transition region, and corona. The coronal component, where temperatures exceed 10^6 K, dominate below 30 nm and also vary largely with solar activity levels. Solar flares produce orders of magnitude variation at x-ray wavelengths. The wavelengths between 20 and 100 nm deposit their energy at heights between 120 and 400 nm and the heating produced creates an increase in temperature that represents the thermosphere. Wavelengths that are shorter than a few nanometers can reach heights of 90 km or lower, which is the D-layer ionosphere.

Solar Radio Burst

Solar Radio Bursts (SRB) are produced by Coronal Mass Ejections and solar flares. There are three types of radio bursts relevant to space weather. The plasma emission mechanism produces intense radio bursts such as Type II, II, and IV at metric wavelengths. At the shorted centimeter wavelengths, the electrons that produce hard x-rays and gamma rays irradiate by the synchrotron emission mechanism. In the decametric wavelength range used by cell phones and GPS there are occasional intense bursts thought to be due to the electron cyclotron maser mechanism.

Cosmic Rays

Cosmic Rays are very energetic protons and atomic nuclei that are present throughout the heliosphere (kinetic energies greater than 10s of MeV/nucleon). They can pose a radiation hazard to systems and crew operating outside the Earth's atmosphere. Cosmic rays are considered energetic particles of an extrasolar origin and separate from SEPs. The flux of cosmic rays, resident in the heliosphere is modulated by solar magnetic fields and solar wind transients. This results in a solar cycle modulation of the cosmic ray intensities. Cosmic rays are more intense during solar minimum than solar maximum in the heliosphere. Solar wind transients also result in shorter scale decreases in cosmic ray intensities during passage of those transients through the heliosphere. These decreases are known as Forbush decreases.

Historical Examples

The earliest written record of a great aurora was from 576 B.C. It was from a clay tablet that was discovered in Babylon. Shaping the account of the event took a lot of work. This indicates that it was a significant event.

A historical example of a geomagnetic storm occurred in 1859. It was known as the Carrington Event and it was the most intense geomagnetic storm in recorded history. It got its name from Richard Carrington, an amateur astronomer. It was documented independently by Richard Carrington and Richard Hodgson on September 1, 1859 as they made the first records of a white light solar flare. Their independent reports were published in Monthly Notices of the Royal Astronomical Society.

A geomagnetic storm was associated with the bright solar flare and was initiated by a major CME. On the morning of September 1, 1859, Carrington observed a cluster of enormous dark spots on the surface of the sun. He suddenly noticed "two patches of intensely bright and white light" that erupted from the sunspots. The light lasted for only five minutes, but within hours, the impact would be felt worldwide.

Auroras were seen around the world and in both hemispheres. The aurora over the Rocky Mountains was so bright that it woke gold miners and hikers. Since the miners thought it was morning and started making breakfast. People that were in the northeastern United States found that they could read their newspaper by the aurora lights.

Another effect of the geomagnetic storm was induced current in telegraph systems. The electromagnetic field induced currents in telegraph systems worldwide. Many of them failed and gave the operators electric shocks and the sparks set papers on fire. Many telegraph pylons threw sparks as a result of the induced currents. Some operators were able to send and receive messages using the GIC in the lines, even after disconnecting their power supplies.
The magnetic deflections allowed the storm's magnitude to be estimated. The deflections were recorded a Kew Observatory in England. This recording was done on photographic paper.

The cause of the Carrington Event was a massive solar flare. It had the energy of 10 billion atomic bombs. It forced large amounts of subatomic particles and electrified gas towards Earth. There were ice core samples taken that demonstrated that the Carrington Event was twice as big as any other solar storm that has occurred in the last 500 years.

Another geomagnetic storm also occurred in 1921. It was less severe than the Carrington Event, but did cause widespread radio disruption. It occurred on May 14-15, 1921, and cut Washington D.C. off telegraphically and caused worldwide disruption of telegraph and telephone services. This was due to a disturbance in the lines of American Telegraph and Telephone Company. It was later written that excessive Earth potentials caused major issues, such as breaking down condensers and insulation, burning out line protectors, and starting fires in terminal offices. The cause was Geomagnetically Induced Currents (GICs) introduced into the telegraph lines, resulting from the impacting CMEs. They caused fires in Karlstad, Sweden and Brewster, New York. Auroras were visible as far south as the equator.

The Sunspot Tornado occurred in March 1940. It was a CME that caused havoc with communications for several hours. This disruption included long distance telephone service. Short wave had a complete blackout between the United States and Europe, and a partial disturbance to South America. Telegraph service was disrupted for five hours when the lines were busiest, with Easter messages. It also disrupted the teletype machines for the press, state police, airports, and railroads. Disturbances were reported by ten power companies in New England, New York, and eastern Pennsylvania, as well as the southern and eastern parts of Minnesota and in Ontario and Quebec. There were also 7 cases of voltage dips, 5 cases of tripped transformer banks, and 4 cases of surges or swings in reactive power.

The Sunspot Tornado was explained by William Barton, Jr, Executive Curator of the Harden Planetarium. Mr. Barton explained that the “tornado” occurred on the sun. It was seven spots. He explained that the Earth’s magnetic field deflected a stream of electrical charges toward the poles. This disrupted other electrical currents that were flowing at right angles. It has been noted from effects of the storm, that locations where anomalies and voltage swings tended to occur in areas where the Earth’s resistivity was greatest.

A geomagnetic storm occurred on February 10, 1958, and disrupted telephone traffic for about an hour. This disruption was on the cable under the Atlantic that had been transmitting for about a year and a half. This was in addition to disrupting power lines. The event tripped many circuit breakers in the Ontario transformer stations, putting many areas into darkness. Aurora could be seen overhead during this time. This was an example of a large and widespread disturbance of long conductor electric power systems, as was the Easter 1940 event. Concern for long conductors became more centered on the electric power grid after the 1958 event.

A geomagnetic storm occurred on March 13, 1989, that caused currents in the ground and knocked out power for large portions of Quebec, Canada within 92 seconds. The geomagnetic storms caused a 9-hour power outage for Hydro-Quebec's power transmission system and the James Bay Network. It was caused by two separate CMEs that occurred on March 10th and 12th. The problems that occurred with the geomagnetic storm were not limited to Canada. There was significant interference that occurred to the United States power grid. Communications blackouts also occurred, especially shortwave radio. Satellite communications were interrupted, causing some disruption in control signals and loss of images. The Space Shuttle Discovery had a sensor malfunction on a hydrogen supply tank. The problem went away after the geomagnetic storm ended. Charged particles induced electrical current in the ground.

The Halloween Storms of 2003 occurred at the end of Solar Cycle 23. This was at a time where it had been over five months since the Sun had produced any activity to note. Two Jupiter sized sunspots had appeared on the Sun in mid-October. A third sunspot appeared by October 28, 2003. The storms began in mid-October and lasted until early-November 2003. The storms affected satellite systems and communications. Aircraft were advised to avoid high altitudes if they were near polar regions. Solar activity caused an hour-long power outage in Sweden. A dozen power transformers in South Africa were damaged and had to be replaced. Numerous spacecraft were damaged by the solar activity.

A similar solar superstorm occurred on July 23, 2012, beginning with a CME coming from the Sun. It narrowly missed Earth by approximately nine days. It happened during high sunspot activity during solar cycle 24. The CME expelled a pair of magnetic clouds adjacent to each other. The clouds drove a shock wave outward from the Sun. The CME did not hit Earth. If it had, it could have inflicted massive damage to electronic systems all over the world.

The data collected from the July 2012 event indicated that the eruption was two separate ejections that had been able to reach extremely high strength.

Research has been conducted to look for the signatures of CMEs and large solar flares. This is by analyzing carbon-14 in tree rings and beryllium-10 in ice core samples. This research has indicated a large solar storm for 774-775 A.D. Carbon-14 shows a possible solar storm in 775 that had 20 times the normal variation of the activity of the sun and 10 times the size of the Carrington Event. Also indicated are events for 993-994 A.D. as well as 7176 B.C.

Systems Impacted by Space Weather

Space weather can have an influence on many systems. Among these are electrical, navigation, aviation, surveying, and communications systems.

Large currents in the ionosphere can induce currents in power lines. Geomagnetic storms can induce currents in power lines and impact power equipment. Power surges from the induced currents (GIC) can cause network failures and damage to the components of the electric grid. Geomagnetically Induced currents can enhance corrosion in pipelines. This corrosion occurs especially if there are breaks in insulation. Corrosion protection electronics can also be damaged. Induced currents can cause railroad signals to be interrupted.

Disturbances in the ionosphere can degrade GPS range measurements. In severe cases it can cause loss of lock on the GPS signal by the receiver.

Aviation can be affected by space weather in several ways. The first is that space weather can cause lost or degraded communications. There can also be radiation hazards to the crew and passengers. Navigation systems can get unreliable information, some due to GPS as stated above. Problems can also occur with flight critical electronic systems due to gamma rays and fast particles damaging the electronics.

Satellite operations problems can occur due to space weather. The high-energy ions penetrate electronic components. This penetration can cause bit flips in a chain of electronic signals, resulting in improper commands within the satellite. It can also result in improper commands from an instrument. Spacecraft surface charging problems can result from less energetic particles. This often occurs during periods of high geomagnetic activity.

Geomagnetic storms cause magnetic field changes that affect operations using the Earth’s magnetic field for guidance. This includes magnetic surveys, directional drilling, and the use of magnetic compasses. Disturbances in the ionosphere cause errors in locations obtained from GPS signals.

Communications is the most noticeable system to be affected by space weather. Communications on all frequencies may be affected. Communications in the HF band are routinely affected by space weather. This is because HF depends on reflection by the ionosphere to carry signals over large distances.

Not only can systems be affected, there can be cascading impacts. This is where a disruption in one infrastructure impacts another infrastructure. At the simplest level, a failure in the electric grid cause a failure in water supply due to not being able to operate electric pumps. It is likely that space weather will have the greatest impact on communications, messaging, and information management systems. It is possible for the national power grid to suffer significant disruptions. If a severe space weather even causes severe communications disruptions, it could result in power grid blackouts.

Due to the possible degradation of communications systems, internal and external messaging may be difficult during a long-term power outage.

Space Weather Hazards

The space weather phenomena previously mentioned can be space weather hazards. The NASA Gap Analysis Report discussed five space weather hazards.

1) Geomagnetically induced currents (GIC). These affect power grids, pipelines, communications cables (non-optical), and rail networks. Currents are created in the ground, which can damage components and cane cause instability in the electric grid (causing the system voltage to collapse).
2) Radiation effects impacting operations, functionality, and health and safety of spacecraft, stations, and aircraft. The specific hazards involved include Even Total Dose (ETD), Single Event Effects (SEE), and internal, subsurface/hybrid, and external charging and discharge. Radiation can also discolor spacecraft surface materials. Flight paths of aircraft over the North Pole yield higher exposure to cosmic rays, due to reduced magnetic field and atmospheric shielding.
3) Disturbances in the ionospheric regions affecting communications and navigation due to electromagnetic signal disruptions in the ionosphere.
4) Thermospheric expansion and neutral density structures that affect satellite drag, orbit estimation and prediction, and collision avoidance.
5) Solar radio busts that affect radio navigation and communications. This includes radar and GPS.

These space weather hazards are categorized and prioritized based on likelihood (frequency or probability of occurrence) and consequence (impact).

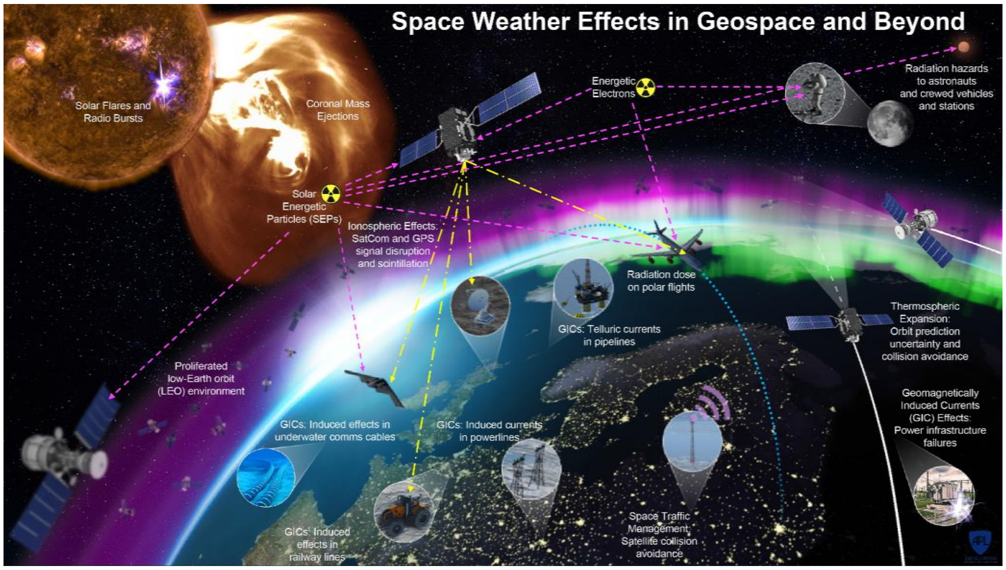


Figure 8. NASA Depiction of space weather events, effects, and hazards in the geospacer and beyond.

Space Weather Forecasting

Space weather conditions are monitored by the Space Weather Prediction Center (SWPC) located in Boulder, Colorado. The SWPC operates 24 hours a day and 7 days per week. It continuously monitors conditions on the Sun using both ground observations and data received from spacecraft or satellites.

The SWPC communicates current and future space weather conditions and the possible effects of the conditions. NOAA has Space Weather Scales that are similar to Earth bound weather and geological phenomena, such as hurricanes, tornados, and Earthquakes. There are space weather scales for radio blackouts (R1 through 5), solar radiation storms (S1 through 5), and geomagnetic storms (G1 through 5). The letter prefix describes the type of space weather event and the number describes the intensity.

The United States Air Force 557th Weather Wing works closely with the SWPC to ensure coordination of forecasts and product compatibility between the civilian and military sectors. The 557th provides products for use by the Department of Defense.

Forecasters use many methods to analyze and understand space weather. One method is to use solar images in the analysis of active solar regions. These are the localized areas containing enhanced sunspots and intensified magnetic fields. They analyze sunspot groups that can be many times the size of the Earth and can contain complex magnetic structures. The SWPC forecasters assess the size and magnetic complexity of these regions. They also analyze the growth and decay of these regions to predict the probability of a solar flare.

The forecasters at the SWPC also use computers to model and understand the current state of the space weather environment, and predict future behavior. This is similar to the way standard weather forecasters attempt to model the behavior of a hurricane or a cold front.

The Space Weather Prediction Center has several notification products. They include watches, warnings, alerts, and summaries. Watches have a longer lead time in the prediction of a space weather event and has a lower confidence in the timing and intensity of a predicted disturbance. Warnings, on the other hand, are high confidence predictions of a space weather event that are issued minutes or hours before the event. An alert is an indication that the Earth is experiencing an even that has the potential to impact critical infrastructure. An event summary is one of the many types of summaries issued by the SWPC and is the one relevant to disaster preparedness.

Watch Center Notifications

There are several types of watches, warnings, and alerts that the SWPC issues. They are for geomagnetic disturbances and radiation events.

Geomagnetic Disturbance Watch

A Geomagnetic Disturbance Watch is where an impending CME is observed. The watch covers up to 90 hours of lead time, although lead times vary significantly. A watch has a lower confidence in intensity and timing than a warning. It is used for longer-range notification of a geomagnetic disturbance.

Geomagnetic Disturbance Warning

A Geomagnetic Disturbance Warning is based on the observation of the solar wind conditions that affect Earth. Warnings carry a higher degree of confidence in timing and intensity than watches. They are issued minutes to two hours in advance. The SWPC will only issue a single warning for an event.

Geomagnetic Disturbance Alert

A Geomagnetic Disturbance Alert is based on magnetometer observations and indicated the specific threshold being reached. It is an assessment of what is currently occurring at the present time.

Radiation Event Warning

A Radiation Event Warning indicates a event of minutes to hours in time. The lead time depends upon the location on the active region of Sun. There are some cases where almost no warning lead-time is present.

Radiation Event Alert

A Radiation Event Alert is issued when the observed values at the NASA GOES satellites exceed event thresholds. They are driven by measured intensity and are issued for each radiation event scale level.

Radiation Event Summary

Radiation Event Summaries are issued after the event. They will indicate the peak intensity as well as start, peak, and end times for each event level.

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