Chapter 7

Space Environment

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Special consideration must be given to the design and fabrication of systems that must operate in the harsh environment of space. Our increased dependence on space-based systems to meet war-fighter objectives and needs, coupled with the increasing use of microelectronics and a move to nonmilitary specifications for satellites, increases our vulnerability to the loss of critical satellite functions or entire systems. Therefore, it is essential to further our understanding of the space environment.

An Introduction to the Space Environment

The study and analysis of the space environment is a relatively new science. Each day we gather and process new information that increases our understanding of this environment and its effects on systems that operate within it. One conclusive fact is that space is a hostile environment for both man and machine. The more we learn and understand about the space environment, the more effectively we can lessen the negative impacts on both our space and ground systems. Events such as solar flares can have a direct impact not only on our terrestrial communications, but also on the functioning and survivability of our satellites.[1]

Our command, control, and communications systems have advanced rapidly, and at the same time we have developed a vulnerable dependence on space-based systems for passing information. From commercial communications to highly secure and survivable military systems, space-based assets provide a link to the information age. The war fighter's reliance and dependence upon space-based assets will continue to grow in the future. The expanding use of microelectronics and nonmilitary, commercial off-the-shelf products increases the risk to the war fighter that operational systems may fail or be degraded because of solar activity. This is why expanding our knowledge of the sun and the space environment is so important.

First, it is important to understand the nature of the space environment.[2] It is neither empty nor benign and is impacted by extreme forces of nature. The primary force in our corner of the universe is our sun. The sun is constantly radiating enormous amounts of energy across the entire electromagnetic spectrum containing x-rays, ultraviolet, visible light, infrared, and radio waves. The sun also radiates a steady stream of charged particles—primarily protons, electrons, and neutrons—known as the solar wind. Threats from electromagnetic and charged particle radiations are enhanced greatly when there is an increase in solar activity.[3]

The magnetosphere is the earth's geomagnetic field. The magnetopause is the outer boundary of the magnetosphere. The magnetosphere is partially flattened on the sunlit side of the earth. This flattening is a direct result of pressure applied to the magnetosphere by the solar wind.[4] As the solar wind passes by the earth and over the magnetosphere, it causes the earth's geomagnetic field lines to be stretched out on the side opposite that facing the sun. These geomagnetic field lines extend past the earth for millions of miles. This is referred to as the magnetotail.[5] Next, we will look at some aspects of solar radiation and energy.

Radiation

Radiation is "the emission or propagation of waves or particles."[6] Particle radiation is the easiest to describe and envision. It is the result of atomic or subatomic particle collision, fusion—which is the primary atomic reaction that keeps the sun burning—or the natural decomposition of a radioactive material such as plutonium. In such events, subatomic particles, generally in the form of protons, neutrons, and electrons, are physically projected from one place to another.[7]

Electromagnetic radiation is sometimes referred to as light or radiant energy. Traditionally, we have viewed it as an electrical-type waveform that can travel through a vacuum as easily as it can travel through air and moves at the speed of light. The sun continuously emits electromagnetic radiation across the entire spectrum. To understand the space environment we need to understand more about electromagnetic radiation.

The orderly arrangement of accepted categories of electromagnetic energy is called the electromagnetic spectrum (fig. 7-1). It ranges from the highest energy and shortest wavelength (cosmic rays) to the lowest energy and longest wavelength (TV and radio).

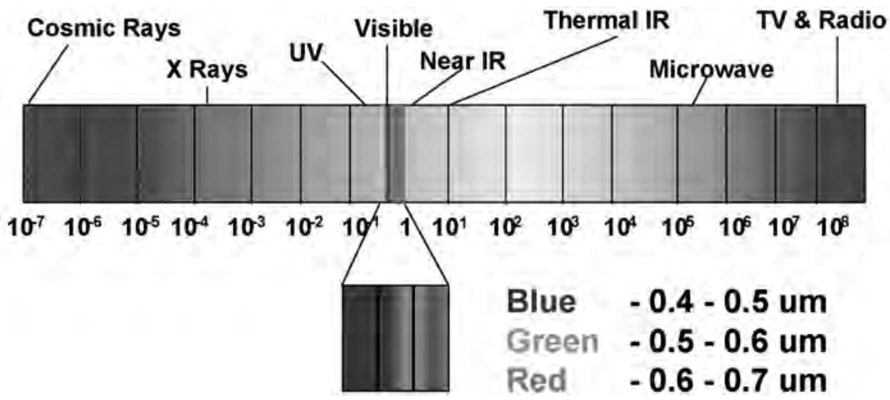

Figure 7-1. **Electromagnetic spectrum**. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2004, 8-4.)

It is interesting to note that visible light, which is by far the most obvious to human senses, occupies a mere 2 percent of the electromagnetic spectrum. Distribution of energy is such that the most intense portion falls in the visible part of the spectrum. Substantial amounts also lie in the near-ultraviolet and infrared portions. Less than 1 percent of the sun's total emitted electromagnetic radiation lies in the extreme ultraviolet (EUV)/x-ray and radio-wave portions of the spectrum.[8] However, despite the bulk of the sun's electromagnetic radiation being in the visible bands, we still have a problem in the other areas. DOD radar, communications, and space systems work in the EUV/x-ray and radio-wave energy bands. The sun's radiation in these bands is of no direct use to us in these DOD applications, and, in fact, their constant presence has to be overcome as naturally occurring "background noise." During periods of increased solar activity, the amount of emitted EUV and x-ray energy can be multiplied by a factor of 100, and radio-wave energy by a factor of tens of thousands over the normal solar output. This can cause numerous extensive DOD system problems.[9]

Coronal Mass Ejection and Solar Flares

Adding to the normal energy output from the sun, there are periodic and random solar activities that result in massive increases in ambient energy. The prime events in solar activity are the coronal mass ejection (CME) and the solar flare. To understand these phenomena, we need to address the forces at work.

The outer solar atmosphere is called the corona. It is structured by strong magnetic fields. Where these fields are closed, often above sunspot groups, the confined solar atmosphere can build up enormous pressure and violently erupt, releasing bubbles or tongues of gas and magnetic fields called CMEs. A large CME can contain 10 billion tons of matter that can be accelerated to several million miles per hour in a spectacular eruption. Solar material streaks out through space, impacting anything in its path, such as planets or spacecraft. CMEs are sometimes associated with flares but usually occur independently.[10]

A solar flare is an explosive release of energy, consisting of both electromagnetic and charged particles, within a relatively small but greater-than-Earth-sized region of the lower solar atmosphere. The energy released is substantial, equivalent to the simultaneous detonation of a trillion five-megaton nuclear weapons, but it represents only one hundred-thousandth of the normal total solar output. However, the enhanced x-ray, EUV, radio wave, and particle emissions from a flare are sufficient to affect DOD space and ground systems significantly.[11]

We now know that sunspots, their magnetic fields, flares, and CMEs are very closely related and can have significant impacts on DOD space systems. Solar flares and CMEs tend to occur in regions of sunspot activity, and the level of sunspot activity generally follows an 11-year cycle. The peaks are known as the solar maximums (sometimes called solar max) and the valleys as the solar minimums. In short, as the number of observed sunspots increases, so does solar activity.

The most recent solar minimum occurred in early 2006, while the most recent solar maximum occurred in late 2000.[12] Although an increase in flares and CMEs generally coincides with the 11-year solar cycle's period of solar max, they can occur at any time. What are the effects on Earth from increased solar activity? One of them is called a geomagnetic storm. A geomagnetic storm is the mechanism by which the solar wind disrupts our magnetosphere and adversely affects radar, communications, and space operations.[13]

Generally, the stronger a solar flare or CME, the more severe the event's impacts on the near-Earth environment and on DOD systems operating in that environment. Unfortunately, the impacts discussed in this section would not likely occur singly or sequentially, but would most likely occur simultaneously in combinations of more than one thing. The stronger the solar activity, the more simultaneous effects a system or systems may experience.

The earth's magnetic field deflects solar particles, preventing direct access to the near-Earth environment, except for the funnel-like cusps above the polar caps. However, when an enhanced solar wind, caused by a solar flare or a CME, sweeps past the earth, its impact sends shockwaves rippling through the magnetosphere. Out in the magnetosphere's tail, drawn-out magnetic field lines reconnect and, like a snapping rubber band, shoot trapped particles back toward the earth's night side, that is, the side of the earth that is in darkness. Some of these particles stay near the equatorial plane and feed into the Van Allen radiation belts; others follow geomagnetic field lines and fall into the high northern and southern latitudes, or auroral zones. The result is a disturbance called a geomagnetic and ionospheric storm.

DOD system impact occurrences make sense when one looks at the night-side particle injection mechanism just described. The vast majority of radar, communications, and spacecraft problems occur in the night sector and not in the daylight sector.

Van Allen Radiation Belts

The outer and inner Van Allen radiation belts are two concentric, toroid (or donut-shaped) regions of stable, trapped charged particles that exist because the geomagnetic field near the earth is strong and field lines are closed. The inner belt has a maximum proton density approximately 5,000 km above the earth's surface and contains mostly high-energy protons produced by cosmic ray collisions with the earth's upper atmosphere. The outer belt has a maximum proton density at an altitude ranging from 16,000 to 20,000 km and contains low- to medium-energy electrons and protons whose source is the influx of particles from the magnetotail during geomagnetic storms.[14]

The Ionosphere

The ionosphere is a part of the earth's atmosphere that has a significant impact on communications. Solar radiation ionizes this layer. When we attempt communication by either ground or satellite, the ionosphere plays a major role in its success or failure.

The ionosphere begins in the mesosphere, around 45 miles above the earth's surface, and continues upward until it merges with the ionized interplanetary medium at the exosphere, normally around 250 miles above the earth. The variation of electron density as altitude increases has led to the subdivision of the ionosphere into what are termed the D-, E-, and F-layers. The F-layer is further divided into two regularly occurring layers, F1 and F2.

The D-layer is the lowest portion of the ionosphere and is characterized by relatively weak ionization. It is mainly responsible for absorption of high-frequency radio waves.

The E-layer is above the D-layer and is useful for returning radio signals to the earth. These layers, however, are only capable of refracting radio signals during sunlight hours and practically disappear after sundown.

The F-layer, the uppermost layer of the ionosphere, is the region mainly responsible for long-distance communications. It ionizes very rapidly at sunrise and decays very slowly after sunset, reaching minimum ionization just before sunrise. During the day, the F-region is split into two layers, F1 and F2. F1 does not impact propagation, and like the D- and E-layers, it decays after sunset but is replaced by a broadened F2-layer. The F2-region is the primary medium supporting high-frequency (HF) communications.[15]

We have now looked at the sun's impact on the space environment and the earth's atmosphere. However, there are other naturally occurring threats that can literally impact satellites.

Comets and Meteor Showers

Comets are space objects believed to be mainly composed of ammonia, methane, carbon dioxide, and water (ice) traveling in large, highly elliptical orbits around the sun. Comets are often referred to as dirty snowballs. When seen from Earth, they are characterized by their long, vaporous tail. As the comet approaches the sun, it heats, and some of the core material begins to slough off, forming the tail. If the comet's orbit crosses Earth's orbit, our planet will cross through it on all subsequent yearly orbits of the sun. This gives rise to rather spectacular meteor showers.[16]

The Leonids meteor shower results from the earth passing through the orbit of the comet 55P/Tempel-Tuttle. The name *Leonids* is derived from the resulting meteor shower, which appears to emanate from the constellation Leo. The Leonids is only one of several passages of the earth through comet trails each year. Some others include the Perseids in August, Geminids in December, and the Lyrids in April.[17]

The most obvious danger from comet debris belts is high-speed collision. There can be physical damage to solar panels, reflective surfaces, and even internal components as a result of particle bombardment. However, there is another potential problem. Today's population of satellites uses circuitry that runs in milli-volt ranges using microcircuits and sensitive chips. Plasma generation can damage and degrade these expensive and possibly defenseless systems.

The Space Environment and System Impacts

It is important to emphasize again the reason that this information on the space environment is of paramount interest to the war fighter. We cannot change the sun's activity level or type. However, we can understand what is happening to us because of solar activity. We can then provide alternate means to ensure that the mission of the war fighter is continued and brought to a successful conclusion.

As we have learned, there are several types of enhanced solar emissions, each with its own characteristics and impacts. We will discuss the impacts that result from the three main categories of emissions:

- Electromagnetic radiation
- High-energy particles
- Low- to medium-energy particles

In the case of solar electromagnetic radiation effects, the enhanced x-rays, EUV, and radio waves reach the earth at the speed of light, in about eight minutes, and can cause environmental and DOD system impacts anywhere over the earth's sunlit hemisphere. Fortunately, these effects tend to last only a bit longer than the flare that produced them, normally a few minutes to an hour or two.

Operational Impacts

Each solar-geophysical phenomenon or event has the potential to affect radar, communications, and space systems.[18] The next sections explore the many operational impacts on DOD and non-DOD systems that a war fighter may experience. Those impacts are presented first in general, then individually.

DOD System Impacts. Generally, the stronger a solar flare, the denser/faster/more energetic a particle stream, or the sharper a solar wind discontinuity or enhancement, the more severe the event's impacts will be on the near-Earth environment and on DOD systems operating in that environment. Unfortunately, the DOD system impacts discussed in this section do not occur one at a time, but will most likely occur in combinations of more than one thing. The stronger the causative solar-geophysical activity, the greater number of simultaneous effects a system may experience. Each of the three general categories of solar radiation has its own characteristics and types of immediate or delayed DOD system impacts (fig. 7-2).

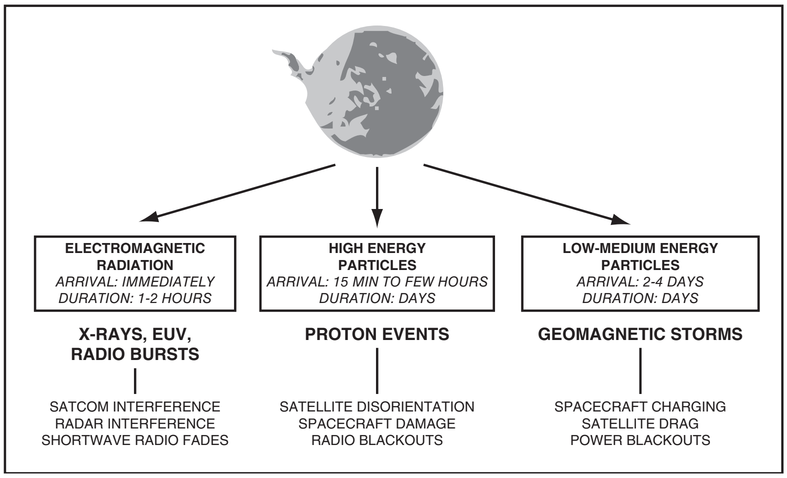

Figure 7-2. **Solar radiation particle types and effects**. (*Adapted from* Air University, *Space Primer*, unpublished book, 2003, 6-2.)

Non-DOD System Impacts. DOD systems are not the only ones affected by solar-geophysical activity. Some of these "non-DOD" impacts can indirectly affect military operations. For example, system impacts from a geomagnetic storm can include (1) induced electrical currents in power lines that can cause transformer failures and power outages and (2) magnetic field variations, which can lead to compass errors and interfere with geological surveys.

Electromagnetic (Immediate) versus Particle (Delayed) Effects

Every solar event is unique in its exact nature and the enhanced emissions it produces. Some solar events cause little or no impact on the near-Earth environment because their enhanced particle and/or electromagnetic (x-ray, EUV, and/or radio wave) emissions are too feeble or their particle streams may simply miss hitting the earth. For those events that do affect the near-Earth environment, effects can be both immediate and delayed, depending on the exact type of enhanced radiation emitted. The following paragraphs summarize the three general categories of solar radiation and the immediate or delayed DOD system impacts they produce.

Electromagnetic Radiation. We detect flares by the enhanced x-ray, ultraviolet, optical, and/or radio waves they emit. All of these wavelengths travel to the earth at the speed of light (in about eight minutes), so by the time we first observe a flare, it is already causing immediate environmental effects and DOD system impacts. These impacts are almost entirely limited to the earth's sunlit hemisphere, as the radiation does not penetrate or bend around the earth. Since enhanced electromagnetic emissions cease when the flare ends, the effects tend to subside as well. As a result, these effects tend to last from only a few tens of minutes to an hour or two. Sample system effects include satellite communications (SATCOM) and radar interference (specifically, enhanced background noise), long-range aid to navigation (LORAN) errors, and absorption of HF (6–30 megahertz [MHz]) radio communications.

High-Energy Particles. These particles (primarily protons, but occasionally cosmic rays) can reach the earth within 15 minutes to a few hours after the occurrence of a strong solar flare. Not all flares produce these high-energy particles (and the earth is a rather small target 93 million miles from the sun), so predicting solar proton and cosmic ray events is a difficult challenge. The major impact of these protons is felt over the polar caps, where, as explained earlier, the protons have ready access to low altitudes through funnel-like cusps (Earth's magnetic field lines that terminate into the North and South Poles) in Earth's magnetosphere. The impact of a proton event can last for a few hours to several days after the flare ends. Sample impacts include satellite disorientation, physical damage to satellites and spacecraft, false sensor readings, LORAN navigation errors, and absorption of HF radio signals. Proton events are probably the most hazardous of space weather events (fig. 7-3). Proton events occur when solar flares eject high-energy particles (mainly protons) that arrive at the earth in 30 minutes.

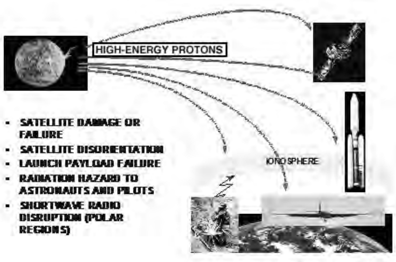

Figure 7-3. **High-energy particle impacts**. (*Adapted from* Air University, *Space Primer*, unpublished book, 2003, 6-3.)

Low- to Medium-Energy Particles. Particle streams (composed of both protons and electrons) may arrive at the earth about two to three days after a flare. Such particle streams can also occur at any time due to other nonflare solar activity. These particles cause geomagnetic and ionospheric storms, which can last from hours to several days. Typical problems include spacecraft electrical charging, drag on low-orbiting satellites, radar interference, space tracking errors, and radio wave propagation anomalies. Again, we frequently experience these impacts in the night sector of the earth.

Electromagnetic (Immediate) Effects

The first of the specific DOD system impacts to be discussed will be the shortwave fade (SWF), which is caused by solar flare x-rays. The second impact covered will be SATCOM and radar interference caused by solar flare radio bursts. These electromagnetic impacts are almost entirely limited to the earth's sunlit hemisphere and occur simultaneously (immediately or within eight minutes) with the solar flare that caused them.

Shortwave Fade Events

The high-frequency (6–30 MHz) radio band is also known as the shortwave band. Thus, an SWF refers to an abnormally high fading (or absorption) of an HF radio signal.

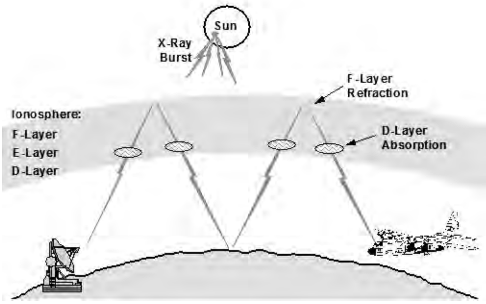

Figure 7-4. **HF communications**. (*Adapted from* Air University, *Space Primer*, unpublished book, 2003, 6-4.)

HF Radio Communications. The normal mode of radio wave propagation in the HF range is by refraction using the ionosphere's strongest (or F-) layer for single hops and by a combination of reflection and refraction between the ground and the F-layer for multiple hops (fig. 7-4). It should be noted that the ionosphere is defined as that portion of the earth's atmosphere above 45 miles where ions and electrons are present in quantities sufficient to affect the propagation of radio waves. HF radio waves are refracted by the ionosphere's F-layer. However, each passage through the ionosphere's D-layer causes signal absorption, which is additive.

Maximum Usable Frequency. The portion of the ionosphere with the greatest degree of ionization is the F-layer (normally between about 155 and 250 miles altitude). The presence of free electrons in the F-layer causes radio waves to be refracted (or bent), but the higher the frequency, the less the degree of bending. As a result, surface-to-surface radio operators use medium or high frequencies (300 kilohertz [kHz] to 30 MHz), while SATCOM operators use very high frequencies (VHF) to extremely high frequencies (EHF) (30 MHz–300 gigahertz [GHz]). The maximum usable frequency (MUF) is that frequency above which radio signals encounter too little ionospheric refraction (for a given take-off angle) to be bent back toward the earth's surface (i.e., they become transionospheric). Normally, the MUF lies in the upper portion of the HF band.

Lowest Usable Frequency. The lowest layer of the ionosphere is the D-layer (normally between altitudes of 45 to 55 miles). At these altitudes, there are still a large number of neutral air atoms and molecules coexisting with the ionized particles. As a passing radio wave causes the ions and free electrons to oscillate, they will collide with the neutral air particles, and the oscillatory motion will be damped out and converted to heat. Thus, the D-layer acts to absorb passing radio wave signals. The lower the frequency, the greater the degree of signal absorption. The lowest usable frequency (LUF) is that frequency below which radio signals encounter too much ionospheric absorption to permit them to pass through the D-layer. Normally, the LUF lies in the lower portion of the HF band.

HF Propagation Window. The HF radio propagation window is the range of frequencies between an LUF (complete D-layer signal absorption) and an MUF (insufficient F-layer refraction to bend back the signal). This window varies by location, time of day, season, and level of solar and/or geomagnetic activity. HF operators choose propagation frequencies within this window so their signals will pass through the ionosphere's D-layer and subsequently refract from the F-layer. Typical LUF/MUF curves show a normal daily variation. During early afternoon, incoming photo-ionizing solar radiation (some x-rays, but mostly ultraviolet) is at a maximum, so the D- and F-layers are strong and the LUF and MUF are elevated. During the night, the removal of ionizing sunlight causes all ionospheric layers to weaken (the D- and E-layers disappear altogether), and the LUF and MUF become depressed.

HF radio waves above the MUF encounter insufficient refraction and pass through the ionosphere into space. Those below the LUF suffer total absorption in the iono-

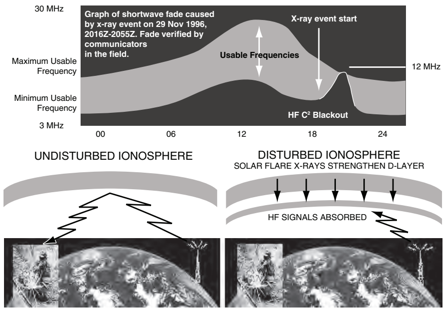

Figure 7-5. **HF propagation windows**. (*Adapted from* Air University, *Space Primer*, unpublished book, 2003, 6-5.)

sphere's lowest layer. The result is a usable frequency window.

The SWF Event. X-ray radiation emitted during a solar flare can significantly enhance D-layer ionization and absorption (thereby elevating the LUF) over the entire sunlit hemisphere of the earth. This enhanced absorption is known as an SWF and may, at times, be strong enough to close the HF propagation window completely (called a shortwave blackout) (fig. 7-5). The amount of signal loss depends on a flare's x-ray intensity, the location of the HF path relative to the sun, and design characteristics of the system. An SWF is an immediate effect, experienced simultaneously with observation of the causative solar flare. As a result, it is not possible to forecast a specific SWF event. Rather, forecasters can only predict the likelihood of an SWF event based on the probability of flare occurrence determined by an overall analysis of solar features and past activity. However, once a flare is observed, forecasters can quickly (within seven minutes of event onset) issue an SWF warning, which contains a prediction of the frequencies to be affected and the duration of signal absorption. Normally SWFs persist only for a few minutes past the end of the causative flare, that is, for a few tens of minutes up to an hour or two.

Other Sudden Ionospheric Disturbances. An SWF is the most common and troublesome of a whole family of sudden ionospheric disturbances (SID) caused by the influence of solar flare x-rays on the ionosphere. Other SIDs describe additional impacts. For example, flare x-rays can also cause the altitude of the D-layer's base to lower slightly. This phenomenon (called a sudden phase anomaly) will affect very low-frequency (VLF) (6–30 kHz) and low-frequency (LF) (30–300 kHz) transmissions and can cause LORAN navigation errors.

SATCOM and Radar Interference

Several kinds of disturbances can interfere with SATCOM and radar systems. Knowing about these disturbances can help the operator diagnose the cause of interference.

Solar Radio Bursts. Radio bursts from solar flares can cause the amount of radio wave energy emitted by the sun—the background level of solar noise—to increase by a factor of tens of thousands over certain frequency bands in the VHF to super-high-frequency (SHF) range (30 MHz–30 GHz). If the sun is in the field of view of the receiver and if the burst is at the right frequency and is intense enough, it can produce direct radio frequency interference (RFI) on a SATCOM link or missile-detection/space-tracking radar. Knowledge of a solar radio burst can allow a SATCOM or radar operator to isolate the RFI cause and avoid time-consuming investigation of possible equipment malfunction or jamming.

Radio bursts are another immediate effect, experienced simultaneously with observation of the causative solar flare. Consequently, it is not possible to forecast the occurrence of radio bursts, let alone what frequencies they will occur on and at what intensities. Rather, forecasters can only issue rapid warnings (within seven minutes of event onset) that identify the observed burst frequencies and intensities. Radio burst impacts are limited to the sunlit hemisphere of the earth. They will persist only for a few minutes up to tens of minutes, but usually not for the full duration of the causative flare.

Solar Conjunction. There is a similar geometry-induced effect called solar conjunction, which occurs when the ground antenna, satellite, and sun are in line. This accounts for interference or blackouts (e.g., static or "snow" on TV signals) in geosynchronous communication satellites during brief periods on either side of the spring and autumn equinoxes. This problem does not require a solar flare to be in progress, but its effects are definitely greatest during solar max when the sun is a strong background radio emitter.

Solar Radio Noise Storms. Sometimes a large sunspot group will produce slightly elevated radio noise levels, primarily on frequencies below 400 MHz. This noise may persist for days, occasionally interfering with communications or radar systems using an affected frequency.

Particle (Delayed) Effects

The discussion of specific DOD system impacts continues with the major delayed (or charged particle–induced) system impacts. These impacts tend to occur hours or up to several days after the solar activity that caused them. They persist for up to several days and are mostly felt in the nighttime sector (as the particles that cause them usually come from the magnetosphere's tail) although they are not strictly limited to that time/geographic sector.

Particle Events. The sources of the charged particles (mostly protons and electrons) include solar flares, CMEs, disappearing filaments, eruptive prominences, and solar sector boundaries (SSB) or high-speed streams (HSS) in the solar wind. Except for the most energetic particle events, the charged particles tend to be guided by the interplanetary magnetic field (IMF), which lies between the sun and the earth's magnetosphere. The intensity of a particle-induced event generally depends on the size of the solar flare, filament or prominence, its position on the sun, and the structure of the intervening IMF. Alternately, the sharpness of an SSB or the density/speed of an HSS will determine the intensity of a particle-induced event caused by these phenomena.

Recurrence. One important factor in forecasting particle events is that some of the causative phenomena (like SSBs and coronal holes, the source region for HSSs) persist for months. Since the sun rotates once every 27 days, there is a tendency for these long-lasting phenomena to show a 27-day recurrence in producing geomagnetic and ionospheric disturbances.

High-Frequency Absorption Events

High-frequency SWFs over the sunlit hemisphere (caused by solar flare x-rays enhancing D-layer absorption) were discussed above. There are similar HF absorption events at high geomagnetic latitudes (above 55°). However, at high latitudes, the enhanced ionization of D-layer atoms and molecules (which produce signal absorption) is caused by particle bombardment from space. Another difference is that these high-latitude absorption events can last for hours up to several days and usually occur simultaneously with other radio transmission problems.

Polar Cap Absorption Events. For a polar cap absorption (PCA) event, the enhanced ionization is caused by solar flare or CME protons that gain direct access to low altitudes (as low as 35 km) by entering through the funnel-like cusps in the magnetosphere above the earth's polar caps.

Auroral Zone Absorption Events. For an auroral zone absorption (AZA) event, the enhanced ionization is caused by particles (primarily electrons) from the magnetosphere's tails, which are accelerated toward the earth during a geomagnetic storm and guided by magnetic field lines into the auroral zone latitudes. These same ionizing particles cause the aurora or northern and southern lights.

Ionospheric Scintillation

The intense ionospheric irregularities found in the auroral zones and at plus or minus 20° of the geomagnetic equator are the primary causes of ionospheric scintillation. Scintillation of radio wave signals is the rapid, random variation in signal amplitude, phase, and/or polarization caused by small-scale irregularities in the electron density along a signal's path (fig. 7-6). Ionospheric radio-wave scintillation is very similar to the visual twinkling of starlight or heat shimmer over a hot road caused by atmospheric turbulence. The result is signal fading and data dropouts on satellite command uplinks, data downlinks, or communications signals.

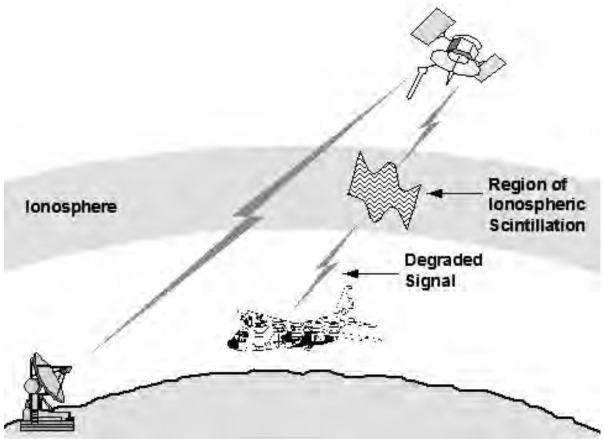

Figure 7-6. Ionospheric scintillation. (*Adapted from* Air University, *Space Primer*, unpublished book, 2003, 6-8.)

Scintillation tends to be a highly localized effect. An impact will be felt only if the signal path penetrates an ionospheric region where these small-scale electron density irregularities are occurring. Low-latitude, nighttime links with geosynchronous communications satellites are particularly vulnerable to intermittent signal loss due to scintillation. In fact, during the Persian Gulf War, allied forces relied heavily on SATCOM links, and scintillation posed an unanticipated, but very real, operational problem.

GPS and Scintillation

GPS satellites, which are located at semisynchronous altitude, are also vulnerable to ionospheric scintillation. Signal strength enhancements and fades, as well as phase changes due to scintillation, can cause a GPS receiver to lose signal lock with a particular satellite.

The reduction in the number of simultaneously usable GPS satellites may result in a potentially less accurate position fix. Since scintillation occurrence is positively correlated with solar activity and the GPS network has received widespread use only recently during a quiet portion of the 11-year solar cycle, the true environmental vulnerability of the GPS constellation is yet to be observed. Nevertheless, even during low solar activity levels, it has been shown under strong scintillation that the GPS signals cannot be seen through the background noise due to the rapid changes in the ionosphere, even with the use of dual-frequency receivers. Figure 7-7 is a plot of the actual signal-to-noise ratio graph measured during a moderate scintillation event. A war fighter may lose total GPS signal lock during such events. This includes dual-frequency systems.

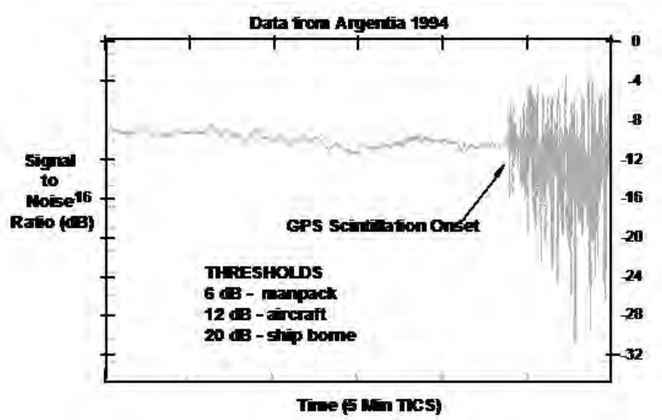

Figure 7-7. Scintillation effect on GPS signal. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-9.)

Scintillation Occurrence

There is no fielded network of ionospheric sensors capable of detecting real-time scintillation occurrence or distribution (fig. 7-8). Scintillation is frequency dependent—the higher the radio frequency (all other factors held constant), the lesser the impact of scintillation. Since we do not presently have a dedicated network of sensors that can detect real-time scintillation, we are heavily dependent on its known association with other environmental phenomena (such as aurora) and scintillation climatology.

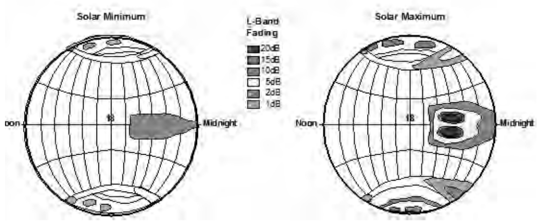

Figure 7-8. Scintillation occurrence. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-9.)

From a war fighter's perspective, it is important to know that scintillation is strongest from local sunset until just after midnight and during periods of high solar activity. At high geomagnetic latitudes (the auroral and polar regions), scintillation is strong, especially at night, and its influence increases with higher levels of geomagnetic activity.

The effects of particle bombardment mostly cause scintillation in the high latitudes by protons. Knowledge of solar activity periods and the portions of the ionosphere where conditions are conducive to scintillation permits operators to reschedule mission-critical activities and/or to switch to less susceptible radio frequencies or satellite links.

GPS and Total Electron Content

The total electron content (TEC) along the path of a GPS signal can introduce positioning errors. Just as the presence of free electrons in the ionosphere causes HF radio waves to be bent (or refracted), the higher frequencies used by GPS satellites will suffer some bending (although to a much lesser extent than with HF radio waves). This signal bending increases the signal path length. In addition, passage through an ionized medium causes radio waves to be slowed (or retarded) somewhat from the speed of light. Both the longer path length and slower speed can introduce up to 300 nanoseconds (equivalent to about 100 meters) of error into a GPS location fix—unless some compensation is made for the effect.

The solution is relatively simple for two-frequency GPS receivers, since signals of different frequency travel at different speeds through the same medium. Measuring the difference in signal phases for the two frequencies allows computation of the local phase delay for a particular receiver and elimination of 99 percent of the error introduced in a location fix. Unfortunately, this approach will not work for single-frequency receivers. For them, a software algorithm is used to model ionospheric effects based on the day of the year and the average solar ultraviolet flux for the previous few days. This method produces a gross correction for the entire ionosphere. However, as already stated, the ionosphere varies rapidly and significantly over geographical area and time. Consequently, the algorithm can eliminate, at best, about 50 percent of the error and a far smaller percentage of the error in regions where an enhanced degree of ionization is found (such as in the auroral latitudes and near the geomagnetic equator during evening hours).

Radar Aurora Clutter and Interference

A geomagnetic and ionospheric storm will cause both enhanced ionization and rapid variations (over time and space) in the degree of ionization throughout the auroral oval. Visually, this phenomenon is observed as the aurora or northern and southern lights. This enhanced, irregular ionization can also produce abnormal radar signal backscatter on poleward looking radars, a phenomenon known as radar aurora (fig. 7-9). The strength of radar aurora signal returns and the amount of Doppler frequency shifting are aspect dependent. Impacts can include increased clutter and target masking, inaccurate target locations, and even false target or missile launch detection. While improved software screening programs have greatly reduced the frequency of false aircraft or missile launch detection, such occurrences have not been eliminated. (Radar aurora is a separate phenomenon from the weak radio wave emission produced by the recombination/de-excitation of atmospheric atoms and molecules in the auroral oval, a process that also produces the much stronger infrared, visible, and ultraviolet auroral emissions.)

Surveillance Radar Errors

The presence of free electrons in the ionosphere causes radio waves to be bent (or refracted) as well as slowed (or retarded) somewhat from the speed of light. Missile detection

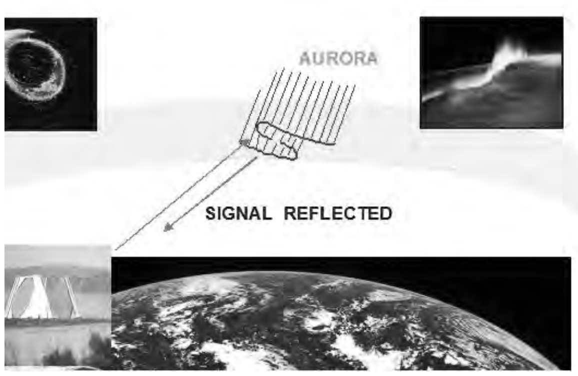

Figure 7-9. Radar aurora. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-10.)

and spacetrack radars operate at ultra-high frequencies (UHF) (300–3,000 MHz) and SHFs (3,000–30,000 MHz) to escape most of the effects of ionospheric refraction so useful to HF surface-to-surface radio operators. However, even radars operating at these much higher frequencies are still susceptible to enough signal refraction and retardation to produce unacceptable errors in target bearing and range.

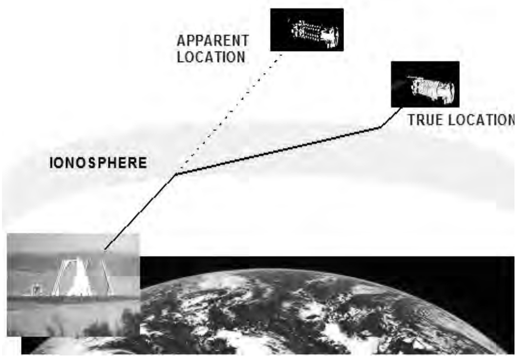

Figure 7-10. Surveillance radar errors. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-11.)

Bearing and Range Errors. A bearing (or direction) error is caused by signal bending, while a range (or distance) error is caused by both the longer path length for the refracted signal and the slower signal speed (fig. 7-10). For range errors, the effect of longer path length dominates in UHF signals, while slower signal speed dominates for SHF signals.

Correction Factors. Radar operators routinely attempt to compensate for these bearing and range errors by applying correction factors that are based on the expected ionospheric TEC along a radar beam's path. These predicted TEC values/correction values are based on time of day, season, and the overall level of solar activity. Unfortunately, individual solar and geophysical events will cause unanticipated, short-term variations from the predicted TEC values and correction factors. These variations (which can be either higher or lower than the anticipated values) will lead to inaccurate position determinations or difficulty in acquiring targets. Real-time warnings when significant TEC variations are occurring help radar operators minimize the impacts of their radar's degraded accuracy.

Space-Based Surveillance. The bearing and range errors introduced by ionospheric refraction and signal retardation also apply to space-based surveillance systems. For example, a space-based sensor attempting to lock on to a ground radio emitter may experience a geolocation error.

Over-the-Horizon Backscatter Surveillance Radars. Over-the-horizon backscatter (OTH-B) radars use HF refraction through the ionosphere to detect targets beyond the horizon. OTH-B operators need to be aware of existing and expected ionospheric conditions (in detail) over a wide geographical area. Otherwise, improper frequency selection will reduce target detection performance, or incorrect estimation of ionospheric layer heights will give unacceptable range errors.

Atmospheric Drag

Another source for space-object positioning errors is the presence of either more or less atmospheric drag than expected on low orbiting objects (generally at less than about 1,000 km altitude). Energy deposited in the earth's upper atmosphere by EUV, x-ray, and charged particle bombardment heats the atmosphere, causing it to expand outward. Low Earth orbiting satellites and other space objects then experience denser air and more frictional drag than expected. This drag decreases an object's altitude and increases its orbital speed. The result is that the object will be some distance below and ahead of its expected position when a ground radar or optical telescope attempts to locate it (fig. 7-11). Conversely, exceptionally calm solar and/or geomagnetic conditions will cause *less* atmospheric drag than predicted, and an object could be higher and behind where it was expected to be found.

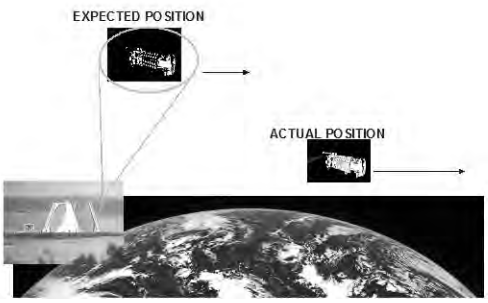

Figure 7-11. **Atmospheric drag**. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-12.)

Impacts of Atmospheric Drag. The consequences of atmospheric drag include: (1) satellite locations may be inaccurate, which can hinder rapid acquisition of SATCOM links for commanding or data transmission; (2) costly orbit maintenance maneuvers may become necessary; and (3) deorbit predictions may become unreliable. A classic case of the latter was *Skylab*. Geomagnetic activity was so severe, for such an extended period, that the expanded atmosphere caused *Skylab* to deorbit and burn in before a planned space shuttle rescue mission was ready to launch.

Contributions to Drag. There are two space environmental parameters used by current models to predict the orbits of space objects. The first is the solar F10 index. Although the F10 index is a measure of solar radio output at 10.7 centimeters (or 2,800 MHz), it is a very good indicator of the amount of EUV and x-ray energy emitted by the sun and deposited in the earth's upper atmosphere. In figure 7-12 the solar flux (F10) graph shows a clear, 27-day periodicity caused by the sun's 27-day period of rotation and the fact that hot, active regions are not uniformly distributed on the sun's surface. The second parameter is the geomagnetic Ap index, which is a measure of the energy deposited in the earth's upper atmosphere by charged particle bombardment. This index shows strong spikes corresponding to individual geomagnetic storms. The upper two graphs, which show upper atmospheric temperature and density (observed by a satellite at 730 km altitude), clearly reflect the influence of these two indices. Since

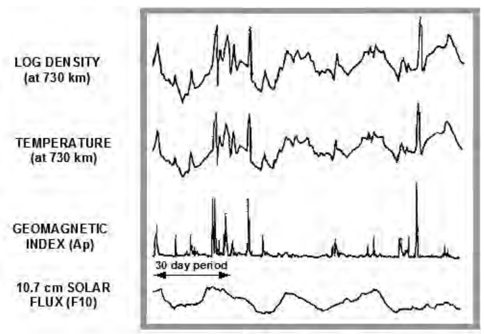

Figure 7-12. Factors contributing to atmospheric drag. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-13.)

it takes time for the atmosphere to react to a change in the amount of energy being deposited in it, drag impacts first tend to be noticeable about six hours after a geomagnetic storm starts and may persist for about 12 hours after the storm ends.

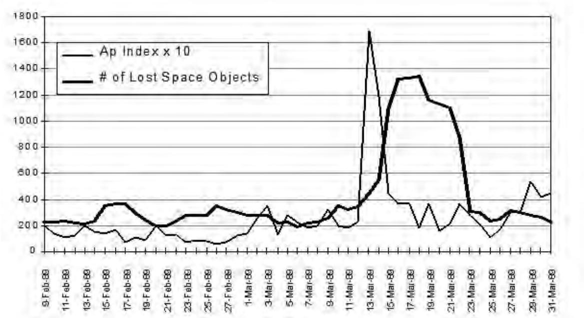

Figure 7-13. Geomagnetic storms and orbit changes. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-14.)

Impact of Geomagnetic Storms on Orbit Changes. We have discussed two impacts of geomagnetic storms on space tracking radar. The first is bearing and range errors induced by inadequate compensation for TEC changes, which cause *apparent* location errors. The second is atmospheric drag, which causes *real* position errors. These effects can occur simultaneously. During a severe geomagnetic storm in March 1989, over 1,300 space objects were temporarily misplaced (fig. 7-13). It took almost a week to reacquire all the objects and update their orbital elements. This incident led to a revision in operating procedures. Normally drag models do not include detailed forecasts of the F10 and Ap indices. However, when severe conditions are forecast, more comprehensive model runs are made, even though they are also more time-consuming. Figure 7-13 demonstrates how a geomagnetic storm can change the orbits of space objects unexpectedly, causing difficulty for those who maintain orbital data.

Space Launch and Payload Deployment Issues

When objects are being launched into space, the potential effects of atmospheric drag and particle bombardment must be considered.

Atmospheric Drag. Excessively high or low geomagnetic conditions can produce atmospheric density variations along a proposed launch trajectory. The ability of a launch vehicle to compensate for these variations may be exceeded. In addition, the atmospheric density profile based on changes in altitude will determine how early the protective shielding around a payload can be jettisoned. If the protective shielding is jettisoned too early, the payload is exposed to excessive frictional heating.

Particle Bombardment. Charged particle bombardment during a geomagnetic storm or proton event can produce direct physical damage on a launch vehicle or its payload, or it can deposit an electrical charge on or inside the spacecraft. The electrostatic charge deposited may be discharged (lead to arcing) by onboard electrical activity such as vehicle commanding. In the past, payloads have been damaged by attempted deployment during geomagnetic storms or proton events.

Radiation Hazards

Despite all engineering efforts, satellites are still quite susceptible to the charged particle environment. In fact, with newer microelectronics and their lower operating voltages, it will actually be easier to cause electrical upsets than on older, simpler vehicles. Furthermore, with the perceived lessening of the nuclear threat, there has been a trend to build new satellites with less nuclear radiation hardening. However, the previous hardening also protected the satellites from space environmental radiation hazards. Both low and high Earth orbiting spacecraft and satellites are subject to a number of environmental radiation hazards, such as direct physical damage and/or electrical upsets caused by charged particles. These charged particles may be: (1) trapped in the Van Allen radiation belts, (2) in directed motion during a geomagnetic storm, or (3) protons/cosmic rays of direct solar or galactic origin.

Geosynchronous Orbit. Geosynchronous orbit (35,782 km or 22,235 statute miles altitude) is commonly used for communication satellites. Unfortunately, it lies near the outer boundary of the outer Van Allen belt and suffers whenever that boundary moves inward or outward. Semisynchronous orbit (used for GPS satellites) lies near the middle of the outer belt (in a region called the ring current) and suffers from a variable, high-density particle environment. Both orbits are particularly vulnerable to the directed motion of charged particles that occurs during geomagnetic storms. Particle densities observed by satellite sensors can increase by a factor of 10 up to 1,000 over a period as short as a few tens of minutes.

Geomagnetic Storms. Charged particles emitted by the sun cause problems primarily on the night side of the earth. Their arrival causes a shock wave to ripple through the magnetosphere, causing magnetic field lines out in the magnetosphere's tail to recombine, and previously stored particles are then shot toward the earth's night-side hemisphere. Some of these particles stay near the plane of the equator and feed the ring current in the outer Van Allen radiation belt, while other particles follow magnetic field lines up (and down) toward auroral latitudes.

Radiation Belt Particle Injections. The particles from the night-side magnetosphere (or magnetotail) which stayed near the plane of the equator will feed the ring currently in the outer Van Allen belt. The electrons and protons, since they are oppositely charged, tend to move in opposite directions when they reach the ring current (fig. 7-14). Furthermore, the protons and electrons have about the same amount of energy, but the electrons (since they are 1,800 times lighter) move 40 times faster. Finally, the electrons are about 10 to 100 times more numerous than the protons. Figure 7-14 shows a cross-section of the magnetosphere taken in the plane of the earth's geomagnetic equator.

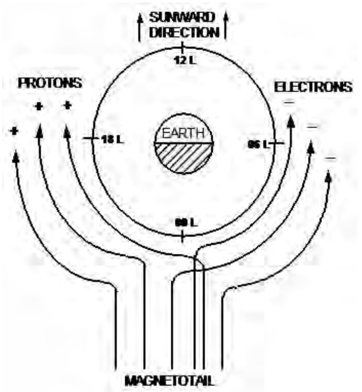

Figure 7-14. Geomagnetic storms—radiation belt particle injections. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-15.)

The result of all these factors is that electrons are much more effective at causing physical damage due to collision and electrical charging than the protons. This fact explains why the preponderance of satellite problems occur in the midnight to dawn (0001 to 0600 local) sector, while the evening (1800 to 2359 local) sector is the second most common location for problems. This explanation is well supported by the rather large number of satellite anomalies which actually can be observed in the midnight to dawn sector.

Auroral Particle Injections. Some of the particles from the night-side magnetosphere follow geomagnetic field lines up (and down) toward the Northern and Southern Hemisphere auroral latitudes. These particles will penetrate to very low altitudes (as low as 35 km) and can cause physical damage and electrical charging on high-inclination, low-altitude satellites or space shuttle missions.

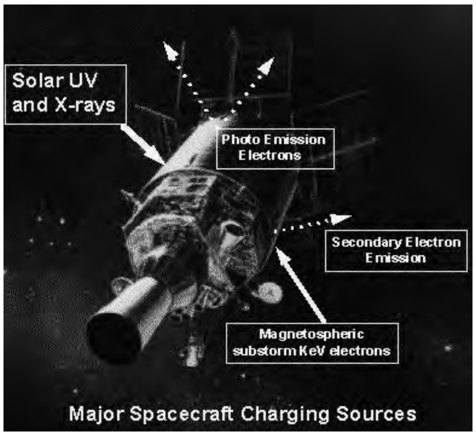

Figure 7-15. **Spacecraft charging**. (*Adapted from* Air University, *Space Primer*, unpublished book, 2003, 6-16.)

Electrical Charging

Spacecraft charging is a problem for satellites and can be produced by an object's motion through a medium containing charged particles. This phenomenon is referred to as wake charging, which is a significant problem for large objects like the space shuttle. Spacecraft charging is also caused by particle bombardment, as occurs during geomagnetic storms and proton events, and even from solar illumination. The impact of each phenomenon is strongly influenced by variations in an object's shape and the materials used in its construction (fig. 7-15).

An electrical charge can be deposited either on the surface or deep within a satellite. Solar illumination and wake charging are surface charging phenomena. During direct particle bombardment, the higher the energy of the particles, the deeper the charge can be placed. Normally electrical charging will not in itself cause an electrical upset or damage. It will deposit an electrostatic charge, which will stay on the vehicle for perhaps many hours until some triggering mechanism causes a discharge or arcing, similar to a small thunderbolt inside the vehicle. Such triggering mechanisms include a change in particle environment, a change in solar illumination such as moving from eclipse to sunlight, or onboard vehicle activity or commanding.

In extreme cases, the satellite's life span can be significantly reduced, necessitating an unplanned launch of a replacement satellite. Warnings of environmental conditions conducive to spacecraft charging allow operators to reschedule vehicle commanding, reduce onboard activity, delay satellite launches and deployments, or reorient a spacecraft to protect it from particle bombardment. Should an anomaly occur, an environmental post-analysis could help operators or engineers determine whether the environment contributed to it and determine if satellite functions need to be reactivated or reset.

Single-Event Upsets

High-energy protons and cosmic rays can penetrate through a satellite and ionize material deep inside the spacecraft. A single particle can cause physical damage and/or deposit enough charge to cause an electrical upset such as causing a circuit to switch, inducing a false command, or causing the computer memory to be changed or lost. High-energy protons can also physically damage satellite components. Hence, these occurrences are called single-event upsets (SEU).

SEUs are random, unpredictable events. They can occur at any time during the 11-year solar cycle. In fact, SEUs are actually most common near solar minimum, when the interplanetary magnetic field emanating from the sun is weak and unable to provide the earth much shielding from cosmic rays originating outside the solar system. During severe geomagnetic storms, particles low in the atmosphere move toward the equator and can therefore similarly affect satellites in lower-inclination orbits.

Satellite Disorientation

Many satellites rely on electro-optical sensors to maintain their orientation in space. These sensors lock onto certain patterns in the background stars and use them to achieve precise pointing accuracy. These star sensors are vulnerable to cosmic rays and high-energy protons, which can produce flashes of light as they influence a sensor. The bright spot produced on the sensor may be falsely interpreted as a star. When computer software fails to find this false star in its star catalogue or incorrectly identifies it, the satellite can lose attitude lock with respect to the earth. Directional communications antennas, sensors, and solar cell panels will then correspondingly fail to acquire their intended targets. The result may be loss of communications with the satellite, loss of satellite power, and in extreme cases, loss of the satellite due to drained batteries (gradual star sensor degradation can also occur under constant radiation exposure). Disorientation occurs primarily when solar activity is high and on geosynchronous or polar-orbiting satellites.

Geomagnetic Storm Surface Impacts

Geomagnetic storms cause rapid fluctuations in the earth's magnetic field and increase the amount of precipitating energetic particles impinging on the earth's ionosphere. The rapid fluctuations can lead to induced currents in power grids, causing the power grid to fail (fig. 7-16). This can—and has—happened, predominately in the higher latitudes. (In March 1989, the Canadian province of Quebec suffered a power grid failure of this type.) Such fluctuations can also cause orientation errors for those relying on magnetic compasses for navigation. In addition to the ionospheric disturbances discussed earlier, localized, rapidly changing ionospheric activity can occur. This activity may not be picked up by space environment sensors but can cause HF communication users to suffer sporadic interference or total localized blackouts.

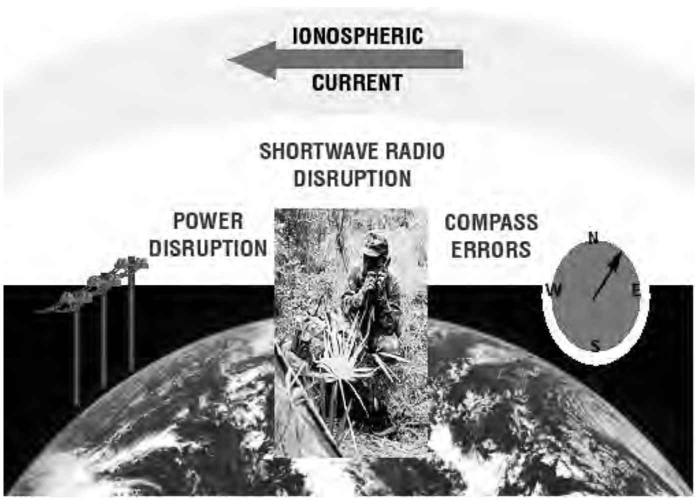

Figure 7-16. **Geomagnetic storm surface impacts**. (*Reprinted from* Air University, *Space Primer*, unpublished book, 2003, 6-18.)

Space Environmental Support

The United States leads the world in the study of the space environment. The space environment is becoming a critical factor in the nation's economy and security. We need to accurately provide reliable space weather predictions, forecasts, and warnings to users whose systems can be affected by solar disturbances. The Space Environmental Center and the 55th Space Weather Squadron lead US efforts to predict space weather for global civil and DOD users.

Space Environmental Center

Non-DOD federal and civilian customers receive support from the Department of Commerce, specifically the NOAA Space Environment Center (SEC), located in Boulder, Colorado. The SEC is one of the nation's official sources of space weather alerts and warnings. The center continually monitors and forecasts Earth's space environment; provides accurate, reliable, and useful solar-terrestrial information; and leads programs to improve services.

The SEC conducts research into phenomena affecting the sun-Earth environment, including the emission of electromagnetic radiation and particles from the sun, the transmission of solar energy to Earth via solar wind, and the interactions between the solar wind and Earth's magnetic field, ionosphere, and our atmosphere.

Together with personnel from the US Air Force, the SEC operates the Space Weather Operations (SWO) Center that monitors solar and geomagnetic activity 24 hours a day. They issue products such as the SEC Space Weather Outlook along with other warnings and predictions. The SWO Center also provides real-time data, or "nowcasts," that include forecasts and summaries of solar activity to customers interested in the solar-terrestrial environment.

In addition to current data slides, the SWO Center provides users with a synopsis of the current space weather. Data from both ground- and space-based observatories and sensors are monitored and analyzed to provide users with the best information currently available. Significant solar events are seen in the forecast centers within two minutes of detection, which allows the forecast centers in turn to issue alerts of potential system impacts to customers within an additional five minutes.

The SEC and the 55th Space Weather Squadron also watch the sun for indications as to when major solar flares might occur. Predictions of solar activity are made in the solar flare watch forecast, in which groups of sunspots are numbered and tracked based upon their type and level of expected activity.

The NOAA space weather scales were introduced in November 1999 as a way to communicate to the public the current and future space weather conditions and their possible effects on people and systems. Many of the SEC products describe the space environment, but few have attempted to define or describe in lay terms the effects that can be experienced as the result of these space environment disturbances. The space weather scales then should be a useful reference to those who are interested in space weather effects. Printable copies of the space weather scales are available on CD as well as from the SEC Web site.[19]

The geomagnetic storm scale index was developed to convey the potential severity of solar storms using numbered levels, analogous to the numerical scales that describe hurricanes, tornadoes, and earthquakes. The index lists the possible effects at each level of geomagnetic storm. It also shows how often such events occur and gives a measure of the intensity of the physical causes.

Air Force Weather Agency Space Weather Flight

Forecasters in the Space Weather Flight, 2nd Weather Squadron, 2nd Weather Group at the Air Force Weather Agency (AFWA) look at the sun's emissions and provide mission-tailored analyses, forecasts, and warnings. Their products are used for mission planning and environmental situational awareness by national agencies, DOD operators, war fighters, and decision makers.

Although solar emissions can occur at any time, the sun undergoes an 11-year activity cycle. The last solar peak, or period of maximum activity, occurred in 2000, producing a large number of solar flares and sun spots. This heightened activity creates an increase in solar emissions traveling to and interacting with the earth's atmosphere. Solar emissions also cause the aurora borealis or northern lights. However, most interactions are not visible to the human eye.

AFWA space weather technicians located at Offutt AFB, Nebraska, and at solar observatories around the globe never let the sun slip from view. Each month, they provide updated space weather information on the Internet for military and DOD personnel issuing approximately 100 textual and graphical products warning of significant solar activity. Under these conditions, the environmental situational awareness of space weather can be as important as thunderstorms or other terrestrial weather phenomena to our nation's military. AFWA is committed to providing a complete terrestrial and space weather program, looking at the environment from "the mud to the sun."[20]

Notes

1. Jerry Jon Sellers, *Understanding Space: An Introduction to Astronautics*, 2nd ed. (Boston: McGraw Hill, 2004), 79.
2. Much of the following discussion of the space environment and its impact is based on Air Force Space Command Pamphlet (AFSPCPAM)15-2, *Space Environmental Impacts on DOD Operations*, 1 October 2003, certified current 7 December 2007.
3. NASA, "The Solar Wind," Solar Physics Web site at Marshall Space Flight Center, http://solarscience.msfc.nasa.gov/SolarWind.shtml (accessed 16 April 2009).
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5. European Space Agency Science and Technology, "Plasma Regions: The Magnetotail," http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=33272&fbodylongid=1171 (accessed 16 April 2009).
6. *American Heritage Dictionary*, 4th ed., s.v. "radiation."
7. Sellers, *Understanding Space*, 93.
8. NASA, "Electromagnetic Spectrum," Imagine the Universe Web site at Goddard Space Flight Center, http://imagine.gsfc.nasa.gov/docs/science/know_l1/emspectrum.html (accessed 16 April 2009).
9. Maj Michael J. Muolo, ed., *Space Handbook: A War Fighter's Guide to Space*, vol. 2, *An Analyst's Guide* (Maxwell AFB, AL: Air University Press, 1993), 16.
10. NASA, "Coronal Mass Ejections," Solar Physics Web site at Marshall Space Flight Center, http://solarscience.msfc.nasa.gov/CMEs.shtml (accessed 16 April 2009).
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12. NASA, "Solar Minimum Has Arrived," NASA Web site, http://www.nasa.gov/vision/universe/solarsystem/06mar_solarminimum.html (accessed 16 April 2009).
13. Muolo, ed., *Space Handbook*, vol. 2, 14.

14. Ibid., 13.

15. National Geophysical Data Center, "Definition of the Ionospheric Regions (Structures)," http://www.ngdc.noaa.gov/stp/IONO/ionostru.html (accessed 16 April 2009).

16. Lunar and Planetary Institute, "About Comets," http://www.lpi.usra.edu/education/explore/comets/ (accessed 16 April 2009).

17. International Meteor Organization (IMO), "IMO Meteor Shower Calendar 2007," http://www.imo.net/calendar/2007 (accessed 16 April 2009).

18. The discussion of the impacts of the space environment is based on AFSPCPAM 15-2, 13–29.

19. AFSPCPAM 15-2, 30–31. See the SEC Web site at http://www.swpc.noaa.gov/.

20. AFWA, "AFWA Space Weather Flight," http://www.afweather.af.mil/library/factsheets/factsheet.asp?id=5090 (accessed 16 April 2009).