**BY ORDER OF THE COMMANDER**
**AIR FORCE SPACE COMMAND**

**AFSPCPAM15-2**
**3 February 1997**

**Weather**

# SPACE ENVIRONMENTAL IMPACTS ON DOD OPERATIONS

This pamphlet provides guidance to developers, operators, and users of DoD systems (such as satellites, radars, or communications) that operate in or through the space environment. It will familiarize personnel with the various types of space environmental activity, their impacts on DoD systems, and support products and services available to mitigate or exploit those impacts. It also describes the methods used to collect solar and geophysical observations, and explains the terminology used to characterize space environmental activity and its effects. (An abbreviated version of chapters 1 to 3 of this pamphlet, in the form of scripted briefing slides, is available through the HQ AFSPC/DORW homepage.) AFCAT15-152, Volume 5, *Space Environment Products* contains detailed information on space environmental analysis, forecast, and warning products and services. AFI15-118, *Requesting Weather Support Assistance*, provides guidance on how to obtain support.

## SUMMARY OF REVISIONS

This pamphlet incorporates and expands on the content of two earlier publications: Air Force Space Forecast Center Pamphlet (AFSFCP) 105-3, *Guide to Space Environmental Effects on DoD Operations*, and AFSPCPAM55-9, *Guide to Space Environmental Effects on AFSPACECOM Site Operations.*

Paragraph





Supersedes AFSPCPAM55-9, 2 Feb 90
Certified by: DOR (Col William H. Rohlman)
OPR: DORW (Lt Col R. A. Frederick)
Pages: 53/Distribution: FX (See page 31.) per LTC DAVIS

**Figures**



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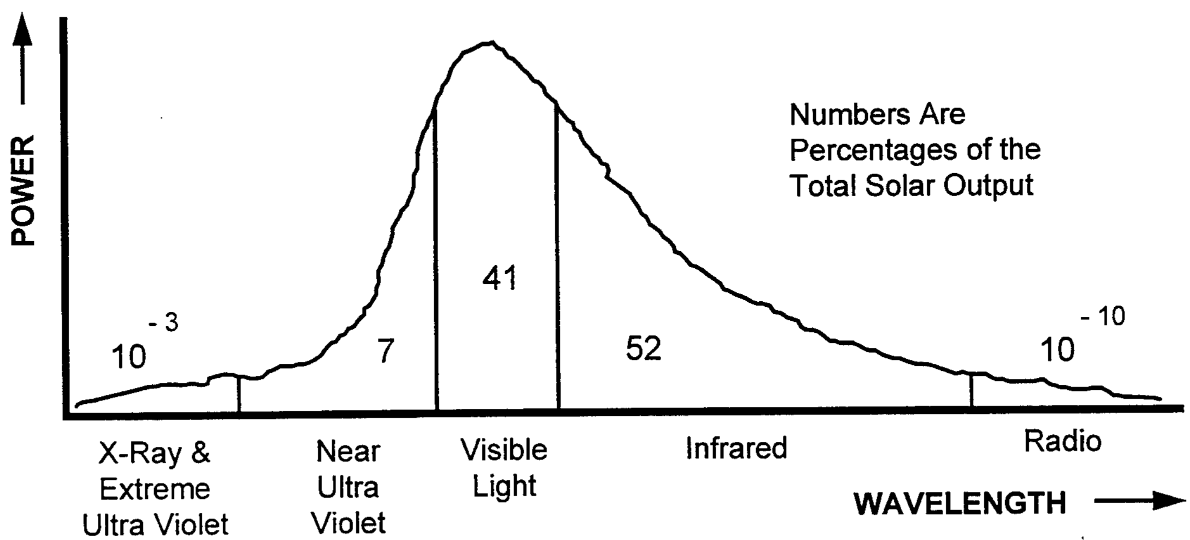
## Chapter 1

## SOLAR AND GEOPHYSICAL ACTIVITY

**1.1. The Space Environment.** The origin of space environmental impacts on radar, communications, and space systems lies primarily with the sun. The sun continuously emits electromagnetic energy and electrically charged particles. Superimposed on these normal (or background) emissions are enhancements in the electromagnetic radiation (particularly at X-ray, Extreme Ultra Violet (EUV), and Radio wavelengths) and in the energetic charged particle streams emitted by the sun. These solar radiation enhancements have a significant potential to influence DoD operations.

1.1.1. Electromagnetic Radiation. The sun emits radiation over the entire electromagnetic spectrum (Figure 1.1.). The distribution of energy is such that the most intense portion of this radiation falls in the visible part of the spectrum (which is why we see in visible light). Substantial amounts also lie in the Near Ultraviolet and Infrared portions. Less than one percent of the sun's total emitted electromagnetic radiation lies in the EUV/X-ray and Radiowave wings. However, we still have a two-fold problem: First, solar activity can cause the amount of emitted EUV and X-ray energy to be enhanced by a factor of up to 100 or more, and radiowave energy by a factor of tens of thousands, over the normal solar output at these wavelengths. Second, it is exactly these wavelengths to which radar, communications, and space systems are most vulnerable.

**Figure 1.1. Distribution of Energy in the Solar Electromagnetic Spectrum.** Not drawn to scale. (After AWSP105-36, "Guide to Solar-Geophysical Activity", Air Weather Service, Scott AFB, IL, 20 February 1975.)




1.1.2. Particle Radiation. In addition to the emission of electromagnetic radiation, there is a continuous out-flow of energetic charged particles (protons and electrons) from the sun called the "solar wind". There is also an "interplanetary magnetic field (IMF)" emanating from the sun, which has a spiral structure near the plane of the Earth's orbit caused by the fact that the sun rotates every 27 days (Figure 1.2.). The spiral IMF guides the outward motion of the charged particles in the solar wind. On the average, solar wind particles travel at over 400 kilometers per second, with a density of about 5 particles per cubic centimeter. Several types of solar activity can cause energetic particle streams to be superimposed on this background solar wind. The resultant enhancements and discontinuities in solar wind particle speed and/or density can disturb the Earth's "magnetosphere" as they sweep by. The magnetosphere (Figure 1.3.) is that volume of space where the Earth's own magnetic field can exclude the sun's IMF and control the motion of charged particles. The distorted shape of the magnetosphere is caused by the pressure of the outward flowing solar wind. It's geomagnetic field lines are compressed on the sunward side, and drawn out in the anti-sunward direction. While the magnetosphere does provide some shielding from solar charged particles (except at the funnel-like cusps over the polar caps), the shielding is not enough to avert some unpleasant impacts on radar, communications, and space systems operating in or through the near-Earth environment.

**Figure 1.2. The Solar Wind and Interplanetary Magnetic Field.** As the outward flowing solar wind particles fall behind the sun's rotation, they drag the interplanetary magnetic field (IMF) lines with them, producing a spiral structure. The alternating magnetic polarity (-, +) of the IMF sectors are associated with the underlying large scale magnetic field sectors in the solar atmosphere.

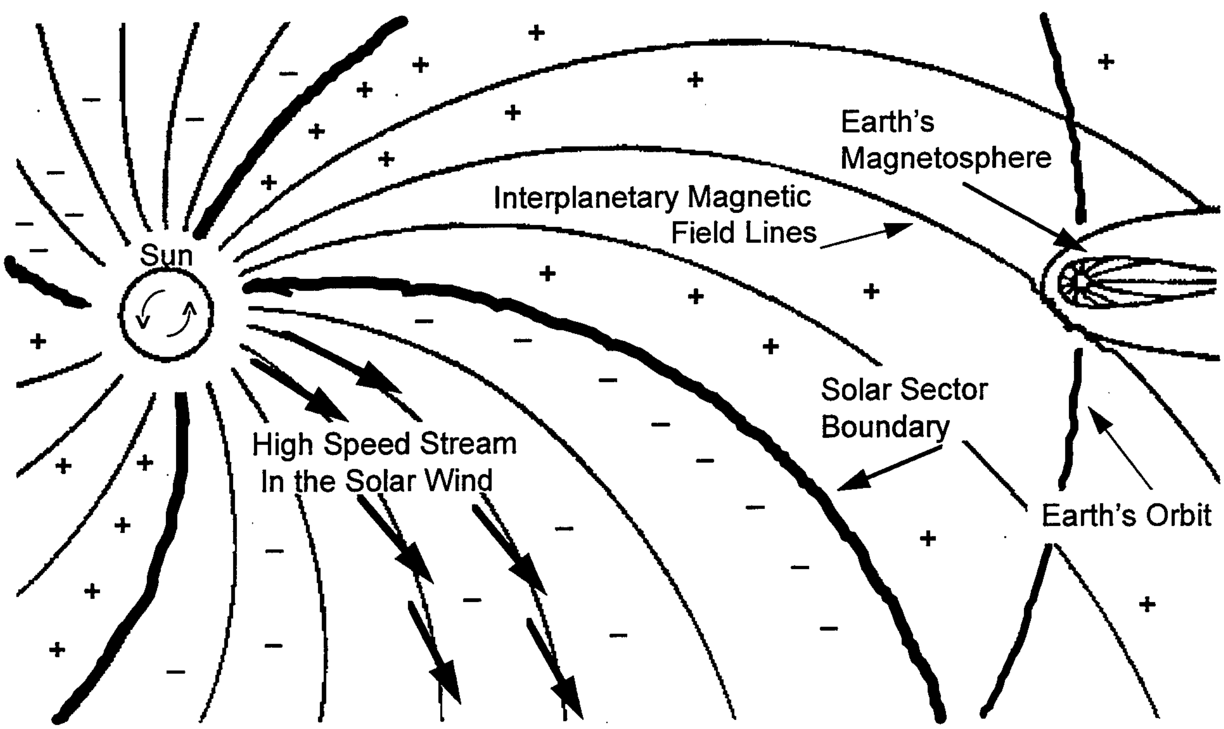
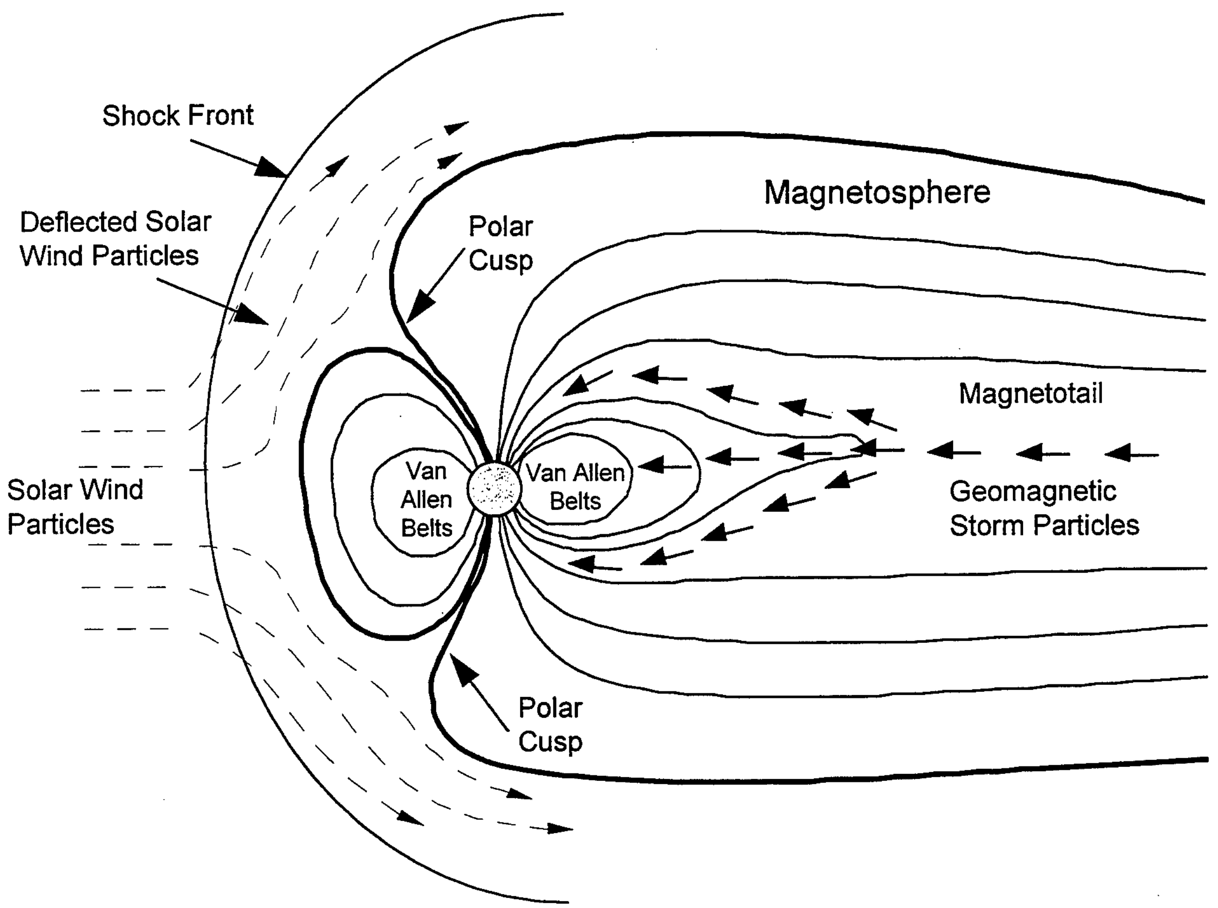


**Figure 1.3. The Earth's Magnetosphere.** The magnetosphere is compressed on the sunward side by the pressure of the solar wind, and it is drawn out extensively on the anti-sunward side. The series of short arrows in the magnetotail represent the flow of previously stably trapped charged particles during a geomagnetic storm. (After "Space Weather Training Program, Student Manual", Air Force Space Command, Peterson AFB, CO, 16 June 1995.)




**1.2. Features on the Solar Disk.**

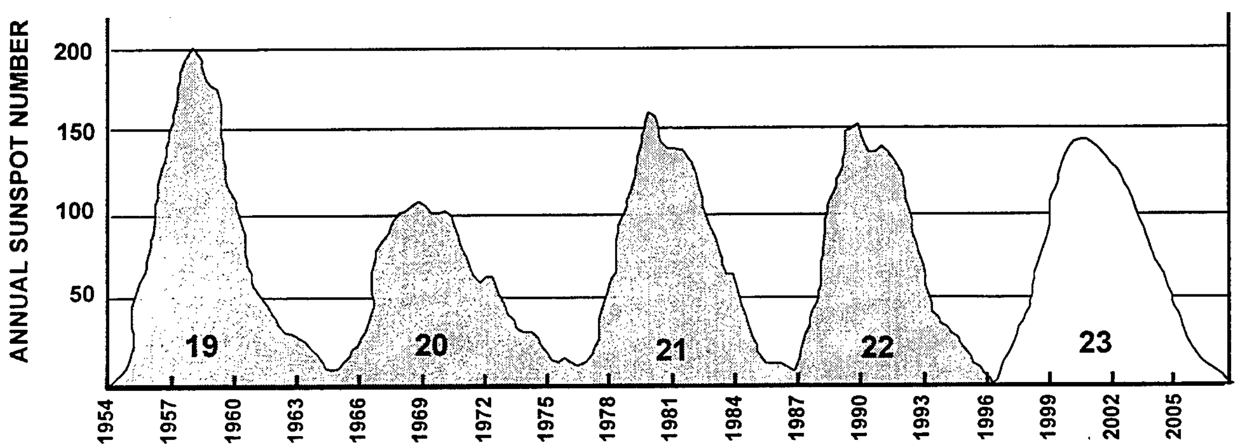
1.2.1. Sunspots. "Sunspots" are regions of intense, localized magnetic fields on the sun's surface (also known as the photosphere). These magnetic fields cause sunspots to be cooler than the rest of the photosphere, so they appear dark compared to the hotter, brighter surrounding surface. Since sunspots are regions of intense magnetic fields, solar flares and other solar activity tend to occur near sunspots. Sunspot groups are categorized according to size, configuration, and magnetic complexity. The number and intensity of operationally significant solar events is positively correlated with the total number of sunspots.

1.2.2. Plage. "Plage" are areas of strong, localized magnetic fields in the sun's lower atmosphere (also known as the chromosphere). These magnetic fields cause the material in a plage to be somewhat denser, hotter, and thus brighter, than in the areas surrounding the plage. Plage can best be observed through a filter that passes only the monochromatic red light of the Hydrogen-alpha wavelength (6563 Angstroms). Growth in plage area and brightness can significantly increase the total output of portions of the solar electromagnetic spectrum, particularly EUV radiation and radiowaves with frequencies near 2800 MHz. Since plage can be produced by lower magnetic field strength than required to produce sunspots, plage are a pre-cursor of sunspots and they will persist longer than any related sunspots. Most solar flares will occur in the vicinity of these "active" regions.

1.2.3. Filaments and Prominences. "Filaments" occur in the upper chromosphere and/or lower corona (the sun's outermost atmospheric layer). The material in a filament is supported by relatively strong magnetic field lines that are horizontal (or parallel) with respect to the sun's surface. This filamentary material has a higher density and lower temperature than its surroundings, and so tends to form dark, ribbon-like features when observed in Hydrogen-alpha light against the brighter, underlying solar disk. Filaments are called "prominences" when they are observed on the limb of the sun, where they will appear as bright features in contrast to the dark, non-Hydrogen-alpha emitting corona. Occasionally, a solar disturbance will cause the supporting magnetic field lines to fling the material (charged particles) in a filament or prominence outward from the sun. This rapid eruption of a filament (observed as a "disappearing filament") or a prominence (called an "eruptive prominence") can result in a geomagnetic disturbance in the near-Earth environment when the ejected particles arrive approximately 72 hours after the eruption, ***if*** the Earth happens to be in the portion of its orbit where the particles cross.

**1.3. The Solar Cycle.** Western sunspot records start with the first telescopic observations by Galileo in 1611. Since that time, the number of sunspots has been found to follow a roughly 11-year cycle, called the "Sunspot or Solar Cycle" (Figure 1.4.). Sunspot cycles in the past have been as short as 8 years and as long as 15 years, but most cycles are very close to the average of 11.1 years. (***NOTE***: There is also a 22-year solar cycle. Every 11 years the overall magnetic polarity of the sun's northern and southern hemispheres reverse. A return to the original polarity requires another 11 years--hence the 22-year cycle.)

**Figure 1.4. The 11-Year Sunspot Cycle.** Each sunspot cycle from 1954 onward is labeled in the figure by its cycle number. The maximum of the last cycle (#22) was in July 1989, and reached the third largest amplitude on record. Projections for Cycle 23 are for a maximum in the spring of 2000, with an amplitude equal to that of Cycle 22.




1.3.1. Solar Cycle Characteristics. Generally, cycles show a rapid, roughly 4-year rise to a "Solar Maximum", followed by a gradual 7-year decline to a "Solar Minimum". Since solar activity is closely correlated with the number of sunspots, solar events and operational impacts also tend to follow an 11-year cycle. Predicting the time and magnitude of future sunspot cycles is a relatively difficult, uncertain process, normally involving the use of a variety of statistical and precursor methods. However, the real operational problem with the Solar Cycle is that Solar Minimum tends to lull system designers, operators, and users into a state of complacency, then the rapid rise to Solar Maximum creates some unexpected and unpleasant surprises.

1.3.2. The Cyclic Nature of Solar Activity. Operators should not be fooled into thinking they are "out of the woods" when a Solar Maximum has passed. The greatest potential for large solar flares is actually during the 2 to 3 years immediately following a Solar Maximum. The reason for this situation is that a decline in the number of sunspots and active regions (or plage) permits solar magnetic fields in those regions that exist to build in intensity and complexity without being prematurely disturbed by neighboring flare events. Furthermore, solar and geophysical activity can and does occur even during Solar Minimum. That is because not all solar activity (and thus system impacts) are solar flare induced. Flares are only the primary cause, other causes include: coronal mass ejections, disappearing filaments (also known as eruptive prominences), solar wind sector boundaries, high speed particle streams emanating from coronal holes, and cosmic rays of non-solar origin. Not all of these phenomena are directly tied to sunspots and plage; in fact, some (like coronal holes and non-solar galactic cosmic rays) are actually more common problems during Solar Minimum!

**1.4. Solar Flares.** The prime cause of solar activity is the solar flare, which is an explosive release of energy, both electromagnetic and charged particles, within a relatively small (but greater than earth-sized) region of the lower solar atmosphere. While the energy released during a flare is very substantial, it represents at most 1/100,000th of the total solar output. Consequently, our daily lives appear to be unaffected. However, a flare's enhanced X-ray, EUV, radiowave, and particle emissions are sufficient to adversely impact radar, communications, and space systems operating in or through the near-Earth environment.

1.4.1. Flare Occurrence. Flares usually occur in the vicinity of sunspots or their pre-cursors, bright active regions called plage. The reason is that the energy released by a flare is the energy stored in the intense, complex magnetic fields which produce those plage and sunspots. Flares are also one triggering mechanism for eruptive prominences or disappearing filaments, which are outward ejections of material (charged particles) previously suspended cloud-like in the solar atmosphere. Unfortunately, on a case-by-case basis, it is almost impossible to predict exactly when a large flare will occur. However, their close correlation with sunspots and plage do permit reasonable forecasts of the likelihood of flare occurrence and probable flare characteristics (size, duration, X-ray and particle emissions, etc.). The strength of a flare, and thus its potential to cause system impacts, is often correlated with the size and complexity of the associated sunspot group or plage active region.

1.4.2. Flare Classification. Flares are classified according to their optical or X-ray characteristics.

1.4.2.1. Optical Flare Classification. The optical (as seen in Hydrogen-alpha light) classification of a flare is made using a two-character designation based on flare area and brightness (Table 1.1.). Example: a 1B designation indicates a "brilliant" intensity flare covering a corrected area between 100 and 249 millionths of the solar hemisphere. (***NOTE***: Flare areas are corrected for geometric foreshortening caused by projection of a spherical object on a flat viewing plane.)

**Table 1.1. Optical Flare Classification by Area and Brightness.**

| SIZE CATEGORY | CORRECTED FLARE AREA (Millionths of the Solar Hemisphere) | TYPICAL DURATION | PERCENTAGE OF ALL FLARES |
|---|---|---|---|
| 0 | 10 to 99 | Several minutes | 75 |
| 1 | 100 to 249 | Tens of minutes | 19 |
| 2 | 250 to 599 | An hour | 5 |
| 3 | 600 to 1200 | An hour or more | Less than 1 |
| 4 | Greater than 1200 | An hour or more | Less than 1 |

BRIGHTNESS CATEGORIES: F: Faint N: Normal B: Brilliant

1.4.2.2. X-Ray Flare Classification. Flares are also classified by the peak X-ray energy flux emitted in the 1 to 8 Angstrom wavelength band, as measured by a geosynchronous satellite (Table 1.2.). These measurements must be made from space, since the Earth's atmosphere absorbs all solar X-rays before they reach the Earth's surface. Example, a M3 flare emitted an X-ray flux of 3 x $10^{-2}$ ergs/cm$^2$/second.

**Table 1.2. X-Ray Flare Classification.**

| CLASS | X-RAY PEAK FLUX |
|---|---|
| A | Greater than or equal to $10^{-5}$, but less than $10^{-4}$ ergs/cm$^2$/sec |
| B | Greater than or equal to $10^{-4}$, but less than $10^{-3}$ ergs/cm$^2$/sec |
| C | Greater than or equal to $10^{-3}$, but less than $10^{-2}$ ergs/cm$^2$/sec |
| M | Greater than or equal to $10^{-2}$, but less than $10^{-1}$ ergs/cm$^2$/sec |
| X | Greater than or equal to $10^{-1}$ ergs/cm$^2$/sec |

**1.5. The Solar Wind.** Another source of space environmental activity, which can strike at anytime during the solar cycle, is enhancements or discontinuities in the outward flow of the energetic charged particles that make up the solar wind.

1.5.1. Influence of the Interplanetary Magnetic Field (IMF). The IMF emanating from the sun normally has 4 to 6 sectors of alternating positive (+) and negative (-) polarity, and a spiral structure near the plane of the Earth's orbit due to the 27-day rotation period of the sun (Figure 1.2.). Charged solar wind particles are guided by the IMF, and those particles in one IMF sector do not normally penetrate into another sector. Since particles tend to move faster in the forward portion of a sector than in the tailing portion, particle density tends to increase and be irregular just behind a "solar sector boundary (SSB)", leading to a "high speed stream (HSS)" of particles. HSSs of particles can also exist within a sector, because there are regions in the sun's atmosphere (called coronal holes) where magnetic field lines are open to space and do not impede the outward flow of charged particles. These coronal holes are most effective in causing HSSs near the plane of the Earth's orbit and during solar minimum periods. Both SSB and HSS enhancements and discontinuities can disrupt the Earth's magnetosphere as the sun's rotation causes them to sweep pass the Earth. (***NOTE***: The sun rotates on its axis once every 27 days. The coupled solar wind and IMF inherit this angular motion. Consequently, the solar wind and IMF can be thought of as a rotating pin wheel, any point on which will sweep pass the much slower moving Earth, which requires 365 days to revolve around the sun, roughly once a month.)

1.5.2. Sporadic vs Recurrent Geophysical Activity. Solar wind enhancements and discontinuities occur throughout the solar cycle, even during Solar Minimum. Fortunately, the magnitude of the disruptions they cause in the Earth's magnetosphere (and thus the severity of their DoD system impacts) tends to be less than with the disruptions caused by solar flares. Also, since these solar wind enhancements and discontinuities are tied to solar features that persist for longer than the sun's 27-day rotation period, they tend to be recurrent, and thus the geomagnetic storms they produce are somewhat easier to forecast than the sporadic geomagnetic storms produced by flares.

**1.6. Geomagnetic and Ionospheric Storms.** What is the mechanism by which charged solar particle streams (whatever their origin) disrupt our magnetosphere and adversely affect radar, communications, and space operations? Except for the funnel-like cusps above the polar caps, solar particles do not have direct access to the near-Earth environment. Instead, when a particle stream enhancement (whatever its solar source) or discontinuity in the solar wind sweeps pass the Earth, its impact sends a shockwave rippling through the magnetosphere (Figure 1.3.). Out in the magnetosphere's tail, drawn-out magnetic field lines reconnect and (like a snapping rubber band) shoot trapped particles toward the Earth's night side. Some of these particles stay near the equatorial plane and feed into the Van Allen Radiation Belts, others follow geomagnetic field lines and penetrate into the high northern and southern latitudes (or auroral zones). The results are disturbances called "geomagnetic and ionospheric storms". Later, the trapped particles in the magnetotail are replenished by the slow diffusion of solar wind particles into the magnetosphere's tail. This nightside particle injection mechanism makes sense when one looks at where DoD system impacts occur. The majority of radar, communications, spacecraft, and satellite problems occur in the ***night*** sector, ***not*** the daylit sector!

1.6.1. Geomagnetic Storms. Geomagnetic disturbances are rapid variations in the Earth's magnetic field as measured by ground-based or space-based magnetometers. A geomagnetic storm tends to occur about 24 to 72 hours after its causative solar event (flare, disappearing filament, eruptive prominence) or in response to the passing of a discontinuity in the solar wind (a sector boundary or high speed stream). A typical geomagnetic storm normally is composed of alternating periods of disturbed and relatively undisturbed conditions, and can last up to around three days. Table 1.3. lists the six levels of geomagnetic activity, based on the most commonly used indices of global geomagnetic conditions: the 3-hour ap index and 24-hour Ap index. These indices are obtained from a network of ground-based magnetometer stations.

**Table 1.3. Levels of Geomagnetic Activity.**

| LEVEL | ap OR Ap INDEX | POTENTIAL FOR IMPACTS |
|---|---|---|
| Quiet | 0 to 7 | Low |
| Unsettled | 8 to 15 | Low |
| Active | 16 to 29 | Moderate |
| Minor Storm | 30 to 49 | Moderate |
| Major Storm | 50 to 99 | High |
| Severe Storm | Greater than 100 | Very High |

1.6.2. Ionospheric Disturbances. Ionospheric disturbances occur when a portion of the earth's ionosphere (generally between 50 and 400 kilometers altitude) experiences a temporary, irregular fluctuation in its degree of ionization--either unusual enhancements or depletions in the number of ions/electrons observed. These fluctuations can be caused by the motion of charged particles within the ionosphere or by the ionizing effect of particle bombardment or solar X-ray and EUV electromagnetic radiations.

1.6.2.1. Ionospheric Storms. The term "ionospheric storm" is normally used when referring to ionospheric disturbances that occur in response to a geomagnetic storm. Like a geomagnetic storm, an ionospheric storm tends to occur about 24 to 72 hours after its causative solar event (flare, disappearing filament, eruptive prominence) or in response to the passing of a discontinuity in the solar wind (a sector boundary or high speed stream). It is also normally composed of alternating periods of disturbed and relatively undisturbed conditions, and may last up to around three days. Ionospheric storms are associated with strong auroral activity (the northern and southern lights), degraded High Frequency (HF) and satellite radio communications, and errors in spacetrack and missile detection radar observations.

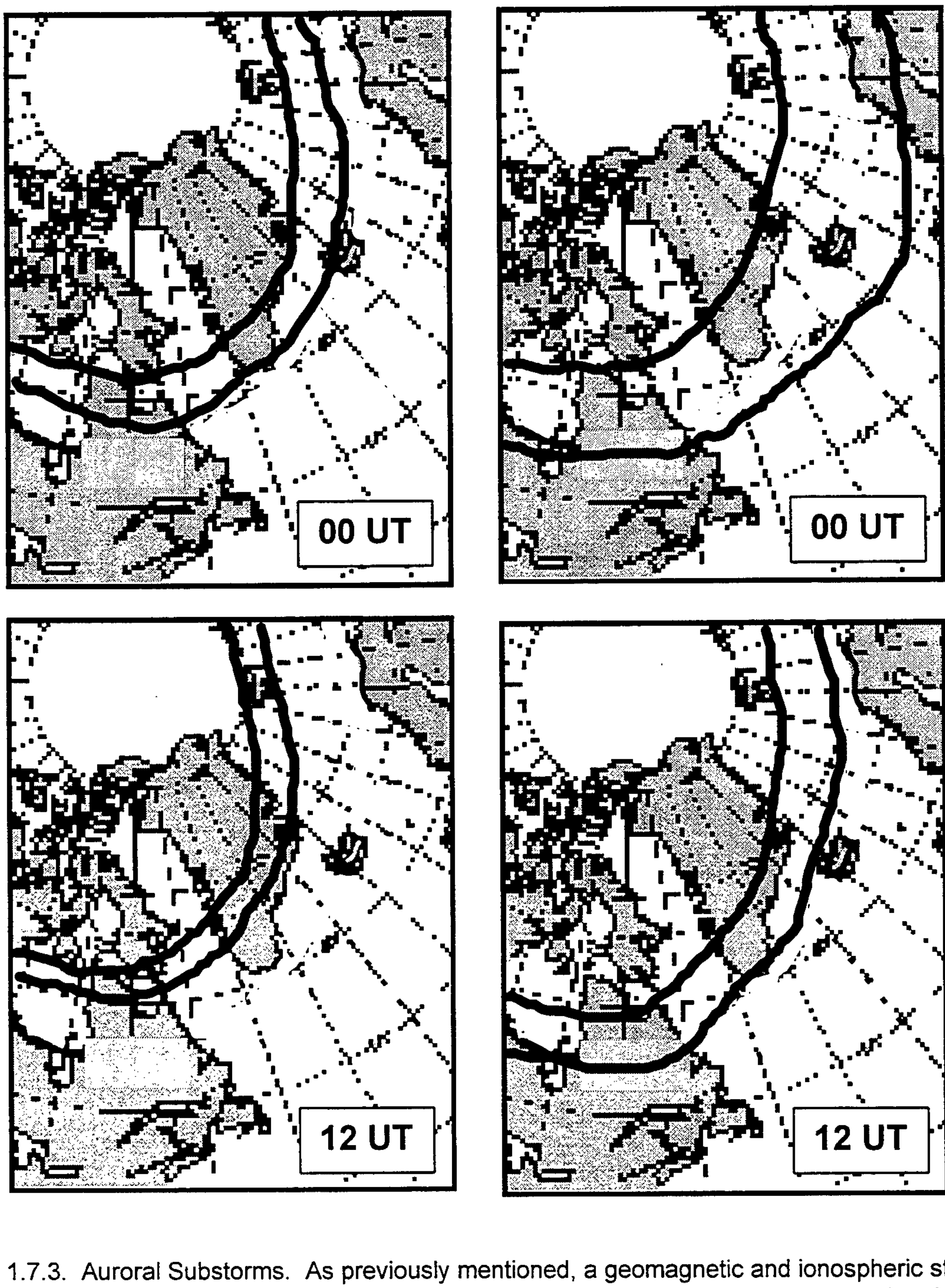
1.6.2.2. Sudden Ionospheric Disturbances (SIDs). Variations in the influx of solar X-ray and EUV radiation can also produce fluctuations in the ionosphere's degree of ionization. However, these fluctuations tend to occur immediately after the onset of the solar flare which produced the enhanced X-ray/EUV emission, will affect only the sunlit hemisphere of the Earth, and will persist only for a few tens of minutes to several hours (i.e., as long as the flare continues to produce the enhanced electromagnetic radiation). Such disturbances are normally referred to as "Sudden Ionospheric Disturbances (SIDs)", rather than ionospheric storms. The best known example of a SID is a Short Wave Fade (SWF), an event that can hamper HF radio propagation by causing severe signal absorption. Other types of SIDs can cause deviations in signal frequency, phase, and/or amplitude.

**1.7. Aurora.** Aurora is the most significant manifestation of the rapid, random variations in the degree of ionization that can be found in the high latitude ionosphere. Aurora is the electromagnetic energy (mostly visible light, but radio and ultraviolet emissions also occur) produced when charged particles from space move into the Earth's upper atmosphere and collide with its atoms and molecules. These collisions cause the atmospheric atoms and molecules to become excited or ionized over an extended range of altitudes within the ionosphere. When they de-excite or recombine, they release the observed electromagnetic energy. Since the charged particles from space follow geomagnetic field lines, they will primarily reach the Earth at high northern and southern latitudes (i.e., in the auroral zones), but not right over the polar caps.

1.7.1. The Auroral Oval and Auroral Zone. The "auroral oval" is a roughly elliptical, hollow band circling both geomagnetic poles, and represents where aurora may be occurring at any particular time. The "auroral zone" is that band of latitudes in which the occurrence of the auroral oval is statistically most likely. In a sense, one can think of the auroral zone as that band swept out by the auroral oval as the Earth rotates under the oval.

1.7.2. Auroral Activity. The size of the auroral oval and the intensity of the auroral activity in it, depend on the condition of the Earth's geomagnetic field and local time (Figure 1.5.). Auroral activity is weakest, has its narrowest latitudinal width, and is farthest poleward during quiet geomagnetic conditions and near local noon. Conversely, auroral activity is most intense, has its greatest latitudinal width, and extends furthest equatorward, during periods of high geomagnetic activity and near local midnight. Auroral effects can extend as far south as the southern United States during the most intense geomagnetic storms. The reason auroral activity is strongest, and the oval has its maximum latitudinal width and extends furthest equatorward, near the local midnight meridian (for any given level of geomagnetic activity) is that the precipitating particles which cause the aurora come from the Earth's magnetotail (i.e., from the anti-sunward direction).

**Figure 1.5. The Auroral Oval.** The panels on the left represent a typical auroral oval during periods of ***low*** geomagnetic activity. Auroral activity is weak and the oval is narrow and contracted. The panels on the right represent a typical auroral oval during periods of ***high*** geomagnetic activity. Auroral activity is more intense and the oval is wide and extends further equatorward. (After Snyder, A., and Ramsay, A., "The Aurora and the 414L Prototype Radar System", Air Force Global Weather Central, Offutt AFB, NE, August 1975.)




1.7.3. Auroral Substorms. As previously mentioned, a geomagnetic and ionospheric storm can persist for a few hours to several days. During the enhanced particle bombardment associated with such a storm, the auroral oval intensifies, broadens, and moves equatorward. A detailed examination of extended storms reveals that they are composed of a series of substorms lasting 1 to 3 hours, separated by 2 to 3 hours, due to irregularities in the causative solar particle streams. The enhanced and very irregular degree of ionization caused by variable particle bombardment will cause problems such as: low altitude, high inclination spacecraft charging; satellite drag; radar interference and clutter; spacetrack errors; and anomalous propagation of High Frequency (HF) and satellite communications (SATCOM) radio signals (e.g., non great circle propagation, absorption, scattering, fading, retardation, refraction, scintillation, etc.).

**1.8. High Energy Proton Events.** The polar cusps in the magnetosphere can provide direct access to the Earth's upper atmosphere for energetic solar protons which are sometimes emitted by the larger solar flares.

1.8.1. Forecasting Proton Events. These high energy protons are normally sufficiently energetic to cut across the solar wind and IMF, and can reach the Earth within a quarter hour to several hours after the causative flare. Fortunately, few flares are capable of producing these high energy protons. Additionally, the Earth represents a rather small target 93 million miles from the sun, so many proton streams will miss the Earth entirely. However, an unfortunate consequence of the rarity of these proton events is that they are very difficult to forecast. The forecaster must determine whether such particles were produced, whether they will arrive at the Earth, when they will arrive, how long they will persist, and what energy ranges they will be in.

1.8.2. Proton Event System Impacts. These high energy protons represent a direct radiation danger to astronauts and high altitude aircraft crews (e.g., U-2 or Supersonic Transport (SST)). They can also produce direct collisional electrical charging on satellites or spacecraft. These impacts are most frequently observed near the Earth's polar caps, where the "polar cusps" in the magnetosphere provide direct access to low altitudes in the Earth's atmosphere. High Frequency (HF) "polar cap absorption (PCA)" events occur when the high energy protons penetrate into the polar ionosphere's lowest region (called the "D-layer"), roughly 50 to 90 km in altitude. As these protons collide with atmospheric atoms and molecules, they cause significantly increased levels of ionization, resulting in severe absorption of HF radio waves used for communication and some radar systems. This phenomenon, sometimes referred to as a "polar cap blackout", may last for several days and is often accompanied by widespread geomagnetic and ionospheric disturbances as lower energy solar protons and electrons arrive. Since the ionosphere's base tends to lower during PCA events, concurrent errors on Low Frequency (LF) navigational systems are also normally observed.

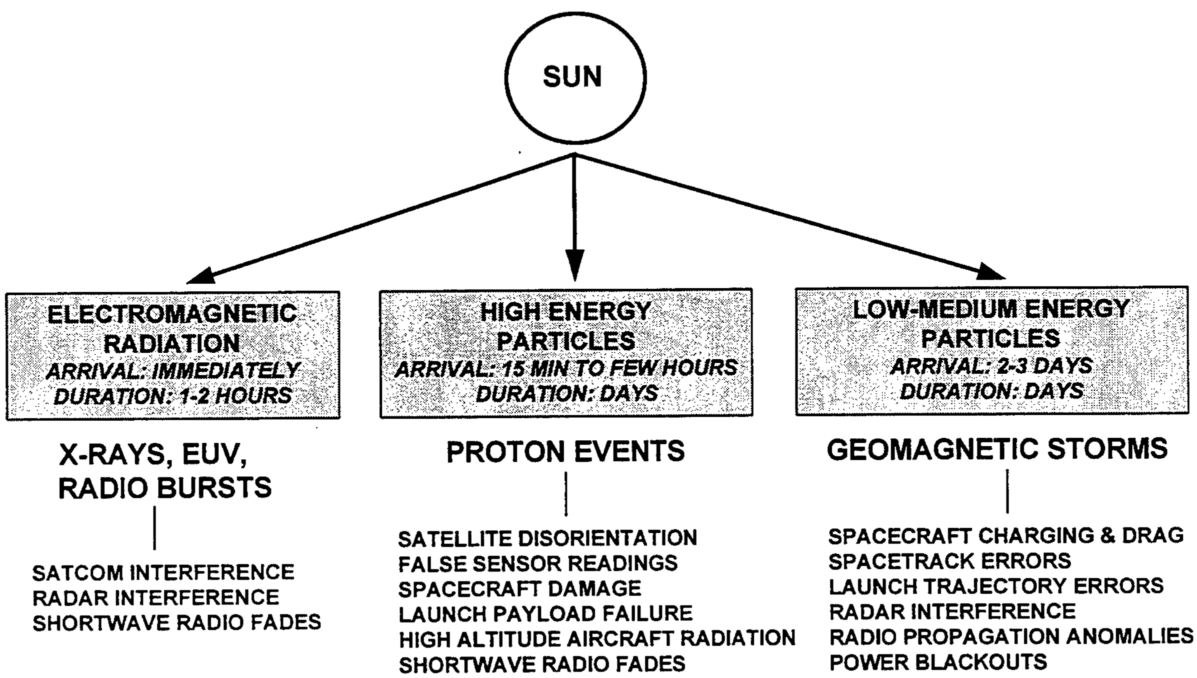
## Chapter 2

## IMPACTS ON DOD OPERATIONS

**2.1. Operational Impacts.** Each of the solar-geophysical phenomena and events described in the previous chapter has the potential to adversely impact radar, communications, and space systems. This chapter will discuss those impacts in general, then individually.

2.1.1. DoD System Impacts. Generally the stronger a solar flare; or the larger a disappearing filament or eruptive prominence; or the denser/faster/more energetic a particle stream; or the sharper a solar wind discontinuity or enhancement, the more severe will be the event's impacts on the near-Earth environment and on DoD systems operating in or through that environment. To add insult to injury, all the DoD system impacts discussed below in this chapter do not occur one at a time. Usually combinations of system impacts are experienced simultaneously; and the stronger the causative solar-geophysical activity, the more different types of impacts will be seen (Figure 2.1.).

**Figure 2.1. Solar Emissions and Impacts.** Each of the three general categories of solar radiation has its own characteristics and types of immediate or delayed DoD system impacts.




2.1.2. 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, which can cause transformer failures and power outages, and in long pipelines (such as the Alaskan oil pipeline), and (2) magnetic field variations, which can lead to compass errors and interfere with geological surveys.

**2.2. Electromagnetic (Immediate) Vs 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

Radiowave) emissions are too feeble, or their particle streams may simply miss hitting the Earth. For those events that do affect the near-Earth environment, there can be both immediate and delayed effects depending on the exact type of enhanced radiations emitted. Figure 2.1., and the three paragraphs immediately below, summarize the three general categories of solar radiation and the immediate or delayed DoD system impacts they produce.

2.2.1. 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 8 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. Since the enhanced electromagnetic emissions cease when the flare ends, their effects tend to subside shortly after the flare ends. As a result, these effects tend to last 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), LORAN navigation errors, and absorption of HF (3-30 MHz) radio communications.

2.2.2. 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--if they arrive at all. Not all flares produce these high energy particles, plus the Earth is a rather small target 93 million miles from the sun, so predicting solar proton and cosmic ray events is a difficult forecast challenge. The major impact of these protons is felt over the polar caps, where the protons have ready access to low altitudes through funnel-like cusps in the 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, collisional damage on satellites and spacecraft, false sensor readings, LORAN navigation errors, and absorption of HF radio signals.

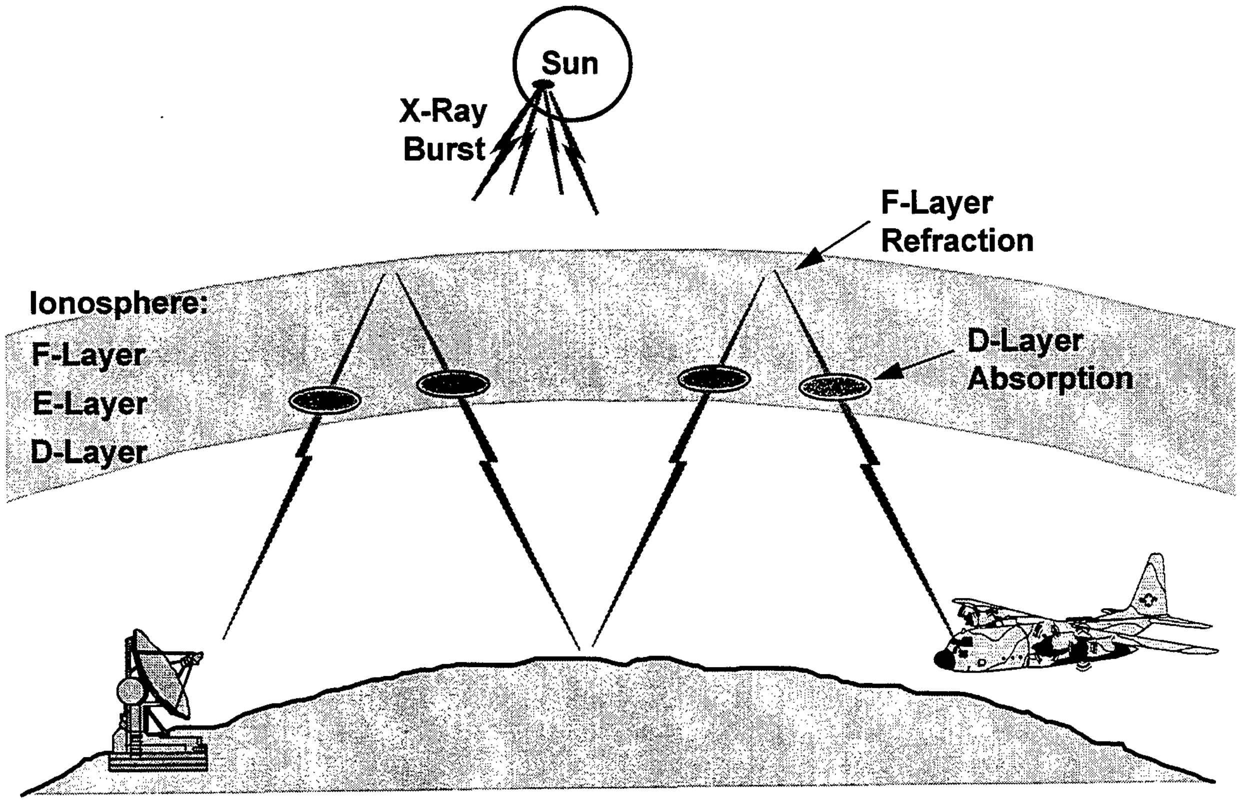
2.2.3. Low to Medium Energy Particles. Particle streams (composed of both protons and electrons) may arrive at the Earth about 2 to 3 days after a flare. Such particle streams can also occur at anytime due to other, non-flare solar activity. These particles cause Geomagnetic and Ionospheric Storms which can last for hours to several days. Typical problems include: spacecraft electrical charging, drag on low orbiting satellites, radar interference, spacetrack errors, and radiowave propagation anomalies. These impacts are most frequently experienced in the nightside sector of the Earth.

**2.3. Electromagnetic (Immediate) Effects.** The first of the specific DoD system impacts to be discussed will be the Short Wave Fade (SWF), which is caused by solar flare X-rays. The second impact will be SATCOM and radar interference caused by solar flare radio bursts. These electromagnetic (or immediate) impacts occur simultaneously with the solar flare that caused them, tend to persist only a bit longer than the flare, and are almost entirely limited to the Earth's sunlit hemisphere.

**2.4. Short Wave Fade (SWF) Events.** The High Frequency (HF, 3-30 MHz) radio band is also known as the short wave band. Thus a SWF refers to an abnormally high fading (or absorption) of a HF radio signal.

2.4.1. HF Radio Communications. The normal mode of radiowave 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 (Figure 2.2.). (***NOTE***: The "ionosphere" is defined as that portion of the Earth's atmosphere above roughly 50 km where ions and electrons are present in quantities sufficient to affect the propagation of radio waves.)

**Figure 2.2. High Frequency (HF) Communications.** HF radiowaves are refracted by the ionosphere's F-layer. However, each passage through the ionosphere's D-layer causes signal absorption, which is additive.

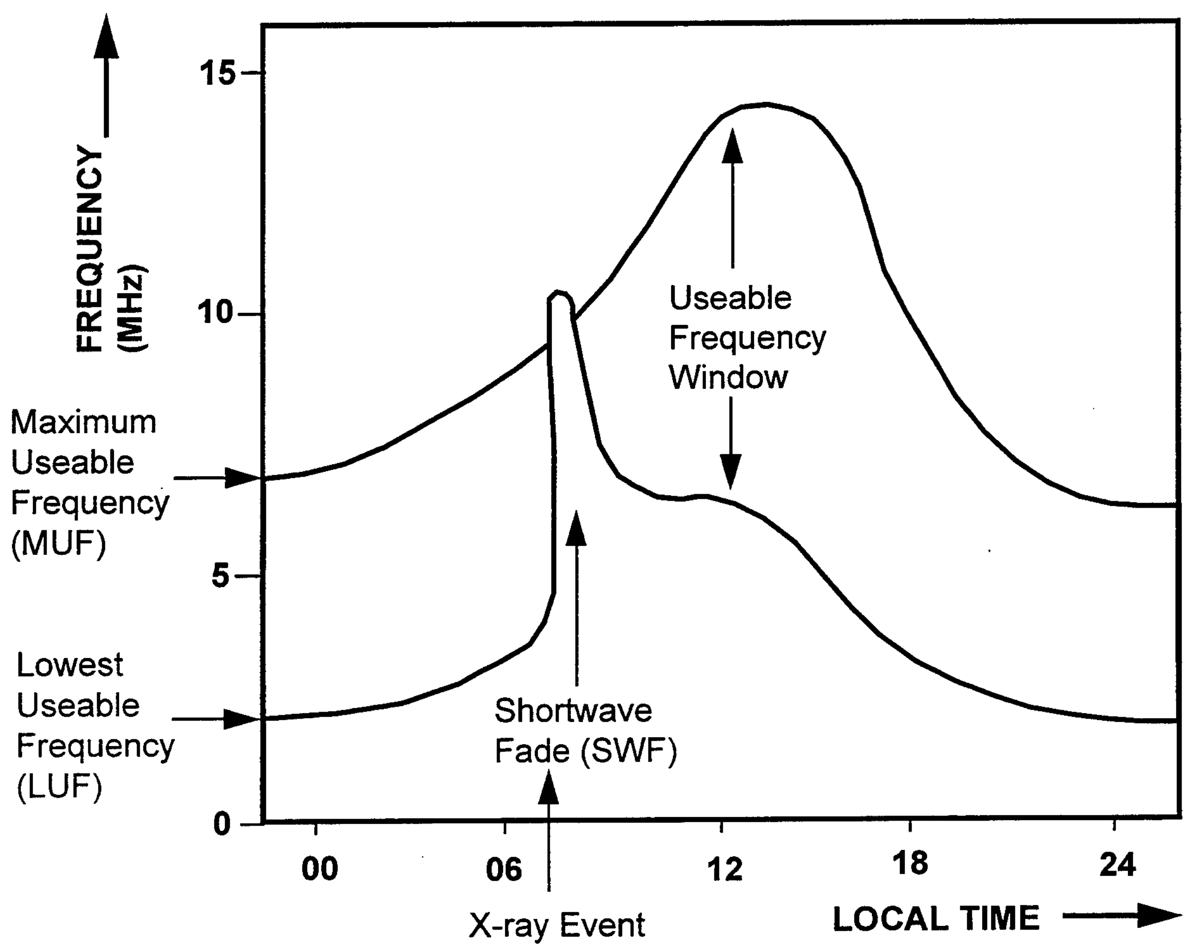



2.4.1.1. Maximum Useable Frequency (MUF). The portion of the ionosphere with the greatest degree of ionization is the F-layer (normally between about 200 and 400 km altitude). The presence of free electrons in the F-layer causes radiowaves to be refracted (or bent), but the higher the frequency the less the degree of bending. As a result, surface-to-surface radio operators use Medium or High Frequencies (300 kHz to 30 MHz), while SATCOM operators use Very to Extreme High Frequencies (30 MHz to 300 GHz). The 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 upper portion of the HF band.

2.4.1.2. Lowest Useable Frequency (LUF). The lowest layer of the ionosphere is the D-layer (normally between 50 and 90 km altitude). At these altitudes there is still a large number of neutral air atoms and molecules coexisting with the ionized particles. As a passing radiowave 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 radiowave signals. The lower the frequency, the greater the degree of signal absorption. The 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 lower portion of the HF band.

2.4.1.3. HF Propagation Window. The HF radio propagation window (Figure 2.3.) is the range of frequencies between a LUF (complete D-layer signal absorption) and a MUF (insufficient F-layer refraction to bend back the signal). This window varies by location, time of day, season, and with the 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. As seen in Figure 2.3., typical LUF/MUF curves show a normal, daily variation. During early afternoon, incoming photoionizing solar radiation (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 (some layers disappear altogether), and the LUF and MUF become depressed.

**Figure 2.3. High Frequency (HF) Propagation Windows.** HF radiowaves above the MUF encounter insufficient refraction and pass through the ionosphere into space. Those below the LUF suffer total absorption in the ionosphere's lowest layer. The result is a useable frequency window. (After "Space Weather Training Program, Student Manual", Air Force Space Command, Peterson AFB, CO, 16 June 1995.)




2.4.2. 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 a SWF, and may at times be strong enough to close the HF propagation window completely (called a Short Wave Blackout). The amount of signal loss depends on a flare's X-ray intensity, location of the HF path relative to the sun, and design characteristics of the system. A 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 a 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 7 minutes of event onset) issue a 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 pass the end of the causative flare; i.e., for a few tens of minutes to an hour or two.

2.4.3. Other Sudden Ionospheric Disturbances (SIDs). A SWF is only the most common and troublesome of a whole family of SIDs 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 phenomena (called a Sudden Phase Anomaly) will affect Very-Low Frequency (VLF, 3-30 kHz) and Low Frequency (LF, 30-300 kHz) transmissions and can cause LORAN navigation errors. Other types of SIDs are described briefly in the attached Glossary.

**2.5. SATCOM and Radar Interference.** Solar flares can cause the amount of radiowave energy emitted by the sun to increase by a factor of tens of thousands over certain frequency bands in the VHF to SHF range (30 MHz to 30 GHz). These radio bursts can produce direct Radio Frequency Interference (RFI) on a SATCOM link, or a missile detection or spacetrack radar, ***if*** the sun is in the field of view of the receiver and ***if*** the burst is at the right frequency and intense enough. 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 intentional jamming.

2.5.1. Solar Radio Bursts. 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 7 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 to tens of minutes, but usually not for the full duration of the causative flare.

2.5.2. Solar Conjunction. There is a similar geometry-induced affect, called "solar conjunction", which accounts for why geosynchronous communication satellites will experience interference or blackouts (e.g., static or "snow" on TV signals) 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 significance is definitely greatest during Solar Max when the sun is a strong background radio emitter.

2.5.3. 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.

**2.6. Particle (Delayed) Effects.** The discussion of specific DoD system impacts will continue with the major delayed (or charged particle induced) system impacts. The "delayed" impacts tend to occur hours to several days after the solar activity that caused them, persist for up to several days, and be mostly felt in the nighttime sector (since the particles that cause them usually come from the magnetosphere's tail), although they are not limited to that time or geographic sector.

2.6.1. Particle Events. The sources of the charged particles (mostly protons and electrons) include: solar flares, disappearing filaments, eruptive prominences, and solar sector boundaries (SSBs) or high speed streams (HSSs) 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 a SSB or density/speed of a HSS will determine the intensity of a particle-induced event caused by these phenomena.

2.6.2. 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, while the sun rotates once every 27 days. As a result, there is a tendency for these long lasting phenomena to show a 27 day recurrence in producing geomagnetic and ionospheric disturbances.

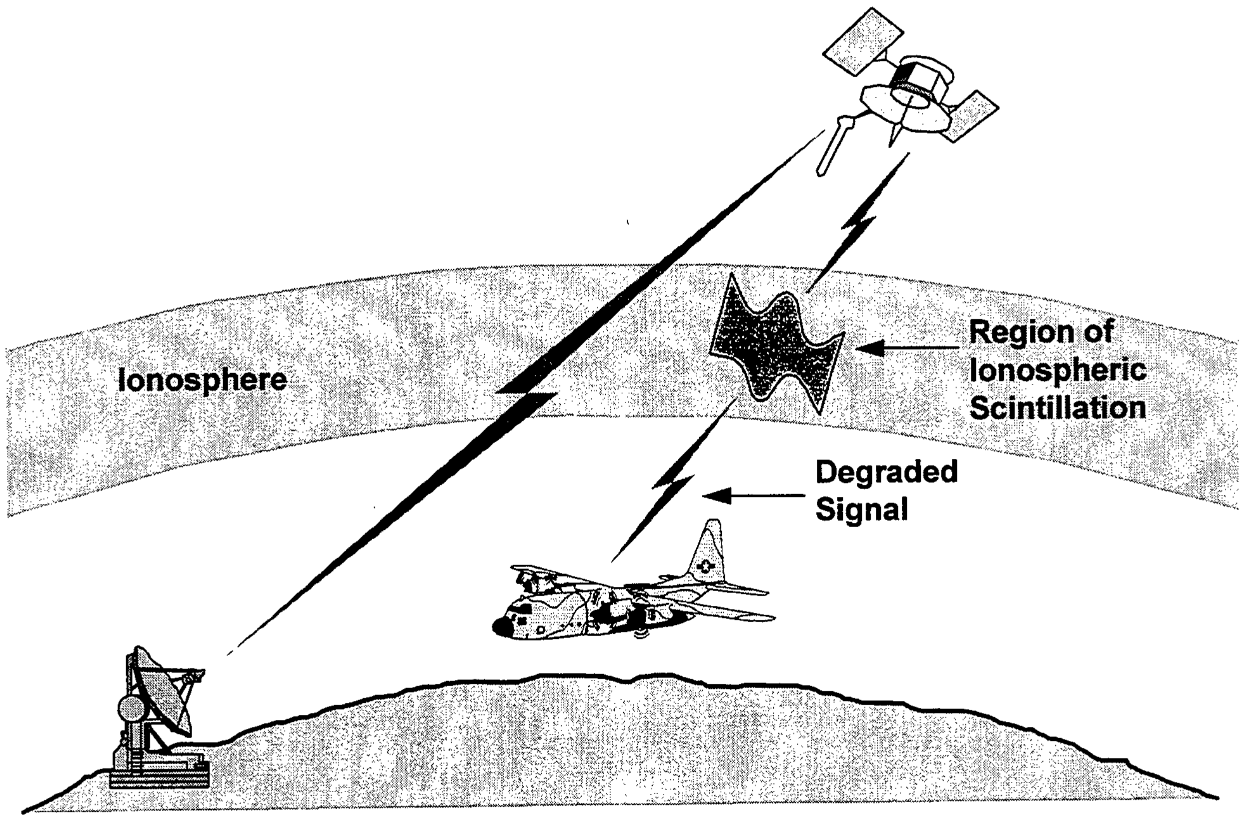
**2.7. High Frequency (HF) Absorption Events.** High Frequency SWFs over the sunlit hemisphere (caused by solar flare X-rays enhancing D-layer absorption) were already discussed. There are similar HF absorption events at high geomagnetic latitudes (above 55 degrees). However, at high latitudes the enhanced 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 to several days, and usually occur simultaneously with other radio transmission problems like non-great circle propagation and multipath fading or distortion.

2.7.1. Polar Cap Absorption (PCA) Events. For a PCA event, the enhanced ionization is caused by solar flare 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.

2.7.2. Auroral Zone Absorption (AZA) Events. For an AZA event, the enhanced ionization is caused by particles (primarily electrons) from the magnetosphere's tail, which are accelerated toward the Earth during a geomagnetic storm and are guided by magnetic field lines into the auroral zone latitudes. These are the same ionizing particles that cause the aurora or Northern/Southern Lights.

**2.8. Ionospheric Scintillation.** The intense ionospheric irregularities found in the auroral zones are also one cause of ionospheric "scintillation", at least at high geomagnetic latitudes. Scintillation of radiowave 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. (Ionospheric radiowave 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 drop-outs on satellite command uplinks, data downlinks, or on communications signals. Scintillation tends to be a highly localized effect. Only if the signal path penetrates an ionospheric region where these small scale electron density irregularities are occurring will an impact be felt (Figure 2.4.). 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.

**Figure 2.4. Ionospheric Scintillation.** Scintillation of radiowave 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. (After "Space Weather Training Program, Student Manual", Air Force Space Command, Peterson AFB, CO, 16 June 1995.)



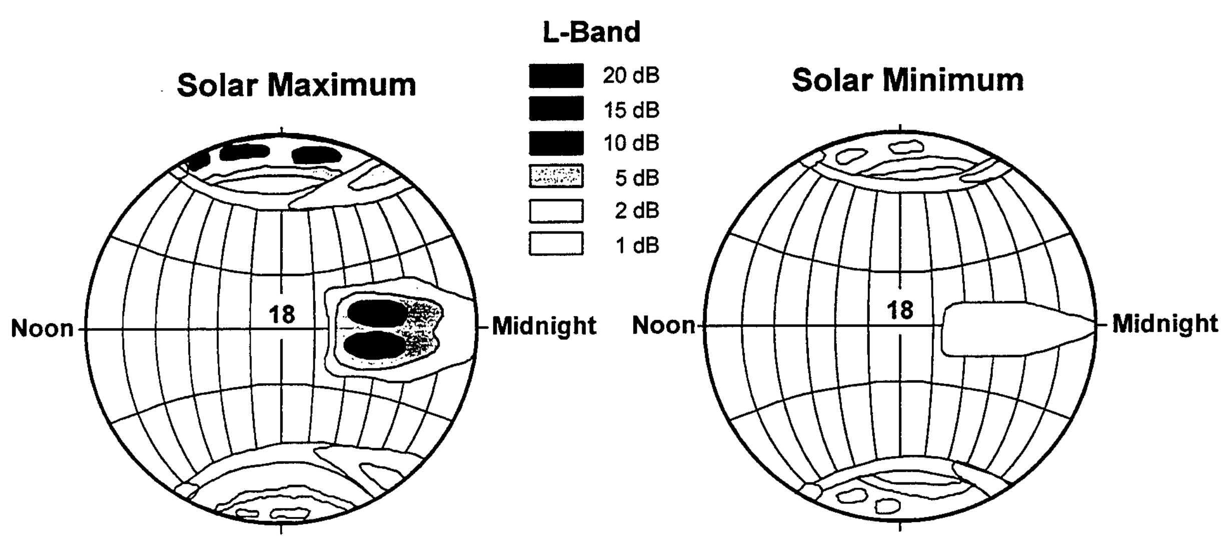

2.8.1. Global Positioning System (GPS).

2.8.1.1. GPS and Scintillation. GPS satellites, which are located at semi-synchronous 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 useable 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 wide-spread 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.

2.8.1.2. GPS and Total Electron Content (TEC). The TEC along the path of a GPS signal can introduce a positioning error. Just as the presence of free electrons in the ionosphere caused HF radiowaves 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 radiowaves). This signal bending increases the signal path length. In addition, passage through an ionized medium causes radiowaves 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 day of the year and the average solar UV flux for the previous few days. This method produces a gross correction for the entire ionosphere. But, as has already been 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 magnetic equator during evening hours.

2.8.2. Scintillation Occurrence. There is no fielded network of ionospheric sensors capable of detecting real-time scintillation occurrence or distribution. So presently space environmental forecasters are heavily dependent on its known association with other environmental phenomena (such as aurora) and scintillation climatology. Scintillation is also frequency dependent; the higher the radio frequency (all other factors held constant), the lesser the impact of scintillation. Figure 2.5. shows where scintillation is statistically most pronounced. Statistically, scintillation tends to be most severe at low latitudes (within ± 20 degrees of the geomagnetic equator) due to ionospheric anomalies in that region (see "Appleton Anomaly" and "spread F" in the Glossary for more information). It is also 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. Knowledge of those time periods and portions of the ionosphere where conditions are conducive to scintillation permits operators to reschedule activities or to switch to less susceptible radio frequencies.

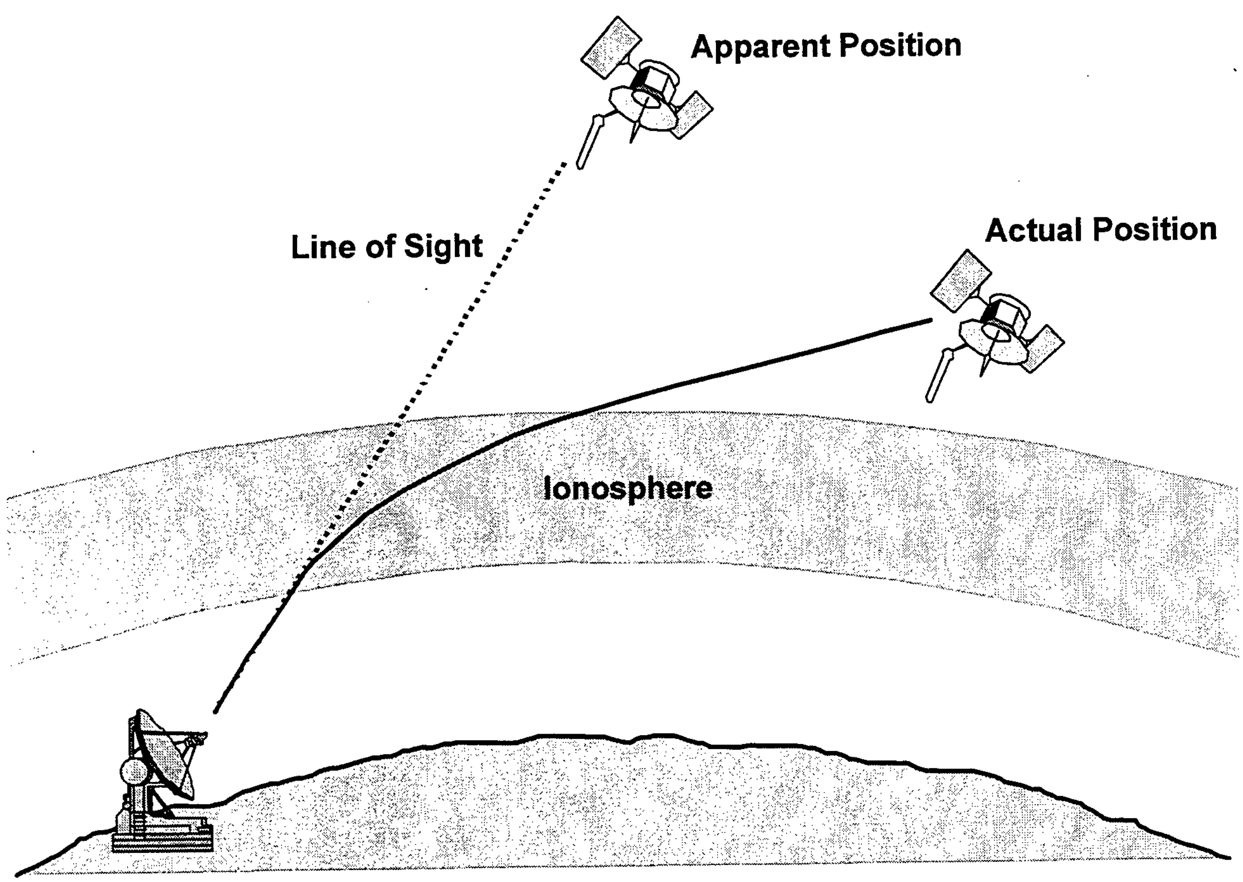
**Figure 2.5. Scintillation Occurrence.** Average scintillation conditions by level of solar activity, time of day, and latitude. L-band refers to about 1.5 GHz. (After Basu, S., and Larson, J., "Turbulence in the Upper Atmosphere: Effects on Satellite Systems", AIAA 95-0548, 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV, 9-12 January 1995.)




**2.9. Radar Aurora Clutter and Interference.** As previously discussed, 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 phenomena is observed as the Aurora or Northern/Southern Lights. This enhanced, irregular ionization can also produce abnormal radar signal back-scatter on poleward looking radars, a phenomena known as "radar aurora". 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 detections. While improved software screening programs have greatly reduced the frequency of false aircraft or missile launch detections, they've not been eliminated totally. (***NOTE***: Radar aurora is a separate phenomena from the weak radiowave emission produced by the recombination or de-excitation of atmospheric atoms and molecules in the auroral oval, a process which also produces the much stronger infrared, visible, and ultraviolet auroral emissions.)

**2.10. Surveillance Radar Errors.** The presence of free electrons in the ionosphere causes radiowaves to be bent (or refracted), as well as slowed (or retarded) somewhat from the speed of light. Missile detection and spacetrack radars operate at Ultra High Frequencies (UHF, 300-3,000 MHz) and Super High Frequencies (SHF, 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 2.6.).

**Figure 2.6. Surveillance Radar Errors.** Refraction of a radiowave signal through the ionosphere causes an error in an object's measured direction. Signal retardation and a longer path length cause an error in an object's measured range. (After "Space Weather Training Program, Student Manual", Air Force Space Command, Peterson AFB, CO, 16 June 1995.)




2.10.1. 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. For range errors, the effect of longer path length dominates for UHF signals, while slower signal speed dominates for SHF signals.

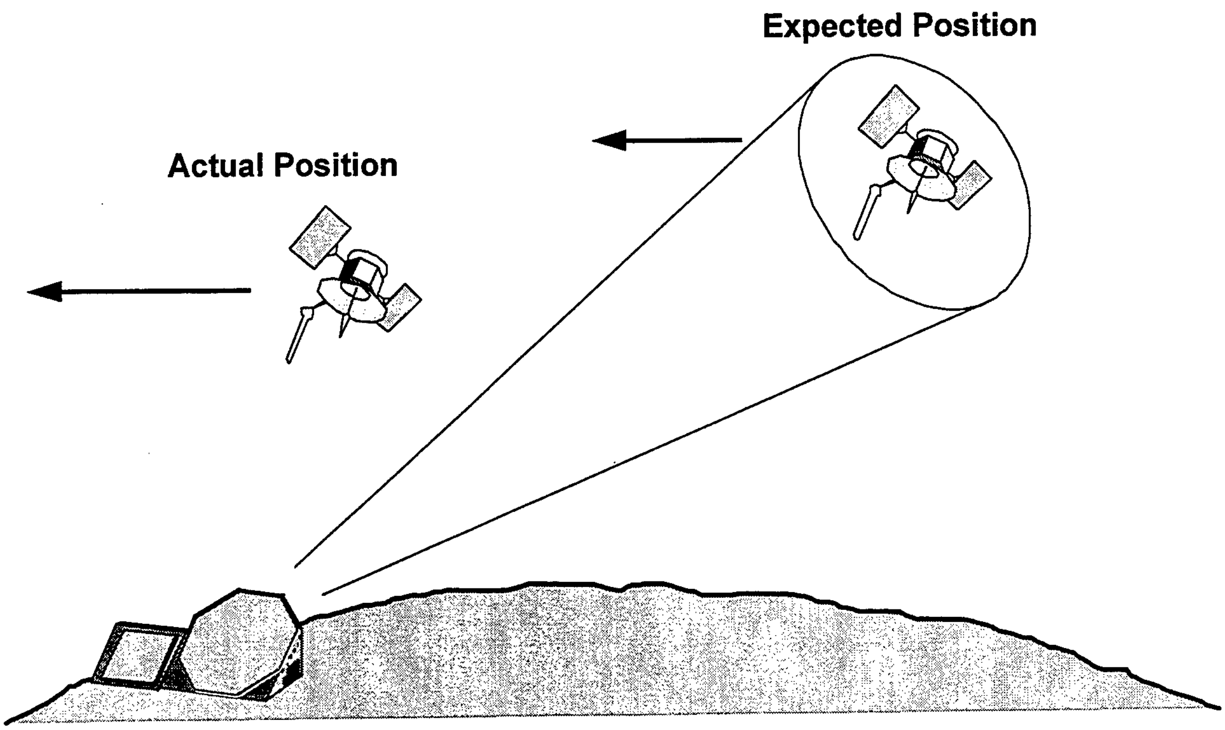
2.10.2. Correction Factors. Radar operators routinely attempt to compensate for these bearing and range errors by applying correction factors that are based on the expected ionospheric "total electron content (TEC)" along a radar beam's path. These predicted TEC values/correction values are based on 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.

2.10.3. Space-Based Surveillance. The bearing and range errors introduced by ionospheric refraction and signal retardation (as described above) 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.

2.10.4. Over-the-Horizon Backscatter (OTH-B) Surveillance Radars. 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 great 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.

**2.11. Atmospheric Drag.** Another source for space object positioning errors is either more *or* less atmospheric drag than expected on low orbiting objects (generally at less than about 1000 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 the object will be some distance below and ahead of its expected position when a ground radar or optical telescope attempts to locate it (Figure 2.7.). (Conversely, exceptionally quiet solar and/or geomagnetic conditions will cause ***less*** atmospheric drag than predicted, and an object would be higher and behind where it was expected to be found.)

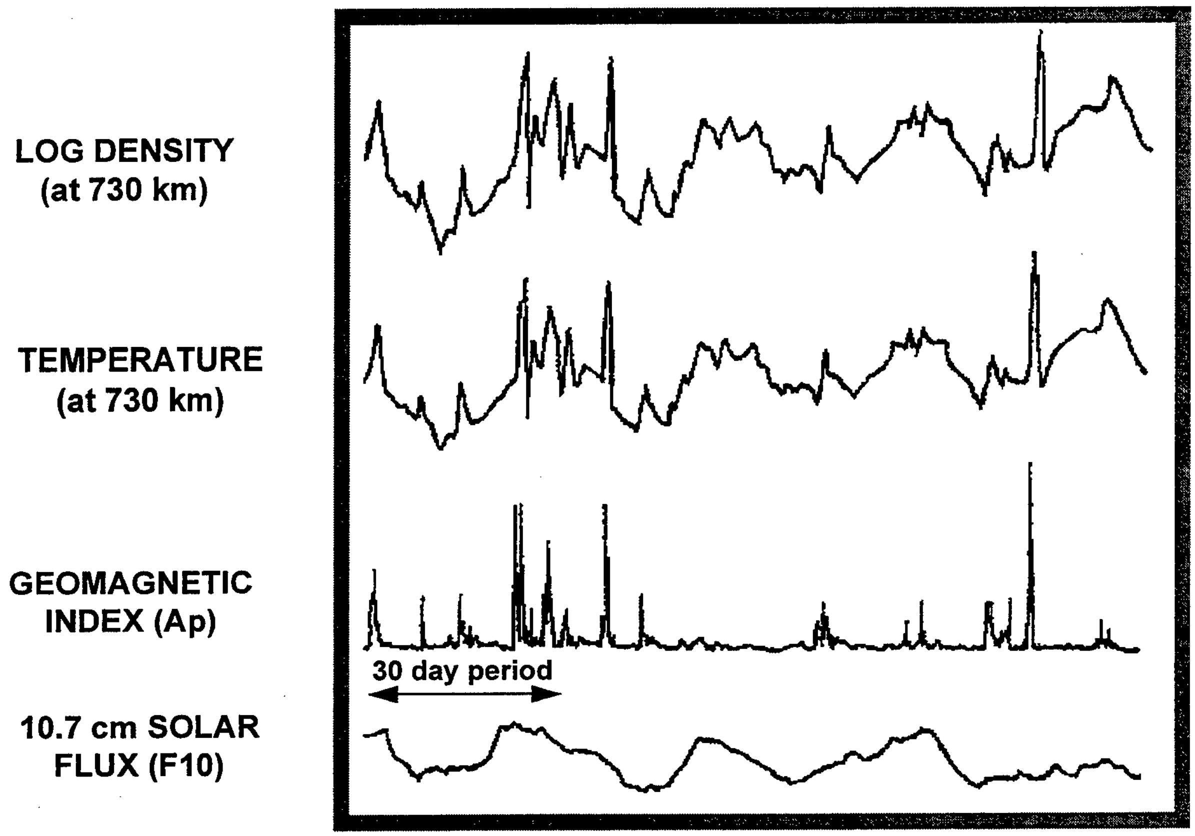
**Figure 2.7. Atmospheric Drag.** A change in atmospheric density at any given altitude can produce more or less frictional drag than expected, which can cause a space object to change its orbit. (After "Space Weather Training Program, Student Manual", Air Force Space Command, Peterson AFB, CO, 16 June 1995.)




2.11.1. Impacts of Atmospheric Drag. The consequences of atmospheric drag include: (1) inaccurate satellite locations can hinder rapid acquisition of SATCOM links for commanding or data transmission, (2) costly orbit maintenance maneuvers may become necessary, and (3) de-orbit predictions may become unreliable. A classic case of the later was Sky Lab. Geomagnetic activity was so severe, for such an extended period, that Sky Lab de-orbited and burned-in before a planned Space Shuttle rescue mission was ready to launch.

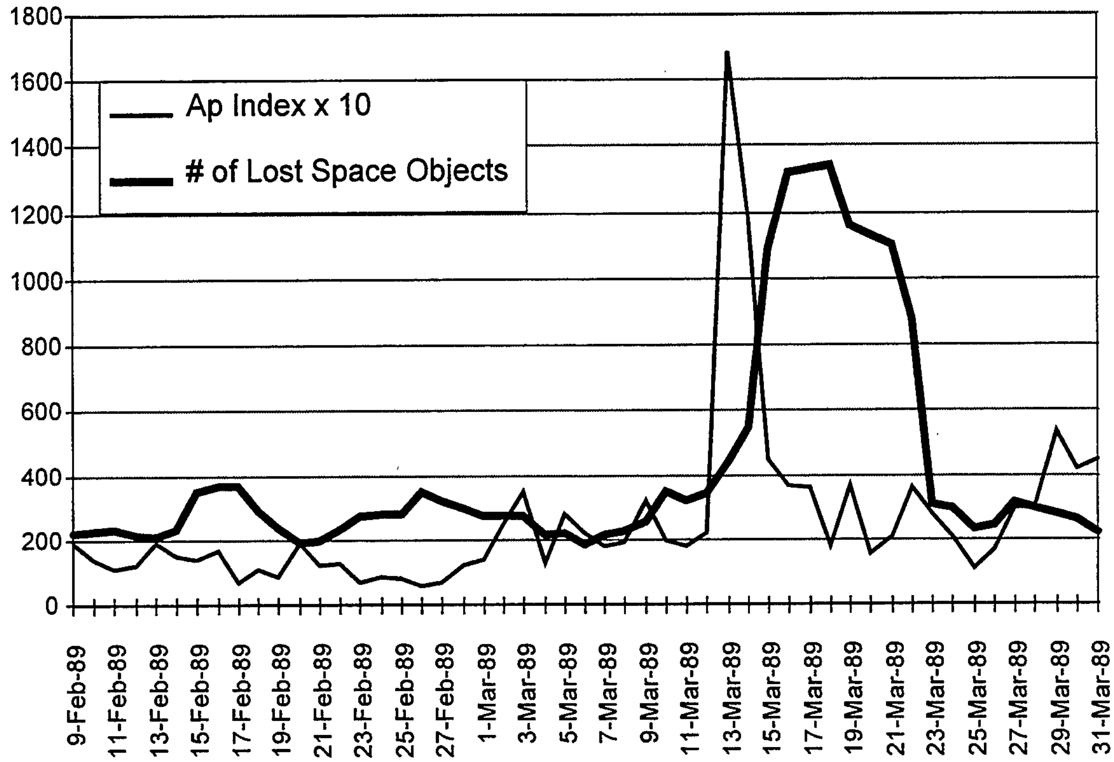
2.11.2. Contributions to Drag. There are two space environmental parameters used by current models to predict the orbits of space objects. The first is the solar "F10 index". Although the F10 index is a measure of solar radio output at 10.7 centimeters (or 2800 MHz), it is a very good indicator of the amount of EUV and X-ray energy emitted by the sun and deposited in the Earth's upper atmosphere. In Figure 2.8., 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 it takes time for the atmosphere to react to a change in the amount 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 2.8. Factors Contributing to Atmospheric Drag.** The influx of electromagnetic radiation (represented by the F10 index) and particulate radiation (represented by the Ap index) deposits energy in the Earth's atmosphere, causing it to heat and expand. (After Jacchia, L., "Atmospheric Structure and Its Variations At Heights Above 200 KM", *CIRA (Cospar International Reference Atmosphere) 1965*, North-Holland Publishing Company, Amsterdam, 1965.)




2.11.3. The Impact of Geomagnetic Storms on Orbit Changes. Two impacts of geomagnetic storms on spacetrack radars have now been discussed. The first was bearing and range errors induced by inadequate compensation for TEC changes, which caused ***apparent*** location errors. The second was atmospheric drag, which caused ***real*** position errors. These effects can occur simultaneously. Figure 2.9. shows the impact of a severe geomagnetic storm in March 1989. Over 1,300 space objects were temporarily misplaced; it took almost a week to re-acquire 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're also more time consuming.

**Figure 2.9. Geomagnetic Storms and Orbit Changes.** This figure demonstrates how a geomagnetic storm can change the orbits of space objects unexpectedly, causing difficulty for those who maintain orbital data.




**2.12. Space Launch and Payload Deployment Problems.**

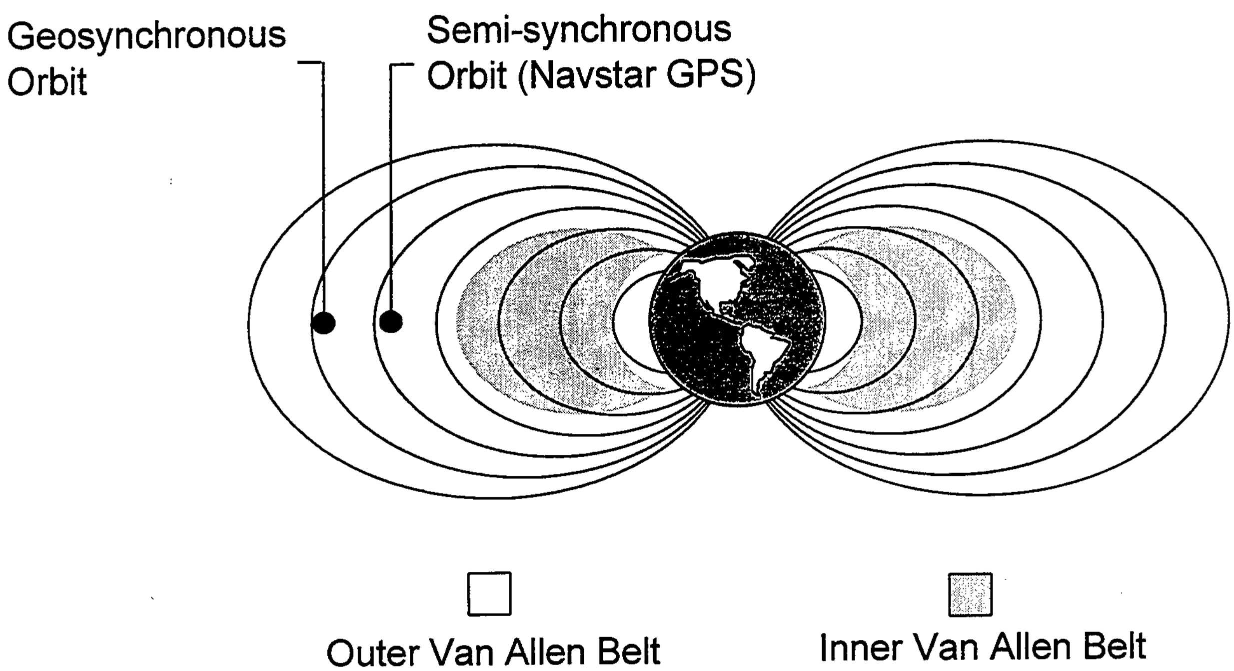
2.12.1. Atmospheric Drag. Excessively high *or* low geomagnetic conditions can produce atmospheric density variations along a proposed launch trajectory which may be outside a launch vehicle's capacity to compensate for. In addition, the atmospheric density profile with altitude will determine how early the protective shielding around a payload can be jettisoned. Jettison too early and the payload is exposed to excessive frictional heating; jettison too late and booster fuel is wasted.

2.12.2. Particle Bombardment. Charged particle bombardment during a geomagnetic storm or proton event can produce direct collisional 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 on-board electrical activity such as vehicle commanding. In the past, payloads have been damaged by attempted deployment during geomagnetic storms or proton events.

**2.13. Radiation Hazards.** Despite all engineering efforts, satellites are still quite susceptible to the charged particle environment; in fact, with the newer microelectronics and lower voltages, it will actually be easier to cause electrical upsets than on the older, simpler vehicles. Furthermore, with the perceived lessening of the man-made nuclear threat, there has been a trend to build new satellites with less nuclear radiation hardening. This lost 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 collisional 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.

2.13.1. Van Allen Radiation Belts. The Outer and Inner Van Allen Radiation Belts are two concentric, toroid (or donut-shaped) regions of stablely trapped charged particles that exist because the geomagnetic field near the Earth is strong and field lines are closed (Figure 2.10.). The Inner Belt has a maximum proton density near 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 near 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.

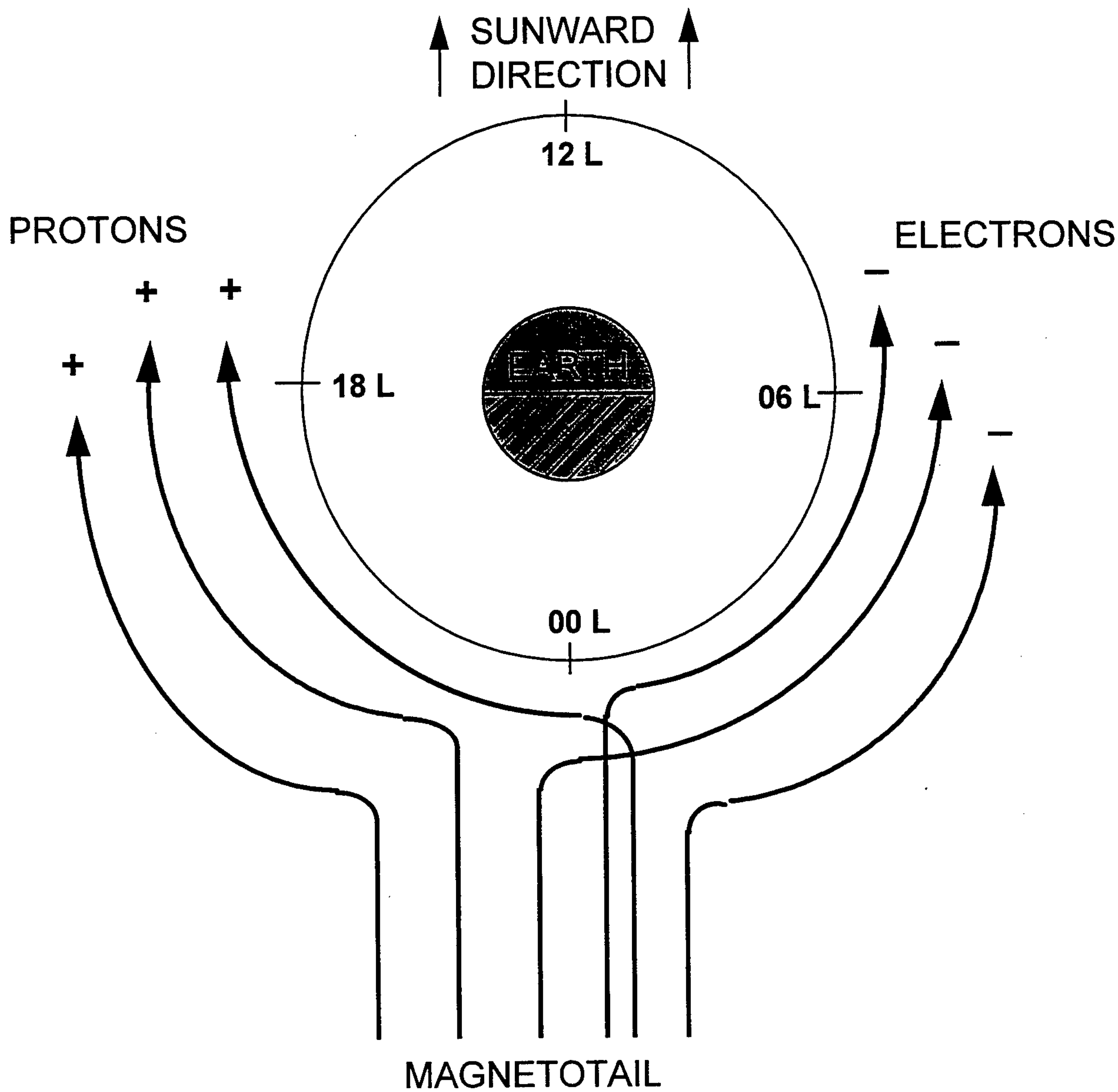
**Figure 2.10. Van Allen Radiation Belts.** The inner and outer radiation belts are regions of stably trapped charged particles. (After "Space Weather Training Program, Student Manual", Air Force Space Command, Peterson AFB, CO, 16 June 1995.)




2.13.2. 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 Belt, and suffers whenever that boundary moves inward or outward. Semi-synchronous orbit (which is 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 to 1000 over a time period as short as a few tens of minutes.

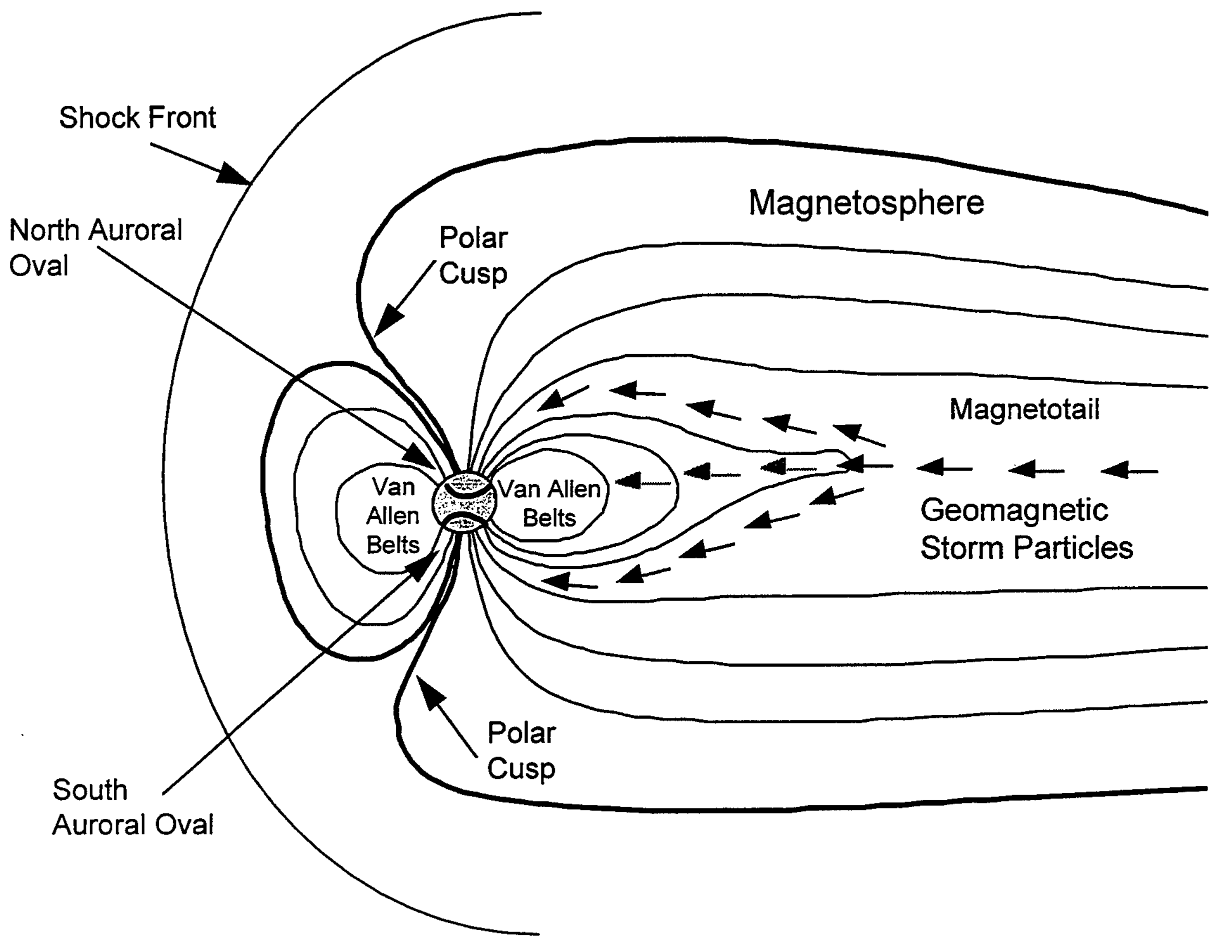
2.13.3. Geomagnetic Storms. As mentioned earlier, charged particles emitted by the sun cause problems primarily on the ***night*** side of the Earth. The reason is the arrival of solar particles causes a shockwave to ripple through the magnetosphere, magnetic field lines out in the magnetosphere's tail recombine, and previously stored particles are shot toward the Earth's nightside hemisphere. Some of these particles (Figure 2.11.) stay near the plane of the equator and feed the ring current in the Outer Van Allen Radiation Belt, while other particles (Figure 2.12.) follow magnetic field lines up (and down) toward auroral latitudes.

**Figure 2.11. Geomagnetic Storms - Radiation Belt Particle Injections.** (View is a cross section of the magnetosphere taken in the plane of the Earth's geomagnetic equator.) Charged particles are injected from the magnetosphere's tail (nightside) into the ring current, which circles the Earth and is part of the Outer Van Allen Radiation Belt. The protons and electrons, being oppositely charged, tend to move in opposite directions.




2.13.3.1. Radiation Belt Particle Injections. Those particles from the nightside magnetosphere (or magnetotail) which stayed near the plane of the equator will feed the ring current in the Outer Van Allen Belt (Figure 2.11.). The electrons and protons, since they are oppositely charged, tend to move in opposite directions when they reach the ring current. Furthermore, the protons and electrons have about the same energy, but the electrons (since they are 1800 times lighter) move 40 times faster. Finally, the electrons are about 10 to 100 times more numerous than the protons. The result of all these factors is that electrons are much more effective at causing collisional damage and electrical charging than the protons. This fact explains why the preponderance of satellite problems occur in the midnight to dawn (00 to 06 Local) sector, while the evening (18 to 00 Local) sector is the second most preferred location for problems. This explanation is well supported by the large number of satellite anomalies actually observed in the midnight to dawn sector.

**Figure 2.12. Geomagnetic Storms - Auroral Particle Injections.** Electrically charged particles will tend to follow geomagnetic field lines as they move toward the Earth. Many particles will arrive simultaneously at high northern (and southern) geomagnetic latitudes. These particles (mostly electrons) can penetrate to very low altitudes where they will produce the Northern and Southern Lights (or aurora) and adversely affect high-inclination, low-altitude satellites. (After "Space Weather Training Program, Student Manual", Air Force Space Command, Peterson AFB, CO, 16 June 1995.)




2.13.3.2. Auroral Particle Injections. Some of the particles from the nightside magnetosphere (Figure 2.12.) 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 collisional damage and electrical charging on high-inclination, low-altitude satellites or Space Shuttle missions.

**2.14. Electrical Charging.** One of the most common anomalies caused by the radiation hazards discussed above is spacecraft or satellite electrical charging. Charging can be produced by: (1) an object's motion through a medium containing charged particles (called "wake charging"), which is a significant problem for large objects like the Space Shuttle or a space station; (2) directed particle bombardment, as occurs during geomagnetic storms and proton events; or (3) solar illumination, which causes electrons to escape from an object's surface (called the "photoelectric effect"). The impact of each phenomena is strongly influenced by variations in an object's shape and the materials used in its construction.

2.14.1. Surface Vs Deep Charging. An electrical charge can be deposited either on the surface or deep within an object. Solar illumination and wake charging are surface charging phenomena. For directed particle bombardment, the higher the energy of the bombarding 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. Such mechanisms include: (1) a change in particle environment, (2) a change in solar illumination (like moving from eclipse to sunlit), or (3) on-board vehicle activity or commanding.

2.14.2. Charging Impacts. Generally, an electrostatic discharge can produce: (1) spurious circuit switching; (2) degradation or failure of electronic components, thermal coatings, and solar cells; or (3) false sensor readings. In extreme cases, a 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 on-board activity, delay satellite launches and deployments, or re-orient a spacecraft to protect it from particle bombardment. Should an anomaly occur, an environmental post-analysis can help operators determine whether the environment contributed to it and the satellite function can be safely re-activated or re-set, or whether engineers need to be called out to investigate the incident. An accurate assessment can reduce down-time by several days. Charging occurs primarily when solar and geomagnetic activity are high, and on geosynchronous or polar-orbiting satellites.

**2.15. Single Event Upsets (SEUs).** Very high energy protons or ions (either from solar flares or the Inner Van Allen Belt) or cosmic rays (either from the very largest solar flares or from galactic sources outside our Solar System) are capable of penetrating completely through a satellite. As they pass through, they will ionize particles deep inside the satellite. In fact, a ***single*** proton or cosmic ray can (by itself) deposit enough charge to cause an electrical upset (circuit switch, spurious command, or memory change or loss) or serious physical damage to on-board computers or other components. Hence these occurrences are called "***single*** event upsets". SEUs are very random, almost 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.

**2.16. 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 impact 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 antenna, sensors, and solar cell panels would then fail to see 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.

## Chapter 3

## THE SPACE ENVIRONMENTAL SUPPORT SYSTEM

**3.1. Space Environmental Support.** This chapter will address where a designer, operator, or user of a radar, communications, or space system should go for environmental assistance. It will also address what kinds of products and services are available to help anticipate, cope with, or even take advantage of situations such as those described in the previous chapter.

**3.2. National Services.** The Space Environmental Support System (SESS) collectively refers to all Federal assets used to monitor, analyze, specify, and forecast the space environment. In the US, space environmental support is provided by two agencies. Non-DoD Federal and civilian customers receive support from the Department of Commerce; specifically the National Oceanic and Atmospheric Administration's (NOAA's) Space Environment Center (SEC) in Boulder, CO. Military customers receive support from the Air Force Space Command's (AFSPC's) 50th Weather Squadron (50 WS), formerly known as the Air Force Space Forecast Center (AFSFC). The 50 WS, located at Falcon AFB in Colorado Springs, CO, is the DoD's sole space environment forecast and warning facility. The two forecast centers work in close cooperation; in fact, there are several USAF personnel assigned to the SEC in Boulder. Both centers operate 24-hours/day, 7-days/week; share all space environmental data and observations each collects; coordinate on the primary forecast parameters and several customer products; and act as a partial back-up for each other.

**3.3. Space Environment Data.** Both centers collect space environmental data from worldwide networks of solar, ionospheric, and geophysical sensors. While these networks are global, the number of data sensors (roughly 30 space-based and 70 ground-based) pales in comparison to the sheer volume of space that needs to be monitored.

3.3.1. Observing Network Overview. The SEC receives energetic particle and other geophysical data from the Geosynchronous Orbiting Earth Satellite (GOES) vehicles. The 50 WS center receives similar data from low-altitude, high-inclination Defense Meteorological Satellite Program (DMSP) vehicles and other military satellites. Both centers receive ground-based magnetometer data collected by the US Geological Service, and ionospheric data collected by a mix of civilian, contract, and military sensors. Solar optical and radio observatories provide extensive information on solar magnetic fields, features, and activity. (More detailed information on solar-geophysical observing instruments and networks is provided in Attachment 2.) Details on exactly where these sensors are currently located can be obtained from HQ AFSPC/DORW.

3.3.2. Data Sharing. All this solar, ionospheric, and geophysical data is quickly cross-fed between the two centers; then it is carefully analyzed or processed through sophisticated computer models, and used to produce alerts, analyses, forecasts, and environmental parameter specifications. The civilian and military forecasters confer throughout the day while preparing their forecasts. As a result, there is full agreement on most forecast parameters; plus some routine, general products are even issued jointly. Most products, however, are issued by one center or the other, so they can be tailored to the specific needs of the intended customer.

**3.4. Space Environment Services.** Services provided by the 50 WS include rapid warnings when a solar or geophysical event is observed; as well as short or long range forecasts of space environmental conditions, either in general terms or very specific numerical data. These products can be either standardized or tailored to the particular needs of an individual customer, and either of an on-going or one-time nature. 50 WS also performs post-analysis assessments on specific radar, communications, or satellite anomalies, to help operators determine whether the environment contributed to a problem they experienced or whether the cause lies elsewhere.

**3.5. Product Catalog.** The 50 WS maintains AFCAT15-152, Volume 5, *Space Environmental Products*. This publication describes the space environmental analysis, forecast, and warning services provided by 50 WS, and defines terms used in space environmental products. However, most of the publication is devoted to a detailed description of each standard product available from the forecast center, plus some samples of customer tailored products.

**3.6. Seeking Support.** The first step in requesting further information, or in arranging support, is to contact your local weather officer or unit. The second step is often submission of a support assistance request in accordance with AFI15-118, *Requesting Weather Support Assistance*. AFI15-118 contains guidance on the proper format and routing for such requests. However, for emergency support customers can contact a 50 WS production team directly 24-hours/day, 7-days/week at DSN 560-6313/6312 (commercial 719-567-6313/6312). The Major Command staff at HQ AFSPC/DORW is also available to help meet your needs or answer your questions (DSN 692-9683/3143; commercial 719-554-9683/3143; 150 Vandenberg Street, Suite 1105, Peterson AFB CO 80914-4250). An abbreviated version of chapters 1 to 3 of this pamphlet, in the form of scripted briefing slides, is available through the HQ AFSPC/DORW homepage.

**3.7. Conclusion.** Clearly the near-Earth space environment is neither empty nor benign. Solar and geophysical activity can produce some quite significant and unpleasant impacts on DoD systems that operate in or through the near-Earth environment. However, careful planning, accurate forecasts, detailed environmental specifications, rapid notification of actual events, and timely anomaly post-analyses can all help a designer, operator, or user of these systems to work around unfavorable environmental conditions or, at times, even take advantage of such conditions. They also allow one to avoid potentially harmful or ineffective actions, or to recover more quickly when adverse events occur.

GERALD F. PERRYMAN, JR., Brig Gen, USAF
Director of Operations

**Attachments:**
1. Glossary of Solar and Geophysical Terms
2. Solar and Geophysical Observing Networks

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## GLOSSARY OF SOLAR AND GEOPHYSICAL TERMS

**Absorption.** The dissipation of electromagnetic wave energy into heat as a result of interaction with matter. For example, as a radio wave passes through an ionized medium, it forces free electrons to oscillate (positive ions are much less mobile and can be ignored). Collisions with particles in the medium converts wave energy into heat. In the ionosphere, this process is most effective at D-layer altitudes, where the product of free electron density and collisional frequency is a maximum. (Also see "Attenuation".)

**Active Region.** A localized, transient region of the solar atmosphere in which sunspots, plage, filaments, and flares are observed. These features are related to strong local magnetic fields.

**Alpha Particle.** A positively charged particle indistinguishable from a helium atom nucleus and having two protons and two neutrons.

**Angstrom (A).** A unit of length equal to 1 x $10^{-8}$ centimeters; used chiefly to express short wavelengths (e.g., X-ray wavelengths).

**Anomalous Propagation.** The propagation of radiowaves through the Earth's atmosphere along a path different from that expected as a result of the normal four-thirds (4/3 rds) curvature caused by standard tropospheric refraction. Less bending that normal is called subrefraction. More bending than normal includes superrefraction, ducting, or trapping.

**ap-index.** A 3-hour "planetary amplitude" magnetic index representing the degree of geomagnetic activity on a world-wide scale. The ap-index is based on observations from a network of automated magnetometers owned and operated by the US Geological Survey. The ap-index is computed hourly (at 01Z, 02Z, 03Z, ..., and 24Z) using magnetometer data observed during the previous 3-hour period. It is a linear index ranging from 0 to more than 400.

**Ap-index.** A 24-hour "planetary amplitude" magnetic index representing the degree of geomagnetic activity on a world-wide scale. The Ap-index is computed hourly as a simple average of the previous eight 3-hour "ap-index" values. The daily (or record) value for the Ap-index is the value computed at 2400Z (using the "synoptic hour" ap values at 03Z, 06Z, 09Z, ..., and 24Z). Like the ap-index, the Ap-index is a linear index ranging from 0 to more than 400.

**Apogee.** The point of furthest recession (or greatest distance) in an orbit.

**Appleton Anomaly.** Two areas of enhanced F-layer electron density centered at +20 and -20 degrees geomagnetic latitude, and extending in local time from noon to midnight. Their origin is horizontal transport of free electrons by high altitude winds, from where the electrons are produced over equatorial latitudes (by solar radiation) and over auroral latitudes (by particle precipitation). Also known as "Subequatorial Ridges", they are characterized by strong horizontal electron density gradients and thus are a source of "non-great circle propagation". They are most distinctive near the equinoxes at average levels of geomagnetic activity. During high geomagnetic activity the ridges tend to merge into a single ridge over the equator. Near the summer and winter solstices a single, broad ridge is found in the winter hemisphere middle latitudes, a phenomena called the "Winter Anomaly".

**Attenuation.** This term includes all power losses experienced by a radio wave. Absorption is only one component of attenuation. Other components include: free space loss due to beam spreading, beam focusing/defocusing (for example power loss in a duct is small), scatter loss, etc. (Also see "Absorption".)

**Aurora.** Sporadic radiant emission from the upper atmosphere over middle and high latitudes. Precipitating charged particles (electrons and, to a lesser extent, protons) are guided by the Earth's geomagnetic field toward the higher latitudes. These particles collide with atmospheric gases, which become excited or ionized. When the atoms and molecules return to a lower energy state, electromagnetic (radio, infrared, visible, or ultraviolet) energy is emitted. Aurora are most intense, and are observed furthest equatorward, at times of geomagnetic storms. Aurora occur simultaneously at high northern and southern latitudes, and are sometimes called the "Northern (or Southern) Lights".

**Auroral Electrojet.** An electric current that flows in the auroral zone at E-layer altitudes. It is most intense during geomagnetic disturbances, and ultimately owes its origin to a convective motion of charged particles in the magnetotail.

**Auroral Es.** An ionospheric irregularity resulting from enhanced ionization caused by particle precipitation in the auroral zone during geomagnetic disturbances, particularly during nighttime hours. (Also see "Sporadic E (Es)".)

**Auroral Oval.** A roughly elliptical band around either geomagnetic pole in which aurora occurs at a particular time. The dimensions of the oval and the intensity of the aurora in it, depend on the condition of the geomagnetic field and local time. Auroral activity is generally most intense, has the greatest latitudinal width, and extends furthest equatorward, during periods of high geomagnetic activity. For a given level of geomagnetic activity, auroral activity is generally most intense, has the greatest latitudinal width, and extends furthest equatorward, near the local midnight meridian, since the precipitating particles that cause aurora come from the Earth's magnetotail.

**Auroral Zone.** A roughly circular band around either geomagnetic pole in which aurora statistically occurs most often. The band's center lies about 23 degrees of latitude from the geomagnetic pole, and has a width of about 12 degrees. In the auroral zones, the aurora is visible at some time, some place, on nearly every clear night.

**Auroral Zone Absorption (AZA).** During a geomagnetic storm, ultraviolet and X-ray auroral emissions in the E-layer can cause an increase in the electron density of the underlying D-layer. The result is an increase in absorption of radio signals transiting the auroral zone D-layer. Also known as "Auroral Zone Blackout".

**Auroral Zone Blackout.** See "Auroral Zone Absorption (AZA)".

**Brilliance.** In describing a solar flare, brightness indicates the width of the H-alpha spectral line, which becomes wider because of the flare. For example, to meet the faint flare threshold , the spectral line width must be at least 0.8 Angstroms. Flare brightness categories are faint (F), normal (N), and brilliant (B).

**Charging.** Spacecraft and satellite electrical charging is caused by directed particle bombardment or solar illumination, combined with variations in the object's shape and materials. The charge can be deposited either on the surface or deep within the object.

*Deep Charging* - The buildup of electrical charge on a space vehicle's internal electrical components due to high energy protons or "cosmic rays" passing through the vehicle. (Also see "Single Event Upsets (SEUs)".)

*Surface Charging* - An accumulation of an electric charge on a space vehicle due to a difference in electrical potential between the vehicle and its space environment, or between differing portions of the spacecraft itself. 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 until some triggering mechanism causes a discharge or arcing (similar to a small thunderbolt inside the vehicle). Such mechanisms include: a change in particle environment, a change in solar illumination (like moving from night to day), or on board vehicle activity or commanding.

**Chromosphere.** The layer of the solar atmosphere lying between the photosphere and the corona. The chromosphere is not visible to the naked eye because, even though it is hotter than the photosphere, it is very tenuous. Many important phenomena, such as plage and flares, occur in the chromosphere.

**Conjugate Points.** Two points on the Earth's surface at opposite ends of a geomagnetic field line.

**Control Point.** The point at which a radio wave is reflected or refracted from the ionosphere back toward the Earth. It is dependent on the location of the transmitter and receiver, and the electron density profile of the ionosphere. For multiple hop paths there is a control point for each hop.

**Corona.** The very extended region of low density and high temperature gas which forms the outermost layer of the solar atmosphere. Much of the solar X-ray and radio emission originates in the corona. The corona extends far into interplanetary space and becomes the solar wind.

**Coronal Hole.** A region of low particle density and open magnetic field lines in the solar corona. Since the field lines are open, solar particles are not trapped. Holes are thus a primary source of high-speed particle streams superimposed on the background "solar wind". These streams can cause geomagnetic storms if they impact the Earth's magnetosphere. Since holes may persist for several months and the solar rotation period is only 27 days, coronal holes are closely related to recurrent geomagnetic storms. (Also see "Geomagnetic Storms".)

**Corpuscular Radiation.** Radiation consisting of particles, specifically atomic particles such as protons (hydrogen nuclei), electrons, neutrons, and alpha particles (helium nuclei). Also known as "Particulate Radiation".

**Corrected Geomagnetic Coordinates.** The spherical "geomagnetic coordinate" system is based on approximating the Earth's actual magnetic field by a centered dipole (bar magnet). A slightly better fit with the actual field is achieved if the dipole axis is offset from the Earth's center by about 450 km toward a location in the Pacific Ocean (15.6 N, 150.9 E). This "eccentric dipole" axis intersects the surface at 81 N, 85 W and 75 S, 120 E. The non-spherical, corrected geomagnetic coordinate system is based on this eccentric dipole. (Also see "Geomagnetic Coordinates".)

**Cosmic Radio Noise.** Radio waves emanating from extraterrestrial sources.

**Cosmic Rays.** Very high energy particulate radiation which permeates interstellar space; primarily protons (85 percent) and alpha particles (13 percent), with some heavier particles (oxygen, silicon, iron, etc.) included (2 percent). Cosmic rays are measured at the Earth's surface by a "neutron monitor", which is an instrument capable of detecting secondary neutrons produced by collisions between cosmic rays and atmospheric gases. Most cosmic rays originate from outside the solar system, and are called "galactic cosmic rays". Their observed flux is modulated by solar activity. During periods of high solar activity counting rates on neutron monitors fall (known as a Forbush Decrease), due to an increase in the shielding effect provided by the disturbed solar wind and geomagnetic field. So the frequency of DoD system impacts caused by galactic cosmic rays actually *increases* during periods of *quiet* solar activity. "Solar cosmic rays" are produced by the most energetic solar flares; in these rare instances, counting rates on neutron monitors are observed to suddenly rise (known as a "Ground Level Event (GLE)"). Cosmic rays can cause "single event upsets (SEUs)" on satellites. They are also a significant radiation hazard to aircrews at high altitudes (about 20 km).

**Critical Frequency.** The limiting radio frequency below which radio waves are reflected by, and above which they penetrate through, an ionized medium (such as an ionospheric layer) at vertical incidence. Also known as "Plasma Frequency".

**D-Layer (D-Region).** A daytime layer in the ionosphere between about 50 and 90 km altitude. During solar flares, the D-layer may be enhanced and lowered by an increased flux of X-ray radiation. This layer is responsible for most radio wave absorption. Major absorption events include: Short Wave Fades (SWF), Auroral Zone Absorption (AZA), and Polar Cap Absorption (PCA). The same physical process causes the dissipation of radio wave energy in each event. However, the events differ in source of the ionizing radiation, location, and time scale:

| Event | Source | Location | Time Scale |
|---|---|---|---|
| SWF | Flare X-Rays | Sunlit Hemisphere | Tens of Minutes |
| AZA | Electrons from the Magnetotail | Auroral Zones | Hours |
| PCA | Flare Protons | Polar Caps | Hours to Days |

**Differential Rotation.** Unlike the Earth, the sun does not rotate as a solid body. On the sun the angular rotation rate at low latitudes, where most solar activity occurs, is about 13 degrees/day, which equates to a rotation period of 27 days. Closer to the poles the rotation rate is about 10 degrees/day, which equates to a rotation period of 36 days.

**Dipole Equator.** The "dip equator" is defined by where the Earth's magnetic field lines are inclined zero degrees to the Earth's surface. The dip equator does not correspond exactly to the "geomagnetic equator", since the dip system includes local variations in the near-Earth magnetic field. The dip poles, known as the "North, or South, Magnetic Poles (NMP, SMP)" are where magnetic field lines are inclined 90 degrees to the Earth's surface. They lie a considerable distance from the geomagnetic poles. (Also see "Geomagnetic Coordinates".)

| Pole | Latitude | Longitude |
|---|---|---|
| NMP (dip NP) | 76 N | 101 W |
| Geomagnetic NP | 79 N | 70 W |
| SMP (dip SP) | 66 S | 141 E |
| Geomagnetic SP | 79 S | 110 E |

**Doppler Shift.** A displacement in the observed frequency of a radiated signal caused by relative motion between an emitter and receiver.

**E-Layer (E-Region).** The ionospheric region between 90 km altitude and about 120 to 140 km. In daylight, the electron-density curve in this region peaks at about 100 km, with maximum density almost entirely dependent upon solar activity and solar zenith angle. At night this layer virtually disappears, except at auroral latitudes where it is partially maintained by precipitating particles.

**Eccentric Dipole.** See "Corrected Geomagnetic Coordinates".

**Electromagnetic Radiation.** Energy propagated through space or a material medium in the form of oscillating electric and magnetic fields.

**Electromagnetic Spectrum.** The ordered array of electromagnetic radiation, extending from the shortest gamma rays, through X-rays, ultraviolet waves, visible light, infrared waves, and on to radio waves.

**Electron Density Profile (EDP).** The variation in density of free electrons with altitude through the ionosphere.

**Electron Volt (eV).** A measure of energy (1 eV = $1.602 \times 10^{-19}$ joules).

**Equatorial Electrojet.** An ionospheric electric current at E-layer altitudes (between 100 and 120 km), centered over the "dipole equator" and roughly 10 degrees latitude in width. It is driven by the dynamic action of a daytime westward drift of free electrons across geomagnetic field lines.

**Erg.** A measure of energy (1 erg = 1 x $10^{-7}$ joules).

**Extraordinary ("x") Wave.** See "Ordinary ("o") Wave".

**F10-index.** The solar radio flux observed at 10.7 cm (2800 MHz) by the Dominion Radio Astrophysical Observatory at Penticton, British Columbia, Canada, at 1900Z daily (local noon). It is reported in Solar Flux Units (1 SFU = 1 x $10^{-22}$ watts/meter$^2$/hertz). The variation of the 10.7 cm radio flux is closely associated with enhanced thermal radiation from solar active regions, and thus the overall level of solar activity.

**F-Layer Trough.** An area of depleted F-layer electron density in the night sector just equatorward of the auroral oval. There is a particularly sharp horizontal electron density gradient between the trough and oval, which causes "non great circle propagation".

**F-Layer (F-Region).** The ionospheric region between about 130 and roughly 1000 km altitude. The F-layer is responsible for most of the refraction suffered by radio waves as they transit the ionosphere. It is subdivided into the F2-layer and the F1-layer. The F2-layer is usually the densest (in terms of electron density) region of the ionosphere and persists throughout the night. The F1-layer, a ledge on the electron-density curve at the bottom on the F-layer, occurs only in daylight.

**Fading.** The variation of radio wave field strength caused by change with time in the transmission path characteristics of a radio wave.

**Filament.** A mass of relatively high density, low temperature gas suspended in the upper chromosphere and/or the lower corona by magnetic fields. It is seen as a ribbon-like absorption feature in H-alpha against the solar disk. (Also see "Prominence".)

**Flare.** A sudden, short-lived brightening of a localized region in the solar chromosphere. Flares nearly always occur in active regions, and are usually only visible in monochromatic light. They are classified according to area (0, 1, 2, 3, or 4) and brightness (F, N, or B), or by X-ray intensity (C, M, or X).

**Flutter.** Flutter fading is the variation of radio wave field strength caused by small scale irregularities in the free electron density gradient at F-layer altitudes (called Spread F). At low latitudes Spread F occurs frequently after sunset, at which time flutter fading is observed on transequatorial circuits. At high latitudes Spread F is associated with ionospheric storms which often accompany geomagnetic disturbances. The resulting variations in F-layer propagation characteristics in turn cause rapid fading of radio signals (called auroral flutter). Spread F, and thus flutter, are less common at middle latitudes. (Also see "Spread F".)

**Flux.** The amount of something (protons, X-rays, radio energy, etc.) passing through a specified area in a given time period.

**fmin.** The minimum frequency observed by a vertical incidence ionosonde. It depends on the electron density in the ionosphere (mostly D-layer), ionosonde power and sensitivity, and the amount of radio noise. (Also see "Lowest Useable Frequency (LUF)".)

**foE.** "Critical Frequency" for the ordinary ("o") wave of the solar (ultraviolet) produced E-layer. It is the highest frequency returned by that layer at vertical incidence, and thus provides a measure of that layer's maximum electron density.

**foEs.** "Critical Frequency" for the ordinary ("o") wave of the sporadic E-layer. It is the highest frequency reflected by that layer at vertical incidence, and thus depends on enhancements in the E-layer's electron density caused by non-solar sources such as particle precipitation, wind shear, or meteor ionization.

**foF2.** "Critical Frequency" for the ordinary ("o") wave of the F2-layer. It is the highest frequency returned by that layer at vertical incidence, and thus provides a measure of that layer's maximum electron density. (Also see "Maximum Useable Frequency (MUF)".)

**Forbush Decrease.** See "Cosmic Rays".

**Galactic Cosmic Rays.** High energy particulate radiation originating from outside the solar system. (Also see "Cosmic Rays".)

**Gamma.** A unit of magnetic field strength (1 gamma = $1 \times 10^{-5}$ gauss = 1 nanotesla). The average surface strength of the geomagnetic field is about 0.5 gauss, while the average strength of the Interplanetary Magnetic Field (IMF) is roughly $6 \times 10^{-5}$ gauss (or 6 gamma).

**Gamma Rays.** Electromagnetic radiation at wavelengths shorter than 0.05 Angstroms. Most commonly generated by nuclear processes.

**Gauss.** See "Gamma".

**Geomagnetic Coordinates.** A system of spherical coordinates ("geomagnetic latitude and longitude"). The system is based on approximating the actual magnetic field of the Earth by a centered dipole (bar magnet) field. The axis of the dipole passes through the Earth's center, but is inclined about 11 degrees to the Earth's rotational axis. Intersection of this axis with the Earth's surface defines the "Geomagnetic North Pole" (at 78.6 N, 69.8 W near Thule, Greenland) and the "Geomagnetic South Pole" (at 78.5 S, 110 E). (Also see "Corrected Geomagnetic Coordinates" and "Dipole Equator".)

**Geomagnetic Disturbance.** See "Geomagnetic Storm".

**Geomagnetic Equator.** The terrestrial great circle that is everywhere 90 degrees from the geomagnetic poles.

**Geomagnetic Field.** The magnetic field observed in the neighborhood of the Earth. The main field is thought to be due to dynamo currents in the Earth's molten, metallic core and is approximately that of a uniformly magnetized sphere. Deviations from this approximation constitute the irregular geomagnetic field. Both long-term and short-term variations are superimposed on the main field.

**Geomagnetic Latitude.** Angular distance from the geomagnetic equator, measured northward or southward through 90 degrees and labeled N (north) or S (south) to indicate the direction of measurement.

**Geomagnetic Local Time.** Time as measured in the geomagnetic coordinate system. Geomagnetic local time at a location is computed from local midnight on the basis that 15 degrees of geomagnetic longitude is 1 hour of time.

**Geomagnetic Poles.** The intersections with the Earth's surface of the axis of the best-fit centered dipole of the magnetic field approximating the source of the actual geomagnetic field of the Earth. The geographic position of the geomagnetic north pole is approximately 79 N, 70 W. The geographic position of the geomagnetic south pole is approximately 79 S, 110 E.

**Geomagnetic Storm.** A widespread disturbance in the Earth's geomagnetic field. A storm is normally defined as being in progress when the ap index is 30 or higher. A geomagnetic storm results when an enhanced stream of solar plasma strikes the magnetosphere, causing a disruption in various electric currents in the magnetotail. Sporadic geomagnetic storms are caused by particle emissions from solar flares and disappearing filaments (sometimes viewed as eruptive prominences). Recurrent geomagnetic storms are caused by discontinuities in the solar wind associated with Solar Sector Boundaries (SSBs) in the Interplanetary Magnetic Field (IMF), or high speed particle streams from coronal holes. In general, recurrent storms are weaker, show a slower onset, but last longer than sporadic storms. (Also see "Substorm".)

**Geostationary Orbit.** See "Geosynchronous Orbit".

**Geosynchronous Orbit.** The orbit of any equatorial satellite with an orbital velocity equal to the rotational velocity of the Earth, and thus a period of 23 hours, 56 minutes. Geosynchronous altitude is near 6.6 earth radii from the Earth's center (i.e., 35,782 kilometers, 22,235 statute miles, or 19,321 nautical miles, above the Earth's surface). To also be "geostationary", the satellite must satisfy the additional restriction that its orbital inclination be exactly zero degrees. The net effect is that a geostationary satellite is virtually motionless with respect to an observer on the ground.

**Granulation.** The tops of small scale convective cells seen in the sun's photosphere; responsible for the mottled appearance of the sun as seen in white (integrated) light.

**Ground Level Event (GLE).** A sudden increase in secondary neutrons produced by collisions between "solar cosmic rays" and atmospheric gases as detected by a ground based neutron monitor. GLEs are important as an indicator that a very energetic solar flare has occurred, and a PCA event and geomagnetic storm are almost certain to follow. (Also see "Cosmic Rays".)

**Group Speed.** The speed (vg) at which energy (i.e., information carrying signals) travel. It is always less than the speed of light. For a radio wave, **vg = c** x **i**, where **c** = speed of light in a vacuum and **i** = index of refraction. (Also see "Phase Speed".)

**H-alpha Line.** A spectral absorption line located at 6563 Angstroms in the red end of the visible electromagnetic spectrum. Most chromospheric features, such as solar flares, are normally observed at this wavelength. (Also see "Monochromatic Light".)

**Hertz (Hz).** A measure of frequency equal to one cycle per second.

**High Frequency (HF).** The 3 to 30 MHz radio wave band. Normally used for long distance communication by refraction in the F-layer of the ionosphere.

**High Speed Stream (HSS).** A high speed stream of energetic charged particles can be superimposed on the normal (or background) solar wind. The primary source for HSSs are coronal holes in the upper solar atmosphere, where magnetic field lines are open and do not impede the outward flow of charged particles. HSSs are one source of recurrent geomagnetic storms.

**Importance.** A numerical rating applied to certain types of solar activity to indicate the magnitude of the disturbance observed. For example, solar flare Importance is determined by total flare area at the time of maximum observed flare brightness.

**Infrared (IR) Radiation.** Electromagnetic radiation with wavelengths between approximately 8000 Angstroms and 1 million Angstroms (or 0.01 cm).

**Interplanetary Magnetic Field (IMF).** The magnetic field that originates with the large scale photospheric magnetic fields found on the sun's surface, and which extends into interplanetary space. The IMF is organized into (typically four to six) sectors where the magnetic field is directed either away from or toward the sun. A sector boundary in the IMF is normally narrow, being convected past the Earth in minutes or hours, compared to days to a week or so required for passage of the sector itself. The IMF strongly influences the motion of charged particles in the solar wind. (Also see "Solar Sector Boundaries (SSBs)".)

**Inversion Line.** See "Neutral Line".

**Ionize.** To cause an atom or molecule to lose an electron (e.g., by X-ray bombardment), and thus be converted into a positive ion and a free electron.

**Ionogram.** A plot of critical frequency (or equivalently, electron density) versus delay time (or equivalently, altitude) obtained by a vertical incidence ionosonde.

**Ionosonde.** An instrument used to produce a sounding of free electron density vs altitude in the ionosphere. Short pulses of radio energy are transmitted, usually at vertical incidence, at frequencies from about 1 to 20 MHz over about a five minute cycle. Delay time between pulse transmission and echo reception is recorded as a function of frequency on a plot is known as an ionogram. The ionogram can also be labeled with "virtual height" and free electron density. Virtual height is the apparent altitude of reflection assuming pulses travel at light speed. Free electron density (Ne, in $\#/cm^3$) is equal to the "critical, or plasma, frequency" (fo, in kilohertz) divided by nine, squared; i.e., $Ne = (fo/9)^2$.

**Ionosphere.** The portion of the Earth's upper atmosphere where ions and electrons are present in quantities sufficient to affect the propagation of radio waves. Normally the ionosphere extends down to about 50 km altitude, but at certain times and locations it can reach as low as about 35 km. The variation of electron density with height leads to the subdivision of the ionosphere into the D-, E-, and F-layers (or regions).

**Ionospheric Irregularities.** Random fluctuations of electron density that occur at E- and F-layer altitudes of the ionosphere. They are capable of causing degradation (e.g., clutter, non great circle propagation, multipathing, and/or scintillation) of radio wave signals propagated by, or through, the ionosphere.

**Ionospheric Penetration Point (IPP).** The geographic point over which a radio wave passes through an altitude of 350 km while in transit between a ground station and a satellite.

**Ionospheric Storm.** A disturbance in the ionosphere which may follow the onset of a geomagnetic storm. During an ionospheric storm the electron densities in the F-layer are typically enhanced for a few hours, then depleted for up to several days. The effect is most noticeable at high geomagnetic latitudes, particularly near the auroral zones. Also, increased absorption of radio energy takes place in the D-layer. Changes that occur during an ionospheric storm are probably due to a combination of photochemical changes, atmospheric heating, and charged particle motions in the Earth's geomagnetic field.

**K-index.** A single station magnetic index representing the degree of geomagnetic activity measured at a particular observing location. A site's reported K-index is adjusted for both diurnal quiet time variations (local time effects) and for geomagnetic latitude, to allow comparisons between stations. Thus K-indices are useful for examining the true geographic variation of a geomagnetic disturbance. It is a dimensionless, quasi-logarithmic index ranging from 0 (very quiet conditions) to 9 (very disturbed conditions) in one unit steps (e.g., 0, 1, 2, ..., 9). The K-index is based on observations from a network of automated magnetometers owned and operated by the US Geological Survey. K-indices are computed hourly (at 01Z, 02Z, 03Z, ..., 24Z) using magnetometer data observed during the previous 1-hour period.

**Kp-index.** A 3-hour "planetary" magnetic index computed from the 3-hour "ap-index", and thus representing the degree of geomagnetic activity on a world-wide scale. It is a dimensionless, quasi-logarithmic index ranging from 0 to 9 in 28 steps (e.g., 0Z, 0P, 1M, 1Z, 1P, 2M, 2Z, 2P, 3M, ..., 9Z, where

Z = zero, P = plus, and M = minus). The Kp-index is computed hourly (at 01Z, 02Z, 03Z, ..., and 24Z) from the ap-index observed during the previous 3-hour period.

**Lowest Useable Frequency (LUF).** The lowest frequency that allows reliable long range HF radio communication between two points on the Earth's surface by ionospheric refraction. It is a function of D-layer absorption, transmitted power, receiver sensitivity, and other equipment parameters.

**Magnetic Index.** A measure of variations in the geomagnetic field during a specified time interval. The most commonly used indices are the quasi-logarithmic K index (K, Kp) and the linear A index (Ap, ap).

**Magnetometer.** An instrument used to record the strength and orientation of the geomagnetic field as observed at a particular point on, or near, the Earth's surface.

**Magnetopause.** The boundary surface between the interplanetary magnetic field (where the solar wind is present) and the Earth's magnetosphere.

**Magnetosphere.** The magnetic cavity surrounding the Earth in which the geomagnetic field dominates and prevents, or at least impedes, the direct entry of the solar wind plasma.

**Magnetotail.** The portion of the magnetosphere in the anti-sunward direction. In the magnetotail, geomagnetic field lines are drawn out to great distances by the flow of the solar wind pass the Earth. The magnetotail is divided into two lobes. In the north lobe magnetic field lines are directed toward the Earth, while in the south lobe they are directed away. These two lobes are separated by a relatively narrow, neutral "plasmasheet" of hot, dense plasma in which the field reversal occurs.

**Maximum Useable Frequency (MUF).** The highest frequency that allows reliable long range HF radio communication between two points on the Earth's surface by ionospheric refraction. It depends on the foF2 (or equivalently, the F2-layer maximum electron density) at the control point and the angle of incidence with which a radio wave enters the ionosphere. Frequencies higher than the MUF do not suffer sufficient ionospheric refraction to be bent back toward the Earth; i.e., they are transionospheric.

**Megahertz (MHz).** A measure of frequency equal to a million cycles per second.

**MeV (Million Electron Volts).** A measure of energy (1 MeV = $1.602 \times 10^{-13}$ joules).

**Monochromatic Light.** Pertaining to a single wavelength or, more commonly, to a very narrow band of wavelengths.

**Multipath.** Implies a radio wave splits and follows several paths to a receiver. Since the paths may be of different lengths, the arrival time and phase via each path will differ. The result may be intermittent fading and/or reinforcement of the signal received.

**Neutral Line.** A line separating solar magnetic fields of opposite polarity. Neutral line analysis of an active region indicates its magnetic complexity and flare producing potential. Neutral line is a misleading term, since it implies no magnetic field. Usually a strong field is present, but it is parallel (a transverse field), rather than perpendicular (a longitudinal field), to the sun's surface. A more accurate term would be an "Inversion Line".

**Neutron.** An electronically neutral subatomic particle with a mass 1839 times that of an electron.

**Neutron Monitor.** An instrument used for ground-based detection of secondary neutrons produced during collisions between high energy "cosmic rays" and molecules or atoms in the Earth's atmosphere. It provides an indirect measure of the cosmic ray flux encountered by the Earth, whether from outside the solar system ("galactic cosmic rays") or the most intense of solar flares ("solar cosmic rays"). (Also see "Ground Level Events (GLEs)".)

**Noise Storms.** See "Solar Radio Emission".

**Non Great Circle Propagation.** Radio waves tend to propagate along the shortest distance between two points on the Earth; i.e., a great circle path. Horizontal gradients in ionospheric electron density will cause refraction in a horizontal plane, resulting in non great circle propagation. Strong horizontal gradients are associated with the equatorward boundary of the "auroral oval" (especially in the night sector), the "subequatorial ridges", and the sunrise terminator. (Also see "F-Layer Trough".)

**Northern Lights.** See "Aurora".

**Ordinary ("o") Wave.** The presence of the Earth's magnetic field in the ionosphere causes a linearly polarized radio wave to split into two circularly polarized components. These components rotate in opposite senses, an ordinary ("o") and an extraordinary ("x") wave. The "o" wave deviates less than the "x" component in propagation characteristics from what is expected in the absence of a magnetic field, and so is used for most ionospheric sounder measurements.

**Particulate Radiation.** See "Corpuscular Radiation".

**Penumbra.** The gray portion of a sunspot that may surround the black "umbra". It is the portion of a spot where magnetic fields are less intense, causing the temperature (and thus brightness) of the sunspot to be closer to that of the overall photosphere.

**Perigee.** The point of closest approach in an orbit.

**Phase Speed.** The speed (vp) at which a wave pattern moves. For a radio wave, **vp = c/i**, where **c** = speed of light in a vacuum and **i** = index of refraction. In matter the phase speed can be more than c, since it is essentially a mathematical concept, not a physical quantity like "group speed". If the phase speed also depends on the frequency of a wave, the material is said to be dispersive (for example, the ionosphere is a dispersive medium). (Also see "Group Speed" and "Refraction".)

**Photosphere.** The sun's visible surface as seen in white (integrated) light. The photosphere is a region of high opacity, responsible for the continuous spectrum of solar electromagnetic radiation. Sunspots are located in the photosphere.

**Plage.** A region in the sun's atmosphere where chromospheric plasma is concentrated by intense magnetic fields. Plage are denser, hotter, and brighter (in monochromatic light) than the overall chromosphere. Nearly all flares occur in the vicinity of plage.

**Plasma.** An ionized gas in which the number densities of free electrons and ions tend to remain almost equal at each point in space, so it is (nearly) electrically neutral throughout.

**Plasma Frequency.** See "Critical Frequency".

**Plasmasheet.** A sheet of hot (i.e., high energy), dense plasma running down the center of the magnetotail. The plasmasheet normally remains beyond geosynchronous orbit, except when it is forced inward during geomagnetic disturbances. (Also see "Magnetotail".)

**Plasmasphere.** A region of cool (i.e., low energy), dense plasma surrounding the Earth. It may be considered an extension of the ionosphere. Like the ionosphere, it tends to corotate with the Earth. The Inner "Van Allen Radiation Belt" lies in the plasmasphere.

**Polar Cap.** The area within about 20 degrees of the geomagnetic poles. It is susceptible to direct bombardment by high energy solar particles deflected by the Earth's geomagnetic field and guided inward through cusps in the magnetosphere.

**Polar Cap Absorption (PCA).** A large increase in the ionospheric absorption of HF radio waves in the polar regions. PCAs are due to increases in the D-layer electron density caused by solar particulate radiation. In particular, some energetic solar flares emit streams of protons which can gain direct access to the polar caps via cusps in the magnetosphere. High energy (mostly 5 to 15 MeV) protons will penetrate to D-layer altitudes before colliding with atmospheric gases and causing an increase in ionization. This increase in free electron density causes a corresponding increase in absorption of HF radio waves transiting the polar caps. A "PCA Event" is most frequently defined by the amount of absorption of cosmic radio noise at 30 MHz seen by a "riometer" at Thule, Greenland. Thresholds for a PCA Event are 0.5 dB at night, and 2.0 dB in the day. The higher daytime threshold allows for additional ionization caused by solar ultraviolet radiation.

**Polar Cusps.** Funnel like features in the magnetosphere over each geomagnetic pole. High energy solar particles can be deflected by the Earth's geomagnetic field and guided in through the polar cusps, allowing the particles direct access to low altitudes over the polar caps.

**Polarization.** The polarization of an electromagnetic wave is defined as the plane of vibration of its electric field. An electromagnetic wave is a transverse wave consisting of an electric and a magnetic field. The two fields oscillate in phase, but are perpendicular to each other and to the direction of propagation. Polarization is defined in terms of the electric field because the existence of point electric charges (and lack of point magnetic charges) means the electric field will interact more strongly with matter than will the magnetic field.

**Pore.** A very small sunspot without a penumbra.

**Prominence.** A mass of relatively high density, low temperature gas suspended in the upper chromosphere and/or the lower corona by magnetic fields. It is seen as a bright, ribbon-like emission feature in H-alpha against the dark corona beyond the solar limb. (The corona appears dark in H-alpha since it is too hot to emit energy at that wavelength.) (Also see "Filament".)

**Propagation.** When speaking of a radio wave, the motion of the wave through a medium like the ionosphere, where its path may be refracted, attenuated, or retarded.

**Proton.** A positively charged subatomic particle (equivalent to a Hydrogen atom nucleus) with a mass 1836 times that of an electron.

**Proton Flare.** Any flare that produces significant fluxes of greater than 10 MeV protons in the vicinity of the Earth.

**Q-index.** A magnetic index used to specify the size of the auroral oval. It is a quarter hour index with a range from 0 to 10.

**Qe-index.** Qe is an estimate of what the Q index would have to be to account for the observed extent of the auroral oval as seen by a Defense Meteorological Satellite Program (DMSP) satellite optical or particle sensor. (***NOTE***: DMSP satellites are high-inclination, low-altitude satellites designed to monitor weather and the near-Earth space environment.) Qe ranges from roughly -4 to +12.

**Quiet Sun.** The sun at a time of minimal solar activity. Specifically, the quiet sun is the source of the background continuum radiation on which the disturbances associated with solar activity are superimposed.

**Radar Aurora.** Radar signal returns reflected off ionization produced by particle precipitation in, or near, the auroral oval. ("Radar Aurora" is distinctly different from auroral emissions at radio, or radar, wavelengths.)

**Radio Burst (Solar).** A transient enhancement of solar radio emission over background levels. Solar radio bursts are normally associated with an active region or flare. (Also see "Solar Radio Emission".)

**Radio Frequency Interference (RFI).** Interference on a radio frequency sensitive system. Examples: For a radar or communications system, RFI could be caused by a solar radio burst or noise storm. In solar observing, RFI is any non-solar radio signal that impairs observing solar radio emissions.

**Radio Noise.** In general, any radio signal which varies randomly with time. Fluctuations in an observed signal may be classified as external noise arising during radio signal generation and propagation, or internal noise introduced during signal amplification. Radio noise may, for example, increase in the auroral zone during geomagnetic disturbances.

**Radio Waves.** Electromagnetic radiation at wavelengths longer than about 0.01 centimeters.

**Refraction.** The physical process of bending an electromagnetic wave (e.g., a ray of light or a radio wave) as it passes from one medium to another medium with a different index of refraction.

*Ionospheric Refraction* - Ionospheric radio wave refraction is a change in the direction of propagation due to passing obliquely through the interface between two areas of differing free electron density (and thus index of refraction). Since the amount of bending also depends on the frequency of the radio wave, the ionosphere is said to be dispersive. For a given angle of incidence, higher frequencies are bent less than lower frequencies. (In ionospheric propagation, the term refraction is often loosely replaced by the term reflection.)

*Tropospheric Refraction* - Tropospheric radio wave refraction is a change in the direction of propagation due to passing obliquely through the interface between two areas of differing pressure, temperature, or moisture content. Since the amount of bending does not depend (to any significant degree) on the frequency of the radio wave, the troposphere is said to be non-dispersive. Below the VHF band the index of refraction (i) in air is very close to that in a vacuum (i = 1), and we can ignore tropospheric refraction compared to ionospheric refraction. However, ionospheric refraction decreases with increasing frequency. In the VHF band both are comparable in magnitude; while in the UHF and SHF bands, tropospheric refraction dominates.

**Relativistic.** Particles with sufficient energy to move at speeds which are an appreciable fraction (10 percent or more) of the speed of light.

**REM.** The dosage of ionizing radiation that will cause the same biological effect as one roentgen of X-ray dosage.

**Ring Current.** A westward electric current that flows above the geomagnetic equator; it is located in the Outer "Van Allen Radiation Belt". The ring current is produced by the drift (eastward for electrons and westward for protons) of trapped charged particles. This drift is superimposed on the spiraling motion of particles as they bounce between conjugate points. The ring current is greatly enhanced during geomagnetic storms by the injection of hot plasma from the magnetotail.

**Riometer (Relative Ionospheric Opacity Meter).** An instrument used to record the strength of High Frequency (HF) "cosmic radio noise" (i.e., radiowaves emanating from extraterrestrial sources) received at the Earth's surface. A decrease in power represents an increase in ionospheric opacity or absorption. Riometers can detect ionospheric disturbances such as Short Wave Fades (SWF), Auroral Zone Absorption (AZA), and Polar Cap Absorption (PCA) events. (Also see "D-Layer".)

**Satellite Charging.** See “Spacecraft Charging”.

**Scintillation.** A rapid, random variation in the amplitude, phase, and/or polarization of a radio signal passing through the Earth's ionosphere. Frequencies involved are normally greater than 30 MHz. Scintillation effects tend to decrease with increasing frequency. Scintillation is caused by abrupt variations in electron density anywhere along the signal path, and is positively correlated with Spread F and (to a lesser degree) with Sporadic E. Like Spread F and Sporadic E, it shows a clear minimum in frequency of occurrence and intensity at middle latitudes. At low latitudes, scintillation shows its greatest range in intensity, with both the quietest and most severe of conditions being observed. At high latitudes, its frequency and intensity are greatest in the auroral oval, although it is also strong over the polar caps.

**SE Asian Anomaly.** See “South Atlantic Anomaly”.

**Short Wave Fadeout (SWF).** A typically abrupt decrease in the intensity of High Frequency (HF) radio signals observed over long transmission paths in the sunlit hemisphere. A SWF is due to increased absorption in the lower ionosphere (D-layer) as a result of increased ionization. The increased ionization is caused by enhanced X-ray radiation accompanying many solar flares. A SWF is one type of “Sudden Ionospheric Disturbance”.

**Single Event Upset (SEU).** An electrical upset caused by a “cosmic ray” or high energy proton passing through a satellite. Each single particle usually has sufficient energy to deposit enough charge deep in the satellite to cause an electrical upset--hence the name “single event upset”. The most common impact observed is a data bit flip in a memory chip. While high energy protons (from solar flares or the “Van Allen Radiation Belts”) have less energy and often a smaller collisional cross-sectional area than cosmic rays, the protons tend to be more effective at causing SEUs simply because their number density is significantly higher than cosmic rays.

**Solar Activity.** Transient perturbations of the quiet solar atmosphere. Sunspots, plage, filaments, prominences, and flares are all forms of solar activity.

**Solar Cosmic Rays.** High energy particulate radiation emitted by extremely energetic solar flares. (Also see “Cosmic Rays”.)

**Solar Cycle.** A quasi-periodic (roughly 11-year) variation in the general level of solar activity. (Also see “Sunspot Cycle”.)

**Solar Flux Unit (SFU).** A measure of emitted radio energy equal to $10^{-22}$ watts/meter$^2$/hertz. It is the standard unit for reporting solar radio background flux and bursts.

**Solar Maximum/Solar Minimum.** The activity peak/minimum in the 11-year “solar, or sunspot, cycle”. (Also see “Sunspot Cycle”.)

**Solar Radio Emission.** Radio emissions from the sun fall into three main categories:

*Background Continuum* - radio radiation caused by the normal, continuous emission from the chromosphere and corona.

*Slowly Varying Component (SVC)* - additional radio radiation produced by active regions (plage). The SVC shows an approximate 27 day periodicity due to solar rotation.

*Noise Storms and Radio Bursts* - transient enhancements associated with active regions and solar flares.

**Solar Sector Boundaries (SSBs).** Boundaries between large scale, unipolar magnetic regions on the sun's surface. These SSBs are the origin of sector boundaries found in the "Interplanetary Magnetic Field (IMF)", which separate regions of opposite magnetic polarity (either toward or away from the sun). A sector boundary in the IMF is normally narrow, being convected past the Earth in minutes or hours, compared to days to a week or so required for passage of the sector itself. SSBs are one source of recurrent geomagnetic storms. (Also see "Interplanetary Magnetic Field (IMF)".)

**Solar Wind.** The continual outward streaming of coronal plasma into interplanetary space. The solar wind is a low density (about 6 ions/$cm^3$) plasma expanding at near sonic speed (about 300 to 500 km/sec) outward from the sun. The motion of its charged particles are strongly influenced by the "interplanetary magnetic field (IMF)". Solar activity often leads to increases in both the solar wind's particle density (over 100 ions/$cm^3$) and velocity (over 900 km/sec).

**Solar Zenith Angle.** The angle formed at the center of the Earth between a line to the sun and a line to the observer's zenith.

**South Atlantic Anomaly.** Like the "SE Asian Anomaly", it is a region of highly variable F-layer electron density. The Earth's actual magnetic field is best approximated by a dipole (bar magnet) field offset from the Earth's center by about 450 km toward the Pacific Ocean. The geomagnetic field is symmetric with respect to this "eccentric dipole", so the altitude at which one encounters any given value of magnetic field strength will be a minimum over the Atlantic and a maximum over the Pacific. The result is trapped particles in the plasmasphere can more easily be precipitated in these locations, increasing the degree of ionization at F-layer altitudes. (Also see "Corrected Geomagnetic Coordinates".)

**Sporadic E (Es).** Transient, localized patches of relatively high electron density occurring at E-layer altitudes. On some occasions Es is opaque and effectively "blankets" the upper layers of the ionosphere by reflecting frequencies normally only returned by those higher layers (a phenomena called "Blanketing Es"). On other occasions the upper layers can be seen through the Es, which suggests that Es is patchy and radio waves are penetrating through the gaps. Sporadic E is independent of the regular solar (ultraviolet) produced E-layer. Es varies markedly with latitude and local time. At high latitudes, Es is related to the "auroral electrojet", is most common at night, and shows little seasonal dependence. At middle latitudes, Es is related to wind shear and meteor ionization, and is most common in the summer daytime. At low latitudes, Es is related to the "equatorial electrojet", is most common during the daytime, and shows little seasonal dependence.

**Spray.** Chromospheric material ejected from a solar flare with sufficient velocity that much of it can escape the sun. (Also see "Surge".)

**Spread F.** Small scale irregularities in the free electron density gradient at F-layer altitudes. Two types of Spread F are identified and named after their appearance on vertical incidence ionograms: Frequency and Range Spread F. Spread F is most common at high and low latitudes, with a clear minimum in frequency of occurrence at the middle latitudes. It is primarily a nighttime phenomena.

**Subequatorial Ridges.** See "Appleton Anomaly".

**Subflare.** A solar flare of Importance category 0 (zero). The corrected area of a subflare is less than 100 millionths of the solar hemisphere.

**Substorm.** A full cycle in auroral activity, from quiet to highly active to quiet conditions. During a substorm, aurora are at their brightest and the auroral oval widens and extends equatorward. A geomagnetic storm can be thought of as a sequence of one or more substorms typically 1 to 3 hours in duration and separated by 2 to 3 hours. Each substorm corresponds to an injection of charged particles from the magnetotail into the auroral oval and the ring current. The initial substorm is caused by the arrival of a shock front in the solar wind (which may be the result of a solar sector boundary, high speed stream from a coronal hole, or a mass ejection from a flare or disappearing filament). Subsequent substorms are produced by irregularities in the post shock plasma. (Also see "Geomagnetic Storm".)

**Sudden Cosmic Noise Absorption (SCNA).** A sudden decrease in the signal strength of cosmic radio noise. SCNA is caused by increased D-layer ionization due to enhanced X-ray radiation from a solar flare. SCNA is one type of "Sudden Ionospheric Disturbance".

**Sudden Enhancement of Atmospherics (SEA).** A sudden increase in the intensity of Low Frequency (LF) radio noise. SEAs are caused by improved D-layer LF reflectivity, which accompanies enhanced ionization produced by solar flare X-rays. As a result of the improved reflectivity, atmospheric signals (atmospherics) generated by distant thunderstorms arrive with amplitudes greater than normal. SEA is one type of "Sudden Ionospheric Disturbance".

**Sudden Enhancement of Signal (SES).** A sudden increase in the strength of Very Low Frequency (VLF) radio signals from a distant radio transmitter. Signal enhancements of this type are due to the same phenomena as the "Sudden Enhancement of Atmospherics (SEA)".

**Sudden Frequency Deviation (SFD).** A small, abrupt change in the frequency of a High Frequency (HF) radio wave received from a distant transmitter. SFDs are caused by increases in the F1- and E-layer ionization resulting from enhanced solar flare X-ray radiation. As the amount of ionization in the F1- and E-layers increase, the exact altitude from which a particular radio wave is refracted lowers. The changing altitude causes a Doppler shift in the frequency of the received signal. SFDs are one type of "Sudden Ionospheric Disturbance", and the only one not related to increased D-layer ionization.

**Sudden Ionospheric Disturbance (SID).** A large, sudden increase in the amount of ionization in the ionosphere (especially the D-layer) over the entire sunlit hemisphere of the Earth. SIDs are caused by enhanced ultraviolet and/or X-ray radiation emitted during a solar flare. SIDs include a number of ionospheric effects: Sudden Cosmic Noise Absorption (SCNA), Sudden Enhancement of Atmospherics (SEA), Sudden Enhancement of Signal (SES), Sudden Frequency Deviation (SFD), Sudden Phase Advance (SPA), and Short Wave Fade (SWF).

**Sudden Phase Anomaly (SPA).** An abrupt shift in the phase of a Low, or Very Low, Frequency (LF, VLF) radio signal received from a distant transmitter. Solar flare X-ray radiation causes increased D-layer ionization, which in turn causes an effective lowering of ionospheric reflection heights. The resulting change in path length is responsible for a phase shift. SPA is one type of "Sudden Ionospheric Disturbance".

**Sunspot.** A relatively dark region in the solar photosphere. Seen in white (integrated) light, it appears dark because it is cooler than the surrounding photospheric gases. Sunspots are characterized by strong magnetic fields, which are mainly perpendicular to the solar surface. Sunspots normally occur in magnetically bipolar groups, and are closely related to the level of solar activity.

**Sunspot Cycle.** A quasi-periodic variation in the number of observed sunspots. The cycle exhibits an average period of 11 years, but past cycles have been as short as 8, or as long as 15, years. Generally there is a 4-year rise to a "Solar Maximum", followed by a gradual 7-year decline to a "Solar Minimum". Overall solar activity tends to follow the same 11-year cycle.

**Sunspot Group.** A relatively compact association of magnetically related sunspots. Spot groups are classified according to their appearance in white light (sunspot class, penumbral class, and sunspot distribution), and magnetic field complexity.

**Sunspot Number.** The Wolf, or relative, daily sunspot number (R) is a measure of the degree of spottiness observed on the sun. It is based on the number of observed sunspot groups (g) and individual spots (s): $R = k(10g + s)$. The k is a subjective correction factor to allow for the difference in observatory equipment, observing conditions, and observer tendencies. Sunspot number is the most frequently used index for the general level of solar activity. In Air Force space environmental forecast center products, the symbol "SSN" (for Solar Sunspot Number) is frequently used to represent the Wolf, or relative, sunspot number.

**Sunspot Number (Effective).** The Air Force space environmental forecast center computes several pseudo-sunspot numbers which are only indirectly related to the number of sunspots actually observed on the sun. These pseudo-sunspot numbers are really ionospheric indices indicative of the ionosphere's overall degree of ionization. A description of the "Effective Solar Sunspot Number (SSNe)" will clarify how such pseudo-sunspot numbers are computed and used. SSNe is a daily index used to specify the overall state of the global ionosphere with respect to ionospheric climatology. The climatological data was organized by latitude, longitude, time, and level of solar activity (in the form of solar sunspot number). A 5-day mean of all available vertical ionosonde foF2 data is compared to the climatological database and a best fit is found. The past sunspot number corresponding to that best fit is taken to be the SSNe. The SSNe index can then be used in reverse to recreate any given day's ionosphere from the climatology. In general, the larger the SSNe, the larger the degree of overall ionization in the ionosphere.

**Surge.** A stream of chromospheric gas ejected outward along magnetic field lines, but which eventually returns to the surface, since it has insufficient speed to escape from the sun. (Also see "Spray".)

**Swept Frequency Interferometric Radiometer (SFIR).** An instrument used to monitor solar radio emissions over a continuous band of frequencies normally produced in the corona. Radio bursts (or sweeps) in this band are produced by particle streams moving through the solar corona. Type II and IV sweeps are caused by proton streams, Type III and V sweeps by electron streams, and Type I and Code 8 continuums by trapped electrons.

**Total Electron Content (TEC).** The total number of free electrons in a unit area column from the ground to a height well above the level of peak ionization. TEC may not be equivalent to the actual column electron content vertically over a station, since the polarimeter measures along a slant path to a geostationary satellite, and responds only to the electron density below about 1000 km. (Also see "Polarimeter".)

**Traveling Ionospheric Disturbance (TID).** A large-scale ionospheric irregularity generated by gravity waves induced by particle precipitation in the auroral zone and polar cap. TIDs are generally a late evening phenomena related to geomagnetic disturbances. They generally move equatorward as a broad wavefront (hundreds of kilometers wide) at speeds of 700 to 2000 km/hour. They manifest themselves as a sharp enhancement in electron density in the F-layer, followed by a rapid depletion. Often the sequence repeats several times. At a single station, a TID appears as a sinusoidal variation ranging from 2 to 5 percent in Total Electron Content (TEC) over the site.

**Ultraviolet (UV) Radiation.** Electromagnetic radiation with wavelengths between approximately 20 and 4000 Angstroms.

**Umbra.** The dark core in a sunspot. It is the portion of a sunspot where magnetic fields are most intense, causing the temperature to be coolest (about 3900 degrees Kelvin) compared to the overall photosphere (6000 degrees Kelvin). (Also see "Penumbra".)

**Van Allen Radiation Belts.** Magnetospheric regions of stablely trapped charged particles. Near the Earth, the geomagnetic field strength is strong and field lines are closed. As a result, the energy associated with magnetic fields dominates particle kinetic energy, producing a region of stable particle trapping. Outside the radiation belts the geomagnetic field is weaker and field lines are more distended or open, and so particle kinetic energy is the controlling factor. The distribution of protons led to a division of the region of stable trapping into two belts. The Inner Van Allen Belt has a maximum proton density near 5,000 km altitude; it is part of the "plasmasphere" and corotates with the Earth. Inner belt protons are mostly high energy (MeV range) and originate from the decay of secondary neutrons created during collisions between cosmic rays and upper atmospheric particles. The Outer Van Allen Belt has a maximum proton density near 16,000 to 20,000 km altitude. Outer belt protons are lower energy (about 200 keV to 1 MeV) and come from the solar wind. They diffuse into the magnetotail, drift toward its center and then earthward. On arrival, they are injected into the "ring current", which lies in the outer belt.

**Virtual Height.** See "Ionosonde".

**Visible Light.** That portion of the electromagnetic spectrum that is perceptible to the human eye, which includes wavelengths between about 4000 and 8000 Angstroms.

**White Light Flare.** A rare solar flare so bright that it can be observed visually in white (or integrated) light. In general, the white light intensity occurs only during a flare's early flash phase and will persist for less than 15 minutes.

**Winter Anomaly.** F-layer electron densities in the winter hemisphere middle latitudes (40 to 50 degrees) are enhanced by as much as a factor of four over the summer hemisphere. The phenomena is strongest near solar maximum, and hardly noticeable near solar minimum. The anomaly is caused by the horizontal transport of free electrons by high altitude winds from where they are produced (by solar radiation) in the summer hemisphere. (Also see "Appleton Anomaly".)

**X-rays.** Electromagnetic radiation with a wavelength of between 0.05 and 20 Angstroms. X-rays impacting the Earth's atmosphere cause neutral gases to become ionized.

## SOLAR AND GEOPHYSICAL OBSERVING NETWORKS

**A2.1. Solar Observatories.** The USAF, through Air Force Space Command (AFSPC), operates a world-wide network of solar optical and radio telescopes. These observatories are unique because they provide ***real-time*** coverage of solar features and activity 24 hours/day, 7 days/week. Significant solar events are reported to forecast centers in Colorado within 2 minutes of observation, which allows the forecast centers in turn to issue alerts of potential system impacts to customers within an additional 5 minutes. This world-wide network allows near continuous coverage of the sun. Overall optical coverage is about 85 percent (due to clouds, equipment outages, and thunderstorm or high wind shutdowns), while radio coverage (which is rarely affected by clouds) is about 97 percent. Collectively these optical and radio telescope observatories are known as the "Solar Electro-Optical Network (SEON)".

A2.1.1. Solar Observing Optical Network (SOON). The SOON optical telescope gathers standardized photospheric (solar surface) data, plus chromospheric and coronal (low and high solar atmospheric) data. It also provides information on the intensity and structure of solar magnetic fields, which are responsible for most solar activity. The SOON monitors and reports in real-time solar activity such as flares, eruptive prominences, and disappearing filaments, which are visible in the Hydrogen-alpha (H-alpha) wavelength at 6563 Angstroms in the visible part of the solar spectrum. The SOON also is used to analyze sunspots, which are observed in integrated (or "white") light. Optical observations are essential for analyzing solar features and predicting solar activity before it occurs.

A2.1.2. Radio Solar Telescope Network (RSTN). The RSTN radio telescopes gather standardized solar radio data, primarily for the detection and analysis of solar radio bursts.

A2.1.2.1. Discrete Frequency Observations. The RSTN provides discrete (narrow-band, or fixed) frequency radio observations near 245, 410, 610, 1415, 2695, 4995, 8800, and 15400 MHz using Radio Interference Measuring Sets (RIMS). This data helps characterize the strength of solar events and their potential to affect DoD systems. The RIMS use three separate radio antennas (with 3-, 8-, and 28-foot diameter dishes), each designed to be sensitive to a particular range of frequencies. Presently it is not possible to determine exactly where on the sun an observed radio burst originated. However, a new radio telescope system, called a Solar Radio Burst Locator (SRBL) is under development. The SRBL will provide some radio burst location capability which will supplement optical observations during periods of cloudiness or precipitation. It would also replace the current, three-antenna discrete frequency RSTN at each observatory with a single, 6-foot diameter antenna.

A2.1.2.2. Swept Frequency Observations. The RSTN also provides swept frequency (wide-band, or spectral) radio observations over a continuous range from 25-75 MHz, using a twin bicone antenna system called a Swept Frequency Interferometric Radiometer (SFIR). An expanded range SFIR is under development; it will replace the current antennas and extend the range of continuous observations to 30-250 MHz. The expanded range will permit detection of more radio events and allow better analysis of their characteristics. The result will be improved prediction of energetic particle events which can affect the near-Earth environment.

**A2.2. Ground-Based Geophysical Observations.**

A2.2.1. Ionospheric Sounders (Ionosondes). Data from vertical incidence ionosondes are very important in determining radio propagation conditions in all frequency bands. These sensors measure ionospheric parameters (primarily free electron density vs altitude) up to the maximum level of ionization (F-layer) directly above the sounder. Every 30 or 60 minutes short pulses of radio energy are transmitted, at frequencies from about 1 to 20 MHz, over about a five minute cycle. Delay time between pulse transmission and echo reception is recorded as a function of frequency on a plot is known as an ionogram. The USAF has access to data from several dozen sounders located worldwide, both military and civilian, US and foreign. The USAF is in the process of expanding its own network of automated

Digital Ionospheric Sounder System (DISS) instruments at critical locations world-wide. Ionospheric models at the Falcon AFB forecast center use the data obtained from these geographically widely-spaced sounders to “fill in the gaps” and produce a global, 3-dimensional specification of the ionosphere's structure.

A2.2.2. Ionospheric Measuring System (IMS). The IMS is a network of automated sensors which measure the total electron content (TEC) of the ionosphere along a path from a ground-based instrument to a Global Positioning System (GPS) reference satellite. TEC data are used to adjust for range and bearing errors measured by ground-based spacetrack and missile detection radars, as well as refraction and speed delay effects on other transionospheric radiowave signals (for example, GPS signals). A planned upgrade to the IMS will permit collection of ionospheric scintillation observations, which are very important for predicting satellite communication reliability and geolocation accuracy.

A2.2.3. Magnetometers. Magnetometers measure variations in the strength and orientation of the Earth's magnetic field at a particular point on, or near, the Earth's surface. Although magnetometers are sometimes flown on satellites, most are ground-based. Their data are used to compute geomagnetic indices, of which the most widely used are the 3-hour “ap” and 24-hour “Ap” indices. Although a limited number of observing stations are used, these indices provide a near real-time indicator (since they are recomputed hourly) of the average level of planetary geomagnetic activity. Since September 1992, the USAF has employed a ground-based, western hemisphere network of automated magnetometers owned and operated by the US Geological Survey. The data are used for, among other things, analysis of satellite drag and for evaluating ionospheric radiowave propagation conditions for radar and communication operations.

A2.2.4. Riometers (Relative Ionospheric Opacity Meters). These instruments record the strength of High Frequency (HF) “cosmic radio noise” (i.e., radiowaves emanating from extraterrestrial sources) received at the Earth's surface. A decrease in power represents an increase in ionospheric opacity or absorption. Riometers can detect ionospheric disturbances such as Short Wave Fades (SWF), Auroral Zone Absorption (AZA), and Polar Cap Absorption (PCA) events.

A2.2.5. Neutron Monitor. The USAF receives neutron monitor data from Thule, Greenland. This instrument detects secondary neutrons produced during collisions between high energy cosmic rays and molecules or atoms in the Earth's atmosphere. It provides an indirect measure of the cosmic ray flux encountered by the earth, whether from outside the solar system (“galactic cosmic rays”) or the most intense of solar flares. The most significant phenomena detected by a neutron monitor is a Ground Level Event (GLE), which is a sudden increase in secondary neutrons produced by collisions between solar cosmic rays and gases in the Earth's atmosphere. GLE's are important as an indicator that a very energetic solar flare has occurred, and a solar proton event and geomagnetic/ionospheric storms are almost certain to follow.

**A2.3. Space-Based Observations.**

A2.3.1. Routine Data Sources. Satellite sensors provide early warning of changes in the near-Earth environment. For example, the USAF receives near-continuous data from two major satellite systems, the Defense Meteorological Satellite Program (DMSP) and the Geosynchronous Operational Environmental Satellite (GOES). DMSP satellites are in sun-synchronous, low altitude (about 840 km), polar orbits, and provide visual aurora, low energy particle, and ionospheric parameter data. GOES satellites are in geostationary orbits (35,782 km or 22,235 statute miles altitude), and provide solar X-ray, energetic particle, and magnetometer data.

A2.3.2. Sporadic Data Sources. From time to time, other satellites or spacecraft provide useful solar and/or geophysical data on a temporary basis. For example, the Sky Lab mission provided Ultraviolet and X-ray observations of the sun. These Sky Lab observations played a major role in the discovery of coronal holes, which are a source of High Speed Streams in the solar wind and the cause of many recurring geomagnetic storms. Another example is the ISEE-3 satellite, which in the early 1980s provided real-time solar wind, interplanetary magnetic field, and X-ray data from its stable orbital position 930,000 miles sunward from the Earth. More recently, NASA's WIND/SWIM satellite has replaced the solar wind and interplanetary magnetic field data previously provided by ISEE-3, but only for a few hours each day.