Chapter 6

SPACE ENVIRONMENT

Why is knowing the space environment important? Our increased dependence on space-based systems to meet warfighter objectives and needs, coupled with the increasing use of microelectronics and a move to non-military specifications for satellites, increases our vulnerability to loss of critical satellite functions or entire systems (see **Fig. 6-1**). The space environment is a hostile environment for satellites.

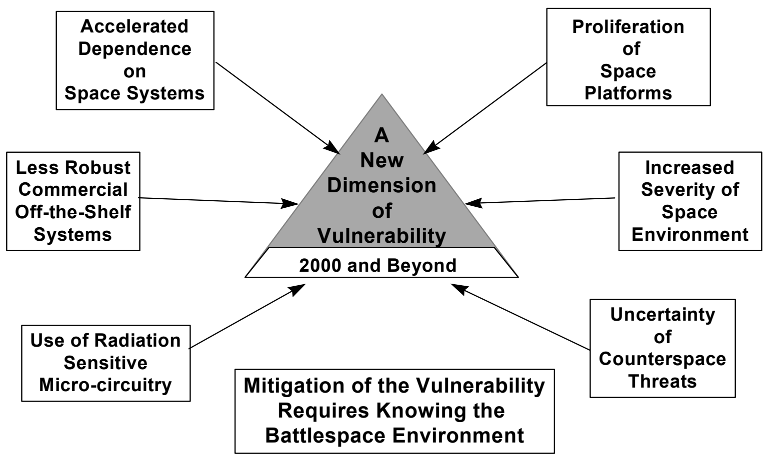


Fig. 6-1. Dimension of Vulnerability

SPACE ENVIRONMENT IMPACTS ON SYSTEMS

The origin of space environmental impacts on radar, communications and space systems lies primarily with the sun. The sun is continuously emitting electromagnetic energy and electrically charged particles. Superimposed on these 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.

Each solar-geophysical phenomena or event has the potential to adversely impact radar, communications and space systems. This section will discuss those impacts in general, then individually.

DOD System Impacts

Generally the stronger a solar flare, the denser/faster/more energetic a particle stream, or the sharper a solar wind discontinuity or enhancement, the more severe will be the event's impacts on the near-Earth environment and on DOD systems operating in that environment. Unfortunately, the DOD system impacts discussed in this section do not occur one at a time, but will most likely occur in combinations of more than one thing. The stronger the causative solar-geophysical activity, the more in number of simultaneous effects a system may experience. Each of the three general categories of solar radiation (**Fig. 6-2**) has its own characteristics and types of immediate or delayed DOD system impacts.

simply miss hitting the Earth. For those events that do affect the near-Earth environment, effects can be both immediate and delayed, depending on the exact type of enhanced radiation emitted.

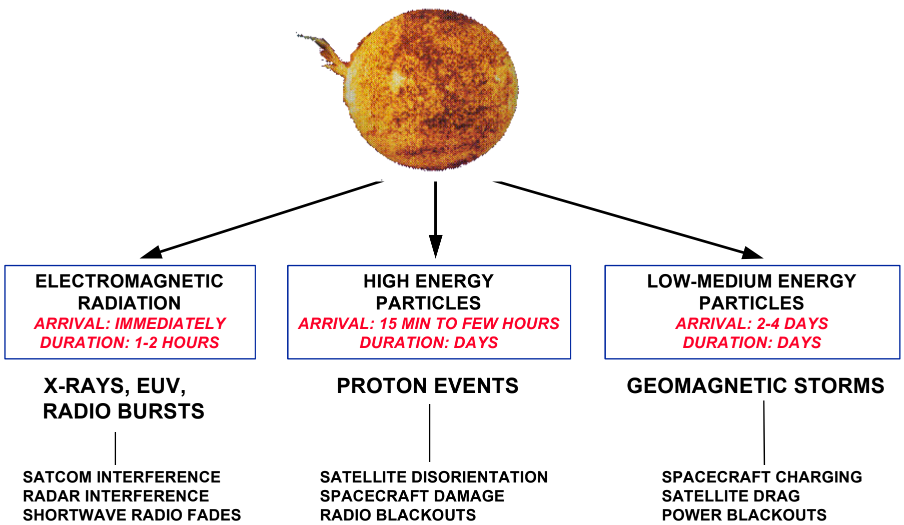


Fig. 6-2. Solar Radiation Particle Types and Effects

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 (2), magnetic field variations, which can lead to compass errors and interfere with geological surveys.

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 Radio wave) emissions are too feeble or their particle streams may

The following paragraphs summarize the three general categories of solar radiation and the immediate or delayed DOD system impacts they produce.

Electromagnetic Radiation

We detect flares by the enhanced X-ray, ultraviolet, optical and/or radio waves they emit. All of these wavelengths travel to the Earth at the speed of light (in about 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, as the radiation does not penetrate or bend around the earth. Since enhanced electromagnetic emissions cease when the flare ends, the effects tend to subside as well. As a result, these effects tend to last 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 (6-30 mHz) radio communications.

High Energy Particles

These particles (primarily protons, but occasionally cosmic rays) can reach the Earth within 15 minutes to a few hours after the occurrence of a strong solar flare. Not all flares produce these high energy particles (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 (earth's magnetic field lines that terminate into the earth's North and South poles) 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, physical damage to satellites and spacecraft, false sensor readings, LORAN navigation errors and absorption of HF radio signals. Proton events are probably the most hazardous of space weather events (**Fig. 6-3**). Proton events occur when solar flares eject high energy particles (mainly protons) that arrive at the earth in 30 minutes.

Low to Medium Energy Particles

Particle streams (composed of both protons and electrons) may arrive at the Earth about two to three days after a flare. Such particle streams can also occur at any time due to other non-flare solar activity. These particles cause geomagnetic and ionospheric storms, which can last from hours to several days. Typical problems include: spacecraft electrical charging, drag on low orbiting satellites, radar interference, space tracking errors and radio wave propagation anomalies. These impacts are most frequently experienced in the nightside sector of the Earth.

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 covered will be SATCOM and radar interference caused by solar flare radio bursts. These electromagnetic impacts are almost entirely limited to the Earth's sunlit hemisphere and occur simultaneously (immediate to eight minutes) with the solar flare that caused them.

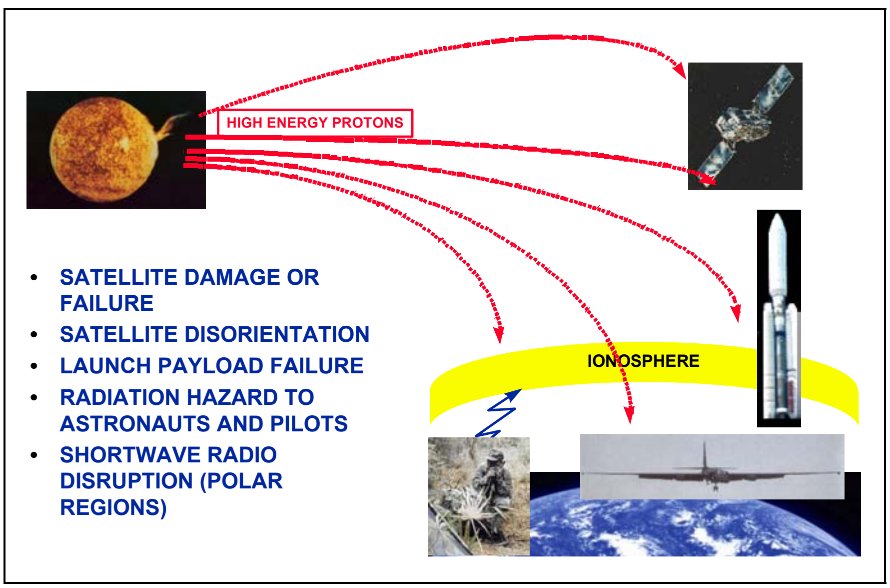


Fig. 6-3. High Energy Particle Impacts

Short Wave Fade (SWF) Events

The High Frequency (HF, 6-30 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.

HF Radio Communications

The normal mode of radio wave propagation in the HF range is by refraction using the ionosphere's strongest (or F) layer for single hops and by a combination of reflection and refraction between the ground and the F-layer for multiple hops (**Fig. 6-4**). It should be noted that the "ionosphere" is defined as that portion of the Earth's atmosphere above 45 miles where ions and electrons are present in quantities sufficient to affect the propagation of radio waves. HF radio waves are refracted by the ionosphere's F-layer. However, each passage through the ionosphere's D-layer causes signal absorption, which is additive.

Maximum Useable Frequency (MUF)

The portion of the ionosphere with the greatest degree of ionization is the F-layer (normally between about 155 and 250 miles altitude). The presence of free electrons in the F-layer causes radio waves to be refracted (or bent), but the higher the frequency, the less the degree of bending. As a result, surface-to-surface radio operators use Medium or High Frequencies (300 kHz to 30 mHz), while SATCOM operators use Very High to Extremely High Frequencies (VHF/EHF 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 trans-ionospheric). Normally the MUF lies in the upper portion of the HF band.

Lowest Useable Frequency (LUF)

The lowest layer of the ionosphere is the D layer (normally between 45 and 55 mile altitude). At these altitudes there is still a large number of neutral air atoms and molecules coexisting with the ionized particles. As a passing radio wave causes the ions and free electrons to oscillate, they will collide with the neutral air particles and the oscillatory motion will be damped out and converted to heat. Thus, the D-layer acts to absorb passing radio wave signals. The lower the frequency, the greater the degree of signal absorption. The LUF is that frequency below which radio signals

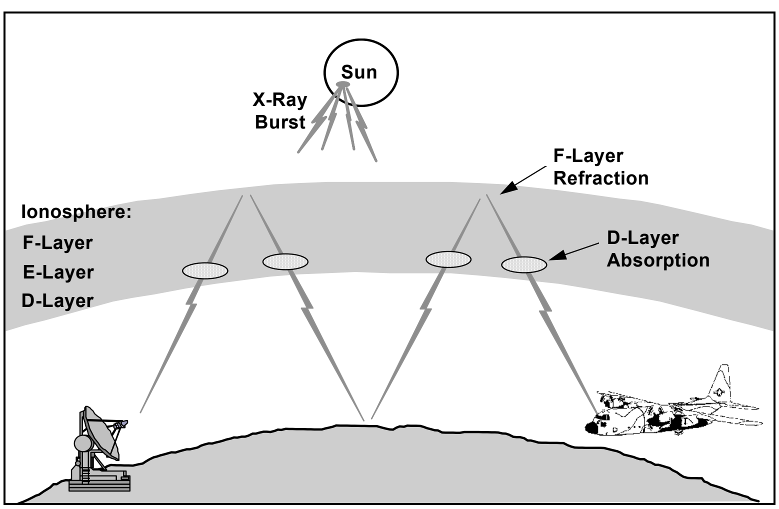


Fig. 6-4. High Frequency (HF) Communications

encounter too much ionospheric absorption to permit them to pass through the D-layer. Normally the LUF lies in the lower portion of the HF band.

HF Propagation Window

The HF radio propagation window is the range of frequencies between 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. Typical LUF/MUF curves show a normal, daily variation. During early afternoon, incoming photo-ionizing 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 (the D and E-layers disappear altogether), and the LUF and MUF become depressed.

HF radio waves above the MUF encounter insufficient refraction and pass through the ionosphere into space. Those below the LUF suffer total absorption in the ionosphere's lowest layer. The result is a useable frequency window.

The Short Wave Fade (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) (see **Fig. 6-5**). 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 seven minutes of event onset) issue a SWF warning, which contains a prediction of the frequencies to

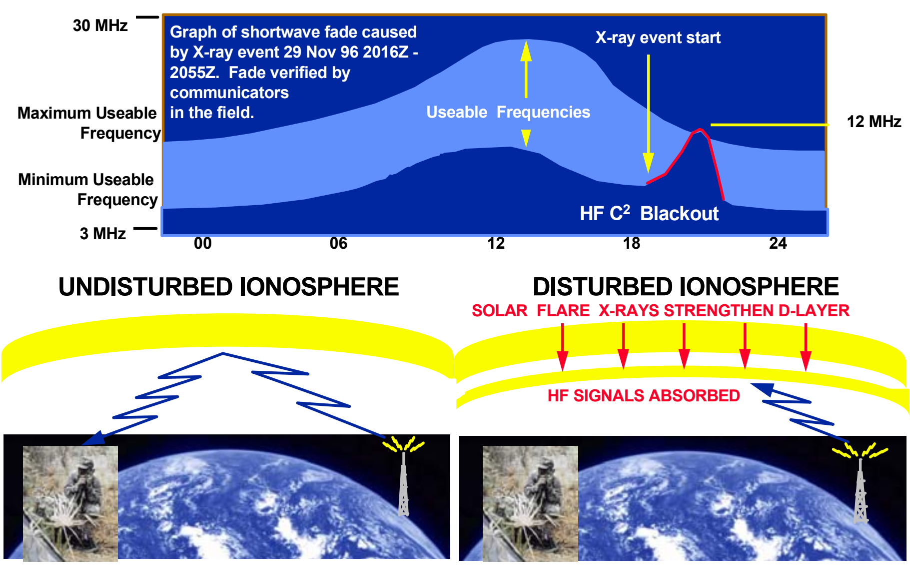


Fig. 6-5. High Frequency (HF) Propagation Windows

be affected and the duration of signal absorption. Normally SWFs persist only for a few minutes past the end of the causative flare, i.e., for a few tens of minutes to an hour or two.

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, 6-30 kHz) and Low Frequency (LF, 30-300 kHz) transmissions and can cause LORAN navigation errors.

Radio bursts from solar flares can cause the background level of solar noise to increase by tens-of-thousands. This can lead to direct Radio Frequency Interference (RFI) of SATCOM and ground or spaced-based radars.

SATCOM and Radar Interference

Solar flares can cause the amount of radio wave 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). If the sun is in the field of view of the receiver and if the burst is at the right frequency and intense enough, these radio bursts can produce direct Radio Frequency Interference (RFI) on a SATCOM link or missile detection/ space tracking radar. (**Fig. 6-6**). Knowledge of a solar radio burst can allow a SATCOM or radar operator to isolate the RFI cause and avoid time consuming investigation of possible equipment malfunction or jamming.

Solar Radio Bursts

Radio bursts are another "immediate" effect, experienced simultaneously with observation of the causative solar flare.

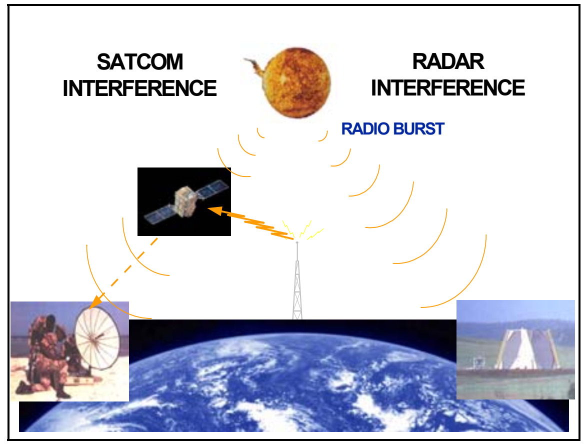


Fig. 6-6. Radio Burst Effects

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

Solar Conjunction

There is a similar geometry-induced affect called "solar conjunction", which is when the ground antenna, satellite and the sun are in line. This 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 effects are definitely greatest during Solar Max when the sun is a strong background radio emitter.

Solar Radio Noise Storms

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

PARTICLE (DELAYED) EFFECTS

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

Particle Events

The sources of the charged particles (mostly protons and electrons) include: solar flares, Coronal Mass Ejections (CMEs), 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.

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.

High Frequency 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.

Polar Cap Absorption (PCA) Events

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

Auroral Zone Absorption (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.

Ionospheric Scintillation

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

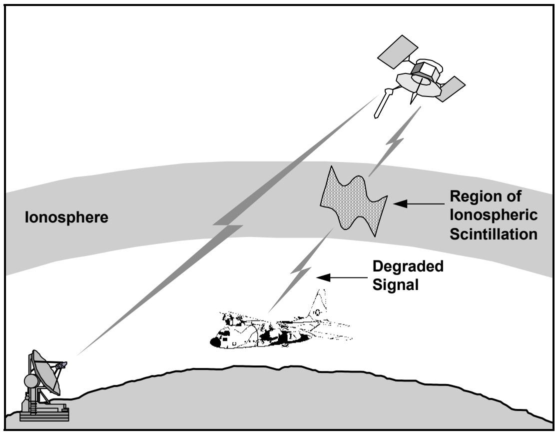


Fig. 6-7. Ionospheric Scintillation

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. Low latitude, nighttime links with geo-synchronous communications satellites are particularly vulnerable to intermittent signal loss due to scintillation. In fact, during the Persian Gulf war, allied forces relied heavily on SATCOM links, and scintillation posed an unanticipated, but very real operational problem.

GPS and Scintillation

GPS satellites, which are located at 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.

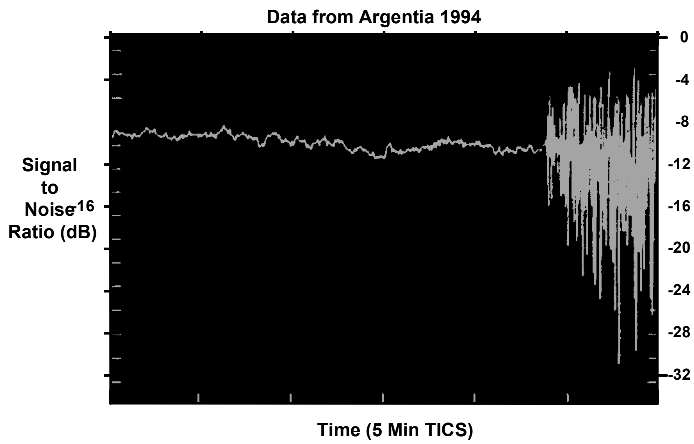
The reduction in the number of simultaneously useable GPS satellites may result in a potentially less accurate position fix. Since scintillation occurrence is positively correlated with solar activity and the GPS network has received wide-spread use only recently during a quiet portion of the 11-year solar cycle, the true environmental vulnerability of the GPS constellation is yet to be observed. But even during low solar activity levels, it has been shown, under strong scintillation, that the GPS signals cannot be seen through the background noise due to the rapid changes in the ionosphere, even with the use of dual frequency receivers (**Fig. 6-8**).

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 radio waves to be bent (or refracted), the higher frequencies used by GPS satellites will suffer some bending (although to a much lesser extent than with HF radio waves). This signal bending increases the signal path length. In addition, passage through an ionized medium causes radio waves to be slowed (or retarded) somewhat from the speed of light. Both the longer path length and slower speed can introduce up to 300 nanoseconds (equivalent to about 100 meters) of error into a GPS location fix--unless some compensation is made for the effect. The solution is relatively simple for two-frequency GPS receivers, since signals of different frequency travel at different speeds through the same medium. Measuring the difference in signal phases for the two frequencies allows computation of the local phase delay for a particular receiver and elimination of 99 percent of the error introduced in a location fix. Unfortunately, this approach will not work for single-frequency receivers. For them, a software algorithm is used to model ionospheric effects based on the day of the year and the average solar 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 geomagnetic equator during evening hours).

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.



This is a plot of the actual signal to noise ratio graph measured during a moderate scintillation event. A warfighter may lose total GPS signal lock during such events. This includes dual frequency systems.

Fig. 6-8. Scintillation Effect on GPS Signal

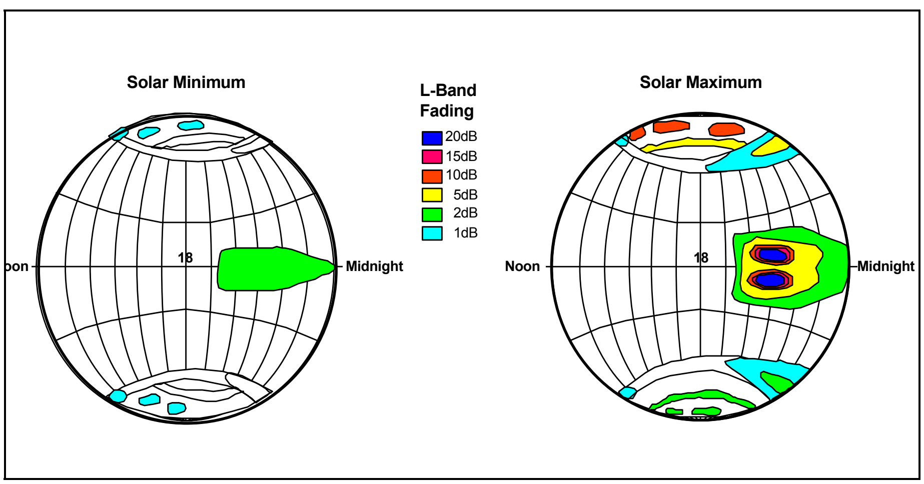


Fig. 6-9. Scintillation Occurrence

Scintillation Occurrence

There is no fielded network of ionospheric sensors capable of detecting real-time scintillation occurrence or distribution (**Fig. 6-9**). Presently space

Statistically, scintillation tends to be most severe at lower latitudes (within ± 20 degrees of the geomagnetic equator) due to ionospheric anomalies in that region. It is also strongest from local sunset until just after midnight, and during periods of high solar activity. At

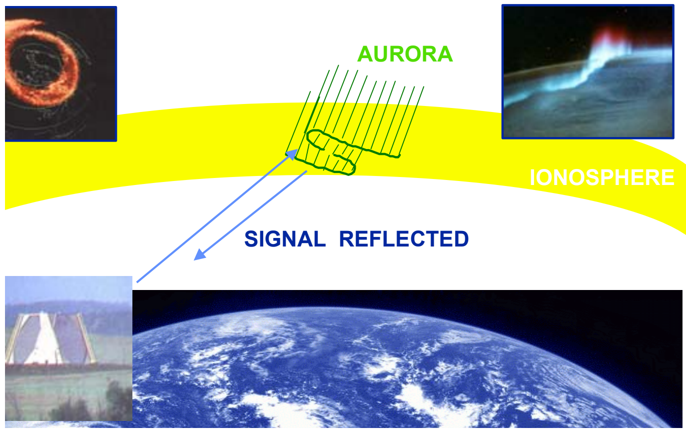


Fig. 6-10. Radar Aurora

higher 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.

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" (**Fig. 6-10**). The strength of radar aurora signal returns and the amount of Doppler frequency shifting, are aspect dependent.

Impacts can include increased clutter and target masking, inaccurate target locations and even false target or missile launch detection. While improved software screening programs have greatly reduced the frequency of false aircraft or missile launch detection, they've not been eliminated totally. (*NOTE*: Radar aurora is a separate phenomena from the weak radio wave emission produced by the recombination/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.)

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.

Bearing and Range Errors

A bearing (or direction) error is caused by signal bending, while a range (or distance) error is caused by both the longer path length for the refracted signal and the slower signal speed (**Fig. 6-11**). For range errors, the effect of longer path length dominates in UHF signals, while slower signal speed dominates for SHF signals.

Correction Factors

Radar operators routinely attempt to compensate for these bearing and range errors by applying correction factors that are based on the expected ionospheric "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.

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.

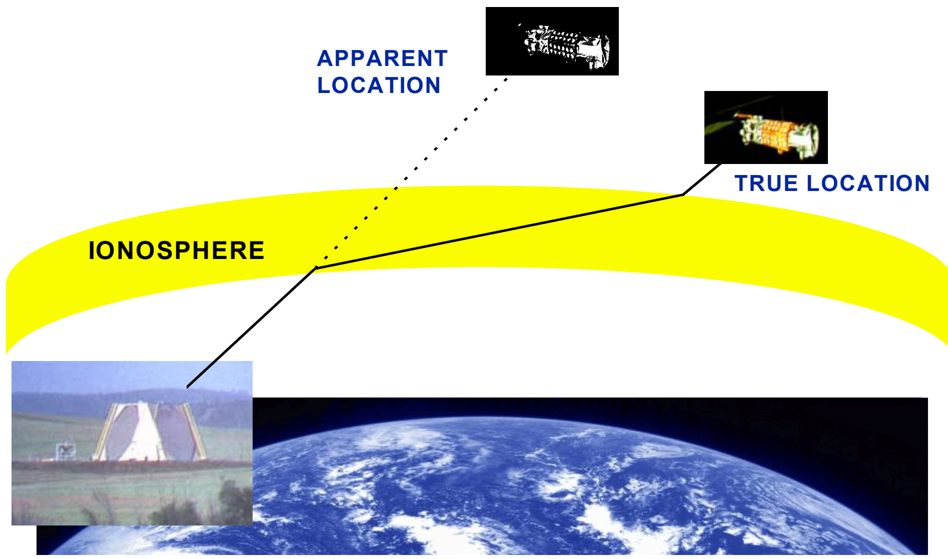


Fig. 6-11. Surveillance Radar Errors

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.

Atmospheric Drag

Another source for space object positioning errors is that of either more *or less* atmospheric drag than expected on low orbiting objects (generally at less than about 1,000 km altitude). Energy deposited in the Earth's upper atmosphere by EUV, X-ray and charged particle bombardment heats the atmosphere, causing it to expand outward. Low earth-orbiting satellites and other space objects then experience denser air and more frictional drag than expected. This drag decreases an object's altitude and increases its orbital speed. The result is the object will be some distance below and ahead of its expected position when a ground radar or optical telescope attempts to locate it (see **Fig. 6-12**). Conversely, exceptionally calm solar and/or geomagnetic conditions will cause *less* atmospheric drag than predicted and an object could be higher and behind where it was expected to be found.

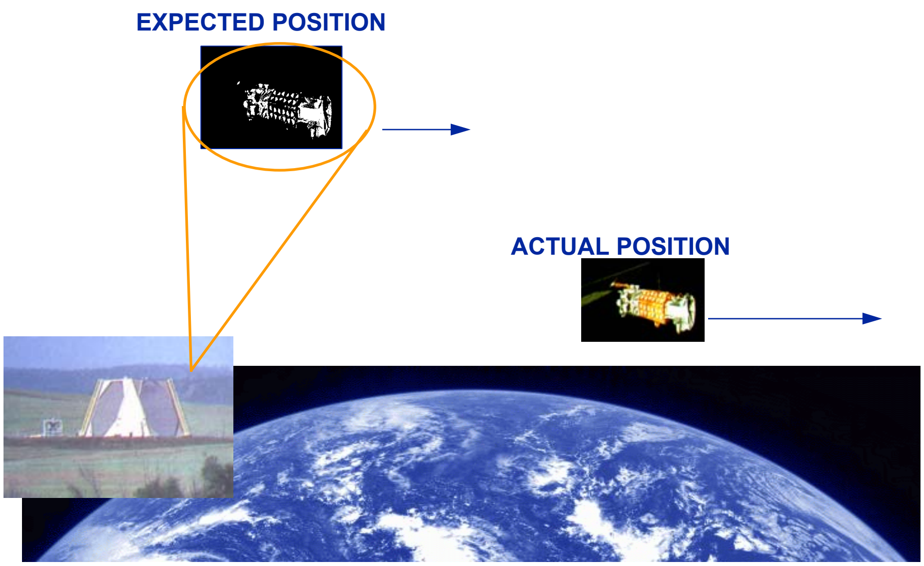


Fig. 6-12. Atmospheric Drag

Impacts of Atmospheric Drag

The consequences of atmospheric drag include: (1) inaccurate satellite locations which 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 latter was Skylab. Geomagnetic activity was so severe, for such an extended period, that the expanded atmosphere caused Skylab to de-orbit and burn-in before a planned Space Shuttle rescue mission was ready to launch.

Contributions to Drag

There are two space environmental parameters used by current models to predict the orbits of space objects. The first is the solar "F10 index". Although the F10 index is a measure of solar radio output at 10.7 centimeters (or 2,800 mHz), it is a very good indicator of the amount of EUV and X-ray energy emitted by the sun and deposited in the Earth's upper atmosphere. In **Fig. 6-13** 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

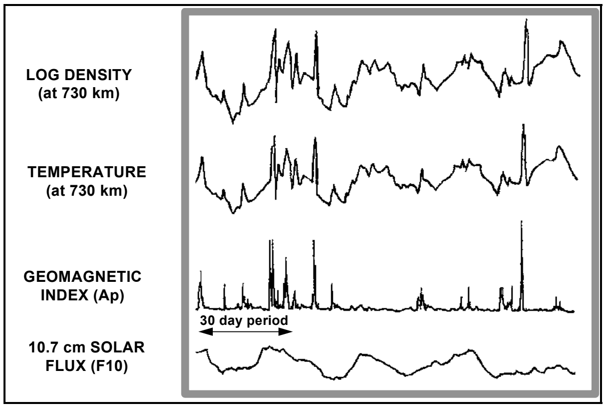


Fig. 6-13. Factors Contributing to Atmospheric Drag

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

The Impact of Geomagnetic Storms on Orbit Changes

Two impacts of geomagnetic storms on space tracking radar's 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. During a severe geomagnetic storm in March 1989, over 1,300 space objects were temporarily misplaced (**Fig. 6-14**). 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.

Space Launch and Payload Deployment Problems

Atmospheric Drag

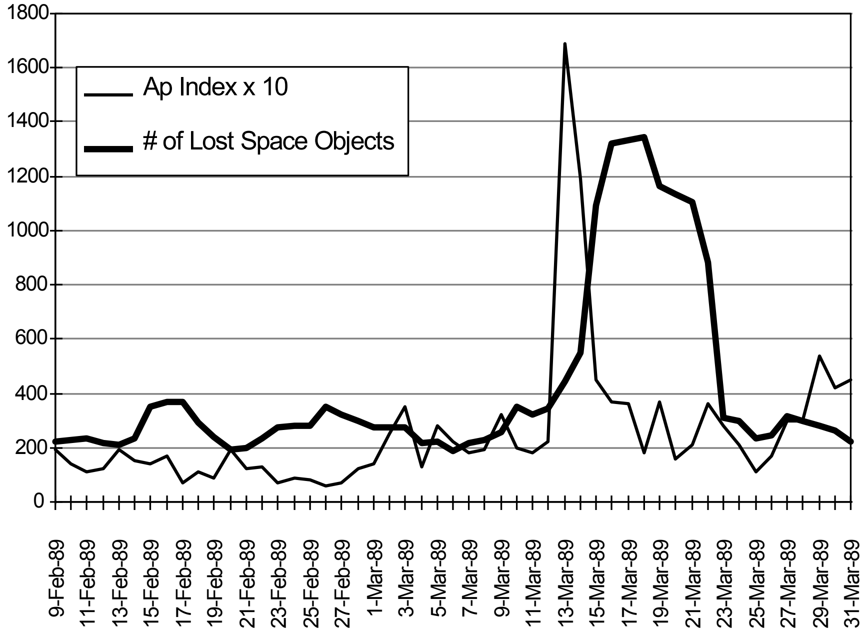
Excessively high *or* low geomagnetic conditions can produce atmospheric density variations along a proposed launch trajectory. The ability of a launch vehicle to compensate for these variations may be exceeded. In addition, the atmospheric density profile based on changes in altitude will determine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

Particle Bombardment

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

Radiation Hazards

Despite all engineering efforts, satellites are still quite susceptible to the charged particle environment. In fact, with newer microelectronics and their lower operating voltages, it will actually be easier to cause electrical upsets than on older, simpler vehicles. Furthermore, with the perceived lessening of the man-made nuclear threat, there has been a trend to build new satellites with less nuclear radiation hardening. This previous hardening also protected the satellites from space environmental radiation hazards.



This Fig. demonstrates how a geomagnetic storm can change the orbits of space objects unexpectedly, causing difficulty for those who maintain orbital data.

Fig. 6-14. Geomagnetic Storms and Orbit Changes

Both low and high earth-orbiting spacecraft and satellites are subject to a number of environmental radiation hazards, such as direct physical damage and/or electrical upsets caused by charged particles. These charged particles may be: (1) trapped in the "Van Allen Radiation Belts," (2) in directed motion during a geomagnetic storm or (3) protons/cosmic rays of direct solar or galactic origin.

Van Allen Radiation Belts

The Outer and Inner Van Allen Radiation Belts are two concentric, toroid (or donut-shaped) regions of stable, trapped charged particles that exist because the geomagnetic field near the Earth is strong and field lines are closed (**Fig. 6-15**). The Inner Belt has a maximum proton density approximately 5,000 km above the Earth's surface and contains mostly high-energy protons produced by cosmic ray collisions with the Earth's upper atmosphere. The Outer Belt has a maximum proton density at an altitude ranging from 16,000 to 20,000 km and contains low to medium energy electrons and protons whose source is the influx of particles from the magneto-tail during geomagnetic storms.

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 1,000 over a time period as short as a few tens of minutes.

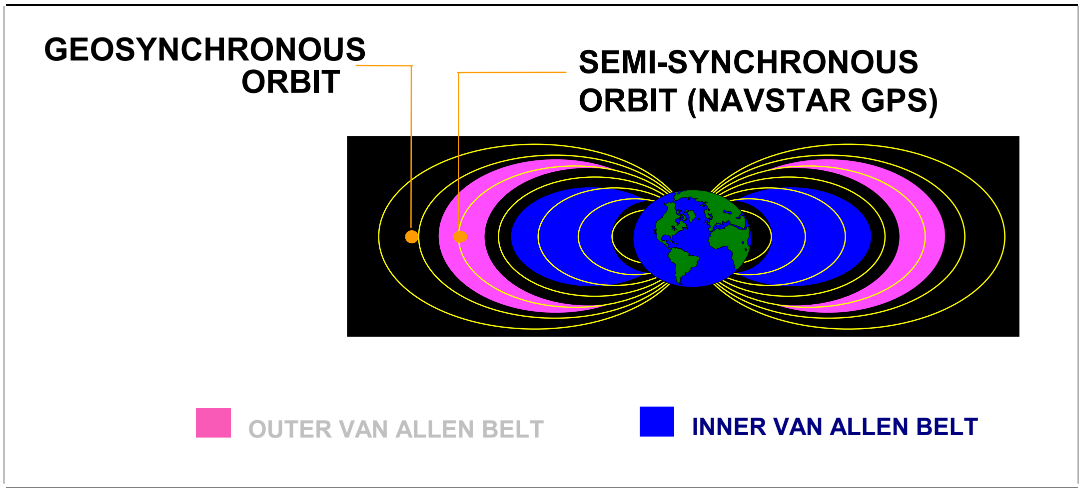


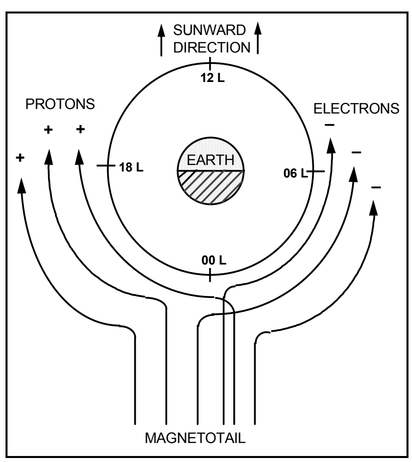
Fig. 6-15. Van Allen Radiation Belts

Geomagnetic Storms

As mentioned earlier, charged particles emitted by the sun cause problems primarily on the *night* side of the Earth. Their arrival causes a shock wave to ripple through the magnetosphere, causing magnetic field lines out in the magnetosphere's tail to recombine, and previously stored particles are then shot toward the Earth's night side hemisphere. Some of these particles stay near the plane of the equator and feed the ring current in the Outer Van Allen Radiation Belt, while other particles follow magnetic field lines up (and down) toward auroral latitudes.

Radiation Belt Particle Injections

The particles from the night side magnetosphere (or magneto-tail) which stayed near the plane of the equator will feed the ring current in the Outer Van Allen belt. The electrons and protons, since they are oppositely charged, tend to move in opposite directions when they reach the ring current (**Fig. 6-16**).



Cross-section of the magnetosphere taken in the plane of the Earth's geomagnetic equator.

Fig. 6-16. Geomagnetic Storms - Radiation Belt Particle Injections

Furthermore, the protons and electrons have about the same amount of energy, but the electrons (since they are 1,800 times lighter) move 40 times faster. Finally, the electrons are about 10 to 100 times more numerous than the protons.

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

Auroral Particle Injections

Some of the particles from the night side magnetosphere follow geomagnetic field lines up (and down) toward the northern and Southern Hemisphere auroral latitudes. These particles will penetrate to very low altitudes (as low as 35 km), and can cause physical damage and electrical charging on high-inclination, low-altitude satellites or Space Shuttle missions (**Fig. 6-17**).

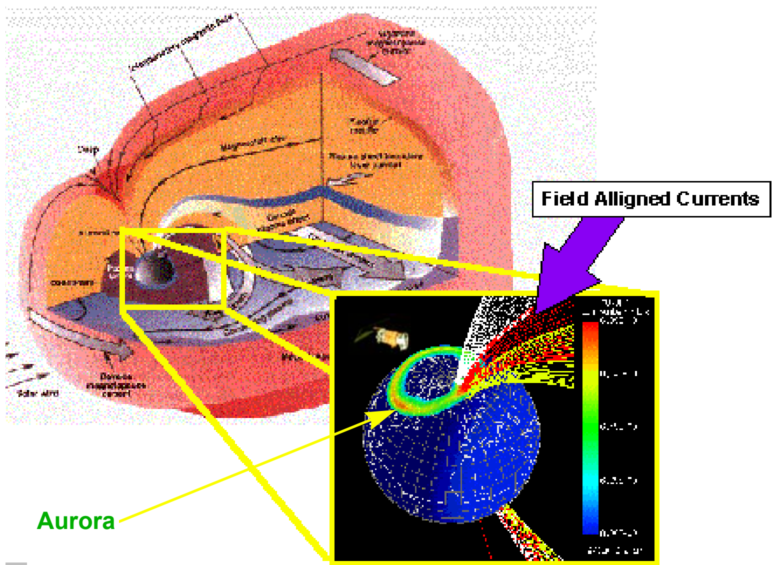


Fig. 6-17 Geomagnetic Storms Auroral Particle Ejections

Electrical Charging

One of the most common anomalies caused by the radiation hazards discussed above is spacecraft or satellite electrical charging. Many things can produce charging. (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) direct 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 phenomenon is strongly influenced by variations in an object's shape and the materials used in its construction (**Fig. 6-18**).

Surface versus 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 direct 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.

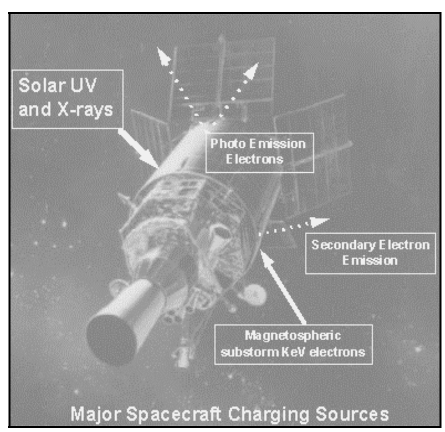


Fig. 6-18. Spacecraft Charging

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.

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.

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.

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.

Geomagnetic Storm Surface Impacts

Geomagnetic storms cause rapid fluctuations in the Earth's magnetic field and increase the amount of precipitating energetic particles impinging on the Earth's ionosphere. The rapid fluctuations can lead to induced currents in power grids that may lead to failure of that grid (**Fig. 6-19**). This can and has happened, predominately in the higher latitudes. (In March of 1989, the Canadian Province of Quebec suffered a power grid failure of this type.) Such fluctuations can also

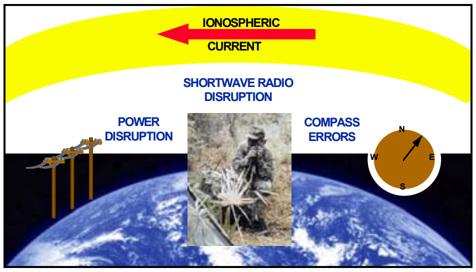


Fig. 6-19. Geomagnetic Storm Surface Impacts

cause orientation errors for those relying on magnetic compasses for navigation. In addition to the ionospheric disturbances discussed earlier, localized rapidly changing ionospheric activity can occur. This activity may not be picked up by space environment sensors, but can cause HF communication users to suffer sporadic interference or total localized blackouts.

SPACE ENVIRONMENTAL SUPPORT

The 55th Space Weather Squadron (55SWXS).

55SWXS is DOD's only space environmental analysis and forecasting facility. It is a subordinate unit of the Air Force Weather Agency (AFWA), Offutt AFB, NE. At the time of this writing the plan is to move the 55SWXS to Offutt's AFWA facilities effective 1 Oct 2001. At that time the 55SWXS will cease operations at Schriever AFB, CO and the mission will be conducted from AFWA.

The squadron is a 24-hour support operation providing tailored space environmental products and services to DOD and national program customers.

The 55SWXS headquarters is at Schriever AFB, Colorado and operates several Geographically Separated Units (GSUs) to monitor the Sun. Known as the Solar Electro-Optical Network (SEON), it is the only network in the world dedicated to observing the Sun at optical and radio wavelengths in real time.

Mission

55SWXS provides space environmental support for worldwide operations (**Fig. 6-20**). The squadron gathers and processes space environmental data from ground and space-based sensor networks, analyzes and models the space environment, forecasts solar and space environmental phenomena and provides alerts, warnings and assessments for operational impacts to Air Force and other DOD agencies. Support to customers can be provided at the unclassified, collateral and Sensitive Compartmented Information (SCI) levels. Systems supported include satellite vehicle and payload operations, ground and satellite-based communications, navigation, surveillance and weapon system radar, as well as high-altitude reconnaissance aircraft and the Space Shuttle.

Products

55SWXS products fall into one of four categories:

<u>Parameter Observations</u>. The 55SWXS monitors solar activity through the data received from SEON, other ground-based ionospheric sounder networks and satellite-based sensors. Critical parameters from this data are used to optimize tailored environmental models used in specifying satellite locations and enhancing HF and satellite communications links, as well as radar and satellite tracking correction and calibration.

<u>Analysis</u>. Near-Real Time and Post Analysis. This category gives system

operators, engineers and decision-makers expert analyses of the role the space environment plays in system anomalies. This provides quicker resolution of anomalies reducing system downtime and saving time searching for other causes.

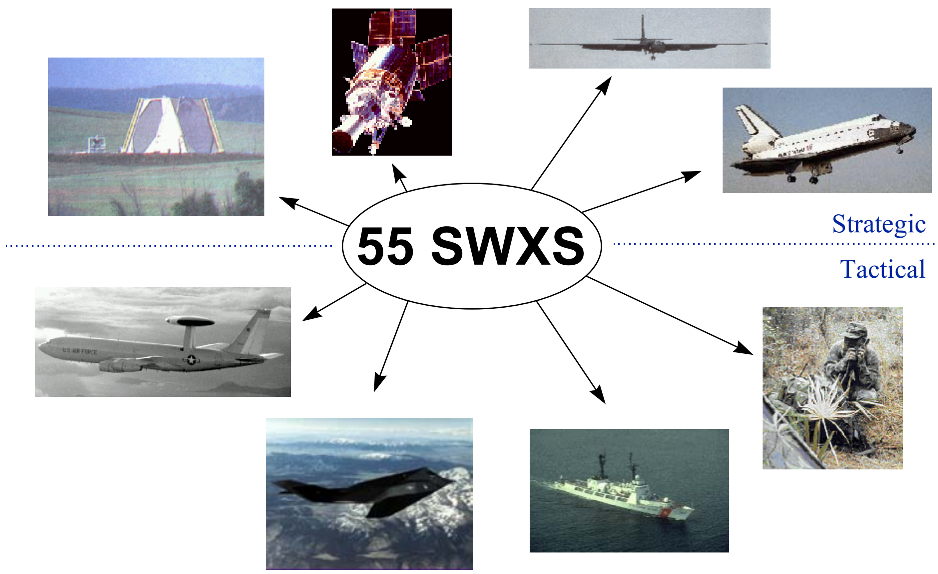


Fig. 6-20. 55SWXS Mission Support

Forecasts. 24-Hours/days, 7 days per week. All portions of the radio spectrum are subject to variability in the ionosphere. The 55SWXS provides predictions of critical parameters for optimizing HF and satellite communications operations and planning, satellite drag prediction and radar and satellite signal correction.

Warnings. Navigation systems are influenced by energetic proton flux into the polar caps as well as geomagnetic activity. Also, energetic protons pose a significant health hazard to high-altitude reconnaissance aircraft pilots and astronauts operating in the space environment. Satellite systems in certain orbits can perform anomalously or be damaged during solar flare induced particle storms. The squadron provides situational awareness products, potential systems effects and aids in system anomaly resolution in support of radar, satellite vehicle and payload operations.

Access to 55SWXS Products

The 55SWXS uses a number of common user systems as well as dedicated point-to-point communication circuits to support the dissemination of data. Products are available over the Automated Weather Network (AWN) and both unclassified and classified AUTODIN. See your local weather support officer to gain access to products disseminated over the AWN and learn how to get them. To receive products via AUTODIN, contact 55SWXS and your address will be added to the product distribution lists.

Web Page

The 55th Space Weather Squadron has a comprehensive web page. This web page is available on Intelink and the Global Command and Control System (GCCS) as well as unclassified, non-DOD Internet systems. The address is: http://www.schriever.af.mil/55swxs/index.htm.

Product Catalog

The 55SWXS maintains AFCAT 15-152, Volume 5, *Space Environmental Products.* This publication describes the space environmental analysis, forecast and warning services provided by 55SWXS 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.

Requests for Support

Eligible organizations may request space environmental support or products. Several ways of dissemination are available, (restrictions based on the product or support may apply) including AWN, AUTODIN, FAX and mail.

AFI 15-118 Support Assistance Request (SAR)

To request continuing, a-periodic or one-time support (i.e., contingency, exercise or customized support), submit an AFI 15-118, Support Assistance Request (SAR) to 55SWXS/DOO (Operations) or DOUX (Payload Management). The format of a SAR is described in AFI 15-118 (available from most USAF base weather units, including Army support units). For additional details or assistance in determining support requirements, contact 55SWXS/DOUX (Payload Management).

Special Support

The 55SWXS/DOO (Operations) personnel can provide immediate support 24 hours a day. They prefer to coordinate requirements beforehand to ensure support is optimum, but short-notice responses may be requested.

Points of Contact:

- **55SWXS Internet Address:**
55swxs@schriever.af.mil

- **55SWXS/DOO (Operations):**
  24 hours a day
  DSN: 560-6313/6312/6311/2404/6322
  Commercial: (719) 567-xxxx
  FAX extensions: 6407/2100/6219

- **55SWXS/DOUX (Requirements):**
  0730 - 1630 MST
  DSN: 560-2420/2422/6331/6332
  Commercial: (719) 567-xxxx
  FAX extensions: 2287/2288

- **55th Space Weather Squadron's mailing address is:**
  55SWXS
  715 Kepler Ave., Ste 60
  Schriever AFB, Colorado 80912-7160

The 614th Aerospace Weather Team (AWT)

The 614/AWT is a unit of 14th Air Force and operates around the clock at Vandenberg AFB, CA in the Commanders Space Air Forces (COMSPACEAF) Aerospace Operations Center (AOC). The AWT receives its space environment strategic products from the AFWA and extracts information directly applicable to space operations. The information is put into reports and forwarded to 14th Air Force units, USSPACECOM and other components such as ARSPACE and NAVSPACE. The 614/AWT also performs a reachback function for units such as Aerospace Expeditionary Forces (AEF) requiring short duration support.

REFERENCES

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Home page of the National Oceanic and Atmospheric Administration. Provides space weather alerts, warnings, and forecasts, and related space weather information.

http://www.sec.noaa.gov/info/Cycle23.html
Overview of NOAA's panel discussion and conclusion on predictions of how Solar Cycle 23 would affect space weather.

http://sohowww.nascom.nasa.gov/
Home page for the Solar and Heliospheric Observatory; capabilities, images, and related information.

http://www.srl.caltech.edu/ACE/
Home page for the Advanced Composition Explorer spacecraft; educational and other information related to capabilities, projects, and goals.

http://www.sel.noaa.gov/today.html
NOAA's Space Environment Center reviews today's space environment and provides links to related space weather information.

http://solar.sec.noaa.gov/primer/primer.html
NOAA tutorial on space weather environment.

http://www.ips.gov.au/papers/
Australian government website providing comprehensive information about the sun and space weather.

http://www.ips.gov.au/papers/richard/calc_inter.html
Provides predictions of solar interference to satellite based on satellite location information entered by user.

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