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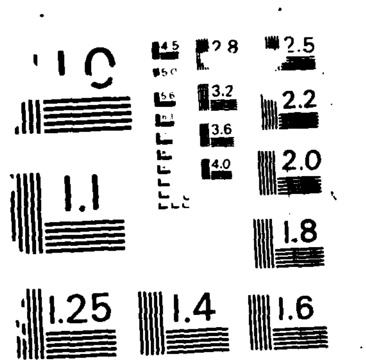

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Spacecraft Requirements for Predictions of Geomagnetic Activity (A Tutorial)

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Operational and research spacecraft require predictions of geomagnetic activity due to various effects of the geomagnetic activity on their operation. At high altitude, electrical charging of spacecraft surfaces, which occurs as a result of hot plasma injected from the geomagnetic tail during substorms, can produce discharges which result in spurious operation of the spacecraft. A reliable prediction of such activity can permit additional vigilance on the part of ground controllers at times of possible spurious operation of the spacecraft. Large magnetic disturbances, which accelerate electrons to high energies in the magnetosphere, increase backgrounds in sensors such as star sensors used for attitude control and also can produce spurious operation through the mechanism of thick dielectric charging which also produces discharge pulses. Again, reliable prediction of such magnetic storms, which requires a knowledge of solar wind conditions, would be of great value in operational management of space assets. For low altitude spacecraft which are subject to orbit perturbations as a result of changes in atmospheric scale height, constituent density, and

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19. ABSTRACT (Continued)

temperature, operational procedures can also benefit from a predictive capability of geomagnetic activity which is closely linked to modifications of the atmospheric density profile.

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INTRODUCTION

Spacecraft users of magnetic field predictions can be classified by the immediacy of their requirements. Operational programs, i.e., those with spacecraft (either manned or unmanned) already in orbit, have a primary requirement for short-term predictions (hours to tens of hours) of magnetic field perturbations. Special data acquisition periods in research programs, such as radio-wave propagation studies, chemical releases, auroral studies, and the like may also require knowledge of the present and near-future (hours) magnetic conditions. A similar class of users with immediacy requirements is rocket research programs, such as those involved in ionospheric or auroral studies, where a specific state of the magnetic field---or magnetic activity---is required for data acquisition. Space system designers, on the other hand, usually require only long-range predictions, and those only indirectly. The predictions for system designers are usually needed in the form of long-term averages or long-term trends of magnetospheric particle populations, the morphology of which is primarily controlled by geomagnetic activity.

In this presentation, we will discuss a number of areas of satellite and rocket operations in which magnetic activity has an impact on the mission, primarily through perturbations of the magnetospheric particle populations; we will show the effect of magnetic perturbations on the magnetospheric particle populations; and then, we will discuss briefly the types of predictions of magnetic activity that are required for spacecraft and mission design and operation. Another environmental impact area, variations in atmospheric density which affect low altitude spacecraft, is only indirectly related to magnetic activity and will not be addressed in detail in this presentation. A more complete discussion of predictive requirements with respect to atmospheric effects is given elsewhere [Vampola, 1979].

OPERATIONAL SPACECRAFT PROBLEMS

HIGH ALTITUDES

For high altitude spacecraft operations, spacecraft charging and energetic particle backgrounds are the major areas of concern which involve environmental factors which are related to magnetic field activity. Spacecraft charging problems can originate in two different mechanisms, both of which are ultimately caused by magnetic field activity. The first mechanism is surface charging. In this process, a hot plasma causes surfaces of spacecraft to charge to high levels, sometimes to many kilovolts; discharging of these surfaces then produces spurious operation of, or damage to, the spacecraft.

Space, both near earth and in the interplanetary region, is filled with plasma. The interplanetary plasma originates at the sun; the magnetospheric plasma originates in the ionosphere and in the entry of the solar wind plasma into the magnetosphere in the tail and at the cusps over the polar caps. An object placed in a plasma will charge negatively due to the greater mobility of the electrons as compared to the ions. As the object charges, a sheath region is created around the object which repulses the particles of like charge and attracts the opposite charge. Equilibrium is reached when the sheath has grown to a sufficient extent that the currents due to the plasma species are balanced. Sunlight modifies the picture in that the photocurrent from a surface is usually orders of magnitude greater than plasma currents; thus, equilibrium in sunlight is normally controlled by emission and reattraction of photoelectrons. For some configurations of surface structure, charged elements may control currents to and from nearby elements, just as a grid in an electron tube does. Equilibrium for those elements is determined by the satellite geometry and may be far different from what would be observed for the elements if they were placed elsewhere on the spacecraft. For satellites in the earth's umbra and for shadowed surfaces on satellites, photoemission control of equilibrium is not available. However, at low and intermediate altitudes (up to the location of the plasmapause, which is usually found at 15,000 to 25,000 km altitude at the equator), the density of cold plasma (which has a temperature of a few eV) is high enough (10^2-10^6 cm^{-3}) that sheaths produced at small potentials are sufficient to maintain current equilibrium to surfaces. At high altitudes, such as the geosynchronous orbit region, the cold plasma density is usually small, of the order of 1 cm^{-3}. Under some magnetic conditions, the density may drop another order of magnitude.

When the cold plasma density is low, the possibility exists that surfaces can charge to very high potentials. The source of the charging current is a high temperature plasma generated in the geomagnetic tail by substorm activity and transported to lower altitudes. The high mobility of the electrons compared to the ions (the result of the large difference in particle mass) may cause surfaces to charge to kilovolt or tens of kilovolt levels [DeForest, 1972]. In umbra, potentials greater than 19 kilovolts have been observed [Olsen, 1987]. The charging of spacecraft surfaces may produce electrostatic barriers which prevent the neutralization of the spacecraft as a whole. This, then, may result in several hundred volt potentials on spacecraft in sunlight. Shadowed surfaces which charge to kilovolt levels may discharge to spacecraft structure which has been maintained at low levels by photoelectron emission. These discharges, which may involve significant capacitance, may couple to signal leads, producing spurious

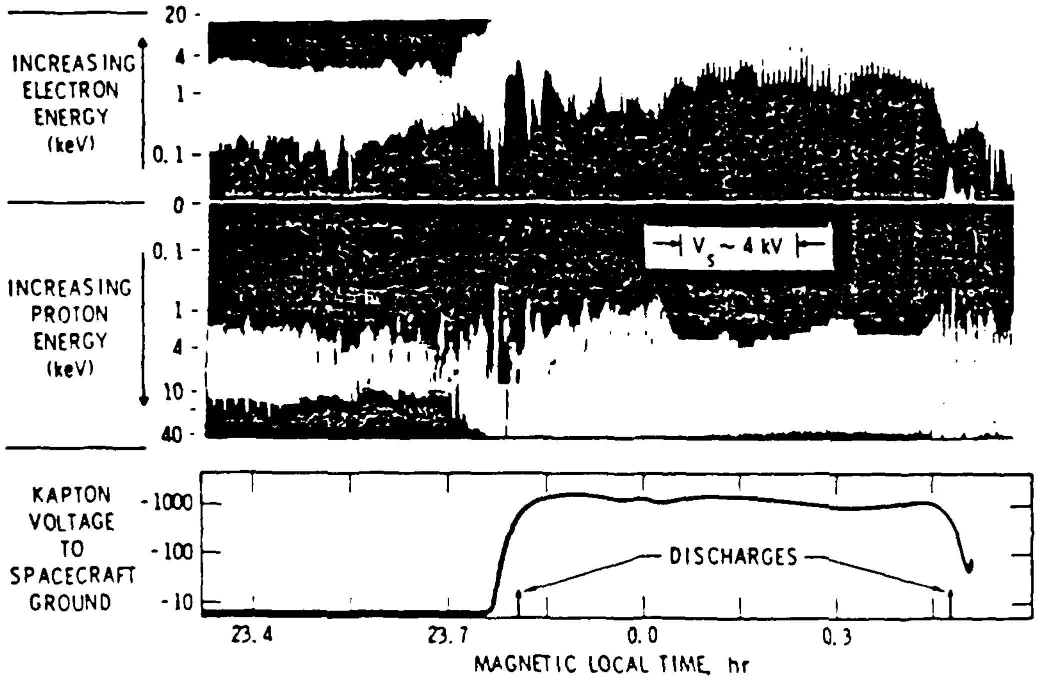
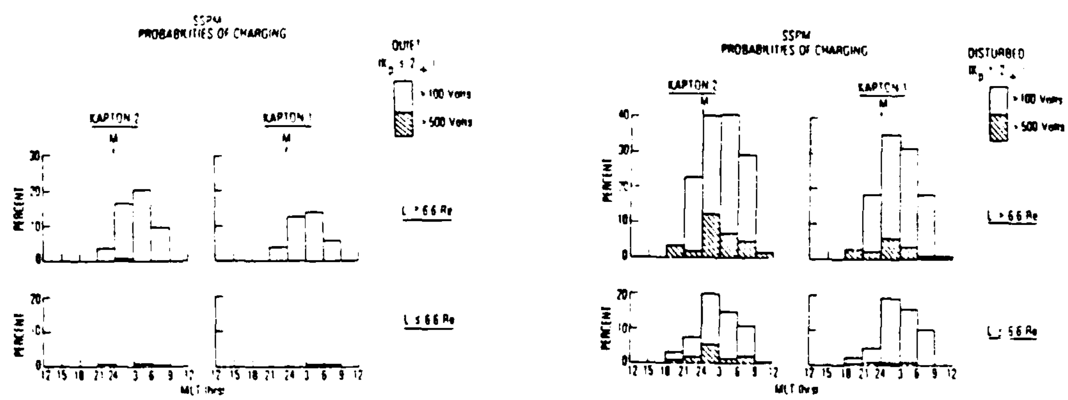


Figure 1. Natural charging event on the P78-2 (SCATHA) spacecraft in eclipse. The upper two panels are spectrograms of the electron and ion fluxes. The lowest panel shows the charging profile for a Kapton sample and two natural discharges detected by the Pulser Analyzer. [Koons, 1983.]

operation of the spacecraft. In extreme cases, the discharges may damage components. Surface charging has been a minor or major problem on most satellites at geosynchronous orbit.

Figure 1 [Koons, 1983] shows discharges associated with a surface charging event on the P78-2 (SCATHA) spacecraft. The upper two panels are spectrograms of the electron and ion fluxes. Lighter areas indicate higher fluxes. The lowest panel shows the potential between the spacecraft structure and a Kapton sample on the surface of the vehicle. The difference in potential is due to the shadowed Kapton sample being charged by the high temperature plasma while the structure is clamped by sunlight-induced photoemission and secondary emission. The spacecraft enters eclipse at about 23.8 MLT. Just prior to this time, it is enveloped in a hot plasma (the average energy of the electrons, top panel, rises from about 1 keV to about 8 keV). The timing of the eclipse passage with the influx of hot plasma is coincidental. An electrical discharge is observed on the vehicle just as the potential is changing at its maximum rate (lowest panel). Upon exiting the hot plasma, there is again a discharge during the maximum rate of change of the potential. In the case of the P78-2 satellite, these discharges did not affect the operation of the vehicle, since the vehicle was designed as a Faraday cage in an effort to study such discharges without being affected by them. However, such discharges on other satellites do have serious effects.

Surface charging is intimately connected with magnetic field activity. Figure 2 [Mizera, 1983] demonstrates that both the probability of charging and the maximum potential attained are related to the level of magnetic activity. Figure 2a is a histogram of charging probabilities as a function of local time and charging potential during magnetically quiet times ($K_p<2+$). Figure 2b is a similar plot for probabilities during more disturbed periods ($K_p>2+$). Note that the level of magnetic activity has a large effect on both the probability of charging and the degree of charging. A foreknowledge of magnetic activity would permit spacecraft controllers to exercise a higher degree of vigilance at times of higher probability of charging or perhaps even to put the spacecraft in states of operation in which they are less subject to damage by this mechanism.



(a) (b)

Figure 2. a) Histograms of the probabilities of charging versus Magnetic Local Time (MLT) observed by the SCATHA Satellite Surface Potential Monitor (SSPM) on two Kapton samples during magnetically quiet times ($K_p \leq 2+$). The voltage indicated is the potential with respect to the spacecraft frame. The probability of charging is very low at $L \leq 6.6\ R_e$. b) Same as a) except the data was obtained during magnetically disturbed times ($K_p \geq 2+$). [Mizera et al, 1983]

Figure 3 [Mizera, 1983] is a histogram of the probability of charging as a function of local time. Note that the maximum probability of charging occurs near midnight, and during the dawn period. The hot plasma generated in the tail is ejected earthward near midnight and the electrons drift eastward toward dawn. The major injection occurs in the pre-midnight region. For more intense events (hotter plasma or denser hot plasma), the injection is to lower altitudes, and thus the maximum probability of charging to very high potentials occurs during this time period. Thus, a prediction that a substorm may (or may not) occur at the time a geosynchronous spacecraft is in the midnight region may be of great significance to the spacecraft controllers.

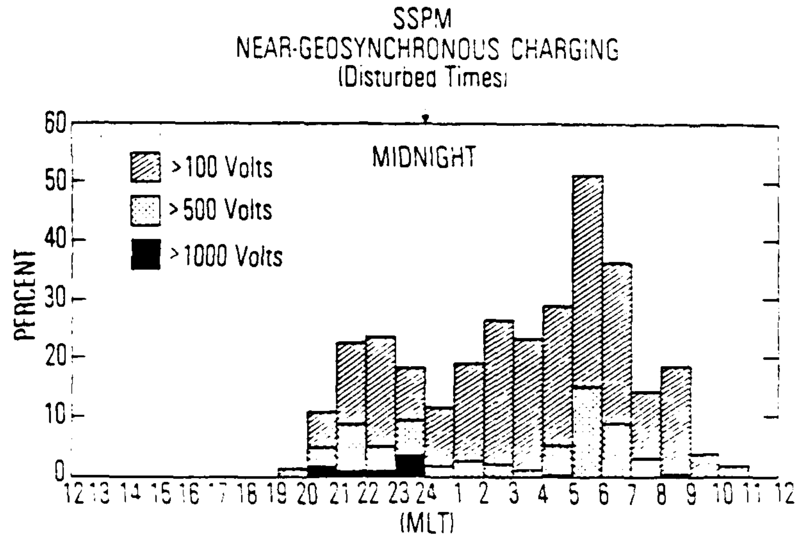


Figure 3. A histogram of the probability of charging to various potentials vs. magnetic local time in the geosynchronous region. The data were obtained by the SCATHA SSPM. Note that potentials in excess of 1000 volts were observed only in the pre-midnight sector, while the maximum probability of charging occurs in the dawn sector. [Mizera et al, 1983]

The energetic electron environment at high altitudes is also intimately controlled by geomagnetic activity. Figure 4 [Vampola, 1971] shows the effect of a major magnetic storm on energetic electrons in the outer zone. In this case, the storm (D_{st}=145γ) occurred on 15 May 1969. Fluxes of electrons with energies above 1 MeV in the outer zone are seen to increase by two orders of magnitude over the pre-storm levels. At 200 keV, the increase is about three orders of magnitude. Note that the most energetic electrons, those with energies above 1 MeV, take the longest to decay away. For the event of Figure 4, electrons above 2 MeV peak two weeks after the storm and are just beginning to decay at three weeks after the storm. Electrons with these energies have been implicated in an additional charging mechanism, known as 'bulk charging' or 'thick dielectric charging,' which also produces operational anomalies [Meulenberg, 1976].

In bulk charging, energetic electrons embed within thick dielectrics, such as cable insulation or circuit boards, and build up to very high potentials. When the potential exceeds the breakdown strength of the dielectric, a discharge occurs. In general, only a very small capacitance is involved in this breakdown and the resulting pulse can be considered as being a fast (tens of nanoseconds) signal pulse. Signal-conditioning circuits can usually identify this type of event, provided the circuit design has made provision for such spurious signals. That such provision has not been made in the past is shown clearly in Figure 5 [Vampola, 1987], where anomalous operation of star sensors is compared with the energetic electron fluxes (E_e > 1.2 MeV) measured in the same region of space by the GOES meteorological satellites. In this case, a number of anomalies occurred to star sensor shutters on the USAF Defense Support Program satellites. Investigation of this set of anomalies concluded that they were due to discharges produced by energetic electrons in a coaxial cable which was routed on the surface of the spacecraft to a sun-sensor (which was part of the star sensor package). Other investigations of anomalies have also resulted in ascribing bulk charging as the responsible mechanism. Since increases in the energetic electron fluxes in the magnetosphere are due to magnetic activity, bulk charging and anomalies due to this mechanism are related to geomagnetic activity.

The energetic particle environment in space, which was shown in Figure 5 to be instrumental in spurious satellite operations, produces other effects which are detrimental to satellite operation. Most sensors on spacecraft, whether they are star or earth-limb sensors for attitude control or photon or particle detectors used for numerous applications (weather and land-resource mapping, surveillance, astronomy, magnetospheric physics studies, etc.), are sensitive to directly penetrating electrons and to bremsstrahlung generated by the electrons when they impinge on the spacecraft. In most cases, the result is a background contamination which may be easily eliminated from the data (and thus is of no serious

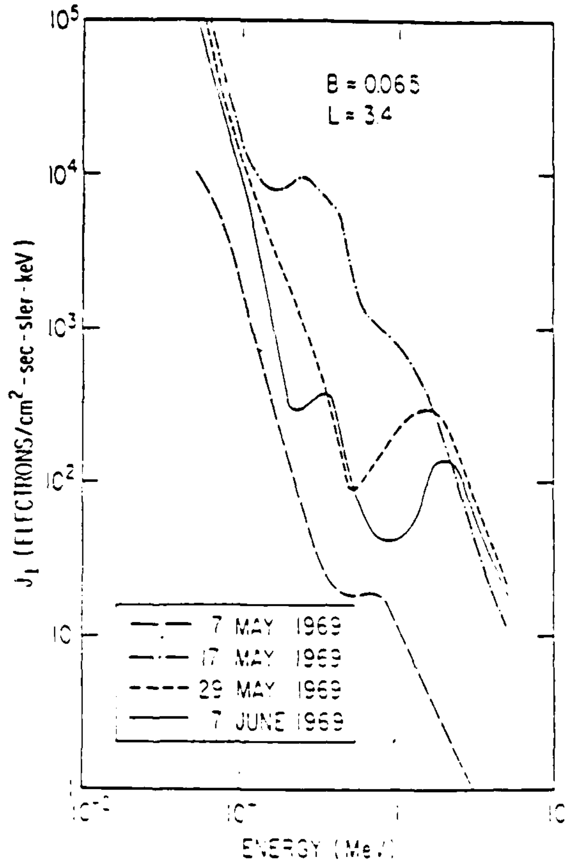


Figure 4. Energy spectra of electrons between 53 keV and 5.09 MeV at L=3.4, B=.065 showing the effect of a magnetic storm (D_{st}=145γ) on 15 May 1969. Significant quantities of electrons between .1 and 5 MeV are produced. [Vampola et al, 1977]

consequence) or which may substantially reduce the quality of data. If the data can be replaced by later operations, the effect may again be minor. However, in some cases, the effect is much more serious. A rocket measurement of ionospheric or auroral parameters which encounters an unexpectedly high background from energetic particles due to magnetic activity may fail to properly achieve its objectives and thus void the entire campaign.

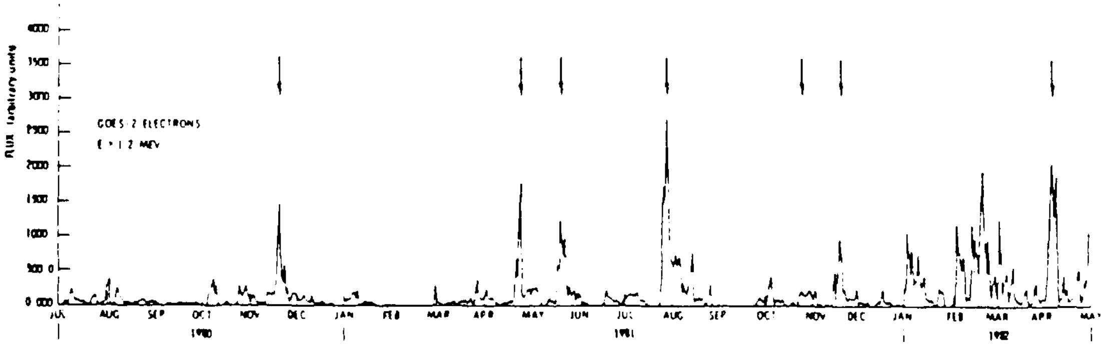


Figure 5. Plot of the daily flux of energetic electrons, E_e>1.2 MeV, observed by the GOES-2 geosynchronous satellite. The arrows indicate times at which Star Sensor anomalies occurred on DSP spacecraft. [Vampola, 1987]

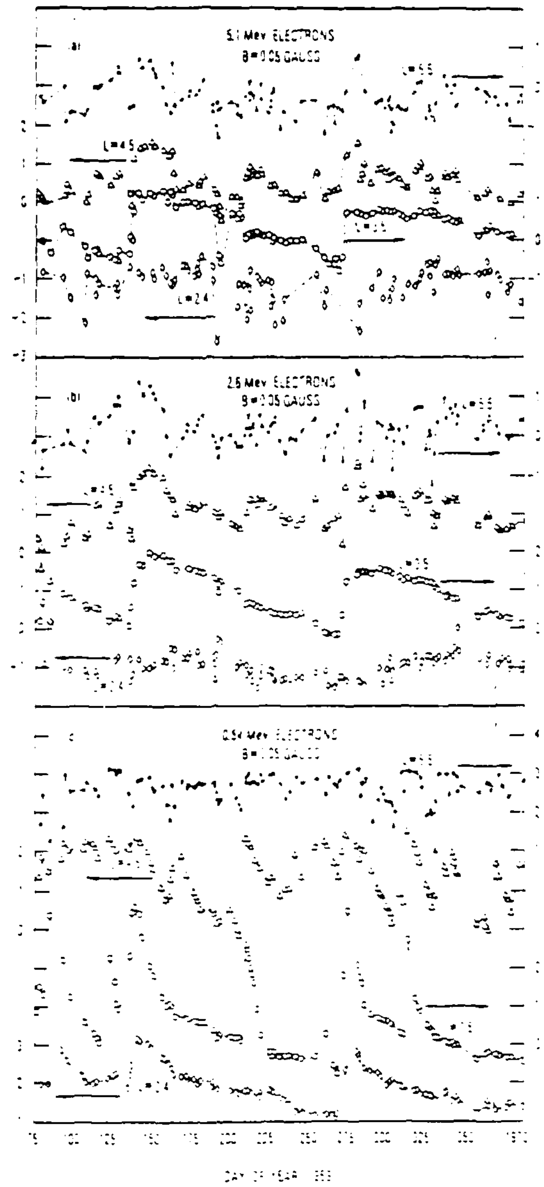


Figure 6. Daily averages of fluxes at .53, 2.6, and 5.1 MeV at L values of 2.4, 3.5, 4.5, and 5.5 for the March 1969 to February 1970 period. Data are normalized to B=.05 gauss. The data were obtained by magnetic electron spectrometers on the OV1-19 satellite. The effects of major ($D_{st}>150\gamma$) and moderate ($D_{st}>80\gamma$) magnetic storms are evident in the flux histories. [Vampola et al. 1977]

Figure 6 [Vampola et al. 1977] shows the response of energetic electrons at various energies and various altitudes to a number of magnetic storms over a period of about one year. Note that at high energy (2.6 and 5.1 MeV), the electron fluxes at L=3.5 responds in a major way only to two magnetic storms, both with $D_{st}>200\gamma$. At lower energy, .54 MeV, the electrons respond to a number of smaller storms with $D_{st}>100\gamma$. At higher altitudes, electrons of all energies respond to relatively small magnetic storms. Advance warning of such events in which elevated fluxes of energetic electrons will be encountered is potentially very useful. A spacecraft which might otherwise lose attitude lock due to spurious data might be put into a manual attitude control mode for the duration of an elevated background period, provided some advance warning of such elevated periods is available. Conversely, if the object of a rocket or satellite mission is to make measurements during times of elevated particle backgrounds, a prediction of appropriate magnetic activity would aid in or be absolutely necessary to the execution of the mission.

LOW ALTITUDES

For low altitude spacecraft, surface charging is not, in general, a significant problem. Because of the high density of the cold plasma, relatively low potentials (few tens of volts) are sufficient to ensure current balance. There are scenarios in which this may not be the case (a surface in the wake of a very large object traversing the auroral zone, for example), but they are rare. Similarly, variations in energetic particle fluxes due to magnetic activity are not normally a major concern because low altitude spacecraft with low orbital inclinations spend all of their time in the inner zone where flux perturbations are small. Figure 7 [Bostrom et al, 1970] shows that no magnetic storm, even those with $D_{st}>300\gamma$, increased inner zone fluxes by more than an order of magnitude. (The overall monotonic decay of flux intensity is the result of the decay of the Starfish electrons which were injected in July, 1962.) At L=2.2, which is in the slot region, large transient increases are seen, however.

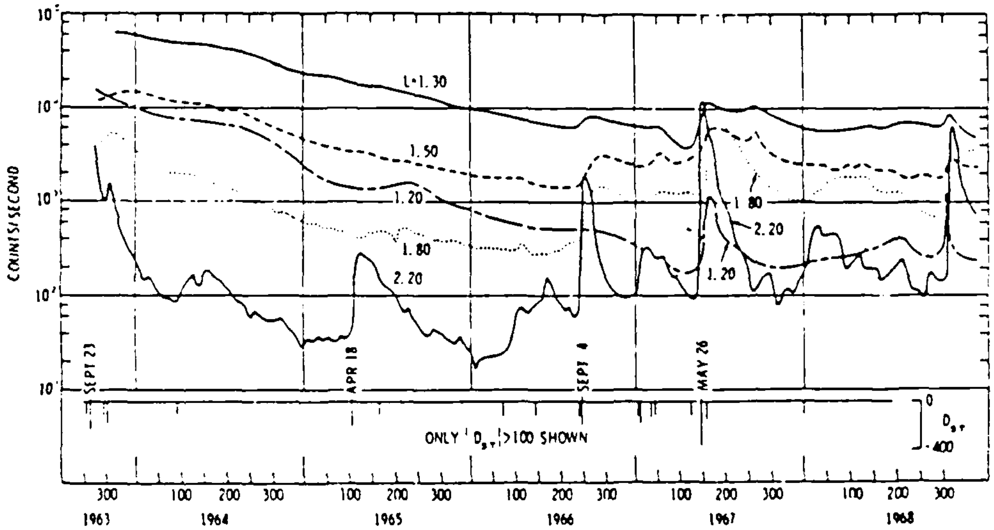


Figure 7. A history of inner zone low energy electrons (E_e>.280 MeV) for L=1.2, 1.3, 1.5, 1.8, and 2.2. Magnetic storms are indicated by the D_{st} scales which shows only values of $D_{st} \geq 100$. The response of these fluxes to magnetic activity is pronounced. [Bostrom et al, 1970.]

At high inclination, a low altitude satellite may traverse the auroral zones and the polar cap. In these regions, two effects may be of importance to missions: a) the geomagnetic control of entry of solar and galactic cosmic rays; b) auroral precipitations. Cosmic rays may constitute either an undesired background in sensors or an enhanced probability of circuit malfunction (due to the SEU--Single Event Upset--a phenomenon caused by a direct creation of electron/ion pairs within a solid-state circuit by a highly ionizing particle which changes the state of the circuit, sometimes destructively). Magnetic activity, of course, changes the cutoff latitude for entry of cosmic rays and thus the probability of SEU events as a function of latitude. Thus, once again, a preknowledge of magnetic activity may be of use to both mission planning and operational control.

The location and intensity of auroral precipitation is of interest for communication purposes because of the effects of ionospheric geometry and density on transmission paths. Also, satellites and rockets investigating auroral phenomena may need magnetically quiet and/or disturbed conditions for particular objectives or may need a good predictive capability for high latitude magnetic topology (as, for instance, when an operational activity must take place near the cusp). For specific campaigns, there may be an absolute requirement for accurate predictions of the magnetic field activity for hours to days in advance. Since such campaigns are usually conducted from remote sites with high logistics costs, the more accurate and the longer the range of accurate predictions, the more useful they are to the projects.

The SAR (Sub Auroral Red) arc is another phenomenon with a relationship to magnetic activity which may affect spacecraft missions. In this mechanism, low energy (20 keV) protons from a ring current produced by magnetic storms precipitate into the atmosphere and produce kilo-Rayleigh light intensities at intermediate latitudes, typically around 55°-65° magnetic latitude [Cornwall et al., 1971]. Accompanying the proton precipitation is relativistic electron precipitation in the same region [Thorne and Kennel, 1971; Vampola, 1971]. The electron and protons energy is degraded via Landau damping. The interaction with the atmosphere produces a diffuse red area which may interfere with optical measuring systems on low altitude satellites.

For either high altitude or low altitude spacecraft, warnings of major magnetic storms would be of use in other areas. During major magnetic storms, the modification of the atmospheric scale height and ionospheric properties produce severe scintillation effects which affect transmission paths, including ground-satellite links in the UHF band. During the February, 1986 magnetic storm, communication links to a number of satellites were interrupted. Links in the SHF band, 4 to 8 GHz, are not subject to severe problems, but some satellites are still being designed with UHF links. For those communication systems with many ground stations, conversion of all these ground stations to SHF may be prohibitively expensive. The scintillation problem will undoubtedly be with us for a long time to come. The other effect is due to the fact that the cutoff in latitude and energy for cosmic rays depends upon the magnetic field configuration. When a major magnetic storm occurs, the change in cosmic ray intensities at lower latitudes in low altitude orbits and at all latitudes at high altitude may be of concern to spacecraft with large numbers of SEU-susceptible devices (which includes most small geometry devices and will probably include virtually all sub-micron geometry devices to be designed in the future).

A final point relates to atmospheric effects on low altitude spacecraft. Variations of drag due to variations in scale-height of the atmosphere during magnetically active periods are well known. However, in the region between 200 km and 500 km, atomic oxygen is a major constituent which has been shown to have major adverse effects on surfaces which are composed of or are coated with materials which have a volatile oxide, such as CO_2. Shuttle experiments have shown, for instance, that atomic oxygen can "burn" virtually all of the carbon out of Kapton films during a one-week mission. The forward-facing surfaces of a vehicle moving at almost 8 km/sec impact low velocity oxygen atoms, giving the oxygen atoms about 5 eV energy with respect to the surface, which is sufficient to produce chemical reactions with many materials. Since the atomic oxygen effect occurs only in "ram", a prediction of a magnetic storm which will be accompanied by an increase in atomic oxygen density in a particular orbit could be used by spacecraft controllers to take measures to protect the spacecraft (e. g., by closing protective covers or by changing the attitude of the spacecraft).

REQUIREMENTS FOR PREDICTIONS

The requirements for magnetic field predictions for spacecraft missions can be categorized by the distance into the future to which the prediction must be made, by the type of activity that must be predicted, and by the data that is required in the prediction. We will cover these requirements by their immediacy, beginning with short-term (tens of minutes to one day) predictions.

Short-term predictions are required by geosynchronous satellites, observing platforms, extra-vehicular activities (EVA's) in high inclination orbits, special satellite operations (such as chemical releases from CRRES), and rocket campaigns. The types of activity that must be predicted are substorms and major storms. In the category of substorms, the primary users would be satellites in the geosynchronous region with concerns about charging, since there are many geosynchronous satellites, and they are operational at all times. Major storms, since their primary mode of impact on missions is through increased energetic particle backgrounds, dose, and dose-rate, are of concern to EVA's, missions with sensitive star-trackers or other attitude systems with background sensitivity, and mission sensors with background sensitivity (virtually any lightly shielded photomultiplier or solid-state detector).

Medium-range predictions (one day to many months) are of use to special campaigns such as rocket campaigns or chemical release campaigns, to manned operations, and to certain classes of data-acquisition missions which are either dose or background sensitive. For these users, changes in the average magnitude or frequency of substorms, estimates of the frequency and magnitude of major storms, and the general time period during which major storms would occur are of interest.

Long-term predictions (years) are of interest primarily because of the dose effects that they will have on satellites. The types of effects to be considered here are the solar-induced effects (solar-cycle effects) and the secular variations. Parameters of interest in the secular variations are both the dipole moment and higher order terms because of the effect these have on the morphology of the energetic radiation belts.

Finally, a predictive capability for very large magnetic storms such as occurred on 8-9 February 1986 would be valuable. Storms of this magnitude can affect the operation of spacecraft which incorporate magnetic sensors as part of their operational attitude control.

DATA REQUIREMENTS

In the case of substorms, the predictions should include at least the following: a) UT of the substorm, with both a ΔUT and a ΔUT_{err} (ΔUT_{err} is the error in the start, not the duration, of the substorm); b) MLT and ΔMLT of the substorm (effectively, the longitude over which the primary effects will be seen); c) magnitude of ΔB; d) $\Delta B / \Delta T$ (the time derivative of ΔB). For major storms, items a), c), and d) are also required; but additionally, a predictive capability of increases in the ring current and energetic particle populations based on the predicted magnetic activity is needed. Currently, there is no such capability; however, there are probably sufficient data on the response of energetic particle populations to magnetic storms (such as that shown in Figures 4-7) to produce an empirical relationship between D_{st} and particle effects. At low altitude, a correlation between indices such as K_p and communications with polar satellites is also required.

The data requirements for meeting these needs include the following: a) the interplanetary solar wind, both density and velocity; b) the direction and magnitude of the interplanetary magnetic field; c) solar activity such as coronal holes, $F_{10.7}$, Lyman-α, and sunspots; d) Ground-based magnetometer networks; e) predictive models of solar activity, interplanetary propagation, earth-field response to the interplanetary activity, ring-current generation models, and energetic particle response models. Tables I through V present these requirements.

Table I. Types of Operations Requiring Predictions

a) Rocket Campaigns
b) Observing Platforms
c) Special Satellite Operations (CRRES, Ionospher)
d) EVA's
e) Communications
f) Surveillance
g) Scientific
h) Virtually all others

Table II. Data Required for Predictions

a) Solar Wind Monitoring
  i. Density
  ii. Velocity
  iii. Interplanetary Field
b) Solar Activity
  i. Coronal holes
  ii. $F_{10.7}$
  iii. Lyman-α
  iv. Sunspots
c) Ground-Stations
d) Predictive Models
  i. Solar Activity
  ii. Interplanetary Propagation
  iii. Earth Field Response to Solar Activity
  iv. Ring-Current Models
  v. Energetic Particle Response

Table III. Short-Term Prediction Requirements

a) Substorms
  i. UT and ΔUT
  ii. MLT and ΔMLT
  iii. Magnitude of ΔB
  iv. $\Delta B/\Delta T$
b) Major Storms
  i. UT and ΔUT
  ii. LT Asymmetry
  iii. Magnitude of ΔB
  iv. Effect on Energetic Particle Populations
  v. Effect on Communications with satellites

Table IV. Medium-Term Prediction Requirements

a) Substorms
   i. Changes in Average Magnitude of ΔB
   ii. Changes in Typical ΔB/ΔT
b) Major Storms
   i. Number and Magnitude of ΔB's
   ii. General Time Period for Events
   iii. Effect on Energetic Particle Populations

Table V. Long-Term Prediction Requirements

a) Solar-Induced (Solar-Cycle Effects)
b) Secular Variations (Parameters)
   i. Dipole Moment
   ii. Higher-Order Terms (Offset, EL, etc)
c) Particle Effects
   i. CR cutoffs
   ii. Inner Zone Protons
   iii. Average Electron Flux Levels
   iv. Electron Zone Structure

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LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security projects, specializing in advanced military space systems. Providing research support, the corporation's Laboratory Operations conducts experimental and theoretical investigations that focus on the application of scientific and technical advances to such systems. Vital to the success of these investigations is the technical staff's wide-ranging expertise and its ability to stay current with new developments. This expertise is enhanced by a research program aimed at dealing with the many problems associated with rapidly evolving space systems. Contributing their capabilities to the research effort are these individual laboratories:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photo-sensitive materials and detectors, atomic frequency standards, and environmental chemistry.

Computer Science Laboratory: Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence, micro-electronics applications, communication protocols, and computer security.

Electronics Research Laboratory: Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, rf systems, electromagnetic propagation phenomena, space communication systems.

Materials Sciences Laboratory: Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; non-destructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

Space Sciences Laboratory: Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation, solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.

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