SURVEY OF SPACECRAFT CHARGING BEHAVIOR FOR THE GEOSYNCHRONOUS SATELLITE 1989-046

by

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Survey of Spacecraft Charging Behavior for the Geosynchronous Satellite 1989-046

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ABSTRACT

This thesis examines the charging behavior of the geosynchronous satellite 1989-046. Survey spectrograms from a 216 day interval were analyzed for spacecraft potential, and to determine the height of the differential charging induced barrier. These data showed enhanced probability of charging in the midnight-to-dawn sector, peaking at 34% from 0600 - 0036 (L.T). The most negative potential observed was 8 kV. The potential barrier generally followed the spacecraft potential, with peak height of ~200 V. These characteristics are similar to those found on previous geo-stationary satellites. Detailed analysis was conducted for 10 days (12 - 21 April 1990). Automatic algorithms were developed and applied to determine potential and barrier height, and compared to the results of an interactive analysis program. The algorithms were ~70% effective.
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I. INTRODUCTION

The phenomena of charging in space has long been an area of interest in geophysics. In 1924, Langmuir detailed the concept of current flow in an object immersed in a plasma, and his findings are still applicable today. Calculations of fluxes for ions and electrons involving interstellar grains and research involving charging of interplanetary dust grains were conducted in the 1940's and 1950's [Whipple, 1961]. The advent of spaceflight, however, introduced a new area of charging research once it was found that a satellite acquires a potential in relation to its environment. Garrett (1980) published a detailed review which surveys the charging principles and gives a coherent picture of the relatively new field of satellite charging.

It was recognized early that satellites in geosynchronous orbit not only charged to extremely high levels, but also sometimes exhibited unusual operational behavior. One of the first proposals offered as to the causes of operational problems was high level charging [McPherson and Schober, 1976, Reasoner et al 1976]. Reasoner et al established the now accepted pattern of midnight-to-dawn charging behavior at geosynchronous orbit with data from ATS-6. McPherson and Schober compared this to the local time distributions for anomalies and found a similar pattern (Figure 1). If a spacecraft charged uniformly then the operations of that particular satellite would not be appreciably affected; however, differential or deep dielectric charging creates potential gradients over the satellite surface, which can induce electrical breakdowns or arc discharges. These can be quite serious and can even lead to
satellite failure should the discharge affect key circuits or components. Even weak discharges can cause problems such as:

- Spurious electronic switching
- Breakdown of thermal coatings
- Degradation of components

Other types of anomalies (which will not be detailed here) include single upset events (SEUs), radiation damage caused by cosmic rays, and high energy solar wind protons. The intense study of spacecraft charging and the satellite environment over the last two decades is a direct result of these system degrading anomalies. [Fredericks and Scarf, 1972, Rosen, 1976, Tascione, 1988]

The purpose of this work is to examine the charging behavior of a recently launched geosynchronous satellite, designated as 1989-046. Satellite 1989-046 carried on board a particle detection instrument known as the Los Alamos Magnetospheric Plasma Analyzer (MPA). A detailed description can be found in Appendix C. Nearly all analysis in this work was based on the data obtained by this instrument. Particle data from this MPA will be utilized to survey the vehicle's potential, differential barriers, and other geophysical events. The results will be compared to similar surveys of geosynchronous satellites, and will also be used to infer the nature of 1989-046's charging mechanisms.

The following sections will review the charging processes, and will provide key definitions, mechanisms and relevant theories associated with spacecraft charging and the geosynchronous environment. They will also examine research conducted on the charging behavior of other satellites.
II. BACKGROUND

A. DEFINITIONS

1. Spacecraft Charging

Spacecraft charging is a result of the interaction between a spacecraft and its environment. Specifically, a satellite in space interacts with charged particles and photons which provide mechanisms for which charging can take place. A satellite is said to be charged when it attains a potential relative to its ambient plasma. This potential can be determined by the current flux of charged particles to and from its surface. A typical equation describing this flux in terms of current densities is:

\[ J_{\text{total}} = J_e + J_i + J_{se} + J_{si} + J_{bse} + J_{\text{photo}} + J_{\text{other}} \]

where \( J_e \) is the ambient electron flux, \( J_i \) is the ambient ion flux, \( J_{se} \) is the secondary electron flux, \( J_{si} \) is the secondary ion flux, \( J_{bse} \) is the backscattered electrons, \( J_{\text{photo}} \) is the photoelectric flux, and \( J_{\text{other}} \) is the current from sources such as ion thrusters and inductive coupling.

In equilibrium, the net current flux is zero (Figure 2); therefore, when a satellite is immersed in the plasma of the space environment the balance between various types of charging currents is changed. Charge will then build on the surface until the equilibrium between the satellite and the ambient plasma is reestablished and the net current flux is once again zero [Robinson, 1989]. These currents can be affected by the spacecraft's charge, material make-up, motion, and local electromagnetic conditions [Whipple, 1981]. The mechanisms
which create the current fluxes necessary for a spacecraft to charge fall under these main categories and include:
- ambient plasma currents
- photoemission
- secondary and backscattered electron emissions
- V x B
- spacecraft induced effects

The first three mechanisms are dominant in the charging process, therefore, they will be the only ones discussed in this work.

**a) Ambient Plasma Currents**

A satellite immersed in a plasma is continually struck by charged particles of various energies. The electron and proton trajectories in the neutral ambient plasma are stopped by the insertion of the satellite's body. The current density to the surface can be found by integrating over each type particle's distribution function:

\[ J = q \int \int v_s \cos \theta f(v_s) d^2v_s \]

where \( q \) is the charge of the particle, and \( v_s \) is the velocity at the surface [Whipple, 1981]. These current flows, in turn, deposit charge on the surface of the spacecraft. Since the average electron velocity is greater than that of the proton, the current flow of electrons is also greater (assuming similar densities). The result is that the spacecraft becomes negatively charged.

**b) Photoemission**

When photons strike the surface of the satellite with sufficient energy, electrons can become dislodged, thereby producing a positive current (Figure 3). This mechanism is material dependent since it is strongly affected by parameters such as the work function of the material. Of course, this process only occurs in
sunlight. It is this particular mechanism which typically dominates the charging process for geosynchronous satellites, since the photocurrent is typically the largest current to the satellite. The current (1 - 10 \( \mu \text{A/m}^2 \)) is emitted as a distribution with a characteristic energy of \(~2 \text{ eV}\). In the absence of differential charging, this typically results in satellite floating potential of \(-2\) to \(+10\) V. Additionally, this current may be influenced by the formation of a finite potential 'sheath' around the surface due to charge build-up, or by irregular surfaces which are exposed to a limited number of particle trajectory paths.

c) Secondary and Backscattered Electron Emissions

The impact of protons and electrons in the ambient plasma surrounding the satellite also eject backscattered and secondary electrons (Figure 4). Although these fluxes are often ignored when calculating the charge, they can exceed other fluxes in certain circumstances. Secondary emission and backscattering are distinguished by the nature of the emitted spectra. Backscattered electrons are those electrons which are reflected back from the surface of the satellite with some loss of energy; typically due to electrons of greater than 1 keV energy. Secondary electrons are those which are emitted due to the energy transfer between the incoming electrons or ions and the surface material. Electrons with less than 1 keV can cause one to five low energy (1 - 2 eV) electrons to be emitted.

In the magnetospheric environment, the incident ion flux is generally less important than the backscattered and secondary electrons because the incident electron flux is so much higher than the ion flux. In a 'low' temperature plasma, the positive current produced by secondary emission can be enough to balance the ambient electron flux. This keeps the satellite positive, even in
eclipse. If a substantial amount of the incident electron flux is above a threshold energy of $>10$ keV [Olsen, 1983], the satellite will charge to negative potentials in eclipse, and the incident ion flux then balances the electron flux.

Satellite charging can be divided into the categories of surface and internal charging. Surface charging can be further categorized into frame and differential charging [Olsen et al, 1981]. Internal charging refers to the buildup of charge in dielectric materials or well insulated floating conductors inside the spacecraft.

2. Surface Charging

Surface charging is divided into two categories: frame and differential. Frame charging is the nearly instantaneous process of the satellite acquiring a net potential relative to the ambient plasma as a result of the current balance between ambient electrons and ions, backscattered and secondary electrons, and photoelectrons. Differential charging is a slower process, involving the buildup of charge on insulators. It is due to this process that geosynchronous satellites can be charged to large negative potentials in daylight. This charging is attributed to the fact that insulated surfaces in shadow lack photoemission and are electrically isolated. This allows these areas to become charged to negative potentials. The result of the differential charging is the formation of a potential barrier which suppresses photoemission and secondary electron emission from nearby illuminated surfaces. This causes the satellite to become charged to an overall negative potential. [Katz and Mandell, 1982]

Mandell et al (1978), demonstrated the complicated nature of differential charging and its effect of suppressing photocurrents by use of a computer simulation involving a 'satellite' covered with a thin ($10^{-4}$ m) Teflon coating. By
utilizing the three dimensional NASA Charging Analyzer Program (NASCAP), they were able to calculate the currents to, the charge distribution, and potential of the sphere while it was immersed in a Maxwellian plasma (similar to one found in a magnetic substorm), and exposed on one side to sunlight. Potentials of $\sim 100$ V on the sunlight side and $-3400$ V on the shaded side were calculated. After several minutes the creation of a potential barrier known as a 'saddle point' suppresses the normal photoemission and allows for negative charging to occur (Figure 5). The saddle point in the figure (indicated by the intersecting potential contours) poses an 'uphill climb' across the contours for the photoemitted electrons which have several eV energy. These findings offered a viable explanation for the large negative potentials found on geosynchronous satellites when simple current balance formulas would indicate a positive potential for the satellite.

3. Internal Charging

The idea of charge being deposited on the surfaces of dielectrics works well in explaining most charging observations. It is simplistic, however, since keV electrons have ranges in dielectrics comparable to the thickness of many satellite materials (e. g., solar array coverslips). Internal or deep dielectric charging is the result of charge being deposited in such dielectric materials (Figure 6). Specifically, if the rate of energetic electrons deposited in the dielectric exceeds the rate of leakage of charge through the conductive materials then a substantial charge can build-up. Assuming no initially stored charge, the
charge density as a function of time in a typical slab of dielectric material would be:

\[ \rho = -\frac{J_i - J_o}{\sigma} \left( 1 - \exp \left( -\frac{t}{\tau} \right) \right) \]

where \( J_i \) and \( J_o \) are the incoming and outgoing current fluxes respectively, \( \sigma \) is the conductivity of the material, \( \varepsilon \) is the dielectric constant, and \( \tau \) is the thickness of the material.

Hot electrons striking a surface will either scatter after some energy loss or will be absorbed by the material. This number of deposited electrons must be determined in order to calculate the charge. The Monte Carlo method of analyzing the statistical nature of charge and energy distributions of electrons in materials is often utilized to accomplish these calculations. [Berger and Seltzer, 1982]

This type of charging offers an explanation for daylight charging events on satellites where geometry, materials, or attitude (spin) do not indicate differential (surface) charging is the dominant process. Examples can be found where deep dielectric charging for satellites in geosynchronous orbit is an important process. [Vampola, 1987, Baker et al, 1965]

**B. THE GEOSYNCHRONOUS ENVIRONMENT**

As mentioned previously, the ambient plasma surrounding the satellite plays a critical part in the charging process, therefore, it is important to briefly examine the environment in which these satellites are found. The earth's magnetic field is responsible for the creation of a barrier between the solar wind plasma and the magnetosphere known as the magnetopause. This creates a cavity in which various particle populations exist (Figure 7). The mapping of the magnetosphere
was performed in 1961 by McIlwain in which he designated L values based on the field lines generated by a rotating dipole. These values are in units of earth radii measured from the earth's center to the magnetic equator of the surface mapped out by that field line. For example, the geosynchronous region is at \( L = 6.6 \).

Geosynchronous satellites are typically in two different plasma regions within the magnetosphere: the plasmasphere or the plasma sheet. The plasmasphere extends out from the ionosphere and consists of a low energy (several eV), dense (\( \sim 10 - 100 \, \text{cm}^{-3} \)) plasma which corotates with the earth. The outer boundary of the plasmasphere fluctuates with variables such as magnetic activity and local time. These variations can extend this cold plasma into geosynchronous orbit, particularly in the dusk sector (Gussenhoven, 1983, Olsen, 1982).

The plasma sheet is a region of less dense (1 \( \text{cm}^{-3} \)), high energy (\( kT \approx 1 - 10 \, \text{keV} \)) plasma. High energy currents exist which can contribute to high levels of spacecraft charging while in this region. An explanation for these currents can be found in the injection of intense high energy fluxes of electrons (plasma clouds) during periods of magnetic substorms (Figure 8). These injections, combined with the less dense cold plasma, create an environment conducive to satellite charging. Such plasma clouds have been observed by geosynchronous satellites, and their source was concluded to be the magnetotail (DeForest and McIlwain, 1971). The flux variations are local time dependent, with the largest fluxes occurring from local midnight to dawn. Correlations with these fluxes and spacecraft charging were made by DeForest (1972). The actual mechanisms of these injections can be explained by various models of magnetic substorms and
their interaction with the magnetosphere. A more detailed description of these models is given by Robinson (1989).

C. PREVIOUS SATELLITE CHARGING EXAMPLES

1. Explorer 8

The Explorer 8 satellite was launched in 1960 into an elliptical orbit with a perigee of 420 km and an apogee of 2300 km. It possessed various instruments to measure electron and ion current densities, temperatures, and mass. The equilibrium potential of the satellite was measured both in eclipse and sunlight by means of an electron trap. A major finding accomplished by this spacecraft was that the measured values of the equilibrium potential generally agreed with the predicted values, and that the calculations did not omit any of the mechanisms necessary to measure the potential. Figure 9 shows measured potentials on a magnetically quiet day. The plot shows the normalized (with respect to the electron temperature (kT)) satellite potential as a function of altitude. The measured electron temperatures were typically 0.17 - 0.34 eV, therefore, the actual sunlight potentials (as shown in Figure 9) were ~ -3.5 to +1.5 V. The night (shadowed) potentials were substantially more negative. As a result of these findings, the mechanisms of charging which had been studied and predicted prior to the launch were validated [Whipple, 1965].

2. OGO

The Orbital Geophysical Observatory (OGO) series of satellites were launched beginning in the early 1960's in order to study the space environment. They were observed to charge to significant levels. Whipple (1978) analyzed Retarded Potential Analyzer (RPA) data from OGO-1, launched in September 1964, and demonstrated substantial effects due to the negative ground on the
solar arrays. Figures 10 and 11 demonstrate the differences in the RPA curves in shadow and sunlight, respectively. In eclipse the solar arrays are at satellite ground. The RPA curve shows that the ion current drops to the background level near zero volt bias (the background is due to electrons). Figure 11 shows the ion current as the satellite comes out of eclipse into sunlight five minutes later. The magnitude of the ion currents in eclipse and sunlight are the same, however, the ion current cuts off at approximately 12 V higher. These RPA curves show that the satellite potential has shifted 12 V in the negative direction in sunlight--for a sunlight potential of ~ -13 V. This shift was attributed to the action of the large solar arrays. The arrays were connected to the positive terminals of the satellite batteries in a manner which allowed the solar arrays to act as large attractive probes for collecting electrons from the surrounding plasma (Figure 12). This effect drove the satellite's potential further negative than it normally would have been. (It is difficult to drive the solar-arrays, or any satellite element very positive with respect to the plasma, because of the high electron currents which can be collected).

Similar processes were observed by instruments flown on the OGO-3 satellite, launched in June 1966. The data were obtained with an ion/electron trap which was situated in order for the experiment to remain in the satellite's orbit plane. For the data shown here (19 July 1966) the satellite passed inward through the plasmapause at L = 5.5. It then continued through perigee at an altitude of 600 km, subsequently leaving the plasmasphere between 1400 and ~600 hours (local time). [Whipple et al, 1974]

At lower altitudes the large solar arrays again acted as electron collectors which forced the negative ground satellite to relatively large potentials. Figure
13 shows that during eclipse (between $L = 2.5$ and $L = 4.3$), the potential dropped to $-1$ V due to the effective disconnection of the solar array power source. Figure 14 shows the satellite's potential versus $L$ value on the outbound portion of its pass, where the satellite passes through the plasmapause at geosynchronous orbit.

2. ATS

The Applied Technology Satellite (ATS)-5 was launched into synchronous orbit in 1969. The spin-stabilized ($\omega = \sim 100$ rpm) satellite, shown in Figure 15, was cylindrically shaped with solar arrays covering a major portion of its surface. Cavities at the top and bottom contained a variety of conductors and insulators. Its fiberglass midsection contained most of the instrumentation and experiments, which provided most of the conducting surfaces on the spacecraft. Particle detectors onboard measured ions and electrons from 50 eV-50 keV [DeForest, 1972]. Such data allowed measurements of potentials with magnitudes above 50V, and the currents responsible for charging. The first reported high voltage charging by a geosynchronous satellite was by DeForest (1972). The right-hand-side of Figure 16 shows a proton flux versus energy peak at $\sim 4$ keV, indicating a negative satellite potential of that magnitude. He found that ATS-5 charged to levels of $-10,000$ V and $-200$ V in eclipse and sunlight respectively (Tables 1 and 2). This charging was explained in part by the injection of high energy plasma into the geosynchronous orbit by magnetic substorms. DeForest (1973) also reported that ATS-5 experienced differential charging with effects in the electron data up to several hundred eV. The differential charging effects were attributed to a shaded cavity on the spacecraft.
The next mission in the Applied Technology Satellite series was launched in 1974. ATS-6 (Figure 17) was a three-axis-stabilized spacecraft which carried a plasma detector on the package shown at the top, with large solar arrays and a dish antenna extending outward from the body. Reasoner et al (1976) showed that ATS-6 charged regularly in the dawn-dusk sector (Figure 1). Whipple (1976) observed that the ATS-6 detectors produced peaks in the electron count rates in the low energy levels (4 - 10 eV). He determined that these low energy electrons were photoelectrons or secondary electrons originating from the satellite's surface. He also inferred the presence of a potential barrier which prevented these electrons from escaping.

Whipple showed that low energy electrons must be trapped by a local barrier by fitting the observed electron distribution function (Figure 18). For a satellite with zero potential, the fits yield reasonable densities for the low and high energy electrons. The intersection of the two lines fitting the data reveals a transition between the low and high energy electron populations at ~50 eV. By integrating the distribution functions (or fitting them), one infers that the low energy electron density is reasonable (0.4 cm\(^{-3}\)) if the spacecraft is assumed to be the source, whereas an absurd density of >10\(^{9}\) cm\(^{-3}\) is inferred if the ambient plasma source is assumed. Since the satellite was in shadow at the time of these measurements, it is a reasonable conclusion that these are secondary electrons trapped by the potential barrier. Whipple concluded that the magnitude of the barrier was "too large to be explained in terms of a simple photoelectron or secondary electron sheath around a uniformly charged spacecraft"; rather, he felt that differential charging would be a more plausible
explanation. Olsen et al, 1981, ultimately showed that the observations were consistent with differential charging on the large mesh antenna.

Other studies revealed voltages which surpassed those found on ATS-5. The record charging events were a -19 kV eclipse event, and a -2 kV sunlight event. It was noted that the ATS-5 and ATS-6 satellites reached similar potentials in an eclipse environment, however, the sunlight environment caused dissimilar charging to take place. This was explained in part to the differences in geometry and materials, spin rates, and the conditions necessary for differential charging [Olsen et al, 1981, Olsen, 1987]. Another study by Reasoner, et al (1976) noted the ATS-6 charging events were anticorrelated with warm plasma encounters (Figure 19). The primary conclusion of this study was the support of DeForest's (1972) and others' theory that severe charging at synchronous orbit is a direct result of hot electron injections into the inner magnetosphere by magnetic substorms.

4. SCATHA

In 1979, the USAF/NASA flew a satellite (P78-2) as part of the program on Spacecraft Charging AT High Altitudes (SCATHA). SCATHA is a spin-stabilized (ω = ~1 rpm), cylindrically shaped spacecraft with a 1.7 m diameter and a 1.75 m length (Figure 20) [Olsen, 1985]. Its spin vector was normal to the earth-sun line. It was specifically designed and carried the necessary instrumentation in order to study the effects of satellite charging and to evaluate techniques which could correct the problem [McPherson and Schober, 1976]. The highest frame potentials observed on this satellite during its first year of operation occurred on 24 April 1979 in which it achieved a -340 V potential in sunlight and >8 kV negative in eclipse [Gussenhoven and Mullen, 1982]. Mullen
et al. (1986), did a statistical study of SCATHA charging, with results as illustrated in Figure 21. The satellite charged to at least \(-10\) V \(-50\%\) of the time at local midnight. They concluded that the 'high' energy electrons provided the current which caused the high negative satellite frame potentials (as shown in Figure 21). Mullen et al. found that threshold energy for 'causal' electrons was 30 keV, and that the ion current from ions of \(>50\) eV energy was not the primary source of the balancing current. The critical energy for charging, \(-30\) keV, is somewhat higher than the threshold level of \(-10\) keV electrons proposed by Olsen (1983).

5. ISEE-1

The International Sun Earth Explorer 1 (ISEE-1) was designed with strict electrostatic charge control requirements. It possessed only grounded conducting exposed surfaces in order to control negative charging events. In spite of this the ISEE-1 did charge, reaching potential levels of \(-150\) V in sunlight. Figure 22 shows inferred potentials over a period of time on 17 March 1978. While ATS-5, ATS-6, and SCATHA were dependent on differential charging in order to reach their measured potentials [Olsen et al., 1981, Purvis and Olsen, 1983], ISEE-1 was considered to be electrostatically 'clean', thereby rendering it an unlikely candidate for negative potentials due to differential effects. Evidence indicated, however, that ISEE-1 did experience differential charging [Olsen and Whipple, 1988, Whipple et al., 1983]. Further research demonstrated that differential charging on such a spacecraft might be explained by internal charging of dielectrics [Young, 1990].

6. METEOSAT

The Meteorological Satellite 1 (METEOSAT P1) was placed in geosynchronous orbit in 1977 by the European Space Agency. Within a few
months anomalies were observed which degraded mission performance. An investigation by Robbins (1979) concluded that the majority of anomalies experienced by METEOSAT during the first year of operation could be attributed to charging effects relating to magnetic activity; which, in turn, implies increased energy and density of the geosynchronous plasma. The flight model lacked particle detection equipment needed to accurately assess current flux, but electron irradiation tests conducted in the SIMLES chamber demonstrated that METEOSAT P1 would indeed charge to several kilovolts in the magnetosphere's plasma. Figure 23 shows a typical record of the rotating spacecraft in the simulation tests showing the rapidly changing surface potentials recorded by probes. The A, B, and C labels represent the results of three tests which measured: the radiometer mirror potentials, spacecraft surface potentials (with the spacecraft floating with respect to the chamber), and surface potentials with the spacecraft structure permanently connected to the chamber.

METEOSAT F2 was launched with an electron spectrometer in order to enable monitoring of the environment and its effect on the spacecraft. Additionally, the electromagnetic cleanliness of the satellite was improved in order to reduce the likelihood of differential charging. Research by Johnstone et al (1986) revealed that this satellite did indeed charge at geosynchronous orbit. Figure 24 shows estimates of the potential on 4 April 1982 made by comparing the difference in energy between electron spectrum during eclipse and shortly after emergence into sunlight. METEOSAT F2 also charged differentially, however, Johnstone et al did not directly correlate these charging events with the majority of the anomalies experienced by this satellite.
METEOSAT-3 was launched in 1988 into geosynchronous orbit carrying an updated Spacecraft Environmental Monitor (SEM-2) which could measure higher electron energies. Studies have concluded that there exists a correlation between METEOSAT-3 anomalies and energetic electron fluxes. Specifically, fluxes of highly energetic electrons (>200 keV), which could contribute to deep dielectric charging, were correlated with 'morning' anomalies. [Rodgers, 1991]

7. GEOS

The Geosynchronous Earth Orbiting Satellites (GEOS)-1 and GEOS-2 carried a payload of various environmental experiments and were constructed to be fully conductive and electrically interconnected by a common ground. This design appears to have been successful in preventing differential charging. Potentials were measured using a floating probe, driven to near plasma potential with a bias current. The satellite potential is then inferred from the probe potential with respect to the satellite. The middle trace in Figure 25 shows the inferred potential utilizing the biased probe technique. Surveys of the data indicate no examples of daylight (negative) charging. Knott et al. (1983) identified periods of high energy particle distributions which affected the equilibrium potential, but the satellite potential was typically +2 V to +10 V with respect to the ambient plasma due to photoemission.

8. DMSP

The Defense Meteorological Satellite Program (DMSP) launched a series of Low Earth Orbit (LEO) polar orbiting satellites which have exhibited charging. Gussenhoven et al. (1985), studied the particle and plasma measurements from two of these satellites (F6 and F7) which were launched into similar polar orbits. Their findings centered on 26 November 1983, when both satellites made a
polar pass within 35 minutes of each other and charged to -317 V and -314 V respectively. Figure 26 shows electron and ion distribution functions for the DMSP F7-314 V charging event. The sharp peak in the ion distribution function (extending out of the figure's box) corresponds to the potential. The peak for count rate versus energy at the same time would be even more dramatic, with the count rates at the potential's energy exceeding adjacent channels by a factor of 100. These charging events were also linked to precipitating high-energy (>10 keV) electron fluxes [Yeh and Gussenbaven, 1987].

Frooominck and Soijk (1991) surveyed DMSP charging for spacecrafts F6-F9, and noted a strong solar dependence in the development of charging. They determined a new DMSP 'record' of -1430 V. Figure 27 shows this dependence by plotting the potential versus various levels of solar activity as measured by the Kp index. Their other findings included: a link between the solar minimum conditions and more frequent charging due to lower ambient plasma density, thermal plasma density of 10^4 cm^-3 or less is a condition for severe charging, and electrons of energies from 2-5 keV contribute to charging while electrons with energies >9.6 keV contributing even more. The latter conclusion was reached by comparing respective energy fluxes to observed charging events.

9. Pioneer and Voyager

In 1974, Pioneer 10 encountered Jupiter's magnetosphere and provided electron data via its plasma analyzer instrument (the Ames Research Center Plasma Analyzer). Intriligator and Wolfe (1974) reported the probable existence of a thermal 'warm' electron plasma filling the Jovian's outer magnetosphere. This conclusion was reached through observations of electron spectra which
consistently indicated a 4 eV peak. Grad et al (1977) commented that "the low energy electrons . . . may actually be photoelectrons from the Pioneer spacecraft surfaces". He observed that the spectrums utilized by Intriligator and Wolfe were remarkably similar to ATS-6 spectra (Figure 28). Whipple (1976) had previously observed that this could be attributed to secondary and photoelectrons trapped by differential charging effects in the vicinity of the instrumentation (Figure 18). Hence, the Pioneer 10 data was probably not properly analyzed in the initial work, and they indicate differential charging in the Jovian environment.

Voyager 1 and Voyager 2 passed through the Jovian system in 1979. They both carried Plasma Science (PLS) measurement instruments which were utilized to observe the low energy plasma. Scudder et al (1981) conducted an extensive analysis of the Voyager PLS solar wind electron measurements during the 'cruise' phase of the mission. From this analysis they were able to determine the spacecraft potential through solar wind electron and ion density comparisons, or by measuring the return current to the satellite's surface, as shown in Figure 29. This return current relation was valid in sunlight, for positive potentials, and in the absence of differential charging.

Barnett and McNutt (1983) also observed that the potential of the Voyager 1 spacecraft could be inferred from the ion data produced by the PLS instruments. The variation of potential from positive to negative over nine different locations (Figure 30) was correlated to the measured electron densities. The lower densities were observed to cause a positive potential due to photoelectron current, while high density regions caused negative potentials due to the ambient electron current. They also observed that the satellite experienced 42 operational anomalies usually associated with large potentials,
however, potentials never exceeded \( \pm 50 \) V. A possible explanation was given in the form of deep dielectric charging caused by energetic (>10 MeV) electrons. Differential charging was deemed unlikely due to the conductive surfaces of the spacecraft.

Voyager 2's journey near the Jovian moon Ganymede revealed a number of cold plasma 'dropouts' inferred from an instrument measuring cold plasma. These voids were originally connected with wake effects since the trajectory of Voyager 2 was downstream of Ganymede with respect to the corotating Jovian plasma. Further studies postulated instability in Jupiter's magnetosphere as a possible source. McNutt et al (1987) attributed the dropouts to changes in the upstream solar wind conditions and the magnetosphere. The dropouts are shown as the boxed areas in Figure 31 showing the measured plasma density dropping to zero.

Khurana et al (1987), however, suggested that negative charging of the spacecraft from a few kV to tens of kV offers an explanation for dropouts in the measured cold ion and electron densities (shown as the shaded areas in Figure 32). This concept is based on a realistic phase space distribution of cold and hot particles in the magnetosphere. Specifically, sufficient increases in energetic electron fluxes could charge the spacecraft to the levels mentioned previously. Such charging would explain dropouts in low energy plasma, and would be consistent with the increased energetic ion flux measurements shown in Figure 33.

Voyager's encounter with Uranus also produced substantial negative charging in a magnetospheric environment similar to earth's. Ion data shown by Selesnick and McNutt (1987) in spectrogram form show evidence of charging.
Figure 34, created by tracing their figure (from Plate 1b), shows that the potential reached $\sim -400V$. It was initially noted that this charging was associated with hot electron fluxes with temperatures exceeding 3 keV (Figure 35) [Sittler et al., 1987]. It should also be noted, however, that the more energetic electrons were also enhanced at the time. When compared to measurements made of higher energy electron fluxes, illustrated in Figure 36, one sees a correlation between an increase in these fluxes beginning $\sim 1920$ UT and the charging event (Figure 34).

Voyager 2 also observed the magnetosphere surrounding Neptune. Charged particle data obtained by the onboard PLS instrument was utilized to derive densities and temperatures. The data were combined with an assumption of spatial charge neutrality in order to calculate the spacecraft's potential, and corrected for the effects of charging on the estimated densities (Zhang et al., 1991). Figure 37 shows the results of these calculations. The stars in the figure are the potentials derived from high resolution ion spectromgrams.

D. CHARGING SURVEYS

The ATS-5, ATS-6, and SCATHA satellites discussed in the earlier sections have been extensively researched in terms of charging and anomalous behavior. Much of the present day theories on satellite charging are based on the results obtained by this research. In order to establish a common measurement technique, the charging behavior of these satellites was surveyed by Purvis and Olsen (1983). They used 12 and 24 hour summary spectromgrams, and visually scanned the data. The resulting surveys shown in Figures 38 - 40 indicate a correlation between midnight-to-dawn time and certain levels of charging. Note that the shaded regions indicate the time interval and corresponding percentage
of days the satellite charged during the surveyed period. Figure 38 shows the local time distribution of ATS-5 charging events for potentials >50 V negative. The majority of charging events occurred from ~01:30 to 06:00, with the peak percentage at 02:00. However, note the exceedingly low (peak) probability of 2%. The distribution of ATS-6 events shows a slight shift in the times that the satellite exceeded 50 V negative (Figure 39). In this case the satellite charged >20% of the time from 22:00 to 05:30, with the peak percentage of 45% found at 02:30. This result is similar the original ATS-6 survey by Reasner et al, 1976. The earlier survey was based on analysis of line plots providing ~1 minute or better resolution over the same 40 day period. Finally, the local time distribution of SCATHA charging events is presented in Figure 40. The satellite charged less frequently and to lesser levels than ATS-6, and a lower threshold (~10 V) was selected. One can still see, however, that the midnight-to-dawn relationship still applies, in that the majority of events occurred from 00:00 to 06:30. The probability distribution differs from the results of Mullen et al (Figure 21) in peak amplitude (~8% versus ~50%). This is probably due to the use of a less sensitive technique (summary plots of partial data versus floating probe data) by Purvis and Olsen. Also, the SCATHA survey by Mullen et al would be more responsive to short-lived charging events (e.g., a few minutes in duration). One main conclusion which can be made from these surveys is that the 3-axis stabilized satellite charged more often than the two spinning satellites, and that the most rapidly spinning satellite (ATS-5) charged less frequently due to its period of <1 second. These differences may be due to the fact that the differential potential builds up with a characteristic time constant of ~10 seconds (Mizera, 1983).
The following sections will provide the results of a similar survey conducted on satellite 1989-046 over a 216 day period. Additionally, other surveys and analysis of data collected by this spacecraft will be presented.
III. ANALYSIS

The data obtained from the MPA was utilized to construct summary, 35mm spectrograms, and interactive displays. These were in turn used to survey various charging behaviors of the spacecraft. The 35mm film spectrograms provided both electron and ion data for 12 hour time periods consisting of ~225 and ~450 energy sweeps respectively. Energy levels were given in 40 bins ranging from 1 eV to ~40 keV. The data were divided into four directional views: north, south, east, and west. This roughly divides data into field-aligned and perpendicular distributions. The LANL film made use of coloration to indicate particle flux intensities. The same approach was used in the spectrograms produced at the Naval Postgraduate School (NPS). Figure 41 shows electron and ion data in spectrogram form created by an interactive computer program. The LANL survey plots (35 mm) are similar in content. The primary difference is the compression of a 24 hour time period into one spectrogram.

A. LOS ALAMOS DATA

The representative spectrogram shown in Figure 41 displays both electron and ion fluxes measured by detector 3 and detector 4 of the MPA (the 'radial' viewing detectors). The rationale for utilization of two detectors versus all six to construct the computer generated spectrograms will be discussed in a later section. Particle flux intensities are represented by a color scale; where red indicates the highest measured fluxes and violet represents the lowest. Note that the numbers associated with these fluxes (2.9 and 0.5 respectively) for electrons are the Log_{10} values of the actual measured count rates. Similarly, the
Log$_{10}$ ion counts were scaled from 0 to 1.6, corresponding to the lowest and highest fluxes (again violet and red respectively). The black coloration seen in both spectrograms indicates a count rate reading below the minimum threshold established in the color scale.

The time scale is presented in universal time (UT) in hours and minutes. For example, the initial time indicated (0.03) would correspond to 00:03 UT. Note that the time scale for the electrons do not precisely correspond to that of the ions. This is due to a difference in timing the electron and ion measurements which are interleaved. Ions are sampled twice as often as electrons (968 measurements versus 474 for a typical 24 hour period with no data gaps).

The 'tick' marks on the vertical axis indicate the 40 energy channels through which the instruments swept during each time interval. The numbers on the right-hand-side of the spectrograms are the energy values (in eV) corresponding to every other channel; beginning with the lowest 'tick' mark. The energy scale is logarithmic: corresponding to the energy step sequence of the detector.

The time periods surveyed for 1989-046 were 29 September-14 November 1989, 15 November 1989-15 January 1990, 4 March-14 April 1990, and 1 July-31 August 1990. The first and third periods contained the semi-annual equinox which allowed for examination of charging in an eclipse situation. Initially the film spectra was studied in order to document the general charging behavior of 1989-046 relating to the charged particle environment measured by the MPA. A typical 24 hour period is illustrated in Figure 41. The data begins near local noon, with local midnight encountered at ~1100 (UT). On this day, the dusk bulge (plasmasphere) is encountered from 0100 to 0400. The intense ion fluxes at ~4 eV indicate a negative ambient frame potential of -2 to -4 V. This period
was followed by entrance into the plasma sheet at ~0645. Entry was marked by sudden increase in hot electron fluxes with energies above 1 keV, and the disappearance of the cold ions. Charging of the satellite corresponded to intense fluxes of hot electrons with energies exceeding 10 keV such as those seen in the plasma sheet. Formation of an electron differential charge barrier from 0700 to 1810 can be identified by the high fluxes of the low energy photoelectrons and secondary electrons trapped by the potential barrier. The 'transition' energy, or barrier height, as described by Whipple (1976) (Figure 18), can be identified by the sudden drop-off or minimum in count rate as one 'climbs' the energy channels. For example, the barrier height at 2200 UT can be estimated as ~16 V, and the height at 1155 UT is ~80 V. The ion charging peak is used to identify the spacecraft potential. The characteristic 'peak' in ion count rates as seen by DeForest (1972) on ATS-5 (Figure 16) indicates the negative potential of the spacecraft. This visually corresponds to an sudden increase in the color scale across one or two energy channels in the ion spectrogram. An example of this is the intense flux (red on the color scale) of ~1 keV ions seen at 1250. This can be easily identified as a charging peak. In many cases, however, the fluxes associated with negative charging are less obvious; such as at 0830. In this case the ~ -400 V potential can be identified by the 'green' flux of ions. The satellite reaches a peak potential of ~ -6 kV in eclipse, then 'drops' to ~ -2 kV at 1200, following exit from eclipse. (Eclipse can be identified by the sudden absence of photoemitted electrons, and often a significant increase in the negative potential of the satellite). On 14 April, eclipse occurs from 1045 to 1115. Note that exit from eclipse at 1115 is accompanied by a sharp increase in the height of the potential barrier, and the flux of electrons trapped by the barrier.
The levels of both potentials and barriers diminish from 1630 to 1800 as the satellite begins to exit the plasma sheet at local dawn.

Another analysis tool was the energy-angle spectrograms for specific time intervals. Figure 42 shows the six ion detector spectrograms for 14 April at 1232 UT. The color scale represents intensity of the Log10 jE ion flux (proportional to count rate), and as before, the 'tick' marks on the vertical axis on each spectrogram represents the 40 energy channels. The roll angle represents the orientation of the detectors through each satellite spin period. Zero degrees roll angle is north while 180° is south. The detectors in this figure indicate a satellite potential of ~ -1 kV. This value is inferred from the distinct increase in flux across all roll angles at that energy channel. The potential also appears to be spin independent. This is also indicated by the line plots of the ion distribution function shown in Figure 43. The charging peak at ~1 kV remains constant through all roll angles of detector 3 (~ radial viewing). An examination of the electron detector spectrograms for the same time interval (Figure 44) yields slightly different results. The barrier height of ~80 to 136 V can be identified by the distinct line across the figures at all roll angles. This peak is followed by the sudden drop in electron fluxes at the 'transition' energy. It corresponds to electrons emitted from a differentially charged surface, and reflected off the differential potential barrier into the detector. Line plots for the electron distribution function at all roll angles for detector 2 is shown in Figure 45. Successive plots are moved upward by multiplying by 10. The plot indicates a lack of spin modulation with a constant barrier 'peak' at ~80 V. However, plots of the distribution function for each detector at a roll angle of 270° (Figure 46) show that the barrier height varies with direction. (Here, successive plots are scaled
up by factors of 20). The satellite is spinning with a period of \( \sim 10 \) s, about an axis which is along the earth-sun line. Detector 1 points \( \approx \) earthward, while detector 6 is oriented \( \approx \) anti-sunward. The magnitude of the barrier increases with polar angle, peaking in detector 6. By analogy to ATS-5 (DeForest, 1973) and METEOSAT (Johnstone et al. 1986), one might suspect a shadowed cavity as the cause.

Another barrier event occurs at 2200 UT (local noon). An examination of the ion energy spectrogram in Figure 41 indicates a lack of spacecraft charging. However, the six electron detector energy-angle spectrograms shown in Figure 47 indicate a differential barrier height of \( \sim 16 - 28 \) V. Distribution function plots (Figure 48) reveal a spin modulation in the barrier height. Line plots for detector 1, beginning with the highest roll angle (345°) and moving downward, show a slight shift in the electron peak fluxes towards the lower energy channels. This perhaps indicates the spin, combined with the sun-satellite orientation, is causing various areas of the satellite to gradually go further into 'shadow'. The shift becomes more apparent at 60° down to 30°. The sudden 'jump' at 0° towards the higher energy channel is an indication that the satellite has completed its revolution, and is now realigned with respect to the sun. As was in the case at 1232, there is a polar variation in the barrier height. The line plots for all detectors at a roll angle of 270° (Figure 49) reveals that the barrier height is highest in detector 1's direction, which is earthward. The satellite is at local noon, hence the barrier is largest in the 'anti-sunward' direction.

B. MANUAL SURVEYS

The first charging survey involved a technique similar to that utilized in earlier studies of ATS-5, ATS-6, and SCATHA. The 35mm film
spectrograms for 216 days were analyzed (some days from the survey period were left out of the survey due to extensive gaps in data). Each 24 hour time period was broken into one-half hour time intervals, and the ion spectrograms were examined for evidence of charging over a level of 50 volts negative. Specifically, the distinctive peak created by increased ion fluxes during charging (such as those used by Gussenboven et al (1985) (Figure 26) and DeForest (1972) (Figure 16)) was utilized to determine the potential of the satellite. The percentage of time the satellite charged >50 V negative during each time interval was calculated. In this way a period of interest could be selected and examined for general charging behavior during a 24 hour cycle (LT). The results were then plotted on a polar scale in order to visually represent the satellite charging behavior for each half hour interval.

The overall survey shown in Figure 50 indicates the strong midnight-to-dawn charging dependency expected from a nonconducting satellite in the geosynchronous environment. This reflects original observations in the 1970's (Figure 1). The ~35% peak level of charging occurrence for events >50 V negative corresponds best with the ~45% peak level of occurrences found on the three-axis-stabilized ATS-6; as opposed to the spin-stabilized satellites (ATS-5 and SCATHA). Figures 51 and 52 show similar plots containing the equinox and non-equinox seasons in order to examine the differences in charging behavior. When comparing combined equinox seasons to the combined non-equinox seasons, one can clearly see a stronger probability for charging during equinox periods. This appears to correspond to a seasonal variation found in spacecraft anomaly records compiled by the Spacecraft Anomaly Manager (SAM is a software package allowing an analyst to access the Spacecraft Anomaly
Database maintained by the National Geophysical Data Center) shown in Figure 53 [Wong, 1991]. However, further analysis of the individual time periods over two month intervals revealed a lesser seasonal dependency than originally anticipated. For example, the equinox season of 29 September-14 November 1989 (Figure 54) charged a lesser percentage of time than did the non-equinox season of 1 July-31 August 1990 (Figure 55). In an attempt to explain this apparent discrepancy, the 216 day period was surveyed again in order to record and plot the number of hours each day 1989-046 was charged >50 V negative. This in turn was compared to a plot of the magnetic index $X_T$ corresponding to the same time period (Figure 56). One can see the relation between increased magnetic activity and subsequent charging by the spacecraft. The unusually high substorm activity in August 1990 would account for charging frequencies exceeding the Fall 1989 levels. An extended survey should demonstrate an increased level of charging activity during the equinox seasons as seen in the March-April period (Figure 57) versus non-equinox periods such as seen in November 1969-January 1990 (Figure 58).

A second survey of the film spectrograms was conducted in order to examine the relationship between measured satellite potential in sunlight and the corresponding differential barrier height. The equinox season time periods were selected due to the increased magnetic and charging activity noted during the general survey of all 216 days. As mentioned previously, the photoelectron population trapped by the saddle point potential creates a substantial signature in electron spectrograms, with fluxes substantially above the normal background electron counts. The barrier height is used to characterize the level of differential charging on the satellite. The average potential and average barrier

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height data over half hour intervals were taken from 35mm film spectrograms of
the equinox seasons and plotted; with the results shown in Figure 59. This
graph shows the non-unique relationship between the barrier height and the
potential of the spacecraft. For any given potential, the barrier height can vary
from zero to a maximum value. This maximum increases with potential. For
example, a satellite potential of ~ -100 V corresponds to barrier height
measurements up to ~70 V; ~1 kV satellite potentials correspond to a barrier
height of 5 to 200 V. This relationship may partly reflect the fact that typical
differential charging fluctuates on a time scale of tens of seconds to minutes.

C. INTERACTIVE SURVEY

The initial, rough survey was followed by more detailed analysis. An
interactive program was developed to create 24 hour spectrograms (Figure 41)
and associated count rate line plots in order to select the charging peak via an
on-screen cursor. Such a period would contain ~900 time intervals requiring
analysis. A similar program was developed to analyze electron distribution
functions and count rates in order to determine the level of the differential
charging barrier. The interactive survey was conducted on data from 12 - 21
April 1990. This time period was selected not only for its charging activity in both
sunlight and eclipse, but also for a range of active to quiet magnetospheric
conditions.

1. Potential Determination

Detailed study of the data indicated that detectors 3 and 4 of the MPA
would provide the best data for determining the potential of the satellite. These
are the two detectors which are approximately perpendicular to the satellite axis,
e.g., perpendicular to the spin axis. Figure 60 shows a series of the count rate
line plots used to determine the potential for a period in 14 April 1990. Each figure is an average over a time interval of ~86 seconds. Data for each of the figures represents a sweep of all 40 energy bins summed over 24 angle bins. The charging peak is "boxed" in each plot. During analysis, an automatic algorithm (described below) was used to make an initial estimate of the potential. The selection was modified interactively, as necessary. Figure 60a shows a typical eclipse charging situation in which the dramatic increase in ion flux at ~5 keV energy creates a noticeably sharp peak. The boxed area is the point chosen as the potential. Figure 60b is indicative of a moderate charging event in sunlight upon exit from eclipse. Again the energy peak at ~400 eV is easily discernible. Figures 60c and 60d are typical cases where the potential is determined from lower energy ion peaks with weaker flux intensities. These sweeps demonstrate the more difficult cases in which an automatic algorithm must select a potential. The smaller peak and slope make the combination of spectrograms and line plots necessary to properly interpret the potential.

2. Barrier Determination

Data from the MPA detectors 3 and 4 were also utilized in determining the electron barrier height. One modification was imposed by the occurrence of a "sun pulse" in the low energy electron data (visible at low energies from 0° - 90° roll angle in Figures 44 and 46). This occurs when the detector view is within a few degrees of the satellite-sun line. These data were eliminated by eliminating data taken in those spin sectors. The determination of the barrier height used both count rate and distribution function line plots, in addition to the spectrogram. The program examined ~450 time intervals for each day, sweeping through the 40 energy bins and the remaining angle bins. Again,
automatic algorithms were used to select the barrier height. The selected point was displayed on the screen on the spectrograms and line plots, and could be modified. Typical line plots for electron distribution functions and count rates are shown in Figure 61. One can easily see the inflection point following a steep downward slope in the distribution plot (Figure 61a). This, in combination with a minimum in the count rate (Figure 61b), was an indication of the barrier height (100 V in this example). The selection of the inflection point refers to Whipple's (1976) study in which the intersection of the least square fit of the low energy and high energy electron distributions can be utilized to infer the barrier height. Similarly, this method (Figure 62) was utilized to confirm the existence of barriers (such as the one on 14 April at 22:04 UT (Figure 41)); where the barrier height (~30 V) can be inferred by the intersection of the two least square fit lines.

3. Results

The results of the interactive analysis were overplotted on the computer generated spectrograms. The overplot can be identified as a thin, white, horizontal tick mark extending across each time interval in a 24 hour period (UT). Figure 63 shows the results of 14 April 1990 (compare Figure 41). The first indication of charging corresponds to the appearance of the dusk bulge ions at 0100 UT. The lack of a potential barrier indicates an absence of differential charging. The observed potential of ~ -4 V is the ambient frame potential of the satellite. The potential is poorly defined from 0400 - 0700, but is near zero (~ +/-. 10 V). Clear charging event resumes at ~0710 UT and lasts until ~1900 UT. It begins shortly after entry into the plasma sheet at ~0650, and is accompanied by high fluxes of electrons with energies >10 keV. From ~710 - 0830, the measured potentials fluctuated from ~ -100 V to ~ -700 V due to the reduced
levels of >20 keV electron fluxes; however, the reappearance of these fluxes at 0930 corresponded to a rise in the potential from ~-100 V to nearly -2 kV prior to entry into eclipse. Similarly, the barrier height corresponded somewhat to the fluctuations in the hot electron fluxes. The variations were not as severe over the same time intervals, however, the barrier height stabilized at ~-35 V from ~0830 - 0930; approximately the same time period as the reduced fluxes of electrons (>20 keV energy). It then increased to ~136 V prior to eclipse. Entry into eclipse at 1045 reduced the barrier considerably due to the absence of the photoelectrons. A reduced barrier remains, however, due to the existence of trapped secondary electrons and in spite of an extremely high potential. The potential ranged from ~ -3.5 kV to ~ -6 kV during the eclipse period. Exit from eclipse at 1115 saw a return to pre-eclipse level in both barrier height (~100 V) and potential (~ -2 kV). Again, the potential of the spacecraft gradually declines to ~ -200 V due to the corresponding decline in hot electron fluxes from 1215 - 1350. A return of hot electrons from 1350 - 1630 causes the potential to rise and fluctuate from ~ -150 V to ~ -600 V. Exit from the plasma sheet at ~1800 causes the potential to continue to drop to near zero, with no clear charging signature. The differential barrier reappears from 2030 - 2300, with a peak height of ~16 V. This is somewhat peculiar given the lack of intense hot electron fluxes associate with these barriers, and the lack of apparent negative charging. A closer examination of the electron energy angle spectrograms (Figure 47) indicated that there is indeed a barrier, which varies in energy with spin (roll angle), and polar angle. The interactive program line plots (separated from the spectrograms) showing the potential and barrier results for the remaining days (12 - 21 April 1990) can be found in Appendix D.
D. AUTOMATED SURVEYS

Speigel et al (1985) developed a count rate algorithm designed to provide a rapid means of analyzing data from particle detectors and determining the potential of the satellite. The flow chart of the algorithm shown in Figure 64 shows that this technique is indeed an automated version of the visual technique utilized in earlier surveys in that the critical trigger mechanism contained in the algorithm for determining potential is a sudden increase in ion fluxes relative to neighboring energy channels. This correlated to detecting the distinctive line created by such ion fluxes in visual spectrograms.

The algorithm was originally developed and tested for data from the SCATHA satellite. It gave satisfactory results during eclipse periods which typically yield the highest charging and strongest corresponding ion fluxes. For 1985-046 the algorithm variables were modified to better detect the equilibrium frame potential and charging during sunlight. Specifically, the critical ratios of count rates between channels and the threshold count rate was reduced in order to compensate for the high levels of background radiation, and the low levels of ion fluxes associated with some periods of daylight charging. Additionally, the ratio test was modified to look at the slope over three channels to compensate for low slopes found during some time periods.

As part of the analysis process, both spin-averaged and selected view directions for the ion data were examined. In the plasmasphere, the low energy ions are typically found drifting in the E-W direction, while in the plasma sheet, the lower energy ions in the charging peak are often field-aligned. Spin averaging therefore had a slight effect in reducing the count rate in the peak, with respect to background. Attempts to modify the data files in order to select
particular subsets of the angular distribution was ultimately deemed undesirable. This is mainly due to an inability to specify ahead of time when the satellite would be in the plasmasphere.

Algorithms were also developed to determine the differential charging barrier height in order to evaluate its usefulness in determining the existence of a barrier without an analyst's interface. It utilized a similar approach to the potential determination algorithm in that it established certain criteria involving the slope of the distribution functions. The algorithm would first find a local minimum in the electron count rate for energies <1 keV. It would then find an inflection point in the distribution within five channels of that point. Points meeting the criteria were selected by the algorithm as being the maximum barrier energies for those particular time intervals. This capability, as in the case of the automated potential algorithm, will be extremely useful in handling the large data sets associated with 1989-046, and subsequent satellites in the series.

Both algorithms were run on the data files for ten consecutive days (12 - 21 April 1990). Representative line plots of the potential and the barrier results can be seen in Figure 65 and Figure 66 respectively. When compared to the overplots of the interactive program on 14 April (Figure 63) one notices that the line plots contain ragged peaks uncharacteristic of the true results. This is a result of the algorithms' return of a zero value for potentials and barriers which failed the established criteria. Further analysis requires some sort of quality flag. The line plots for the remaining days can be found in Appendix E.

In order to better evaluate the reliability of the selected points, various 'confidence' flags were assigned. The confidence flags assigned to the
potentials determined by automation were twofold. First, a point which met the ratio and critical count rate tests was subjected to a test which determined whether the point was indeed a charging peak. This was done by verifying the existence of a negative slope within the next two higher energy channels. Successful passing of this test assigned the point a "high" probability flag indicated by the open boxes. Failure of the test assigned the point a "suspect" probability flag indicated by the crosses.

More levels of confidence were assigned to barrier heights chosen by automation due to the more subtle criteria necessary for the algorithm to properly identify a point. The highest level of confidence was assigned a point which not only met the initial requirements of the original test, but also corresponded to high flux levels (>10^2.5 counts/accumulation) in the lowest four energy channels. These are represented by a solid square. The next lowest confidence flag, an open square, was given to a point which did not have the highest flux levels in its lowest channels, but did correspond to hot electron fluxes normally seen with differential charging. The lowest level of confidence was assigned a cross. This meant that the point merely met the basic criteria of the selection algorithm.

The potential and barrier analysis results for 14 April, with quality flags, are shown in Figures 67 and 68 respectively. One now can see that a majority of the suspect points are contained in the <10 V potential range. Qualitatively, charging points which are clear in the spectrogram (Figure 41) have high confidence levels in the algorithm. The results for the remaining days can be found in Appendix F.
The first test of the accuracy of the algorithms was made by plotting the results of the interactive analysis against the automated results. Success of the algorithms can be seen by the number of points which correspond to a diagonal straight line. (Note, each data point plotted typically corresponds to more than one measurement pair). The results from 14 April clearly show such a trend both for the potential (Figure 69) and the barrier (Figure 70). Again, note that the majority of points which were in disagreement, e.g., those which deviated from the diagonal line were in the <10 V region. The remaining comparisons can be found in Appendix G.

Statistical success of the algorithms was measured by the percentage of times it determined the potential to within zero, one, two, or four channels of the actual value (as determined in the interactive program) for each time interval. Additionally, the algorithms’ effectiveness as to whether it indicated a ‘false positive’ potential was measured. A false potential was defined as one which the automated algorithms chose which were more than five energy channels higher than the actual value. This criteria is primarily designed to identify the cases where there was no barrier (or potential), but the algorithm indicated a non-zero value, and cases where there was a barrier (or potential), but a seriously wrong value was obtained. The statistical results are shown in Table 3 and Table 4.

1. Potential Algorithm

The success or failure of the algorithm appears to depend on the amount of ion flux it had to ‘pick out’ from the background. The overall success rate of 61.64% for correct identification of potential to within zero channel difference is indicative of this factor. The associated ion fluxes commonly seen during periods of higher levels of charging (>50 V) were considerably greater than
those typically seen with lower potentials; particularly in the absence of >10 keV electron fluxes. For this reason low potentials proved more difficult to determine automatically. A majority of suspect data points were in the energy range of <10 V. This is primarily due to the difficulty in selecting the correct ambient frame potential to within zero or one channel accuracy.

When one considers only the points which meet the "good" selection criteria, the success rate increases to 82.38% overall. It should be noted that the algorithm was highly successful in that it rarely indicated false potentials (0.87% of all points). Additionally, nearly all automatically selected data points were within four channels of their actual values (99.17% overall).

2. Barrier

The algorithm for differential charging height performed best when the flux of trapped photoelectrons was the strongest, e.g., during higher levels of charging in sunlight; particularly near local midnight. Lesser levels of charging were associated with distribution functions which failed to properly 'trigger' the algorithm. Periods where the satellite was gradually discharging and returning to near zero frame potential were typical of these failures to identify barriers. The overall success rate of 78.48% is testimony to these problems. An additional problem was the frequent selection of a higher energy channel associated with a 'dropout' in electron count rates. This was later corrected by introducing a maximum barrier height criteria of ~1000 V. There is a curious difference between the success rates of the 'good' versus the 'suspect' points. One would expect the success rates of 58.65% and 70.42% to be reversed. This is primarily due to the fact that many of the 'suspect' points corresponded to a zero volt value for the barrier height. These selections were indeed correct even
though they did not meet the criteria which would have warranted a higher confidence flag.

As in the case of the potential algorithm, the number of false barrier readings was minimal (2.12%). Increasing the success criteria from zero to four energy channels usually resulted in nearly 100% correct identification rates, and the 'excellent' flagged points attained a 88.44% level of success to within a zero channel difference.
IV. DISCUSSION

Surveys of available spectrograms revealed that satellite 1989-046 charged to high negative potentials in sunlight and eclipse. Negative potentials in sunlight reached levels approached -2 kV (recorded on several days during both equinox seasons). Potentials were recorded as high as -8 kV (recorded on 10 April 1990) during eclipse. Polar plots of local time distributions of charging events show the satellite exhibits midnight-to-dawn charging characteristics seen previously in other satellite surveys conducted by Punvis and Olsen (1983), and Reasoner et al (1976). A comparison of charging event percentages show that the spin-stabilized 1989-046 demonstrated charging behavior comparative to that of the 3-axis-stabilized ATS-6. This is somewhat surprising since 1989-046's spin period (\( \tau \sim 10 \) s) is similar to that of SCATHA's (\( \tau \sim 60 \) s). Due to this correlation, one might expect similar charging characteristics, however, SCATHA's spin vector attitude was perpendicular to the sun-satellite line. This differs from the 1989-046 spin axis, which remains perpendicular to the earth's surface. As a result, 1989-046's surface is more conducive to 'shadowing' effects, due to the changing satellite/sun orientation over a 24 hour period. On the other hand, ATS-5's rapid spin period (\( \tau < 1 \) s) prevented the satellite from charging to the levels experienced by the other satellites.

An additional survey showed a correspondence between the duration of charging (>50 V negative) and the level of magnetic activity due to magnetic substorm activity (responsible for the injection of hot electrons into the magnetosphere). This, in turn, substantiates the observation that high fluxes of
>10 keV electrons were a necessary pre-condition for charging activity; as reported by Olsen (1983). Detailed examination of electron distribution functions during sunlight charging events reveal potential barriers, indicating that differential charging is responsible for 1989-046's negative potentials. Additionally, the barrier height appears to be spin modulated.

The interactive computer program worked well in that it incorporated both visual and computational analysis to select potential and barrier height. The output data files obtained utilizing this technique were accurate because the analyst had several criteria upon which to base a decision. However, the interactive process is time intensive, and therefore is not suitable for analysis of lengthy time periods. In contrast, the automated algorithms were rapid, but were highly accurate only during ideal charging conditions. The 61% and 76% overall accuracy results for the potential and barrier determination is indicative of this dependence on clear charging signature. High counts due to penetrating radiation caused a background which frequently prevented the algorithm from identifying charging at lower levels. Data 'artifacts' such as telemetry upsets were sometimes identified as charging peaks; highlighting the fact that a sharp peak in the ion count rate in itself does not necessarily correlate to a potential. Similarly, the barrier algorithm had difficulty identifying barriers which contained lower fluxes of trapped photoelectrons. It should be noted, however, that the algorithms rarely indicated 'false' potentials or barriers, and a majority of the points in disagreement with the interactive results were in the <10eV energy. Therefore, they will not introduce an error greater than a simple assumption that the potential is zero volts. The algorithms will be effective as charging survey tools for large data sets due to their consistent performance in correct
identification during 'significant' (>−50 V negative) charging events. Detailed analysis of geophysical phenomena will require more careful analysis, in general, but for geophysical survey purposes, these algorithms would still be useful.
V. CONCLUSIONS

The data in this work provide several areas of continued research. The computer generated spectrograms revealed several interesting geophysical phenomena which warrant further investigation. The follow-on launches of four additional satellites in similar orbits pose the possibility of analyzing data from five MPA's at various time intervals and locations. The obvious drawback is the sheer volume of data already available for processing. For this reason an automated algorithm which could handle large data files would be preferable to interactive or manual surveys. However, further efforts are required to improve the current algorithms' accuracy for all situations. The utilization of other physical criteria which link charging and barrier formation, or use of artificial intelligence to substitute for the analyst's 'judgement calls' would improve the results. Finally, a comparison between upset/anomaly logs on 1989-046 and the charging behavior observed in the interactive and manual surveys could demonstrate the impact of high negative potentials on operational performance.
# APPENDIX A

**TABLE 1. Densities of Low-Energy Plasma Inferred from ATS 5 Charging During Eclipse**

<table>
<thead>
<tr>
<th>Day</th>
<th>Counting Rate</th>
<th>Potential Density/E&lt;sub&gt;0&lt;/sub&gt;</th>
<th>&lt;nolabel&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept. 15, 1969</td>
<td>2500</td>
<td>3500</td>
<td>0.015</td>
</tr>
<tr>
<td>Sept. 19</td>
<td>1800</td>
<td>1800</td>
<td>0.022</td>
</tr>
<tr>
<td>Sept. 20</td>
<td>1600</td>
<td>1500</td>
<td>0.008</td>
</tr>
<tr>
<td>Oct. 1</td>
<td>1500</td>
<td>5000</td>
<td>0.007</td>
</tr>
<tr>
<td>March 9, 1970</td>
<td>2000</td>
<td>4300</td>
<td>0.010</td>
</tr>
<tr>
<td>March 11</td>
<td>900</td>
<td>3000</td>
<td>0.007</td>
</tr>
<tr>
<td>April 6</td>
<td>2200</td>
<td>7000</td>
<td>0.007</td>
</tr>
<tr>
<td>April 7</td>
<td>700</td>
<td>5000</td>
<td>0.016</td>
</tr>
<tr>
<td>Sept. 8</td>
<td>400</td>
<td>1500</td>
<td>0.009</td>
</tr>
<tr>
<td>Sept. 12</td>
<td>3000</td>
<td>9000</td>
<td>0.005</td>
</tr>
<tr>
<td>Sept. 16</td>
<td>400</td>
<td>3000</td>
<td>0.003</td>
</tr>
<tr>
<td>Oct. 12</td>
<td>2200</td>
<td>7000</td>
<td>0.007</td>
</tr>
</tbody>
</table>

**TABLE 2. Occurrences of Charging of ATS 5 to Greater Than 50 Volts in Sunlight**

<table>
<thead>
<tr>
<th>Day</th>
<th>Time, UT</th>
<th>Maximum Potential, Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept. 30, 1969</td>
<td>1000-1215</td>
<td>−150</td>
</tr>
<tr>
<td>Oct. 9</td>
<td>0640-0720</td>
<td>−200</td>
</tr>
<tr>
<td>Jan. 2, 1970</td>
<td>0710-0750</td>
<td>−200</td>
</tr>
<tr>
<td>Feb. 2</td>
<td>1130-1230</td>
<td>−300</td>
</tr>
<tr>
<td>Feb. 26</td>
<td>1130-1410</td>
<td>−50</td>
</tr>
<tr>
<td>March 4</td>
<td>1340-1220</td>
<td>−70</td>
</tr>
<tr>
<td>March 30</td>
<td>1100-1300</td>
<td>−200</td>
</tr>
<tr>
<td>April 19</td>
<td>0810-0900</td>
<td>−200</td>
</tr>
<tr>
<td>Sept. 13</td>
<td>1100-1300</td>
<td>−180</td>
</tr>
<tr>
<td>Oct. 22</td>
<td>0830-1400</td>
<td>−60</td>
</tr>
<tr>
<td>Nov. 6</td>
<td>0940-1200</td>
<td>−200</td>
</tr>
<tr>
<td>Nov. 9</td>
<td>1100-1130</td>
<td>−60</td>
</tr>
<tr>
<td>Nov. 10</td>
<td>0900-1000</td>
<td>−60</td>
</tr>
</tbody>
</table>

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### Table 3
**Automated Count Rate Algorithm Results (%)**

<table>
<thead>
<tr>
<th>Quality Flag</th>
<th>False Positives</th>
<th>Channel Difference = 0</th>
<th>Channel Difference = 1</th>
<th>Channel Difference = 2</th>
<th>Channel Difference = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>0.87</td>
<td>61.64</td>
<td>69.42</td>
<td>83.80</td>
<td>99.17</td>
</tr>
<tr>
<td>Good</td>
<td>0.78</td>
<td>82.36</td>
<td>88.40</td>
<td>90.99</td>
<td>99.07</td>
</tr>
<tr>
<td>Suspect</td>
<td>1.01</td>
<td>56.66</td>
<td>64.79</td>
<td>81.55</td>
<td>99.24</td>
</tr>
</tbody>
</table>

### Table 4
**Automated Barrier Algorithm Results (%)**

<table>
<thead>
<tr>
<th>Quality Flag</th>
<th>False Positives</th>
<th>Channel Difference = 0</th>
<th>Channel Difference = 1</th>
<th>Channel Difference = 2</th>
<th>Channel Difference = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>2.12</td>
<td>78.48</td>
<td>78.83</td>
<td>81.62</td>
<td>98.25</td>
</tr>
<tr>
<td>Excellent</td>
<td>3.51</td>
<td>88.44</td>
<td>88.44</td>
<td>90.99</td>
<td>96.90</td>
</tr>
<tr>
<td>Good</td>
<td>0.17</td>
<td>58.65</td>
<td>58.65</td>
<td>61.35</td>
<td>99.83</td>
</tr>
<tr>
<td>Suspect</td>
<td>1.86</td>
<td>70.42</td>
<td>72.88</td>
<td>79.63</td>
<td>99.87</td>
</tr>
</tbody>
</table>

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APPENDIX 8

Fig. 7 Local time distribution of ATS-6 spacecraft charging events.

Fig. 1 Distribution in local time of anomalies observed on various geosynchronous satellites.

Figure 1. Correlation Between Charging Events and Anomalies [Reasoner et al., 1976]
Figure 7. Across any imaginary surface within the plasma, there are an equal number of positive and negative charges flowing in opposite directions across the surface and the net current is zero.

Figure 2. Net Current [Wong, 1991]
Fig. 2. Qualitative illustration of the charging of a surface by a plasma. The width of the arrows is proportional to the flux of each particle species; the equilibrium potential is reached when the sum of the currents collected and emitted by a surface element is zero. (a) Surface in shadow: the current balance requires equality between the flow of the plasma ions and that of the plasma electrons impinging on the surface. (b) Surface in sunlight: equilibrium is achieved when the flow of escaping photoelectrons is equal to the difference between the incoming flows of plasma electrons and ions.

Figure 3. Photoemission [Grard et al, 1983]
Figure 1. In surface charging, currents from the movement of ambient electrons, ions, secondary electrons, and photoelectrons result in a net current on the external surface of the satellite body. (after Robinson, 1989)

Figure 4. Secondary and Backscattered Emission
Figure 5. "Teflon Cube" [from Mandell, 1978]
Figure 2. Internal discharge results from charges deposited directly on or in well insulated regions inside the Faraday cage of the spacecraft. (after Robinson, 1989)

Figure 6. Deep Dielectric Charging
Figure 5.1 Cross section of the magnetosphere. For a quiet magnetosphere, geostationary altitudes are between the plasmasphere and plasma sheet (nighttime), and between the plasmasphere and dayside boundary layer (daytime). During active geomagnetic periods, geostationary satellites may become engulfed by the inward moving nighttime plasma sheet, and may pass through the daytime boundary (entry) layer (after National Research Council, 1985).
Figure 8. An Injection Event [DeForest and McIlwain, 1971]
Figure 37. Measured and Calculated Equilibrium Potentials for Explorer VIII on Magnetically Quiet Days

Figure 9. Explorer VIII Potentials (Quiet Days) [Whipple, 1965]
Figure 10. OGO-1 Potential in Eclipse [Whipple, 1978]
Figure 11. OGO-1 Potential in Sunlight [Whipple, 1978]
Figure 12. Negative Ground Circuit on Solar Arrays and Current Flows for OGO-1
Fig. 9. Ogo 3 satellite potential from ion trap data for inbound pass on July 19, 1966; the aperture potential was $-5.4 \text{ V}$. Time of satellite eclipse is shown near the bottom of the figure.

Figure 13. OGO-3 Potential on Inbound Pass [Whipple et al, 1974]
Fig. 7. Ogo 3 satellite potential from ion trap data for outbound pass on July 19, 1966. The circles and crosses are for aperture potential of $2500$ and $-5.4$ V, respectively.

Figure 14. OGO-3 Potential on Outbound Pass [Whipple et al, 1974]
Figure 15. ATS-5 [from Olsen, 1985]
Figure 3. Particle data immediately after start of eclipse.

Figure 16. Proton Peak Indicating Spacecraft Potential [DeForest, 1972]
Figure 17. ATS-6 [from Reasoner et al., 1976]
Fig. 5. Electron velocity distribution function for September 30, 1974. The plasma electron temperature of 320 eV was obtained by considering other data points out to 500 eV in addition to those shown in the figure. There is also a higher-energy component with a mean kinetic energy of about 8 keV.

Figure 18. Best Fit to Electron Distribution Functions on ATS-6 [Whipple, 1976]
Fig. 7 Local time distribution of ATS-6 spacecraft charging events.

Fig. 8 Local time distribution of ATS-6 encounters with low-energy plasmaspheric plasma. For these events, ion densities ranged between 1 and 10 ions/cm$^3$.

Figure 19. ATS-6 Charging Versus Warm Plasma Encounters [Reasoner et al, 1976]

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Figure 20. SCATHA Satellite [from Olsen et al, 1986]
Fig. 8. Distribution of levels of frame potential ($-\Phi_f$) of $>10$ V, $>50$ V, and $>100$ V in local time.

Figure 21. SCATHA Potentials [Mullen et al, 1986]
Figure 4. ISEE spacecraft potentials on March 17, 1978, inferred from the plasma composition experiment.

Figure 22. ISEE Potentials [Whipple et al, 1983]
Fig. 28  Typical surface potentials during electron irradiation (spacecraft rotating 0.5 rpm)

Figure 23. METEOSAT P1 Potentials in SIMLES Test [Robbins, 1979]
Fig. 5 The electron spectrum just before and after the spacecraft emerged from the eclipse of figure 4. The ordinate is proportional to phase space density so the difference in energy between points with the same density is an estimate of the potential of the spacecraft. As marked on the diagram it ranges from 4.5 kV to 5.1 kV.

Figure 24. METEOSAT F2 Potentials [Johnstone et al. 1986]
Figure 7. Thermal plasma density determined by Plasma Analyzer (upper trace) and Mutual Inductance Measurement (lower trace). The middle trace gives the GEO spacecraft potential measured by the biased probe technique. The lower trace shows the high-energy electron fluxes at times when this population appears to control the spacecraft potential.

Figure 25. GEOS-2 Potentials [Knott et al, 1983]
Fig. 3. Distribution functions for electrons (left) and ions (right) for $A_x = -314$ V on November 26, 1983. The ions are corrected for electron contamination.

Figure 26. DMSP F2 Charging Event [Gussenhoven et al, 1985]
Fig. 1. Comparison of electron spectra in the magnetospheres of Earth and Jupiter.
Top: Pioneer 10 electron spectrum in the outer Jovian magnetosphere, 17 Nov., 1973, 21.50 UT
(IIterus, 1975).
Bottom: ATS-6 electron spectrum at 6.6 earth radii on 17 July, 1974, 03:36 UT. The electron energy flux is proportional to the instrument counting rate. The photoelectron density here is only about 10 cm\(^{-3}\) probably because of oblique solar illumination of the emitting surface.

Figure 28. Comparison Between ATS-6 and Pioneer 10 Spectra [Grard et al., 1977]
Fig. 1. Empirical relation between the plasma return current striking the spacecraft (normalized to 1 AU) and the spacecraft potential. (Errors of mean are in all cases smaller than characters plotted.) This relation was derived from an extensive analysis of Voyager 2 PLS electron measurements taken during the cruise phase of the mission between 1.36 AU and 4.70 AU. Data points above one volt are well represented by a power law with negative slope. Best fit line computed using method discussed in Stilater and Scudder (1980). Saturation current shown dashed was estimated using charge neutrality condition and the PLS positive ion charge density at 64/06/39 within Io’s torus when the spacecraft went negative.

Figure 29. Voyager Potential Derived From Return Currents [Scudder et al, 1981]
Fig. 6. Spacecraft potential versus distance from Jupiter at nine locations in the Jovian magnetosphere.

Figure 30. Voyager 1 Potentials at Jupiter [Barnett and McNutt, 1983]
Fig. 5. Plasma parameters on day 190 between 0400 and 1300 SCET. The top three panels show estimates (solid lines) and fit (heavy data) for the three components of the bulk velocity vector ($V_x$, $V_y$, $V_z$) of the magnetospheric plasma. The $x$ axis of the cylindrical coordinate system is aligned with Jupiter's spin axis. The dotted line indicates the values expected for plasma flow rigidly convecting with the planet. The boxes indicate the positions of the plasma depressions as determined from the density estimates for positive time (lower panel) and for low energy electrons (not shown).
Figure 32. Plasma Dropouts in the Jovian System [Khurana et al, 1987]
Fig. 8. Voyager 2 differential flux spectra when the spacecraft was not charged (SCET 0534:47) and after it charged (SCET 0541:11). Calculated spectra are for assumed spacecraft potentials of −200 and −40.0 kV.

Figure 33. Increased ion Current in Conjunction with Charging on Voyager 2 at Jupiter [Khurana et al, 1987]
Figure 34. Voyager 2 Charging Event at Uranus [from Selesnick and McNutt, 1987]
Fig. 7. Density and temperature of the suprathermal (hot) electron component within the inner magnetosphere of Uranus. At the top of the upper panel we indicate radial distance \( r \), dipole \( L \) and magnetic latitude \( \lambda_m \) of Voyager 2 spacecraft.
Figure 36. Electron Fluxes Responsible for Voyager 2 Charging Event [from Mauk et al., 1987]
Fig. 8. The electric potential of Voyager 2 in the magnetosphere of Neptune.

Figure 37. Voyager 2 Potentials at Neptune [Zhang et al., 1981]
Figure 38. Local Time Distribution of ATS-5 Charging Events [Purvis and Olsen, 1983]
LOCAL TIME DISTRIBUTION OF ATS-6 CHARGING EVENTS

$\delta_S/C < -60V$

14:00
16:00
18:00
20:00
22:00
00:00
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
00:00
02:00
04:00
06:00
08:00
10:00
12:00

DAYS 187 TO 206 OF 1974

Figure 39. Local Time Distributions of ATS-6 Charging Events [Purvis and Olsen, 1983]
Figure 40. Local Time Distributions of SCATHA Charging Events [Purvis and Olsen, 1983]
Figure 43. Ion Distribution Function Line Plots (1232 UT 14 April)
Figure 45. Electron Distribution Function Line Plots (1232 UT 14 April)
Figure 46. All Detectors (270° Roll Angle 1232 UT 14 April)
Figure 48. Electron Distribution Function Line Plots (2201 UT 14 April)
Figure 49. All Detectors (270° Roll Angle 2201 UT 14 April)
LOCAL TIME DISTRIBUTION OF 1989-046 CHARGING EVENTS

Figure 50. 216 Days: Fall Winter Spring Summer 1989-1990
Figure 51. Equinox Seasons: 29 Sept-14 Nov 1989 and 4 Mar-30 Apr 1990
Figure 52. Non-Equinox Seasons: 15 Nov 1989-16 Jan 1990 and 1 Jul-31 Aug 1990
Figure 20. Monthly distribution of all anomalies in the SAM database.
Figure 54. Equinox Season: 29 Sept-14 Nov 1989
LOCAL TIME DISTRIBUTION OF 1989-046 CHARGING EVENTS

Figure 55. Non-Equinoc Season: 1 Jul-31 Aug 1990

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LOCAL TIME DISTRIBUTION OF
1989-046 CHARGING EVENTS

Figure 57. Equinox Season: 4 Mar-30 Apr 1990
Figure 58. Non-Equinox Season: 15 Nov 1989-16 Jan 1990
Figure 59. Barrier Height During Equinox Daylight Charging Events
Figure 60a. 14 April 12 11.12 (UT)

Figure 60b. 14 April 13.15 (UT)

Figure 60. Sample Ion Energy Sweeps
Figure 60c. 14 April 18.12 (UT)

Figure 60d. 14 April 1.32 (UT)

Figure 60. Sample Ion Energy Sweeps (continued)
Figure 61a. 14 April 12:47 (UT) Distribution Function

Figure 61b. 14 April 12:47 (UT) Count Rate

Figure 61. Sample Electron Energy Sweeps

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Figure 62. Fit to Electron Distribution Functions (1032 UT 14 April)
Figure 2. Flowchart of the Count Ratio Algorithm. The algorithm is based on comparisons of ion count rates in adjacent energy channels [CR11 and CR11 + 1].

Figure 64. Potential Algorithm Flowchart [Speigel et al, 1985]
Figure 65. 14 April Automated Potential Line Plot (all values)
Figure 66. 14 April Automated Barrier Line Plot (all values)
Figure 67. 14 April Automated Potential Results (with quality flags)
Figure 68. 14 April Automated Barrier Results (with quality flags)
APPENDIX C

The following description of the MPA was taken from an instrument characteristics draft from the Los Alamos National Laboratory:

The Magnetospheric Plasma Analyzer (MPA), designed and built by Los Alamos National Laboratory in collaboration with Sandia National Laboratory (D. J. McComas, Principal Investigator), is a spherical sector electrostatic analyzer designed to make 3-dimensional measurements of magnetospheric ions and electrons on a spinning spacecraft. Incident particles that enter the entrance aperture and have the right energy per charge to pass through the analyzer are detected in one of 6 channel electron multipliers (CEMs), depending on the polar angle of their velocity at incidence. The azimuthal angle of their velocity at incidence is determined by the spin phase of the spacecraft. The particle energy is determined by the voltage applied to the analyzer plates, which is swept exponentially in time to scan velocity space or held constant to obtain higher angular resolution, depending on the mode of operation. The ion and electron measurements are made alternately with the same set of analyzer plates by switching the voltage applied to the plates and at the same time changing the voltage configuration of the CEMs. The basic characteristics of the instrument response are as follows:

Energy per Charge Range:
- 1.0 eV/e - 40.4 keV/e (electrons)
- 1.1 eV/e - 43.6 keV/e (ions)

Energy Bins (sweep cycles): 40
Exponential Energy Sweep Time Constant: 34 msec
Accumulation Time per Bin (sweep cycles): 9 msec
Intrinsic Energy Resolution: $\Delta E / E \approx 0.40$

Centers of Polar Angle Response (rel. to spin axis): 32.5, 55.5, 78.5, 101.5, 124.5, 147.5°

Polar Angle Response of Each Detector (FWHM): 15 degrees
Intrinsic Azimuthal Angle Response (FWHM): 21, 12, 8, 8, 12, 21 degrees
Analyzer Bending Angle: 60 degrees
Center Radius: 5.30 cm
Analyzer Constant (Center Radius / Plate Separation): 27.5
Angular Length of Aperture: 13.7 degrees

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Geometric Factor for Hot Plasmas ($C = E_\text{je}G$):

\[
\begin{align*}
3.26 \times 10^{-4} \text{ cm}^2 \text{ sr} & \text{ (32.5 and 147.5° dets)} \\
4.90 \times 10^{-4} \text{ cm}^2 \text{ sr} & \text{ (55.5 and 124.5° dets)} \\
5.74 \times 10^{-4} \text{ cm}^2 \text{ sr} & \text{ (78.5 and 101.5° dets)}
\end{align*}
\]

For Spacecraft 1989-046, in geosynchronous orbit with the spin axis pointing continuously at the Earth, the nominal spin period is 10.1 seconds, so that the instrument sweeps through 0.3 degrees of azimuth during one 9-ms accumulation and repeats an energy sweep every 15.1 degrees of azimuth. Thus, a full spin of three-dimensional data consists of 40 energies x 6 polar angles x 24 azimuthal angles.

In the normal mode of operation, the instrument performs an 8-cycle sequence of measurements every 86 seconds. The eight cycles in the sequence are: P3 P6 E3 E2 E9 P3 E2 E2. Where "P" and "E" stand for ion and electron, respectively; "3" indicates 3-dimensional data as described above; "2" indicates 2-dimensional data, in which counts from the 6 polar angle detectors are summed together so that one spectrum consists of 40 energies x 24 azimuthal angles; and "9" indicates a cycle in which the plate voltage is held constant for 10.692 seconds (a little more than one full spin) while counts are accumulated in 99-msec bins so that one cycle of data consists of 1 energy x 6 polar angles x 108 azimuthal angles. In a 9 cycle, each bin represents a sweep through 3.5 degrees of azimuth, so that higher angular resolution is obtained. The energy level for the accumulation is the level at which the count rate was a maximum in the preceding 3-D cycle. If the peak occurred at energies below ~100 eV, the level is set at ~100 eV.
APPENDIX D

APR 12—ELECTRON RESULTS

Energy (eV)

APR 12—ION RESULTS

Energy (eV)

Time (Hrs)
Electron Barrier (eV)
(8) Spacecraft Potential (V)
Spacecraft Potential (V)
Electron Barrier (eV)
LIST OF REFERENCES


187
1. Defense Technical Information Center  
   Cameron Station  
   Alexandria, Virginia 22304-6145
2. Superintendent  
   Attn: Library, Code 52  
   Naval Postgraduate School  
   Monterey, California 93943-5000
3. Department Chairman, Code PH  
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