Spacecraft Charging at High Altitudes: SCATHA Satellite Program

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Satellites at synchronous altitude exhibit unexplained behavior in the operation of electronic circuits and in the performance of thermal controls. A possible explanation for this behavior is the fact that satellites can be charged to large negative voltages by energetic electrons in the space environment. A space measurements program entitled SCATHA has been formulated to determine the characteristics of the charging process, to measure the response of the satellite when charging occurs, and to evaluate the utility of various corrective techniques, which can minimize differential charging on the satellite. The instrumentation will measure charging levels and rates of several samples of satellite materials, some of which will be modified to prevent buildup of electrostatic charge. Simultaneous measurements of electron and ion properties will be performed over an energy range of 1 to 10^7 ev to correlate with the electrical charging data.

Introduction

SATELLITES in synchronous orbit are observed to exhibit unexplained operation of electronic circuits and degradation of thermal control properties. A possible cause for some of this behavior may be the fact that satellites can be electrically charged by electrons in the space environment. The absolute potential between the satellite and the surrounding space plasma can exceed thousands of volts. The potential distribution about the satellite is a function of photoelectric emission from satellite surfaces by solar radiation, of plasma flux to the satellite, and of the satellite geometry. The plasma flux is dependent upon the number density and energy distribution of plasma particles, particularly the electrons, because of the high electron mobility relative to the ions.

A satellite measurements program entitled Spacecraft Charging at High Altitudes (SCATHA) has been formulated to measure the characteristics of the charging process, to determine the response of the satellite to charging, and to evaluate techniques which may correct the problem. It is planned to launch the SCATHA satellite in April 1978.

Background

Table 1 provides a summary of certain unexplained events observed on various DOD and commercial satellites. A thorough study of all synchronous satellites for unexplained behavior has not been made. However for each satellite investigated, with the exception of ATS-6, some sort of unexplained behavior was found.

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The first two vehicles launched in the Defense Satellite Communication System II (DSCS II) program exhibited three different actions for which the cause is unknown. The reset generator assembly has a function of resetting satellite logic to some initial state. This circuit was observed to be activated without signals from the assembly sensor. The observed resets occurred when the satellite was between midnight and dawn in satellite local time and appeared to be coincident with geomagnetic substorms.[1] On one satellite, a power supply failed and the contractor has tentatively attributed the failure to an arc between the power line and the satellite frame when the satellite was charged to a large negative voltage by the space environment.[2] The third unexplained activity involved the gain control logic, which controls the gain of the mission radio frequency communications system. This logic was observed to change state without any ground command.

After the launch of the first two DSCS II satellites, a corrective measures program was undertaken to prevent reoccurrence of the behavior exhibited by the first two vehicles. The actions taken to correct the reset assembly triggering and the power supply arcing were successful. However on satellites 3 and 4, spurious switching of the gain control and

Table 1 Synchronous satellites exhibit unexplained performance

Satellite	Action
Defense Satellite Communication System II: satellites 1, 2, 3, 4	Reset generator assembly trigger (satellites 1 and 2 only) Gain control logic switching
Defense Support Program	Thermal control degradation Sensor data noise Control circuits switching
Intelsat III; five satellites	Mechanical despun assembly switching
Intelsat IV: flights 3, 4, 5, 7	Erroneous operation of attitude control system
Telesat: flights 1, 2	Telemetry logic switching

other logic circuits remained a problem. Sufficient data are available to show that the logic changes occur predominantly between midnight and dawn, satellite local time.

The next system listed in Table 1 is the Defense Support Program (DSP). Three types of unexplained behavior are exhibited by DSP vehicles. Occasionally characteristic noise pulses are detected in data from an optical sensor. These noise pulses occur predominantly between midnight and dawn, satellite local time. Also, the occurrence of the noise is more probable during geomagnetically active times than during geomagnetically quiet times.

A small but systematic change in operating temperature has been observed on the DSP satellites. Although the rate of temperature change is quite small, sufficient data are available to show that there is a weak dependence of the rate of temperature change with geomagnetic activity. The confidence level that this dependence exists is greater than 99%.

As is the case with the DSCS II satellites, logic circuits on the DSP satellites will occasionally change state without ground command. These spurious changes tend to occur between midnight and dawn, satellite local time.

On Intelsat III, switching of circuits related to the mechanical despun assembly were observed. Most of these switching events occurred between midnight and dawn, satellite local time.

On flights 3, 4, 5, and 7 of the Intelsat IV satellites, erroneous operation of the antenna pointing system caused errors in the antenna pointing direction. These events occurred predominantly between midnight and dawn, satellite local time.

On flights 1 and 2 of Telesat, spurious switching of logic which selects telemetry modes occurred. It is not known whether these events were correlated with satellite local time or geomagnetic activity.

There are many examples which demonstrate the dependence of satellite unexplained behavior on geophysical parameters such as local time and geomagnetic activity. Figure 1 shows the dependence on local time of logic circuit upsets observed in several satellites. Figure 1 is a view of the equatorial plane divided into local time segments. Noon is at the top of Fig. 1 and midnight is at the bottom. A synchronous altitude satellite will, of course, travel through all local times once each day. The data points show the local time at which spurious changes in logic circuits occurred for several different satellites. The radial position of each point is irrelevant. The exact times of the DSCS II RGA upsets are not known. The times during which they could have occurred are indicated by the connected squares.

It is clear from Fig. 1 that the events occur predominantly between midnight and dawn, satellite local time. Excluding the DSCS II RGA upsets, the probability of observing 31 of the other 47 events in the midnight to dawn quadrant is 3.3×10^{-9}, if there were no correlation with local time.

In summary, five different satellite systems involving nearly 20 flights have been investigated. All vehicles have exhibited some type of behavior which cannot be explained. With exception of Telesat, for which there are insufficient data, the unexplained events are dependent upon either satellite local time or upon geomagnetic activity and, in some cases, are dependent upon both of these geophysical parameters.

Spacecraft Charging

DeForest has determined that the surface of the ATS-5 satellite could be negatively charged to hundreds of volts when the satellite was in sunlight and thousands of volts when the satellite was eclipsed.[3] Figure 2 illustrates the charging phenomenon. There are three processes contributing fluxes of charged particles to a satellite. Photoelectrons are emitted from surfaces illuminated by the sun. The current density emitted is around 5×10^{-5} amp/m^2, and depends upon the surface material. The second contribution is the flux of electrons and ions from the space plasma to the satellite. The magnitudes of these fluxes are dependent upon the charged particle density and energy distribution. The third contributor is secondary emission of electrons resulting from incident energetic electrons. As a result of these three processes contributing to the charged particle fluxes, a potential distribution exists about the satellite so that the net current to the satellite is zero. Because the various particle fluxes are anisotropic and because the potential distribution is dependent upon satellite geometry, the potential distribution about the satellite can be highly asymmetric.[4]

At altitudes beyond three earth radii, the ambient plasma density is generally less than 10^6m^{-3}.[5] In this case, as indicated in Fig. 2, the photoelectric current density is much greater than the flux of electrons from the plasma and the total satellite potential is dominated by photoelectric emission. For example, it has been determined that the Vela satellites, which are at 111,000-km altitude, can be charged positively by photoelectric emission. Potentials up to 100 v relative to the space plasma have been observed on the Vela satellites.[6]

At altitudes less than two earth radii, of 13,000 km, the plasma density is generally greater than 10^9 m^{-3} and the temperature is similar to the ionospheric source of this plasma; namely, less than 1 ev. In this case, the flux of plasma electrons to the satellite is much greater than the photoelectron flux and the satellite potential is slightly negative relative to the space plasma.

In summary, as one proceeds from low to high altitudes, the satellite potential will vary from negative to positive as the plasma electron flux becomes less than the photoelectric flux.

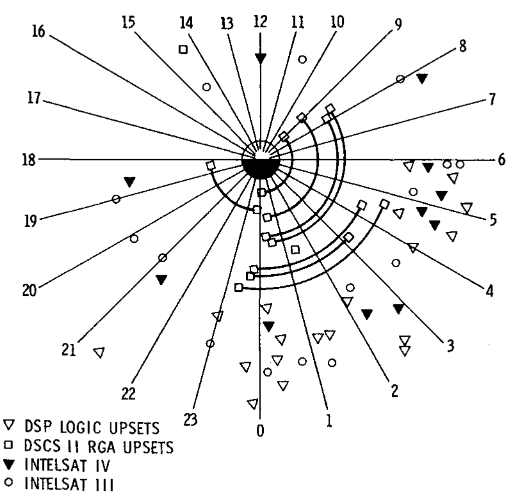
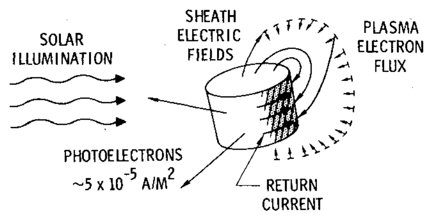


Fig. 1 Local time dependence of circuit upset for several DOD and commercial satellites.



ELECTRON DENSITY, m^{-3}	TEMPERATURE, eV	PLASMA ELECTRON FLUX A/m^2	SHEATH THICKNESS m
10^6	1	10^{-7}	7
3×10^5	1000	10^{-6}	400
10^7	1000	3×10^{-5}	70

Fig. 2 Model of satellite differential charging by photoelectric emission and plasma flux.

An analysis of data from electric field probes on the Explorer 45 satellite, which had a 222-km altitude perigee and 26,900-km altitude apogee, clearly shows the shift from a plasma dominated potential distribution to a photoelectric dominated potential distribution with increasing altitude.[4]

At synchronous altitude, the spacecraft potential will generally be dominated by photoelectric emission. It is believed that at times, the electron density and energy spectrum of the surrounding plasma are sufficient to charge the shadowed insulated parts of the satellite to hundreds and perhaps thousands of volts. If the surfaces of the satellite are insulated, which is usually the case, large differential voltages can be developed between the exposed shadowed surface and the satellite frame beneath the surface. The electric fields across dielectrics can be large enough to break down the material or to generate vacuum arcs at the edge of the material.[7] Of principal interest has been insulation material which consists of multiple layers of aluminized plastic films. Arcs from one aluminized layer to the next can constitute strong sources of electromagnetic interference (EMI).

Another mechanism for generating discharges is based on the fact that electrons in the energy range of 1 to 40 kev can penetrate materials to depths of roughly 1 μm for each 10 kev of energy. Therefore it may be possible for electrons to be trapped below the surface of insulators. The trapped electron charge will attract ions from the nearby plasma to the surface of the material. A separated charge layer will then be established at the surface with very small separation between the ions and electrons. When the dielectric strength of the materials is exceeded, breakdown will occur. The resulting surface discharge can generate EMI and can damage the surface of the material. It is believed that discharges of this type have been observed in laboratory experiments.[8]§ Very early investigations of surface discharge phenomena were conducted by Malter.[9]

The voltage to which a surface can be charged relative to the surrounding plasma is approximately 3.6 kT_e for a Maxwellian hydrogen ion plasma of temperature T_e.[10] Although the plasma at synchronous orbit is probably by no means Maxwellian, it is reasonable to expect that the sheath potential between the plasma and shadowed surfaces of the satellite is proportional to the characteristic energy of the electron energy spectrum. There is evidence that during times of geomagnetic activity, energetic electrons are injected into the region of synchronous altitude near the midnight meridian. The motion of the electrons in the magnetic field is such that they drift from the midnight meridian towards the dawn meridian. It is believed that the charging effects observed on satellites are caused by these electrons, which are accelerated as a result of geomagnetic activity, are injected near the midnight meridian, and then drift around the earth from midnight to dawn.

Figure 3 illustrates the geometry of this process. The geomagnetic field at high altitude is shown in the midnight meridian being swept back into a long tail as a result of interaction between the solar wind (not shown) and the geomagnetic field. During times of geomagnetic activity, it is known that the geomagnetic tail collapses into a more dipolar configuration. Electrons trapped on these field lines are accelerated during the compression process. Kaufmann, who has analyzed the accelerating process, has concluded that increases in electron energy by a factor of three would be reasonable.[11] Furthermore, the flux of electrons to the satellite will scale exponentially with the energy increase if the distribution is Maxwellian.

To summarize, there is evidence that satellites at synchronous orbit can be charged to large voltages. On the basis of this information, it has been assumed that the unexplained upset of electronic circuits on synchronous satellites is caused by electromagnetic interference from arcs induced when the satellites become charged. There has not been a direct observation of circuit upset coincident with satellite charging. However the dependence of circuit upsets upon geophysical parameters is consistent with the charging thesis.

§A. Meulenberg, Comsat Labs., private communication; F. G. Walther, Lincoln Lab., private communication.

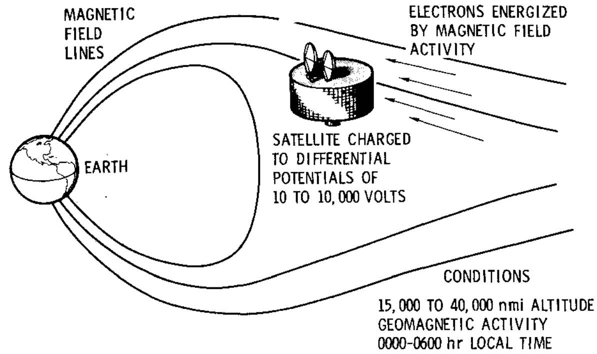


Fig. 3 Pictorial view of spacecraft charging in the high altitude magnetosphere.

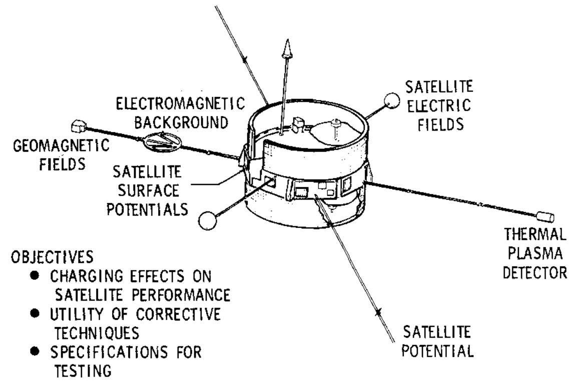


Fig. 4 Concept for instrument layout on SCATHA satellite.

To determine electrical charging of a satellite, special instrumentation is required, such as DeForest's electron spectrometer on ATS-5 or ATS-6. Normally, such instruments are carried only on special-purpose scientific satellites. With the exception of an electrostatic discharge detector flown on a DSP satellite, there have been no measurements of surface charging and arcing on satellites.[12-14] At the present time it cannot be demonstrated that spacecraft charging is the cause of the unexplained behavior observed in so many DOD and commercial satellites. However, the evidence is fairly conclusive that spacecraft charging can be the cause of the problem, but very little is known about the details of the process.

Spacecraft Charging Experiment

An integrated satellite experiment has been formulated: to measure the characteristics of the spacecraft charging phenomenon, to determine the response of the satellite to the charging process, and to evaluate corrective techniques. Figure 4 is a conceptual view of the satellite.[15] It is basically a right circular cylinder 1.5-m diam and 1 m high. The total weight is 227 kg, with a payload weight of 68 kg. The satellite will be placed in near geosynchronous orbit (35,800-km altitude). There will be no stationkeeping and the satellite will drift at a rate of less than 4°/day. This is desirable because data from vehicles 3 and 4 of the DSCS III program indicate that there may be a longitudinal dependence of the anomalous behavior. The satellite will spin about the cylinder axis at a rate of 1 rpm. The desired direction of the spin vector is in the equatorial plane of the earth and normal to the earth-sun line. This orientation maximizes utility of data from the particle detectors because it permits detection at all angles relative to the geomagnetic field. A brief description of each instrument is provided here.

Spacecraft Surface Potential Monitor

This instrument will measure the surface potential of several types of materials relative to some common reference point on the satellite. The reference point could be established by a conducting band about the satellite. Photoelectric emission will tend to keep the reference point at a small positive potential relative to the plasma.

Figure 5 shows the technique planned for measuring surface potentials of insulating materials. The sensor assembly consists of four disks of the sample materials bonded to a conducting substrate. One of the samples will be a metal foil mounted on an insulating disk. The sensor is a small electrode mounted on a rotating arm, which is successively stepped from one sample to the next. As shown by the schematic diagram in Fig. 5, the sample surface and the conducting substrate constitute a capacitance of approximately 200 pf. This capacitor is charged by the current source constituted by photoelectric emission, plasma flux, and secondary emission. It is expected that the potential across the capacitor will be in the range 10 to −10,000 v.

When the sensor is positioned over the sample surface, another capacitively coupled circuit is established between the sample surface and the reference. In this case, the potential is divided between the capacitance of the sensor to the sample and the capacitance of the sensor to ground. For the design being considered, the ratio of these two capacitances is 1000:1. Therefore it is expected that the voltage input to the preamplifier will be in the range 1 mv to −1 v. The purpose of a conductor on the fourth sample is to provide a means for shorting the whole circuit periodically to prevent build-up of leakage current on the capacitors.

Materials to be used in sensors for the spacecraft surface potential monitor include: 1) silica and carbon cloth fabric with and without interwoven conducting wires over multilayer insulation, 2) solar cell cover glasses with and without tin doped InO coatings,[16,17] 3) two black paints with different conductivity, 4) one standard white paint and one conducting white paint, 5) silver-TFE bonded to a conducting substrate, 6) gold (reference), 7) aluminum (two surface finishes), 8) quartz, 9) kapton multilayer insulation, 10) mylar multilayer insulation, and 11) other samples to be determined.

Fourteen of the samples will be placed on the sides of the satellite, to be rotated in and out of sunlight. Seven samples will be located at the end in shadow. The quartz sample (No. 8 above) will also be viewed by the rotating sensor on electron spectrometer. This will provide data on the variation of photoelectric emission of a surface as a function of charging and of aging in the space environment.

Charging Electric Effects Analyzer

This instrument will measure electromagnetic interference in the frequency range 100-10^7 Hz. Three separate instruments will be used. A swept frequency analyzer will monitor the frequency band 0.1 to 10 MHz. The frequency band 100-50 kHz will be monitored by a 10-channel, fixed-frequency analyzer. There will also be capability to telemeter broadband, undetected signals from sensors in the frequency band 100-5000 Hz.

The analyzer will sample signals from a variety of sensors: 1) solar array bus, 2) power line bus, 3) typical command line, 4) internal loop, 5) external loop, 6) external short dipole, and 7) electric field detector boom. These sensors will permit measurement of radiated and conducted EMI both external and internal to the satellite.

Quartz Crystal Microbalance

Two quartz crystal microbalances placed in retarding potential analyzers will be used on the satellite. One instrument will be on the side of the satellite and one will be placed on the end and maintained in continuous shadow. The basic instrument is similar to that used on OGO-6.[18] The instruments will have active temperature control so that the quartz sensors can be operated over a range of temperatures from −60 to 100°C. The minimum temperature of the sensor in the shadow will probably be less than −60°C.

The microbalances will be placed in retarding potential analyzer structures, as shown in Fig. 6. The objective of this configuration is to determine the dependence of contamination rate upon surface potential. Charged surfaces can affect contamination rates in two ways. If there is a gradient of electric field at the surface, contamination molecules which can be polarized will be attracted to the surface, reducing evaporation rate. Secondly, those neutral contamination molecules which are photoionized in the sheath will be attracted back to negatively charged surfaces on the satellite, thereby increasing the contamination rate.

On the basis of measurements of outgassing on OGO-6 it has been estimated that the return flux of contaminants to a synchronous altitude satellite may be 1.4×10^8 ions/cm^2-sec, which is about twice the sensitivity of the quartz crystal microbalance. The retarding potential analyzer will be used to exclude ions from the microbalance and to maintain a zero electric field condition at the sensor. Measurements of contamination rates with and without the retarding potential analyzer bias will determine the dependence of contamination rate upon surface charge.

Thermal Control Sample Monitor

This instrument measures the back-face temperature of eight thermal control material samples.[19] These instruments will be positioned contiguous with the quartz crystal monitors. Provision has been made to heat the samples and to purge contaminants which freeze out on the test surfaces. The objective of the experiment is to evaluate performance of thermal control materials as a function of on-orbit contamination conditions.

Electric Field Detector

The sensor for this instrument is a 100-m tip-to-tip dipole antenna. The antenna elements are copper-beryllium STEM

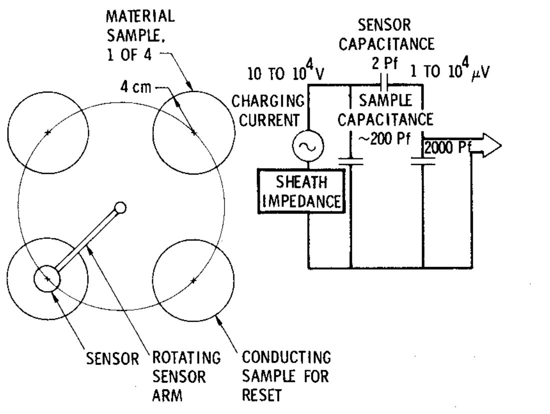


Fig. 5 Technique for measuring surface potentials on insulating surfaces.

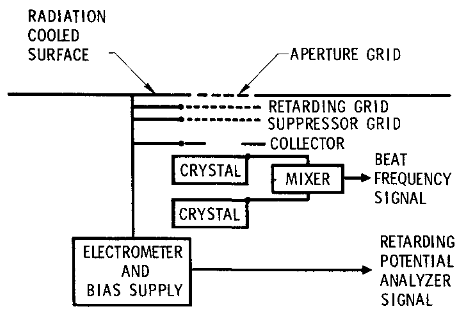


Fig. 6 Combined quartz crystal microbalance and retarding potential analyzer.

extendible antennas, which are 0.64-cm diam tubes when extended. The antenna elements will be insulated except for a few meters at the end. The absolute potential between the satellite and the plasma will be measured with these booms. The 50-m length of the booms should be sufficient to extend beyond the satellite plasma sheath in most conditions.

Spacecraft Sheath Fields Detector

This instrument consists of three electrostatic analyzers. Two analyzers are mounted in the diametrically opposed spheres denoted as "satellite electric fields" in Fig. 4. The third analyzer is mounted on the body of the satellite. The three instruments have the same look direction so that if there were not electric fields about the satellite, all three instruments would record the same flux, spectrum, and angular distribution of electrons and protons in the energy range 1-1000 ev. Because there is a potential distribution about the satellite, the analyzers will detect three different spectra, each shifted according to the potential at each analyzer.

Because of the need to maintain electrical isolation at the analyzers so that potentials are not distorted, an optical data transmission system will be used to telemeter digital data from the analyzers to the satellite data processing system. The potentials of the spheres relative to the satellite reference point will also be measured.

Electron Gun

The electron gun will be used to control the satellite potential for instrument calibration and to evaluate the efficacy of an electron gun to reduce *differential* charging of a satellite. It has been shown on ATS-5 and ATS-6 that the electron neutralizer of a cesium ion thruster is very effective in controlling the *absolute* potential of a satellite.[20]

The electron gun will supply currents between 0.01 and 30 ma at acceleration voltages between 0 and 3 kv. Beam focusing can be varied from none to maximum capability. An argon ion gun is also planned for the spacecraft charging experiment if power and weight are available. The characteristics will be 1-3 ma beam current at 2kv accelerating potential.

Particle and Fields Instrumentation

The remainder of the instrumentation is typical of the particle detectors and magnetometers used on previous scientific satellites. The electron spectrometer is the same instrument used by DeForest on ATS-5 and ATS-6 to detect spacecraft charging. This instrument measures energy spectra in 64 steps between 1 and 70,000 ev. The acceptance angle of the telescope is 5° half angle. This instrument will provide good energy and angular resolution of electron and proton fluxes. The rapid scan particle detector will provide fast time resolution, hopefully within 1 msec, of electron and proton fluxes. In order to obtain sufficient counting rates, the acceptance angle is 15° half angle and the energy spectra will be measured in only four steps. Because of the high detector counting rates, standard channeltron multipliers probably would not survive. Other detectors are under consideration.

The light ion spectrometer is basically the same instrument as flown on OGO-5.[21] One additional sensor will be added and retarding potential grids will be incorporated so that plasma drift can be measured.

The plasma probe is a spherical electrostatic analyzer using an electrometer for a detector.[22] The measurement of prime interest is electron temperature. The difficulty of this measurement is contamination of the sensor signal by photo and secondary electrons from the satellite.

The particle flux, energy spectra, and angular distribution measurements from the light ion spectrometer, electron spectrometer, rapid scan particle detector, and plasma probe are considered to be critical to the success of the spacecraft charging experiment. It is the particles in the energy range 1-50,000 ev which are believed to control spacecraft charging. Figure 7 shows the energy ranges for which the various particle detectors are designed.

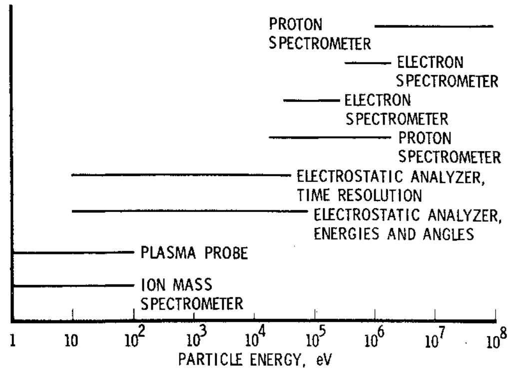


Fig. 7 Energy spectra detected by SCATHA particle detectors.

Conclusion

The unexplained behavior exhibited by synchronous altitude satellites is not a common every day experience. A given satellite may experience no more than 10-20 circuit upsets in a year. It has been necessary to accumulate years of orbital data in order to demonstrate conclusively that the unexplained or spurious behavior depends upon geophysical parameters such as local time and geomagnetic activity. This evidence plus the independent observations of DeForest on ATS-5 have led to the thesis that the anomalous behavior of satellites may be a result of satellite charging by the space environment. There has been no direct observation that this is the case.

Because the problem exists today, it is necessary to assume that the spacecraft charging thesis is correct and to implement corrective measures. It is not known whether the corrective measures, such as grounding thermal insulation blankets, are valid. Furthermore, it is not possible to test the utility of the corrective measures, because there are insufficient data regarding the response of the satellite to the space environment. The spacecraft charging experiment has been designed to obtain the data necessary to specify design criteria and test procedures to assure that satellite operation is not degraded by charging effects.

In addition to the spacecraft charging experiment, there is planned a complementary ground-based program to be conducted before the satellite launch in 1978. The objectives of this program are: 1) Characterize the relevant space environment properties such as particle flux and energy distributions so that the limits of electric stress imposed on satellites can be determined. 2) Summarize engineering details and orbital histories of satellites, such as ATS-6, DSCS II, and Intelsat IV, so different design approaches can be evaluated on the basis of performance data. 3) Determine the basic phenomenology of typical satellite surface materials when subject to electrostatic charging by the space environment. 4) Develop materials with properties which will resist electrostatic charging; properties such as low resistivity and high secondary emission coefficients. 5) Establish practical design criteria and test procedures to assure that satellites will not be subject to performance degradation by spacecraft charging.

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