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10. The Effects of the Geosynchronous Energetic Particle Radiation Environment on Spacecraft Charging Phenomena

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Abstract

The energetic electron environment at the geosynchronous orbit is very intense, dynamic, penetrating, and responsible for a variety of adverse charging effects on spacecraft components. The most serious of these is the degradation and failure of widely used complementary-metal-oxide-semiconductor (CMOS) electronic components as a result of internal charge-buildup induced by the energetic electrons. Efforts to accurately determine the expected lifetime of these components in this orbit have been hampered by the lack of detailed knowledge of the electron spectrum and intensity, particularly of the more penetrating energies > 1.5 MeV. Large uncertainties therefore exist in current radiation models for this region as a result of these deficiencies. This problem is illustrated through the calculation of the dose received by a CMOS device from the energetic electrons and associated bremsstrahlung as a function of aluminum shielding thickness using the NASA AE-6 and the Aerospace measured electron environments. Two computational codes which have been found to be in good agreement were used to perform the calculations. For a given shielding thickness the dose received with the two radiation environments differ by as much as a factor of seven with a corresponding variation in lifetime of the CMOS. The important rôle of bremsstrahlung to the problem at the larger shielding thicknesses is evident from the results. These discrepancies, which adversely impact spacecraft shielding designs, will be resolved on the SCATHA mission since the High-Energy Particle Spectrometer experiment (SC-3) will provide fine resolution measurements of the electron fluxes, energy spectra, and pitch-angle distribution over the energy range 100 keV to 4 MeV and the integral flux between 4 to 10 MeV. Protons from 1 MeV to 100 MeV and alpha particles from 6 MeV to 60 MeV will also be measured. The differential and accumulated dose received as a function of shielding thickness will be determined in real time throughout the mission from the measured quantities and the calculational codes.

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1. INTRODUCTION

A satellite in the geosynchronous orbit is subjected to an intense, continuous, highly dynamic, and very penetrating radiation environment. The energetic electron population (> 100 keV) exhibits large variations in intensity and spectral shape associated with geomagnetic storms and substorms. In addition, the particle population exhibits diurnal and longitudinal variations that are significant. At the time of solar particle events, high-energy protons, electrons, and alpha particles of solar origin also have ready, efficient, access to the geosynchronous orbit. This complex radiation environment, which is difficult to model, is responsible for a variety of adverse charging effects on spacecraft components. The most serious of these problems, just identified in recent years, is the degradation and ultimate failure of complementary-metal-oxide-semiconductor (CMOS) electronic components due to internal-charge-buildup induced by the ionizing radiation in the gate oxide and at the semiconductor-insulator interface of the devices. This process occurs at radiation dose levels approximately two to three orders of magnitude below the level where bulk radiation damage occurs in typical semiconductor devices. The overwhelming attractiveness of CMOS devices including their low power consumption and large-scale-integrated circuit capabilities has resulted in increased usage of these devices for satellite applications, including long-lived geosynchronous satellite orbit applications, despite these problems.

Contending with the charge-buildup problem requires that three distinct areas be investigated: (1) the sensitivity of CMOS, PMOS, and other components to ionizing radiation must be determined as a function of radiation particle type and energy, component part type, manufacturing process, and application; (2) the radiation environment to which the devices will be exposed in orbit must be established; and (3) based on the environment and the mission lifetime desired, the added shielding to maintain the radiation dose below the damaging levels must be determined.

Radiation sensitivity tests on a variety of components are underway in several laboratories employing principally radioactive gamma-ray emitting sources and electron accelerators. Both of these sources only approximate the actual complex electron spectrum encountered in geosynchronous orbit but the accuracy of the technique is felt to be better than our present knowledge of the environment itself.

The principal models of the electron radiation environment in the geosynchronous orbit are provided by NASA and are referred to as the AE-4[1] and the AE-6 models.[2] Both models are thought to have accuracies of only a factor of two to three. Recently, energetic electron measurements made on the ATS-6 synchronous satellite by the Aerospace group[3] suggest that the actual electron flux is higher and the spectrum more energetic than the NASA model predicts. The consequences of the adoption of the latter environment are significant to spacecraft designers in that greater shielding is required to maintain the CMOS devices below the damage level. Increased shielding means increased weight which always has an adverse effect on spacecraft design. The principal reasons for the inaccuracies and discrepancies in the model environments are the limited measurements available over long time periods, extended energy ranges and with sufficient spectral resolution. Until this situation improves, the spacecraft designer will be unable to optimize his shielding treatment and must design conservatively.

In this paper an experiment will be described that will be flown aboard the SCATHA satellite in near-synchronous orbit in 1979. A prime goal of the experiment, identified as SC-3, will be to define the energetic particle radiation environment in considerable detail and to determine the actual dose received in this orbit by devices such as CMOS behind various shielding thickness. The experiment will be operated continuously for at least a year and the differential and accumulated radiation dose will be determined in near-real time. The dose will be determined from the measured differential spectrum of electrons, protons, and alpha particles in conjunction with particle transport calculations that establish the surface dose behind different thicknesses of aluminum shielding.

Until the above measurements are available, determination of the dose acquired in the geosynchronous orbit and the required shielding of CMOS devices will have to be made with the available environmental models. Extensive dose calculations have been performed at Lockheed and are described in this paper using both the NASA and Aerospace electron environments and employing two different transport codes to develop confidence in the technique. The calculations have included the dose acquired from the bremsstrahlung generated by the electrons in the shielding. Solar flare proton doses as a function of shielding thickness have also been determined for an extended mission satellite operating over the solar maximum period.

2. RADIATION ENVIRONMENT

The dose in the synchronous orbit comes principally from the outer radiation belt electrons. Figure 1 shows the integral flux of these electrons as a function of energy obtained from the latest NASA AE-6 model[2] and from the Aerospace measurements.[3] The AE-6 model fluxes are mean values applicable in the 1980 time period for a magnetic L-shell of 6.6, representative of the synchronous orbit. It should be noted that no substantial differences exist between the AE-6 and the earlier AE-4 models in this region of space. As mentioned earlier, the NASA model is believed to be accurate to within ± X2 to ± X3. The Aerospace values are based on a few hundred days of data obtained in 1975-76 with an instrument on the

ATS-6 satellite and confirmed by earlier data obtained on the ATS-1 synchronous satellite.

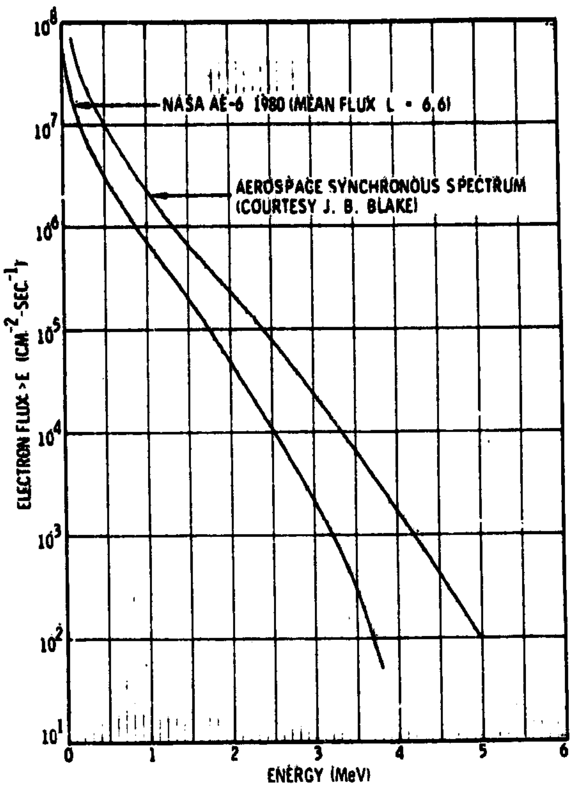

Figure 1. Integral Electron Fluxes in the Geosynchronous Orbit as a Function of Energy. The mean values of the AE-6 model in the 1980 time period at L = 6.6 are shown along with the mean values obtained from the Aerospace measurements

The most significant differences in the two environments exist at the higher energies > 1.5 MeV. At 1 MeV energy the Aerospace flux values are ×3 higher than the mean AE-6 values, but the upper limit of the latter model would be consistent with the former values. Above this energy the differences become progressively larger with the Aerospace fluxes being a factor of 5 and 12 higher than the AE-6 values at energies of 2 and 3 MeV, respectively. These differences are due to a softer electron spectrum used in the AE-6 model, that is, the flux decreases more rapidly with increasing energy.

Because of the quasi-random nature of the occurrences, fluences, and spectra of solar particle events, solar proton fluxes must be treated statistically. For a synchronous satellite mission operating for four years in the 1978 to 1982 time period encompassing the next maximum in solar activity, the solar proton fluences were derived from the model generated by King.[4] This model is based heavily on the data obtained during the last solar cycle-20 which is assumed to be typical of the upcoming cycle-21. It should be noted that approximately 85 percent of the fluence experienced in cycle-20 was acquired during the single large event of August 1972.

3. DOSE CALCULATIONS

The electron spectra shown in Figure 1 have been used as input to two independent computer programs that calculate dose. The first program called AURORA was originally developed at Lockheed to treat the energy deposited in the atmosphere by precipitating electrons.[5] The program was adapted for this purpose by substituting plane-parallel sheets of aluminum as the absorbing media in place of the atmospheric constituents. The program utilizes finite difference techniques to numerically solve the Fokker-Planck steady-state equation for electrons diffusing through the medium. The derivation of the diffusion equation is rigorous and takes into account changes in the electron distribution function as a function of time, pitch angle, energy, and the radial distance from the axis of the electron beam. The diffusion coefficients used to describe the pitch-angle scattering in the diffusion equation are valid down to electron energies of ~ 1 keV. The treatment is relativistic and therefore valid at all higher electron energies. The AURORA code does not, however, include the surface dose at the CMOS chip due to the production of bremsstrahlung in the slabs by the input electrons.

In Figure 2 the surface dose accumulated per year in the synchronous orbit at the surface of a CMOS chip sandwiched between two infinite plane aluminum shields of equal thickness is shown for both the AE-6 and the Aerospace electron fluences as inputs. The 0.010-in. nickel cover on the CMOS elements provides a measure of shielding and this has been included in the calculations. The shielding thickness shown in Figure 2 is the additional shielding required around the component.

The second set of electron dose calculations were kindly performed by the Air Force Weapons Laboratory (AFWL)[6] using their Monte Carlo technique. This program includes the secondary dose due to bremsstrahlung. Comparison in Figure 2 of the AFWL and AURORA code outputs for the Aerospace flux profiles reveals essential agreement for shielding thicknesses up to 0.15 inch. For greater shielding the bremsstrahlung dose included in the AFWL code begins to dominate. This illustrates the impracticality of utilizing large thicknesses of low-density material to shield "soft" devices in this environment. If a soft component requires greater than ~0.2 in. (1.39 g/cm^2) of aluminum shielding to survive the mission duration then additional consideration must be given to using high-density shielding such as lead, tungsten, copper, etc., inside the aluminum to attenuate the bremsstrahlung dose. This latter effort is much more difficult and weight-demanding than shielding the direct electrons and is not addressed further in this paper.

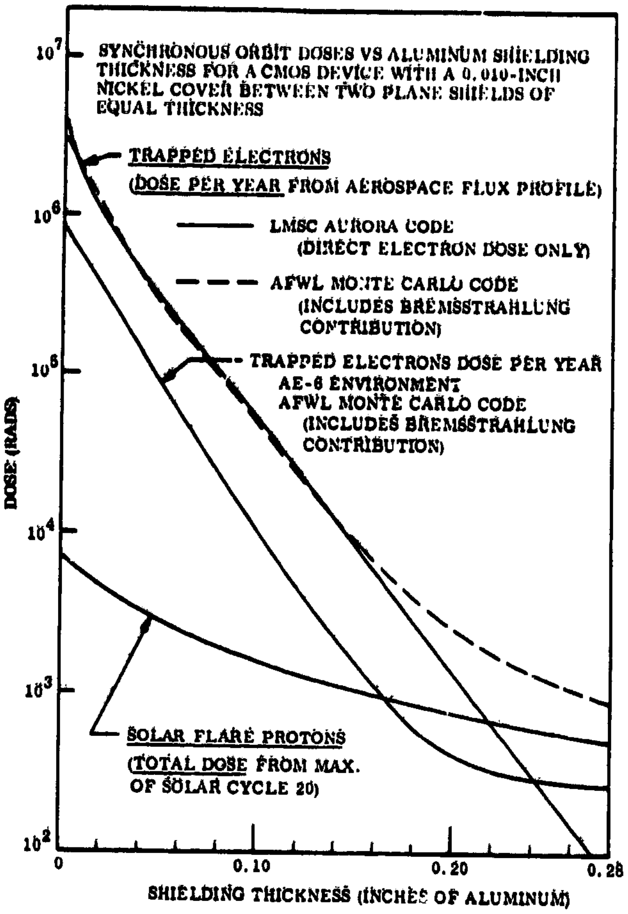

Figure 2. The Dose Acquired in Synchronous Orbit From Trapped Electrons and Solar Protons as a Function of Shielding Thickness. The annual electron dose has been calculated for the Aerospace Environment utilizing two independent computer codes described in the text. The annual dose due to the AE-6 electron environment and the associated bremsstrahlung has been calculated with the AFWL code

The impact of the two electron environments can also be easily seen in Figure 2. For a shielding thickness of 0.10 in., a thickness that typically surrounds a CMOS chip encased in an electronics box within a spacecraft skin, the CMOS chip would receive a yearly dose of 10,000 rads in the AE-6 environment but a dose of 70,000 rads in the Aerospace environment. An equivalent way of expressing this impact is that a CMOS device behind 0.1-in. aluminum that has a damage level at 10,000 rads would function for one year in the environment represented by the AE-6 model but only 51 days in the Aerospace environment. The impact on mission lifetime is obviously very significant and at present the spacecraft designer must shield conservatively.

The most probable dose received in a mission near the solar maximum period from solar protons is also shown in Figure 2. The total fluence experienced in cycle-20 as a function of proton energy was obtained from King[4] and was assumed to be typical of the maximum fluences to be encountered in cycle-21. A proton energy deposition computer program called PROTON[7] developed at Lockheed was used to determine the dose behind plane-parallel slabs of aluminum shielding. To determine the total dose received by a CMOS device behind a given shield thickness, the contribution from the solar protons must be added to the contribution from the trapped electrons.

The relationship between the dose level shown in Figure 2 to the damage levels of CMOS, PMOS, and most bipolar junction transistors is illustrated in Figure 3. The annual dose due to electrons and bremsstrahlung in both the AE-6 and Aerospace environments is shown out to shielding thicknesses of 0.7 inch. The relatively constant bremsstrahlung dose of between 250 to 800 rads per year (AE-6 vs Aerospace models) accumulated behind thick shields is quite evident and along with the solar proton dose becomes the limiting factor on the radiation softness of a device that can be tolerated in a long duration synchronous orbit mission.

Currently available soft CMOS and PMOS devices exhibit serious degradation at levels between 4000 to 16,000 rads due to the charge-buildup problem. Reliable utilization of these devices in even a one-year mission would require aluminum shielding of approximately 0.2-in. thickness. Hardened CMOS devices, now becoming available, have degradation levels in excess of 150,000 rads. A nominal shielding thickness of 0.08 in. aluminum will protect a hard CMOS device for a minimum of one-year operation in the synchronous orbit. Many linear integrated circuits have exhibited damage levels as low as 20,000 rads and correspondingly greater shielding is required with these devices. As mentioned earlier, knowledge of the radiation sensitivity of the electronic components to be used in an application is essential to long-lived, reliable operation. Unfortunately, the radiation sensitivity of currently available devices having identical part types can vary greatly from supplier to supplier depending upon the manufacturing process used and can even vary significantly from wafer to wafer within the same manufacturing process. Extreme caution is the watchword.

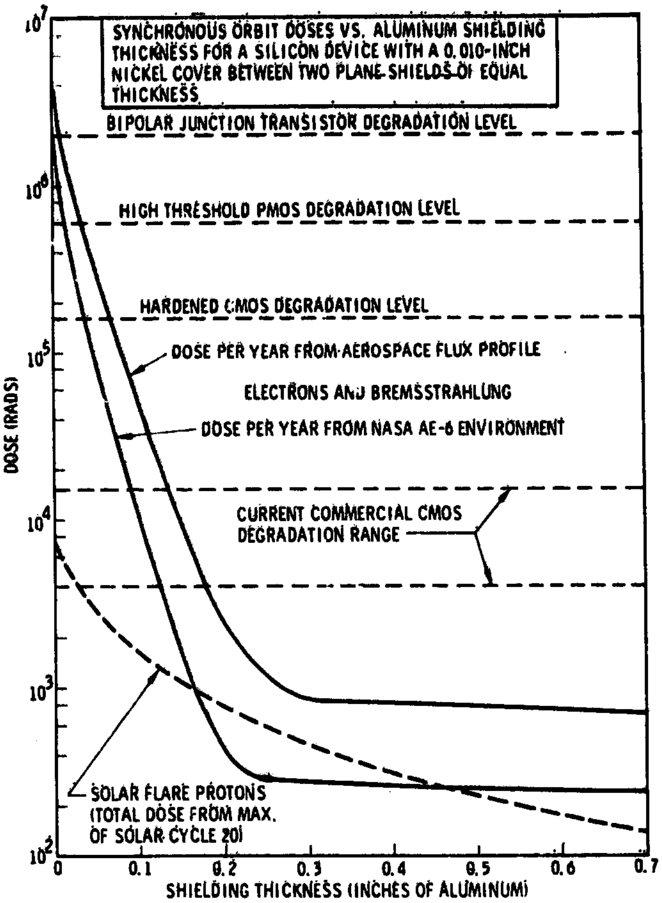

Figure 3. Relationship Between the Annual Dose vs Shielding Levels Acquired in the Synchronous Orbit From Electrons and the Associated Bremsstrahlung and the Damage Levels of Typical Electronic Devices. The solar flare proton dose is that likely to be acquired on a long-duration mission operating during the solar maximum period 1978-1982

4. EXTENDED DURATION MISSIONS

Most synchronous satellite missions are designed to operate for more than one year in orbit. To illustrate the impact of the radiation environment on these extended missions the total dose accumulated as a function of shielding thickness has been tabulated in Table 1 for a four-year mission operating in the solar maximum period 1978 to 1982.

Assuming that a typical payload containing CMOS or equivalent components would be shielded with a minimum of 0.1 in. of aluminum, Table 1 shows that the chip would receive a total dose over the 4-year period of 43,600 rads or 193,600 rads depending on whether the AE-6 or the Aerospace environment, respectively, is used. Hard CMOS with this shielding would survive in the AE-6 environment but could be marginal in the Aerospace environment. Most linear integrated circuits would require 0.2 in. of shielding to survive the Aerospace environment for four years, but less than 0.15 in. if the NASA environment is more representative.

Table 1. Total Dose (rads-Si) vs Aluminum Shielding for 4-Year Synchronous-Orbit Mission 1978 to 1982

Aluminum Shielding Thickness* (in.)	Electron Plus Bremsstrahlung Dose		Solar Protons	Total Mission Dose	
	AE-6	Aerospace		AE-6	Aerospace
0.050	340,000	1,200,000	2,800	342,800	1,202,800
0.075	116,000	460,000	2,050	118,050	462,050
0.100	42,000	192,000	1,600	43,600	193,600
0.150	6,200	37,200	1,050	7,250	38,250
0.200	1,720	9,600	760	2,480	10,360
0.250	1,140	4,720	580	1,720	5,300
0.500	1,000	3,200	230	1,230	3,430
0.700	960	2,800	140	1,100	2,940

*CMOS chip with 0.010-in. Ni cover behind two plane aluminum shields of equal thickness.

Finally, since soft CMOS and PMOS devices can experience problems at dose levels as low as 4000 rads, shielding of these devices for a 4-year mission should conservatively consist of an outer layer of aluminum approximately 0.25-in. thick with an inner layer of lead or equivalent foil (0.02 to 0.05 in.) to further reduce the bremsstrahlung contribution. Other sandwich combinations of aluminum and high-density metals can be used effectively but caution must be exercised. High density materials are more weight-effective in reducing the transmission of the incident electrons since a higher fraction of the electrons backscatter out of a high-density shield. However, the bremsstrahlung production in a high-density shield is greater than in a low-density shield of the same electron shielding effectiveness by a factor of approximately the ratio of the atomic numbers. Hence, the bremsstrahlung production is 7.5 times higher in a lead shield than in an aluminum shield of the same electron stopping power. A good compromise in shielding soft devices is to stop most of the incident electrons in a low-Z material such as aluminum and to follow this, if necessary, with a high-Z material to attenuate the bremmstrahlung photons generated in the outer shield.

5. SCATHA HIGH-ENERGY SPECTROMETER

The SCATHA satellite, which will be launched in 1979 into a near-synchronous orbit, will carry a high-energy particle spectrometer, referred to as the SC-3 experiment. One of the prime objectives of the experiment is to define the energetic radiation environment in this orbit in considerable detail and to determine in near-real time the dose acquired by the payloads and spacecraft equipment. To accomplish this, the spectrometer will be operated continuously and the measured differential spectra of electrons and protons will be used as inputs to the dose calculation codes described in this paper.

The spectrometer is very similar in design to one described in an earlier paper[8] that has been successfully flown in space four times on two low-altitude missions. The spectrometer consists of a stacked array of surface-barrier silicon detectors surrounded by an active plastic-scintillator. Passive shielding consisting of an outer layer of aluminum and an inner layer of tungsten surrounds the entire assembly to shield against electrons with energy <4 MeV and against the associated bremsstrahlung. The stacked silicon detectors are arranged with a thin (200-μ) detector in front to measure the rate of energy loss by the incoming electrons, protons, and alpha particles. Since these three particle types have significantly different characteristics in passing through matter, the energy loss in the thin detector can be used to uniquely identify the particle type under analysis. Behind the thin de/dX detector is an array of five detectors that are used to stop and to measure the incident energy of the particle under analysis. By arranging several different combinations of coincidence and anticoincidence between the two detector systems, different particle types over a wide energy range can be analyzed in a time-multiplexed manner. The active plastic scintillator is always used in anticoincidence with pulses in the main detectors and thus only particles entering through the narrow collimation system are analyzed.

The collimator is designed to have a 3-deg field-of-view and because the satellite is spinning, pitch-angle distributions of the particles will be obtained with this angular accuracy. The spectrometer will have the broad energy coverage listed in Table 2. Electrons from 100 to 4100 keV will be measured with 12-channel differential energy resolution. The channels can be programmed in flight to cover the entire energy range or a limited energy range with high-energy resolution. The flux of electrons between 3500 to 10,000 keV will be measured in a differential channel. Solar protons from 1 to 100 MeV will also be measured with 12-channel energy resolution in several different modes of operation selectable by command. Thus, all the particle types and energy ranges of concern to the radiation dose problem will be measured in this single instrument.

Table 2. SC-3 High-Energy Particle Experiment on SCATHA Mission Characteristics

Particle Type	Energy Range	Resolution	Comments
Electrons	100 to 4100 keV >3500 keV	12-channel integral	Channel widths programmable from 15 keV to 100 keV
Protons	1 to 100 MeV	12-channel	Multiple energy modes required to cover energy range
Alphas	6 to 60 MeV	12-channel	

The capabilities of the SC-3 experiment to resolve the fundamental difference between the NASA and the Aerospace environment is illustrated in Figure 4. As mentioned earlier, the AE-6 model exhibits a much steeper fall-off of the higher energy electrons than the Aerospace measurements indicate. In the former case this results principally from a lack of experimental data above ~2 MeV in energy. As shown, the SC-3 experiment will define in great detail the shape of the electron spectrum out to 4.1 MeV through the several operating modes available in the instrument.

In the future the spacecraft designers will have a better definition of the energetic radiation environment as input to his shielding analysis. Until that data becomes available, however, he must design component shielding in a conservative manner using the more severe and adverse environment suggested by the Aerospace measurements.

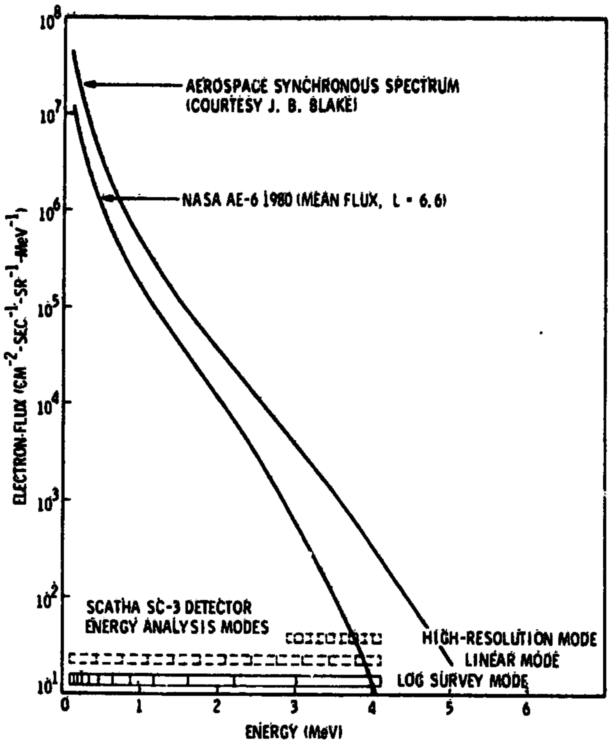

Figure 4. Illustration of the Various Energy Analyses that the SC-3 Experiment on SCATHA Will Provide on the Synchronous Orbit Electron Environment

Acknowledgments

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