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OPERATIONS OF THE ATS-6 ION ENGINE*

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ABSTRACT

The ion engine experiments on ATS-6 have been operated in daylight and eclipse. The effect on particle fluxes to the spacecraft was monitored with the UCSD Auroral Particles Experiment. These data also provide information on the potential of the spacecraft with respect to the ambient plasma and on the local electric fields caused by the charge distribution on the satellite.

Daylight operations of the plasma bridge neutralizer and the cesium thruster in fall, 1974, served to hold the spacecraft between -3 and -8 volts with respect to the ambient plasma. Neutralizer operation reduced differential charging effects, while operation of the thruster usually reduced the effects below the detectors sensitivity. Eclipse operations of the neutralizer reduced kilovolt negative potentials to a few volts. Operation of the thruster prevented possible charging of the satellite during substorms, making it possible to study low energy particle spectra which are at times obscured by charging during substorms.

INTRODUCTION

Applied Technology Satellite 6 carried two cesium ion thrusters up to geosynchronous altitude in 1974. Also on board was the UCSD Auroral Particles Experiment, designed to count electrons and ions in the 0-80 kev range. The ion engines were operated in 1974, and met most of their objectives. Unfortunately, neither engine could be restarted after their initial tests, but in 1976 and 1977 the plasma bridge neutralizers were successfully operated. These operations have been monitored with the UCSD instruments to determine the spacecraft potential and to try to understand the local electric fields.

ATS-5 and ATS-6 have experienced charging of several hundred volts in daylight, and potentials up to 18 kilovolts in eclipse. DeForest (1972) has reported on the former satellite. This charging accelerates ions into the spacecraft and repels electrons, degrading measurements of the environment. Differential charging is even more serious in its effect on data. (Grard, DeForest, and Whipple, 1977). Whipple (1976) has studied the trapping of photoelectrons by ATS-6. He shows that a barrier can be set up around the spacecraft, returning spacecraft generated electrons (primarily photoelectrons) to the spacecraft, and shutting out the ambient electrons.

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The ion engine operations are being studied as a means of controlling charging. Based on preliminary results from the 1974 operations, the neutralizers were operated with the objective of modifying large potentials. Goldstein and DeForest (1976) have reported on the engine operations and on some of the similar tests run on ATS-5. A report cataloguing the data up through 1976 was compiled by Olsen and Whipple (1977).

Following are more detailed descriptions of ATS-6, its ion engines, and the UCSD detectors. The electrostatic characteristics of the spacecraft will be emphasized. Following this is an analysis of the operations of the two engines in daylight and an operation of the plasma bridge neutralizer in eclipse with the spacecraft highly charged.

ATS-6

The satellite is a large (~ 15 meters) inhomogeneous array of materials (see figure 1). The UCSD experiment sits on top of the satellite in the environmental measurements package (EME). The exterior of the EME package is nominally conducting. It is flanked by solar arrays (insulators) which are on booms extending 25 feet on either side. Below the EME package is a parabolic antenna 9 meters in diameter. Its electrostatic properties are not well known. Constructed from dacron mesh, it is coated with copper, which is in turn covered by a lubricant (insulator) to aid deployment. Five meters below the antenna is the earth viewing module (EVM) which contains the ion engines. The surface of the EVM is conducting. In short, ATS-6 is a large electrostatically complicated satellite. Geometrically, the ion engines and the particle detectors are well separated.

ION ENGINES

The ion engines are cesium bombardment engines utilizing the magneto-electrostatic containment concept (see figure 2). Two grids are used to extract and accelerate the plasma. Neutralizing electrons are supplied by a plasma bridge neutralizer. The neutralizer generates its own cesium plasma at the plasma probe potential. This plasma provides the necessary electrons to the ion beam. The neutralizer is the main link between the engine, beam, and the spacecraft mainframe. The main thruster is essentially floating. The beam is nominally .1 amp accelerated through 1.1 kv, with the outer grid at -560 volts. It produces 4.45 mN (1 millipound) of thrust (see Worlock, et al., 1975).

DETECTORS

The UCSD Auroral Particles Experiment consists of two sets of rotating detectors and one fixed detector. The rotating detectors are paired ion and electron detectors; the fixed detector measures only ions. All count particles as a function of energy (0-81 keV in 64 exponential steps, 16 sec.)

and angle (220° in 2 1/2 minutes). These instruments can be considered differential in angle, area, and energy (Mauk and McIlwain, 1975).

OPERATIONS

The ion engines were operated in two main experiments. The first lasted about one hour and was conducted in a low energy environment. The second operation lasted 92 hours, began during a fairly active period, and included a variety of environments.

Day 199/74

The first ATS-6 ion engine operation was on July 18, 1974. The data is presented in spectrogram form in figure 3. The spectrogram provides the count rate as a function of time (horizontal axis) and energy (vertical axis). The energy scales are logarithmic, with the ion scale inverted. Electrons are in the top band, ions in the lower. The intensity is proportional to the count rate. In these spectrograms, the intensity cycles, that is, it reaches a maximum lightness, and then cycles to black and starts over again. This occurs in figure 3 for the 10 eV ions. The pitch angle for this detector is plotted over the spectrogram, and is seen here cycling between 10° at the bottom and 150° at the top. The spectra varies as the detector rotates, showing the pitch angle distribution.

There is a band of low energy electrons from 0-50 electron volts visible in the spectrogram. The bottom few eV of the spectra are photoelectrons, the rest ambient plasma. There is no apparent differential charging. When the neutralizer ignites at 3:10, there is a change in the low energy spectra for electrons and ions. The decrease in intensity of the electrons is mirrored by an increase in the ion intensity. This and the absence of ions below 4 eV are interpreted as a shift in potential to about 4 volts negative. By comparison of the particle spectra before and after neutralizer ignition, we infer the spacecraft was 4 or 5 volts positive before the neutralizer ignited. After the potential shifts, the photoelectrons are repelled by the spacecraft.

The neutralizer arced off at 3:16, and both it and the ion engine turned on at 3:32. The spectra changes promptly at both transitions. The spacecraft then goes to -5 to -7 volts potential, and remains there until 4:03, when the engine and neutralizer flamed out. The engine reignites at 4:08, and stays on until 4:35, when the experiment ended. At each of these shutoffs the spectra resumes the form it had before the test. The ambient plasma can be considered constant over this time period.

These data show that operation of the plasma bridge neutralizer, with and without the engine, causes the spacecraft to shift from a small positive potential to a negative potential of a few volts. Simple current balance arguments show that in the neutralizer-only mode the neutralizer was emitting a net positive current, i.e., ions.

Day 292/74

The second ion engine test was conducted under different environmental conditions, and lasted for a much longer period of time (92 hours). The engine ignited in the latter stages of a substorm. The spacecraft was charged to -50 volts, accompanied by a differential charging barrier of about 90 volts. These effects can be seen in figure 4, which shows the ignitions of the neutralizer and thruster. These transitions are at 7:44 and 8:05 respectively. The shorter time period of the spectrogram emphasizes the angular variations in the spectra. The effects of the differential charging before the engine ignites can be seen in the low energy band of electrons in the top half of figure 4. The sharp transition at low energies is the signature of this effect. It implies that some surface of the spacecraft is at least 100 volts negative with respect to the satellite mainframe and our instrument.

The potential of the mainframe is plotted in figure 5. The spacecraft potential was inferred from the first (lowest) energy channel of the detector containing an appreciable number of ions. We have assumed that we are not seeing any cesium ions from the engine. To add consistency to the data most of the data points were taken with the detector at $\approx 90^{\circ}$, which corresponds to looking straight out from the spacecraft. The detector was not pointed at 90° during the ignition of the neutralizer at 7:40 so two data points taken at 170° were included. It can be seen that the neutralizer quickly brings the spacecraft within a few volts of the ambient plasma. Uncertainties in the spacecraft potential are largely due to a lack of low energy particles at 90° thus making most of the points between 7:40 and 8:05 an upper bound on the magnitude of the potential. The potential leveled off at about -4 or -5 volts when the thruster stabilized.

The differential barrier around the spacecraft shows a more interesting variation. The value plotted in figure 6 is the energy of the transition from high to low counts. The error bars are basically plus or minus one energy channel. When the neutralizer ignites at 7:40 there is a sharp drop in this energy but it does not reach zero. The thruster comes on at 8:05, and by 8:10 the differential charging signature is gone. This behaviour could be explained by the need of negatively charged insulators for an extra ion source to discharge them. The neutralizer is not putting out enough ions to do the job. The thruster provides a source of charge exchange ions which could be diffusing around the spacecraft, drawn by the local fields.

This ignition process showed that a plasma bridge neutralizer is capable of discharging a negative satellite. In contrast to the previous operation, it is supplying a net negative current, i.e. emitting electrons. The spacecraft again attains an equilibrium potential of a few volts negative. This is effectively the coupling potential between the spacecraft (the neutralizer probe) and the ion beam. Differential charging is reduced by the neutralizer but is not completely eliminated until the thruster has been on for 3-5 minutes.

Days 292-296/74

The spacecraft was held at about -4 or -5 volts throughout the 92-hour operation. A number of magnetospheric substorms occurred during this time period. During similar storms outside this time period, the spacecraft charged several hundred volts negative and was accompanied by severe differential charging. Data from this time period are displayed in figure 7. The engine operation begins on day 292 at 8:00 and ends on day 296 at 04:00. The largely constant band of ions at 10 eV show the constancy of the potential. The potential is fluctuating before and after this operation, negative before (up to -300 V) and probably positive afterwards. The white blotches at the middle of the spectrogram, centered around hour 18 ot each day, are due to an instrumental effect, and are effectively data dropouts in that energy region. The electron data is undisturbed by differential charging.

We see here an example of the improvement in the data when the spacecraft potential is controlled.

Day 98/77

If the spacecraft goes into eclipse, the absence of photoelectrons changes the balance of currents to the spacecraft. It is common for the spacecraft to be at equilibrium at a few volts negative in eclipse. When the plasma bridge neutralizer was operated under these conditions, there was little or no change in the spacecraft potential. However, if the environment is energetic, as in the aftermath of a geomagnetic substorm, spacecraft at geosynchronous orbit sometimes reach several kilovolts. On April 8, 1977 (day 98), ATS-6 reached -8 kV. The neutralizer was operated during the eclipse to modify the spacecraft potential. The data for this event are presented in figure 8. The solar array current is a function of the spacecraft illumination. The neutralizer probe voltage shows that the neutralizer is on, but the telemetry saturates at 15.7 volts. Ignition of the neutralizer (into "plume" mode), is recognized more sensitively by the spacecraft potential, the bottom graph. The break in the probe voltage curve at 9:22 is the neutralizer entering "spot" mode. Prior to eclipse, the spacecraft was at -50 V. Upon entering eclipse (9:05) it charges even higher and then discharges quickly when the neutralizer begins supplying electrons (9:12). When the neutralizer is turned off (9:30), the spacecraft promptly charges back up. Upon exiting eclipse (9:35) the spacecraft discharged again. This and other operations under similar conditions showed that the plasma bridge neutralizer is capable of discharging kilovolt potentials.

SUMMARY

ATS-6 ion engine operations from 1974 and a neutralizer operation from 1977 have been analyzed. These operations showed that the plasma bridge neutralizer operating alone could discharge a negatively charged spacecraft, or shift a positive spacecraft to slightly negative. The neutralizer reduced but did not eliminate differential charging. Operation of the main thruster clamped the spacecraft at $\approx$ -5 volts, the potential difference between the spacecraft and the ion beam, and eliminated differential charging at the startup of the thruster.

To further understand these results, more work needs to be done in characterizing ion engines as particle sources, particularly in the low energy region, and as a function of time at ignition.

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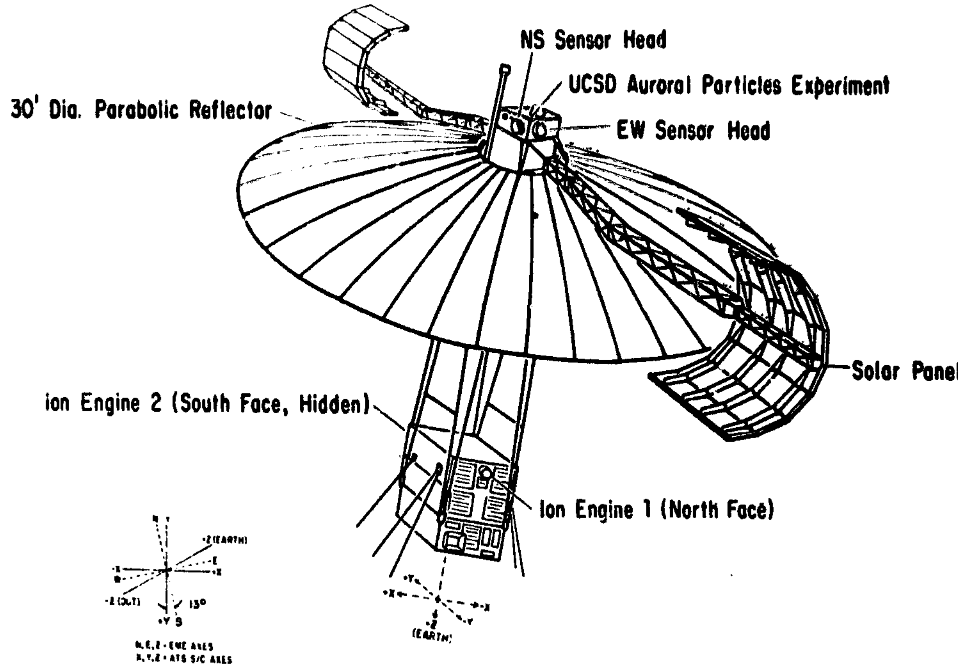

Figure 1. - ATS-6: Detectors and ion engines.

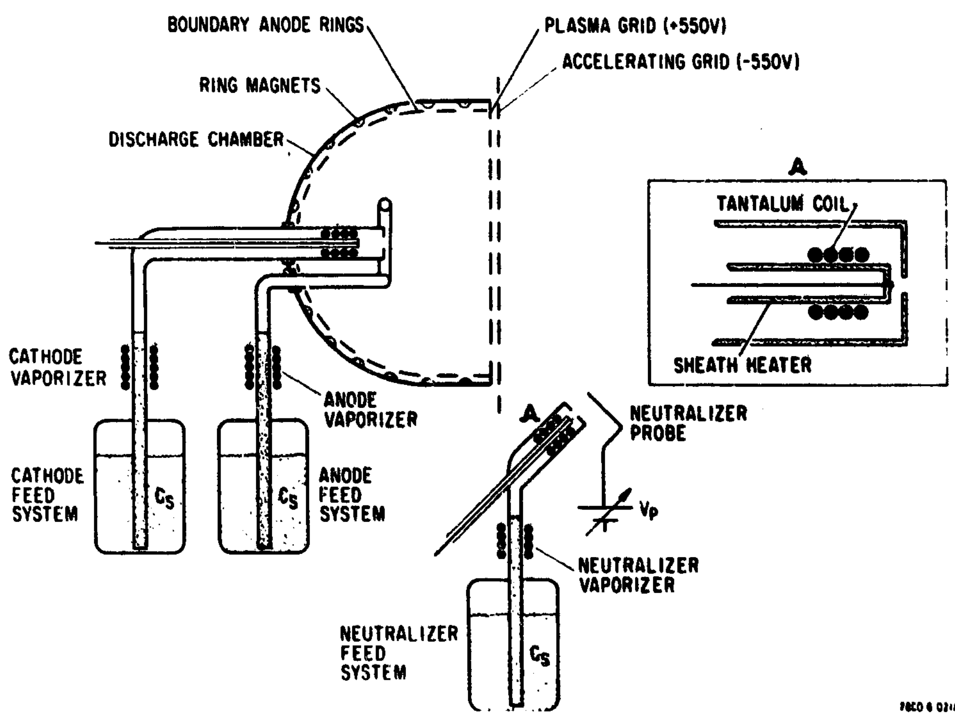

Figure 2. - ATS-6 ion engine.

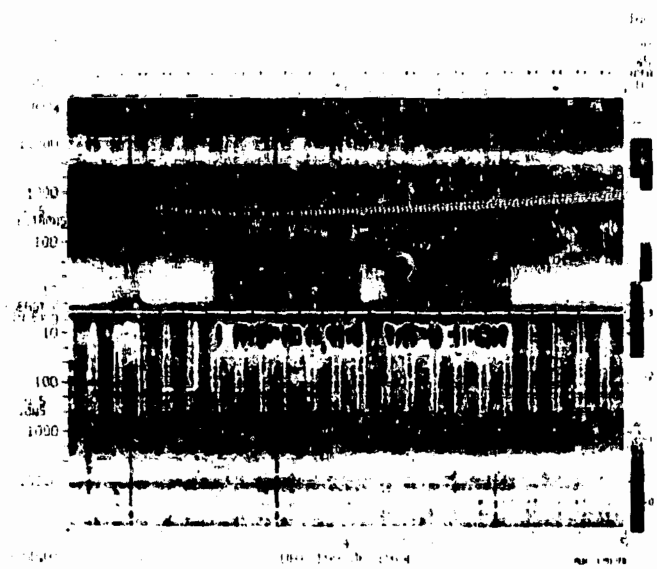

Figure 3. - Day 199/74: Spectrogram for ion engine operation.

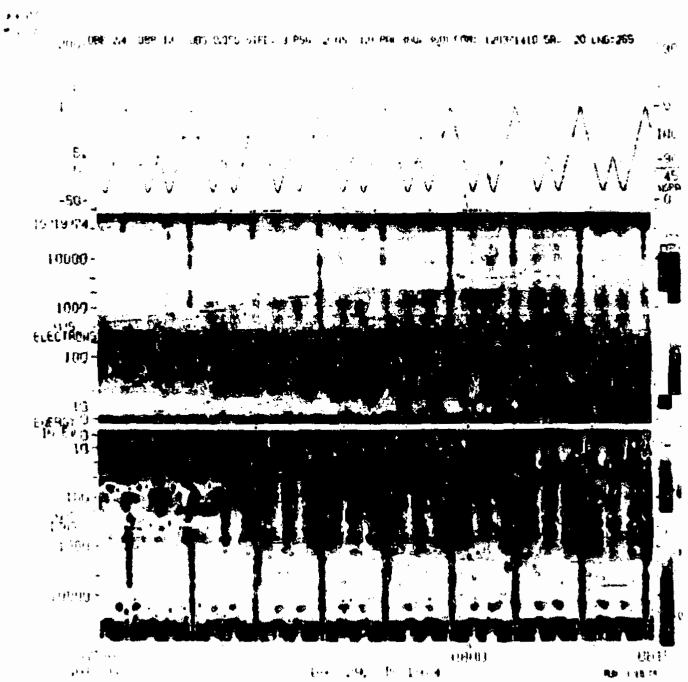

Figure 4. - Day 292/74: Spectrogram for ion engine operation.

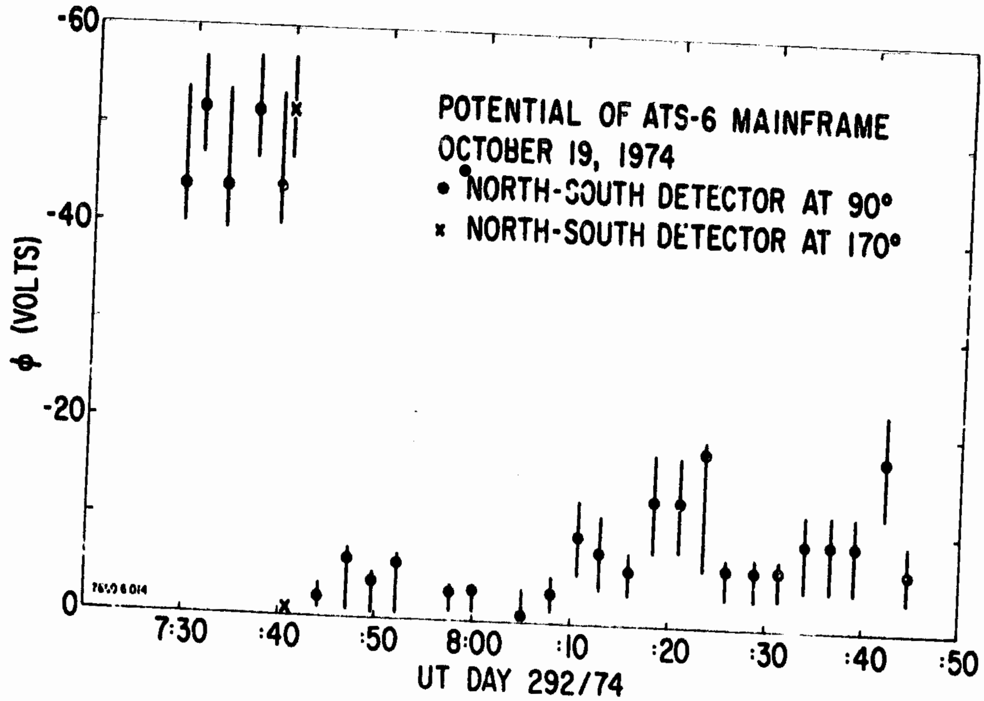

Figure 5. - Potential of ATS-6 mainframe.

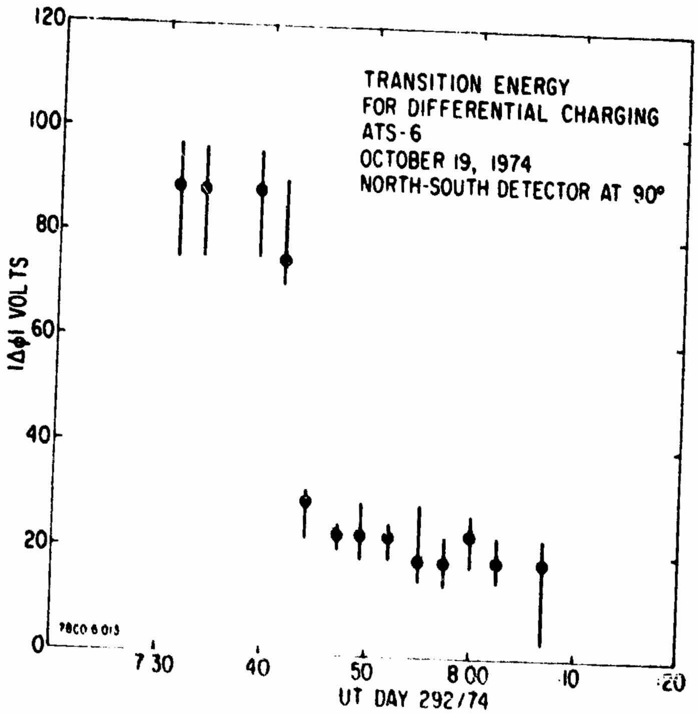

Figure 6. - Transition energy for differential charging.

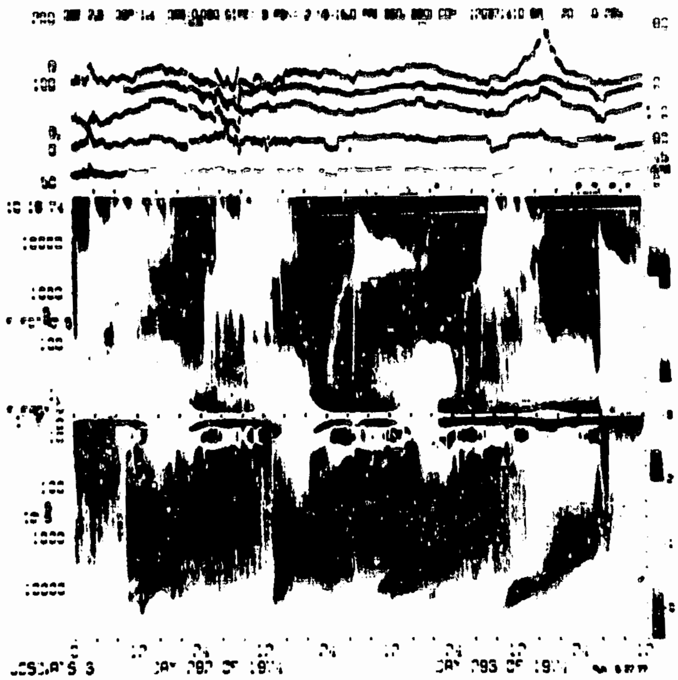

Figure 7. - Days 292-296/74: Spectrogram for ion engine operation.

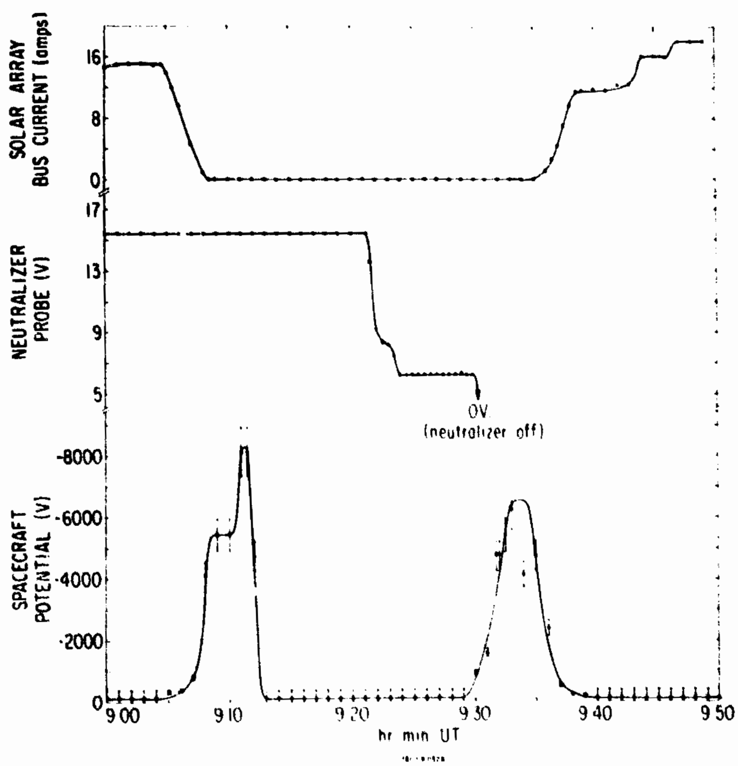

Figure 8. - Day 98/77: Spacecraft potential in eclipse.