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EFFECTS OF CHEMICAL RELEASES BY THE STS-3 ORBITER ON THE IONOSPHERE

by

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ABSTRACT

The Plasma Diagnostics Package, which was flown aboard STS-3 as part of the Office of Space Science first Shuttle payload (OSS-1), recorded the effects of various chemical releases from the Orbiter. Changes in the plasma environment were observed to occur during flash evaporator system releases, water dumps and maneuvering thruster operations. During flash evaporator operations, broadband Orbiter-generated electrostatic noise was enhanced and plasma density irregularities ($\Delta N/N$) were observed to increase by 3 to 30 times with a spectrum which rose steeply and peaked below 6 Hz. Ions with energies up to several hundred eV were also observed during one flash evaporator operation. In the case of water dumps, background electrostatic noise was enhanced at frequencies below about 3 kHz and suppressed at frequencies above 3 kHz during the dump, and $\Delta N/N$ was also seen to increase by 5 to 6 times. Various changes in the plasma environment were effected by primary and vernier thruster operations, including increases in electron density by as much as 3 orders of magnitude, neutral pressure increases to as high as 10^{-4} torr from the nominal 10^{-7} torr, and perturbations in the spacecraft potential by several volts, particularly when measured relative to the plasma potential in the wake. Thruster activity also stimulated electrostatic noise with a spectrum which peaked at approximately 0.5 kHz. In addition, ions with energies up to 1 keV were seen during some thruster events.

1. INTRODUCTION

Since the first Space Shuttle launch in April of 1981, considerable interest has been generated in ionospheric modifications effected by the Shuttle, both during launch and during orbital operations. The effects of rocket exhaust on the ionosphere have been studied and recorded in considerable detail since Booker [1961] first reported a local diminution in ionization density forming a hole through the F-region associated with the firing of Vanguard II in 1959. A review of the findings to date, particularly with regard to large space systems, was given by Rote [1980] and included such environmental effects as plasma depletion, temperature change and airglow excitation. A brief history of rocket-induced perturbations upon the upper atmosphere was also given by Mendillo [1980]. In addition, he described a method for assessing how the Space Shuttle's engines would affect the ionosphere in the vicinity of the engine burns. A review of the effects on the ionosphere due to the deliberate release of known quantities of highly reactive chemicals such as H_2O and CO_2 was given by Pongratz [1981]. The environmental impact on the D and E regions of the ionosphere of chronic discharges of water vapor from large rockets was investigated by Forbes [1980].

The purpose of this paper is to present observational evidence of ionospheric modification using data taken by the Plasma Diagnostics Package (PDP) [Neupert et al., 1982] during Space Shuttle Orbiter chemical releases. The Space Shuttle is an ideal vehicle for experiments involving ionospheric modification. Not only does it initiate chemical releases, but it also provides the platform from which to monitor the effect of those releases. While not intended to be scientific ventures, the Orbiter water dumps, flash evaporator system (FES) releases and thruster operations are, in effect, chemical releases.

An outline of the paper is as follows: Section 2 contains STS-3 mission and operational considerations, including an overview of orbit and ionospheric characteristics, shuttle operations and PDP instrumentation. The observations of the effects of flash evaporator system releases, water dumps and thruster operations are presented in Section 3. Finally, some concluding remarks and possible explanations for the physical processes involved are offered in Section 4.

2. MISSION AND OPERATIONAL CONSIDERATIONS

2.1 STS-3 Mission

During March 22-30, 1982, the Plasma Diagnostics Package (PDP) was flown on the third Space Shuttle Mission (STS-3) as part of the Office of Space Science (OSS-1) first Shuttle payload [Neupert et al., 1982]. Figure 1 shows the OSS-1 instruments as they were mounted on the aft pallet and points out the external sensors on the PDP. The Orbiter was placed in a circular orbit at an altitude of 241 km and an inclination of 38° which resulted in an orbit period of approximately 1 1/2 hours. The STS-3 mission's primary objective was to analyze the Orbiter's operation over a wide range of thermal extremes, thus many different Orbiter attitudes were achieved. Eighty hours out of approximately 192 were spent in a nose-to-sun attitude, to cause low temperature extremes in the engine compartments, with a roll rate which was twice the orbit rate (see Figure 2); this attitude interval was when most of the PDP data were taken. At the ascending node (equator crossing moving northward), the Orbiter attitude was such that atmospheric gases were ramming into the bay. As the Orbiter headed toward descending node and night, it completely blocked the flow of gases into the bay and a wake condition prevailed in and just above the bay.

2.2 Ionospheric Characteristics

Using satellite measurements as well as numerical models, the F2 region of the ionosphere can be characterized as follows: it extends from approximately 225 to 400 km with a neutral component of $\leqslant 10^9$ cm^{-3} and an average plasma density of 10^5 to 10^6 cm^{-3}. The dominant ion of this region is O^+ which is created by ionizing UV and the dominant neutral is O. In addition N_2 and O_2 are important constituents since they are believed to play an important role in the principle loss process of the O^+ ion [Banks and Kockarts, 1973].

2.3 Shuttle Operations

During orbital operations, the flash evaporator may discharge water to supplement heat rejection when the Orbiter attitude is thermally unfavorable. A secondary function of the evaporator is to expend excess potable water produced by the fuel cells that has accumulated in the potable water tanks. The vaporized water produced by the FES during these two processes is discharged through two nozzles, one on each side of the aft fuselage, which are known as topping FES vents (see Figure 3). The water vapor is discharged in pulses with a variable pulse rate and a pulse width equal to 200 ±30 msec. The maximum pulse rate is 4 Hz at 30 lb/hr (Hamilton Standard Engineering Memorandum, SEM #62408, 1982). For example, for an average FES release of 3 lb/hr., the pulse rate is 0.4 Hz, which means every 2 1/2 seconds there is a 0.2-second pulse of water vapor and a 2.3-second gap. It should be noted that a plot of mass flow rate vs. pulse rate is not linear since mass flow rate also depends on feedwater pressure. Therefore, if the mass flow rate is known, only an estimate of the pulse rate can be obtained. The plume expands along the $\pm Y_0$ axes of the Orbiter and in some cases is reflected by the wings (European Space Agency Spacelab Payload Accommodation Handbook, Document No. SLP/2104, 1982). A high load FES vent is also pointed out on Figure 3 which was used primarily at the beginning and end of the mission when the payload bay doors were closed. During the STS-3 mission, there were 20 FES releases of varying lengths from a minute to more than 2 hours. The PDP was turned on during 4 of these FES releases, all of which were topping FES releases. Table 1 lists these releases and the location of the PDP.

Water management on the Orbiter includes storing, distributing and disposing of excess water generated by the fuel cells. This excess water is dumped overboard in a nonpropulsive fashion at predetermined times (European Space

Agency Spacelab Payload Accommodation Handbook, Document No. SLP/2104, 1982). The water relief vent for water dumps is located on the port side, rearward of the forward bulkhead and about 5 feet down from the door hinge (see Figure 3). A total of 9 water dumps were made during the mission, each of which lasted for approximately 45 minutes to an hour. The average dump rate was 140 lb/hr with the amount of water being dumped varying from 91 to 204 lb. Most of the water dumps began around sunset and ended shortly after sunrise. The water dumped at night turned to ice upon release. The ice sublimated as the Orbiter passed into sunlight.

The Reaction Control System (RCS) is used on the Orbiter to control attitude. The system consists of 38 primary (870 lb) thrusters and 6 vernier (25 lb) thrusters. Figure 3 shows the location of these thrusters from a side view. Both verniers and primaries are located in the front and rear of the Orbiter. In this view the circular designation means the thrust is directed sideways and the oval means the thrust is directed down. The other side of the Orbiter has a matching set of these thrusters. In addition, there is a set of primaries which thrust up and forward in the front of the Orbiter and a set of primaries which thrust up and back in the rear of the Orbiter. Because of the location and direction of thrust of some of the RCS thrusters, a certain amount of the thruster exhaust is reflected off of Orbiter surfaces. (European Space Agency Spacelab Payload Accommodation Handbook, Document No. SLP/2104, 1982).

Table 2 shows thruster plume characteristics for both the vernier and primary thrusters, including composition of the exhaust and numbers of ions and neutrals ejected in a typical firing (while maintaining orbit) and in a long firing event (while maneuvering to a new orbit attitude). The velocity of the exhaust gases at all points in the plume after all energy has been converted is 3.5 km/sec. During the mission there were over 40,000 thruster firings of varying lengths from 0.08 seconds to 10's of seconds. When the PDP was turned on and taking data, nearly all of these firings, as well as every FES release and water dump, were evident in the data through one or more measured parameters.

2.4 PDP Instrumentation

A primary objective of the PDP was to measure aspects of the Orbiter's induced environment both in the payload bay at the pallet level and above the bay to a 50 ft. height through use of the Remote Manipulator System (RMS). The PDP carried a complement of 14 instruments that measured electrostatic and electromagnetic waves, DC magnetic and electric fields, ion composition and flow, ion and electron energy distribution functions, plasma temperature and density, and neutral pressure. Some of the instruments which showed effects during chemical releases are briefly described below. A more detailed description of the instrument complement, the associated receiver systems and the range of measurements possible can be found in Shawhan et al. [1984] and Shawhan and Murphy [1984].

A 2-inch diameter, gold-plated spherical Langmuir Probe measured electron density and temperature and electron density irregularities ($\Delta N/N$) in the frequency range 0 to 40 Hz. Two spectrum analyzers were used to look at electrostatic and electromagnetic waves and $\Delta N/N$ irregularities in the frequency range 31 Hz to 178 kHz. One of the spectrum analyzers was dedicated to observing the electric component of waves using a double probe with two 20 cm diameter black spherical sensors separated by 1.6m. The other analyzer was periodically switched between the electric dipole antenna, the magnetic search coil and the Langmuir Probe (see Figure 1 for location of these sensors on the PDP). DC electric fields in the range ± 4.8 V/m were measured using the electric dipole antenna and spacecraft potential with range ± 8.2 V was measured by taking the average potential between the 2 spheres with respect to the PDP ground, which was the same as the Orbiter ground. A cold cathode ionization gauge measured ambient pressures from 10^{-7} to 10^{-3} torr. Finally, pitch angle and flux of energetic electrons and ions with energies 2 eV to 36 keV were detected with a low energy proton and electron differential energy analyzer.

3. OBSERVATIONS

3.1 Flash Evaporator System Releases

Figure 4 provides Langmuir Probe and plasma wave data taken during the 2-minute FES release on day 82 (GMT) under daytime conditions. The top panel shows that for every 1.6 second sample plotted during the release, the Langmuir Probe saw peak to peak voltage outputs which covered the full dynamic range of the instrument. By applying a fast Fourier transform (FFT) algorithm to these data, the $\Delta N/N$ plasma turbulence spectrum shown at the top of Figure 5 was obtained. This spectrum shows that the turbulence was increased by as much as 30 times over background below 10 Hz and increased by approximately 3 times at frequencies 10 to 40 Hz. The FES release spectrum was seen to rise steeply below 6 Hz and peak at approximately 0.5 Hz which was, in all probability, the pulse rate of the FES release at this time. The basis for this assumption will be discussed at the end of this subsection.

Associated with the $\Delta N/N$ increase was an enhancement in the background Orbiter-generated electrostatic noise [Shawhan et al., 1984], which in panel 2 of Figure 4 was shown to be 10^{-2} V/m at 1 kHz before the release. The average value of the 1 kHz electric field (based on the average seen during each 1.6-second sample) during the release rose only slightly while the peak value (the maximum encountered during each 1.6-second sample) was at least half an order of magnitude greater than before the release. An effect in the electric field during FES releases was seen at all frequencies from 31 Hz to 31 kHz and sometimes as great as 100 kHz depending on Orbiter attitude, and on day/night and ram/wake conditions. The bottom half of Figure 5 shows electric field spectral density for the FES release on day 82. It can be seen here that electric field spectral density was clearly enhanced by as much as 20 dB up to 31 kHz. Other data available show there were no obvious effects on the wave magnetic field, spacecraft potential, DC electric field or neutral pressure.

The FES release discussed above took place during the nose-to-sun attitude. It is apparent from Figure 1 that the PDP sensors, i.e. Langmuir Probe and electric field sensors, were located well inside the bay and were shielded by other instrument packages from flow in some directions. Since the plume of water vapor expands along the $\pm Y_O$ axes of the Orbiter, a more ideal location for the PDP would be on the RMS near the back of the Orbiter. Of the two releases that took place while the PDP was on the RMS, essentially the same effects as noted above were seen. In addition, a pulsing effect was seen in the fluxes of low energy electrons and ions. This was particularly obvious in the ion data when the PDP was on the RMS near the back of the Orbiter as seen in Figure 6a. At this time, which was shortly after noon, we saw a pulsing effect in the ion fluxes up to about 1 keV. A line plot of counts vs. time for 92.1 eV ions, shown at the bottom of this figure, clearly shows the variation.

A careful analysis of the data, which showed a cycle of about 5/minute, the sweep time of the particle detector (1.4 sec plus 0.2 seconds rest), and the pulse rate of the flash evaporator system (which we know to be less than 4 Hz) indicated that the pulsing effect was due to a beat frequency between the sweep of the particle detector and the FES pulse rate. In fact, computer modeling has shown that a FES pulse rate of 1.8 Hz would give a spectrum similar to that shown at the top of Figure 6a. In addition, output amplitude vs. time from the Langmuir Probe clearly showed a periodic variation at 1.8 Hz for this release (see Figure 6b) and the $\Delta N/N$ plasma turbulence spectrum peaked between 1 1/2 to 2 Hz. A pulse reate of 1.8 Hz for the FES at this time is consistent with what engineering models from Hamilton Standard predict (A. Decrisantis, personal communication, 1984). The production of hot ions up to 1 keV is not yet fully understood, however, a few remarks concerning a mechanism which could possibly explain this phenomenon is given in Section 4.

3.2 Water Dumps

Figure 7 is a plot which shows Langmuir Probe and plasma wave measurements as a water dumping operation ended. The water dump had begun 35 minutes prior to the beginning of this plot. The end of the dump was characterized by an abrupt decrease in $\Delta N/N$ turbulence at 1654 GMT on day 83. A total of 93 lb of water was dumped at an average dump rate of 143 lb/hr. Panel 1 shows that during the water dump the Langmuir Probe recorded peak to peak voltage outputs which covered the full dynamic range of the instrument. At water shut-off the voltage output dropped to background level almost immediately which was the case with FES releases. However, the turbulence spectrum was much broader and extended to higher frequencies than that observed during FES operations as shown at the top of Figure 8. Plasma turbulence appeared to be increased 5 to 6 times over background at all frequencies 0-40 Hz.

Panel 2 of Figure 7 shows that the background noise at 0.178 kHz had been elevated slightly during the water dump. Figure 8 shows that, in fact, amplitudes at all frequencies up to about 3 kHz were elevated during the dump and amplitudes at all frequencies from 3 kHz to 100 kHz were suppressed. However, this spectrum depression was not seen in the FES releases as shown at the bottom of Figure 5. It should be noted that sunrise occurred at approximately 1651 GMT on day 83 in Figure 7 which is also a near ram condition. Even though the water dump had begun during nighttime conditions, peak to peak voltage outputs covering the full dynamic range from the Langmuir Probe were seen during most of the dump. A water dump that occurred on day 84 also showed similar effects. As seen in Figure 9, the beginning of this water dump at 0111 was evident only at the low frequencies, possibly because the bay was in a wake condition at this time and the Orbiter-generated noise was almost absent. The near lack of effects seen when the electrostatic noise was absent might imply that the effect of the water dump was not to generate the noise, but merely to amplify it if it was already present. Wave magnetic field, spacecraft potential and DC electric field were not affected by the water dumps, as was the case with FES releases. However, neutral pressure appeared to be affected only during that part of the orbit in which density was lowest, i.e. in wake. During this part of the orbit, neutral pressure readings were slightly greater with water being dumped than without it.

Smiddy et al. [1983] reported that on another shuttle mission during a water dump there was a $\Delta N/N$ increase at frequencies between 30 Hz and 503 Hz, an enhancement of electrostatic noise, a decrease in the spacecraft potential and an unchanged DC field. With the exception of a decrease in spacecraft potential, the results seem to be similar to that of the PDP.

3.3 Thruster Operations

Most of the plasma effects observed by the PDP during thruster firings are shown in Figure 10. This plot covers a 10-minute time period during the daytime (sunset occurred at 1540) with the payload bay in a near wake condition up to 1536 and during which several primary thrusters were fired. The PDP was in the bay at this time, but the effects were similar when the PDP was on the RMS. Note that the PDP provided a resolution of 1.6 seconds for most of these measurements which was considerably longer than the typical 80 msec firing of a primary thruster. When thrusters fired, the Langmuir Probe, which responded to variations in the electron density near the PDP, typically saw peak to peak voltage outputs which covered the full dynamic range of the instrument with frequency components in the 0 to 40 Hz range. At the same time the electric field at frequencies from 30 Hz to $\gtrsim$ 10 kHz was seen to increase by almost two orders of magnitude to 0.1 V/m. The 1 kHz channel, which is representative, is shown here. In the third and fourth panels, low energy ions (58.9 eV) and electrons (2.56 eV) are displayed which showed increases in flux with nearly every thruster firing up to 1536. Ions with energies up to 1 keV were seen with some thruster firings during the mission. Pressure spikes (Panel 5) were seen for several firings, with some producing increases up to 2 x 10^{-6} torr. Pressure spikes up to 10^{-4} torr were observed during certain thruster firing tests [Shawhan et al., 1984]. The resolution of the pressure gauge is 1.6 seconds which explains why many of the thruster firings showed no effect on pressure. In Panel 6, the potential of the PDP spheres with respect to the Orbiter ground (SC POT) shows a 2 volt change with each firing up to 1536. The electric field in the vicinity of the PDP (E_{DIFF}) was occasionally perturbed by as much as 1 V/m. Finally, Panel 7 shows that only primary thrusters were fired during this 10-minute time period. The firing of one thruster is indicated by a half line, with a full line indicating the firing of two or more thrusters at approximately the same time.

Although not shown in Figure 10, electron density was seen to increase by up to 3 orders of magnitude during a thruster firing. This effect was most pronounced, however, when the Orbiter was in a wake condition, i.e., low initial density ($< 10^3$ cm^{-3}). At higher electron density ($> 10^5$ cm^{-3}) and thus at a different attitude, a thruster firing tended to reduce the density. In addition, the Ion Mass Spectrometer which was flown on the PDP [Grebowsky et al. 1983] saw order of magnitude enhancements in H_2O^+ and NO^+ during thruster firings. NO^+ is a constituent of the plume (See Table 2). However, H_2O^+ must be produced by charge exchange between ambient O^+ and neutral water, which is a constituent of the plume. It should be noted that the lack of effects in the ion and electron data and in the electric field and spacecraft potential after 1536, was certainly a result of the payload bay coming out of wake and/or approaching the day/night terminator.

Vernier thruster firings produced the same effects as noted above, although in many cases the effects were minimized due to the smaller amount of gas being ejected. Some vernier thruster firings are noted on Figures 4, 7, and 9. The spikes seen in the $\Delta N/N$ data (panel 1) in Figures 4 and 7 and not noted as thruster firings are an instrumental effect and are in no way related to thruster firings. In addition, the turbulence spectrum and electric field spectral density spectrum for a vernier thruster firing are shown in Figure 11. These plots show that $\Delta N/N$ electron density irregularities during thruster firings were increased over background by as much as 10 times at all frequencies 0 to 40 Hz and background electrostatic noise stimulated by the thruster firing was most intense at frequencies below 10 kHz and peaked around 0.5 kHz. For more details on the effects of thruster firings during STS-3, see Murphy et al. [1983]. Similar effects to the ones mentioned above have been reported on other shuttle flights [Smiddy et al., 1983; McMahon et al., 1983; and Narcisi et al., 1983].

4. DISCUSSION AND CONCLUSIONS

The Space Shuttle provides an excellent platform from which to study the effects of chemical releases on the ionosphere as evidenced by measurements made by the PDP on STS-3. A summary of the effects observed by the PDP and possible explanations for them are as follows:

4.1 The flash evaporator system released vaporized water at a variable pulse rate. During this time, the plasma density irregularities ($\Delta N/N$) were increased by 3 to 30 times. In addition, the fast Fourier transform of the Langmuir Probe data showed a spectrum that rose steeply and peaked below 6 Hz, in agreement with the possible pulse rates, and extended to 40 Hz, which was the limit of the detector. At the same time, the plasma wave data (Figure 4) showed an enhancement in the background Orbiter-generated electrostatic noise at frequencies 30 Hz to 31 kHz and as high as 100 kHz depending on the orbit and attitude characteristics. Figure 6a illustrates the periodic variation in energetic ion particle flux which was consistent with an FES pulse rate of 1.8 Hz. The fact that this variation exists is evidence that the time scale of the onset of plasma modification by the water vapor was fast. For releases of only a few grams of water vapor per pulse, the plume dispersed rapidly (within a few seconds) which reasonably explains the decay time of any plasma effect. The fast (< 1 sec) onset time is consistent with the O^+/H_2O charge exchange reaction which occurs at the kinetic rate (2.4×10^{-9} cm^3/sec) [Ferguson, 1973]. The fact that this charge exchange reaction occurs 1000 times faster than the dominant F-region O^+ loss process [Mendillo et al., 1975] causes it to dominate the local ionospheric chemistry.

Additional evidence of the rapidity of the plasma/H_2O interaction is provided by the Lagopedo ionospheric depletion experiments conducted in September 1977 [Pongratz, 1978; Sjolander and Szuszczewicz, 1979] which involved releasing water vapor into the F-region of the ionosphere. These experiments comfirmed that charge exchange and dissociative recombination took place shortly after the releases and persisted for nearly a half hour. The hole was nearly isotropic and Gaussian in profile with a thickness at half depletion of 60 km.

Day vs. night effects are summarized by Bernhardt [1976] when he states that water vapor is acceptable as a daytime release from the Shuttle, but loses efficiency at creating a hole in the plasma at night due to its condensation into ice crystals upon release. Zinn and Sutherland [1980] pointed out that such ice crystals have an evaporative lifetime of about 5 minutes which is long enough for them to traverse a great distance (km) before they evaporate. This would seem to indicate that the PDP should see little or no change in electron or ion flux during night releases. This prediction can neither be confirmed nor denied for the case of FES operation since not enough data were taken under appropriate conditions.

During the time the PDP was on the RMS (see Figures 6a and 6b), the flash evaporator was releasing 0.6 grams of water vapor each time it pulsed. This means that approximately 4 x 10^{22} water vapor molecules were being released every second. Because this release is pulsed and occurs in vapor form, the FES should be very efficient at creating a plasma hole at F-region altitudes. The PDP data taken during the daytime support this. Section 4.4 further examines the plasma/H_2O physics, seeking to understand the phenomenon which could take place after the charge exchange reaction occurs.

4.2 Plasma effects noted during water dumps include increased pressure in the shuttle wake, plasma turbulence increases at all frequencies up to 40 Hz and enhancement of the background Orbiter-generated electrostatic noise at frequencies from 30 Hz to approximately 3 kHz and a suppression at frequencies above 3 kHz. This observation is consistent with a theory proposed by Papadopoulos and Ko [1983], which attributes the broadband electrostatic noise and glow phenomena to lower hybrid drift instabilities driven by plasma density gradients. When the bay is in ram and thus the density is very high ($\sim 10^6$ cm^{-3}), there appears to be a critical frequency which determines whether the background Orbiter-generated electrostatic noise is enhanced or suppressed. PDP data show this critical frequency to be approximately 3-4 kHz, which is near the lower hybrid resonance frequency. Electromagnetic noise was recorded during the large liquid water release at 105 km on the second flight test of the Saturn booster in 1962 [Debus, 1964]. Signal strength measurements during that release at frequencies ranging from 10 kHz to 230 MHz indicated that radio frequency waves generated by electrical discharge were associated with the cloud that developed after the release.

It is expected that liquid water would be less efficient at creating a plasma hole in the ionosphere than vaporized water since at release, only a small amount would be vaporized and the remainder would become ice particles as was the case with the Saturn booster experiment [Debus, 1964]. In view of the PDP measurements and the releases which were recorded during STS-3, it is not possible to state whether or not liquid water was less efficient at creating a hole than vaporized water.

4.3 Finally, a summary of the effects of thruster firings includes the following: an increase in plasma turbulence over the 0 to 40 Hz spectrum, increases or decreases in electron density which were orbit dependent, enhancement of the background electrostatic noise from 30 Hz to above 10 kHz, neutral pressure spikes up to 10^{-4} torr, perturbations to the spacecraft potential by as much as 2 volts and to the DC electric field by as much as 1 V/m primarily under wake conditions, and occasional changes in the low energy ion and/or electron fluxes. Once again the theory by Papadopoulos and Ko [1983] would explain the enhancement in broadband electrostatic noise. Ion-atom interchange and subsequent dissociative recombination could explain the particle flux changes, but not the production of hot ions. Perturbation to the spacecraft potential and DC electric field could have an explanation rooted in the qualitative description of plasma/H_2O physics contained in the next section.

4.4 Further examination of the physics which could take place in a cloud of water (from FES releases, water dumps or thruster operation) released into the ionosphere hints at some possible explanations for the observed phenomena.

Charge exchange between the ambient O^+ ions moving at 8 km/s relative to the H_2O molecules in a plume produces stationary H_2O^+ ions (in the reference frame of the plume) and fast O atoms which are rapidly lost from the plume. Since in this moving frame there is a motional electric field ($\underline{E} = -\underline{V} \times \underline{B} \approx 2$ mV/m), the newly created ions experience a force $\underline{F} \alpha \underline{E} + \underline{V} \times \underline{B}$. The subsequent motion is cycloidal, thus the guiding centers of the H_2O^+ ions are displaced in the direction of the electric field. This displacement contributes a current, the so called pick-up current [Goertz, 1980], which will lead to a buildup of charge at the end of the plume. These charges will partially screen the motional electric field from the inside of the magnetic flux tube connected to the plume. The electric field in the plume must then be calculated by balancing the pick-up current with field aligned currents carried by Alfven waves [Goertz, 1980].

It can be shown that if the plume is fairly dense, $N_{H_2O} \gtrsim 10^{14}$ cm^{-3}, (which would occur during the first few tenths of a second after an FES release) the electric field in the plume flux tube (PFT) is significantly reduced.

Ambient O atoms enter this nearly field-free region and are photoionized (at a rate of 10^3 cm^{-3} S^{-1}) and form a ring distribution in velocity space which is unstable to electrostatic waves [Harris, 1959]. It is known that such a ring distribution will quasilinearly diffuse in velocity space with a rapid formation of a high energy tail [Kulygin et al., 1971].

It needs to be investigated quantitatively what the plasma density and composition is in the PFT and whether the O^+ ions stay in the plume long enough to be affected by charge exchange with the H_2O molecules. If charge exchange occurs before the O^+ ions leave the plume along magnetic field lines, the ring distribution may not be strong enough to cause rapid growth of electrostatic waves and heating.

Further measurements by the Plasma Diagnostics Package coordinated with ground-based observations, both of which are investigations of the Spacelab-2 mission scheduled for a March 1985 launch, will provide an opportunity to further study the plasma/H_2O interactions through orbiter chemical releases. In situ measurements by the PDP will be extended to the regime around the Orbiter far beyond the reaches of the RMS (the PDP will be released as a free-flying satellite) and coordinated with simultaneous ground observations to provide much more extensive input to theory. Further, it is hoped that the measurements obtained by the PDP on Spacelab-2 will aid other experimenters who plan to use the Space Shuttle as an experimental platform.

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TABLE 1.
STS-3 FES WATER USAGE

Start Time (Day/GMT)	Duration (HR:MIN)	Type	Location of PDP	Usage lb.
82/0117:58	0:02	Topping	Pallet	< 1
85/1230:00	2:32	Topping	RMS[a]	58
85/1501:44	1:30	Topping	RMS	34
86/2010:00	0:01	Topping	Pallet	< 1

[a]Remote Manipulator System Arm

TABLE 2

THRUSTER PLUME CHARACTERISTICS

Primary Thruster (PRCS)	Vernier Thruster (VRCS)
$\dot{m}$ = 1419.8 g/s/engine	$\dot{m}$ = 40.8 g/s/engine

Composition - Neutrals

Species	Mol. Wt.	Mole Fraction
H_2O	18	0.328
N_2	28	0.306
CO_2	44	0.036
O_2	32	0.0004
CO	28	0.134
H_2	2	0.17
H	1	0.015
$MMH-NO_3$	46	0.002

Composition - Dominant Ions

NO^+	30	1.7×10^{-8}
CO_2^-	44	2.7×10^{-10}
OH^-	17	4.3×10^{-10}
Electrons	--	2.4×10^{-9}

Total Number of Neutrals and Ions Ejected

	Number of Neutrals	Number of Ions (Electrons)
VRCS		
Typical[a]	1.3×10^{25}	3.1×10^{17}
Longest[b]	1.7×10^{26}	3.8×10^{18}
PRCS		
Typical[c]	9.2×10^{24}	2.1×10^{17}
Longest[d]	5.5×10^{25}	1.2×10^{18}

[a] Based on 2 firings ejecting 163g over 2 sec.

[b] Based on 14 firings ejecting 2100g over 30 sec.

[c] Based on 1 firing ejecting 114g over 80 msec.

[d] Based on 5 firings ejecting 682g over 720 msec.

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FIGURE CAPTIONS

Fig. 1 Plasma Diagnostics Package in pallet location as part of the Office of Space Science first shuttle payload. The various wave sensors are identified on the Plasma Diagnostics Package.

Fig. 2 Sketch of the orbit of the third Space Shuttle flight during the nose-to-sun attitude with the Orbiter roll at 2 times the orbit rate leading to a ram condition near the ascending node and a wake condition at the descending node.

Fig. 3 Identification of the flash evaporator system vents which release water vapor, the water relief vent which releases liquid water and the maneuvering thrusters (primary and vernier) which release many neutrals and ions as shown in Table 2.

Fig. 4 Effects of a flash evaporator system release at 0118. The top panel shows that the Langmuir Probe registered peak-to-peak voltage outputs covering the full dynamic range of the instrument. The bottom panel shows the peak intensity of 1 kHz electric waves rose substantially over the background during the release while the average did not. A vernier thruster firing is also pointed out at 0116.

Fig. 5 $\Delta N/N$ plasma turbulence spectrum and electric field spectral density for the flash evaporator system release shown in Fig. 4. The $\Delta N/N$ spectrum rose steeply below 6 Hz and peaked at about 0.5 Hz which was the pulse rate of the flash evaporator at this time. The bottom plot shows that background electrostatic noise was enhanced at all frequencies up to about 31 kHz. Zero dB corresponds to 1 $V^2/M^2/Hz$.

Fig. 6a Ion energy spectrum during a flash evaporator system release while the Plasma Diagnostics Package was on the Remote Manipulator System. The spectrum shows a beat frequency between the sweep time of the ion detector and the pulse rate of the flash evaporator. Ions with energies up to about 1 keV are seen at this time (see discussion in 4.1). The bottom panel shows the 92.1 eV energy channel plotted to show the flux variation with time.

Fig. 6b Plasma density fluctuations during an FES release while the PDP was on the Remote Manipulator System (see Fig. 6a). The data show 11 cycles in 6.1 sec for a periodic variation at 1.8 Hz, which other data and modelling show to be the pulse rate of the flash evaporator at this time.

Fig. 7 Effects of a water dump that ended at 1654. The top panel shows that the Langmuir Probe registered peak-to-peak voltage outputs covering the full dynamic range of the instrument during most of the dump. The bottom panel shows that 1 kHz electric waves were elevated over background during the dump. Vernier thruster firings are also pointed out at 1655 and 1658.

Fig. 8 $\Delta N/N$ plasma turbulence spectrum and electric field spectral density for the water dump shown in Fig. 7. The $\Delta N/N$ spectrum was elevated over background at all frequencies from 0 to 40 Hz. The bottom plot shows that background electrostatic noise was enhanced at all frequencies up to about 3 kHz and suppressed at all frequencies above that. Zero dB corresponds to 1 $V^2/M^2/Hz$.

Fig. 9 A 30-minute plot of VLF electric field data which shows that a water dump began at about 0111. Effects are noticed only at low frequencies since the bay of the Orbiter was in a wake condition. Vernier thruster firings are also pointed out.

Fig. 10 A 10-minute sample plot of measurements made by the Plasma Diagnostics Package indicating the pressure and plasma effects of primary thruster firings. Some of the effects disappeared as the bay came out of a near wake condition at about 1536.

Fig. 11 $\Delta N/N$ plasma turbulence spectrum and electric field spectral density for the vernier thruster firings shown in Fig. 4. The $\Delta N/N$ spectrum was elevated over background at frequencies from 0 to 40 Hz. The bottom plot shows that electrostatic noise was stimulated at all frequencies up to about 10 kHz. The spectrum peaked at about 0.5 kHz. Zero dB corresponds to 1 $V^2/M^2/Hz$.

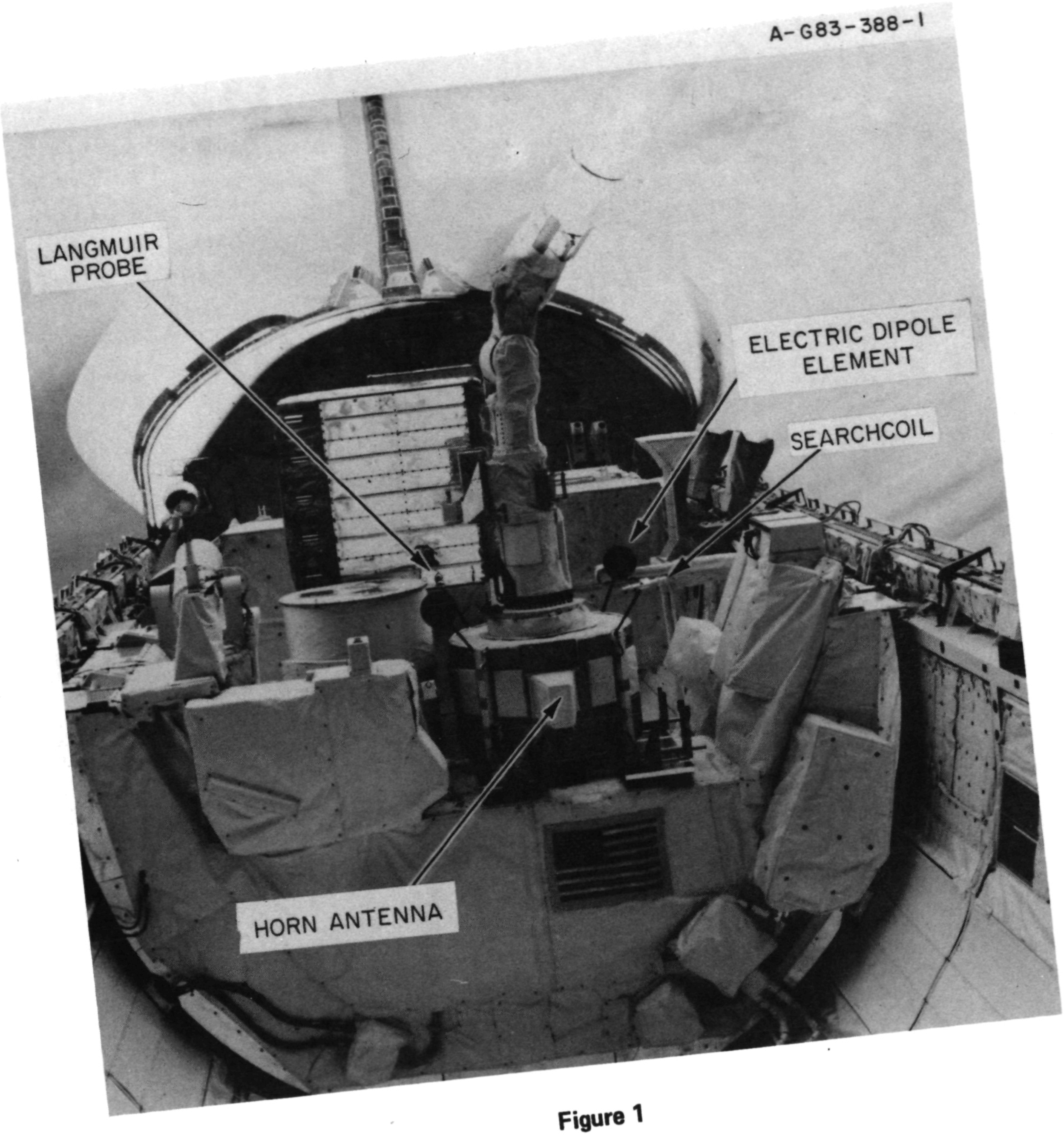

A-G83-388-1
LANGMUIR PROBE
ELECTRIC DIPOLE ELEMENT
SEARCHCOIL
HORN ANTENNA

Figure 1

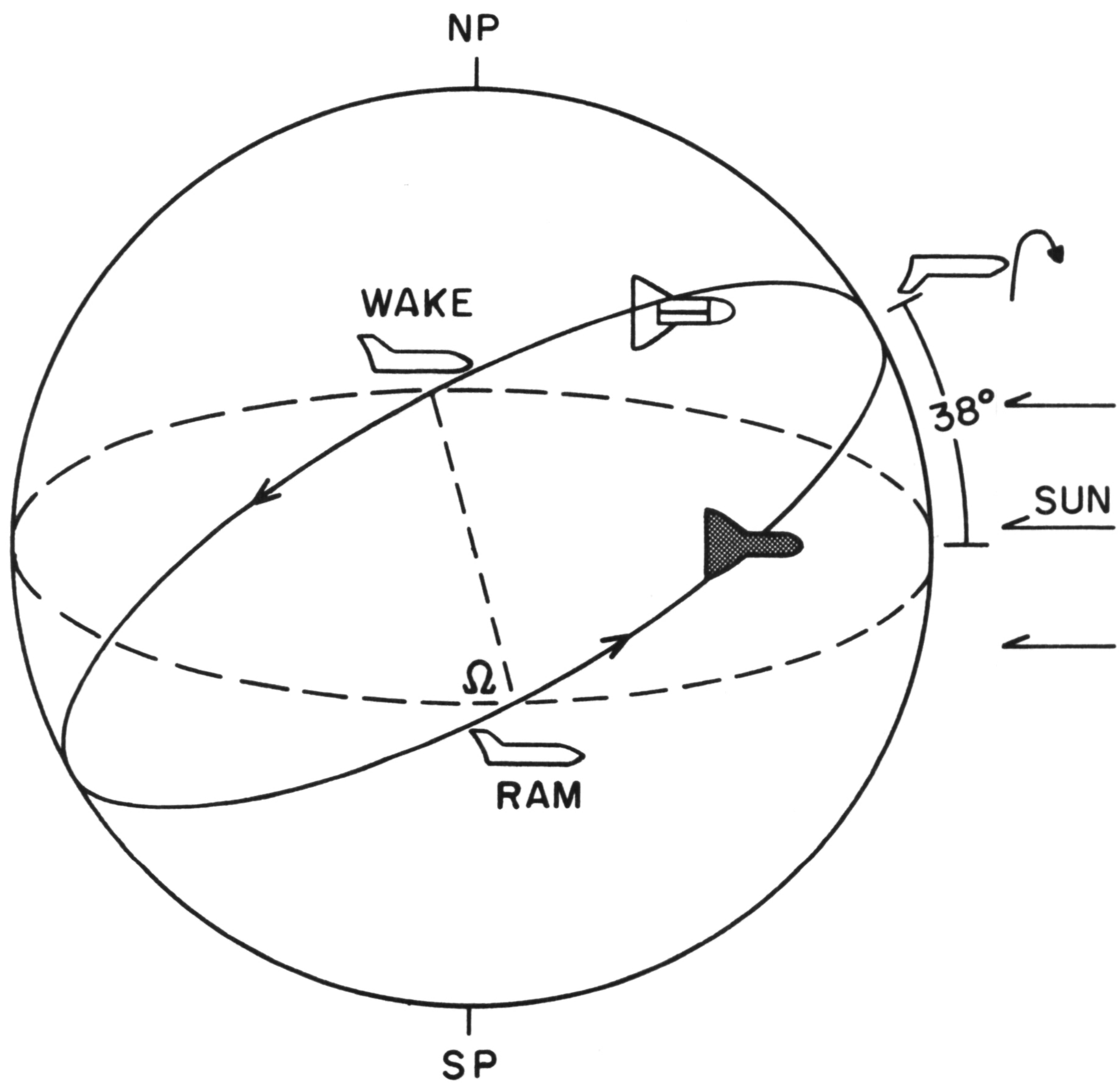


Figure 2

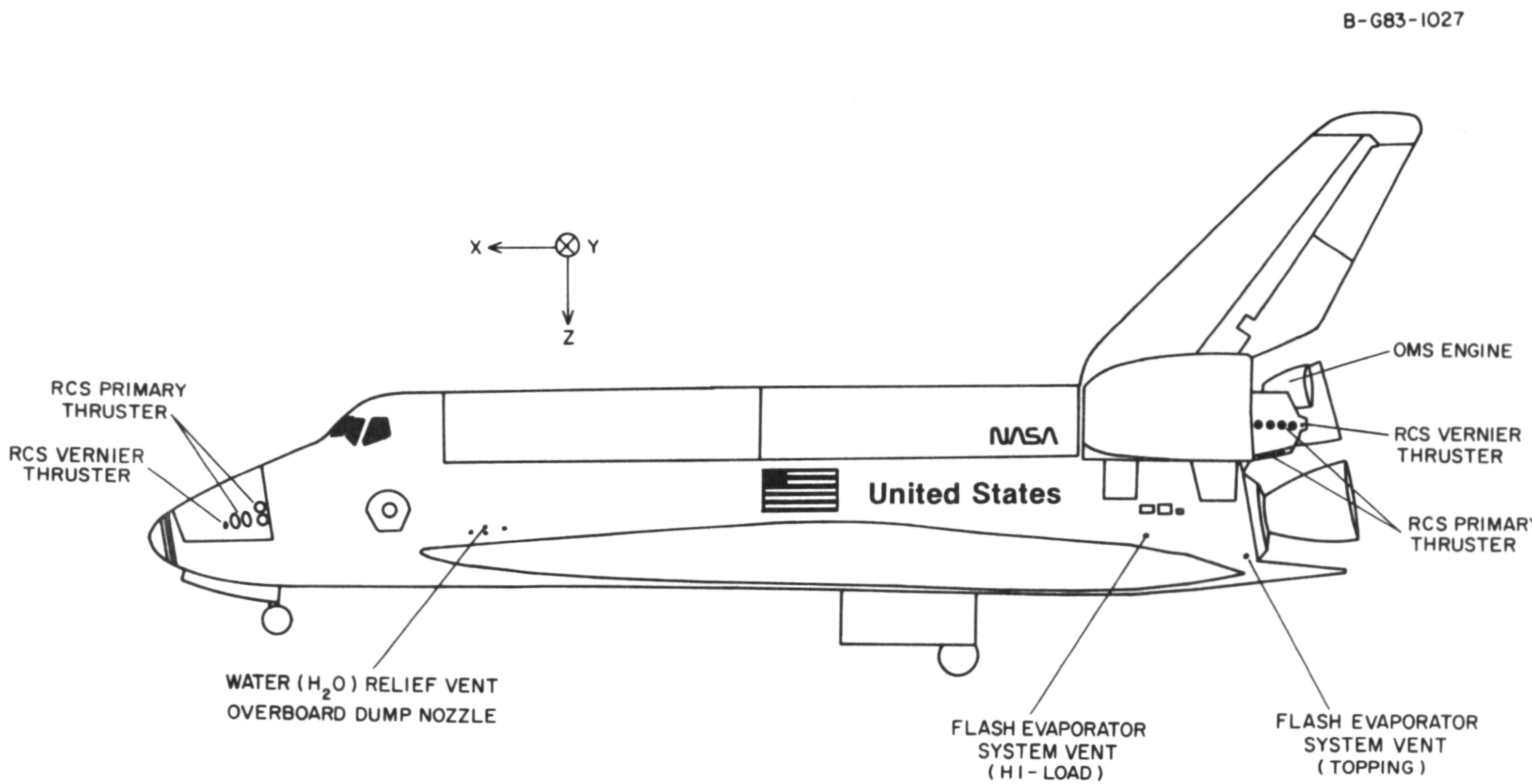

B-G83-1027
X
Y
Z
RCS PRIMARY THRUSTER
RCS VERNIER THRUSTER
NASA
United States
WATER (H_2O) RELIEF VENT OVERBOARD DUMP NOZZLE
FLASH EVAPORATOR SYSTEM VENT (HI-LOAD)
FLASH EVAPORATOR SYSTEM VENT (TOPPING)
OMS ENGINE
RCS VERNIER THRUSTER
RCS PRIMARY THRUSTER

Figure 3

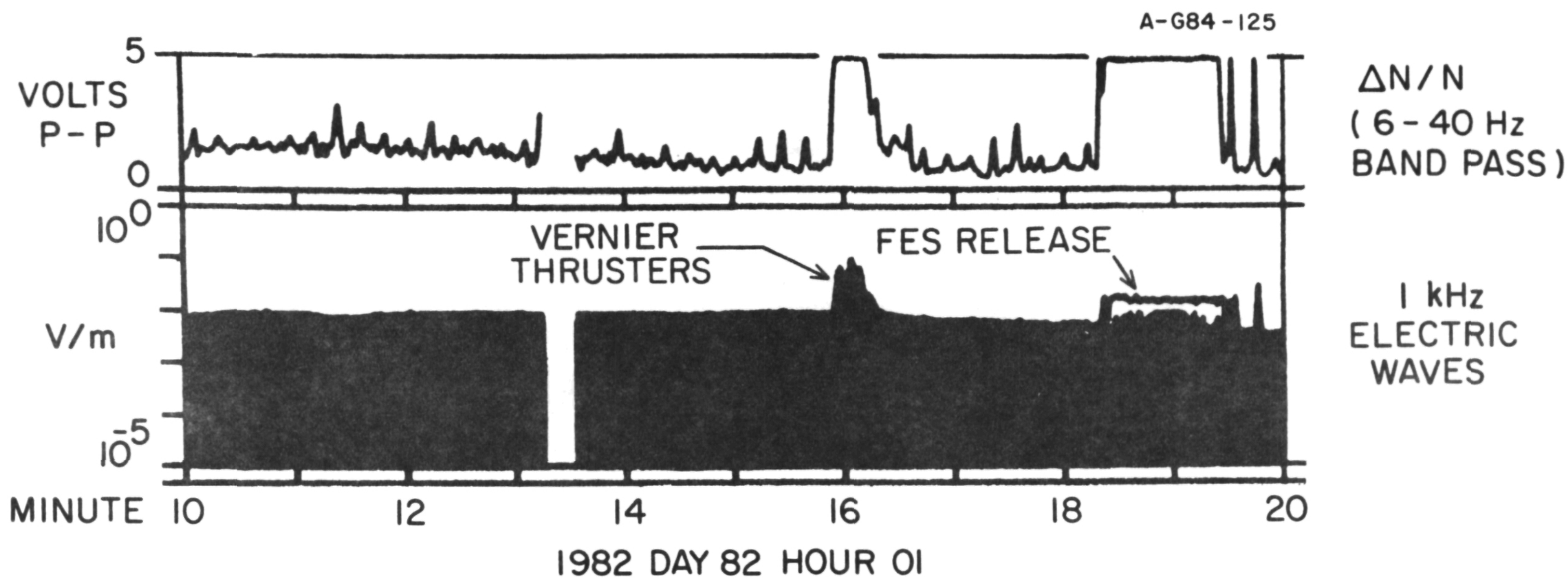

A-G84-125
5
VOLTS
P-P
0
ΔN/N
(6-40 Hz
BAND PASS)
10^0
V/m
10^-5
VERNIER
THRUSTERS
FES RELEASE
1 kHz
ELECTRIC
WAVES
MINUTE 10
12
14
16
18
20
1982 DAY 82 HOUR 01

Figure 4

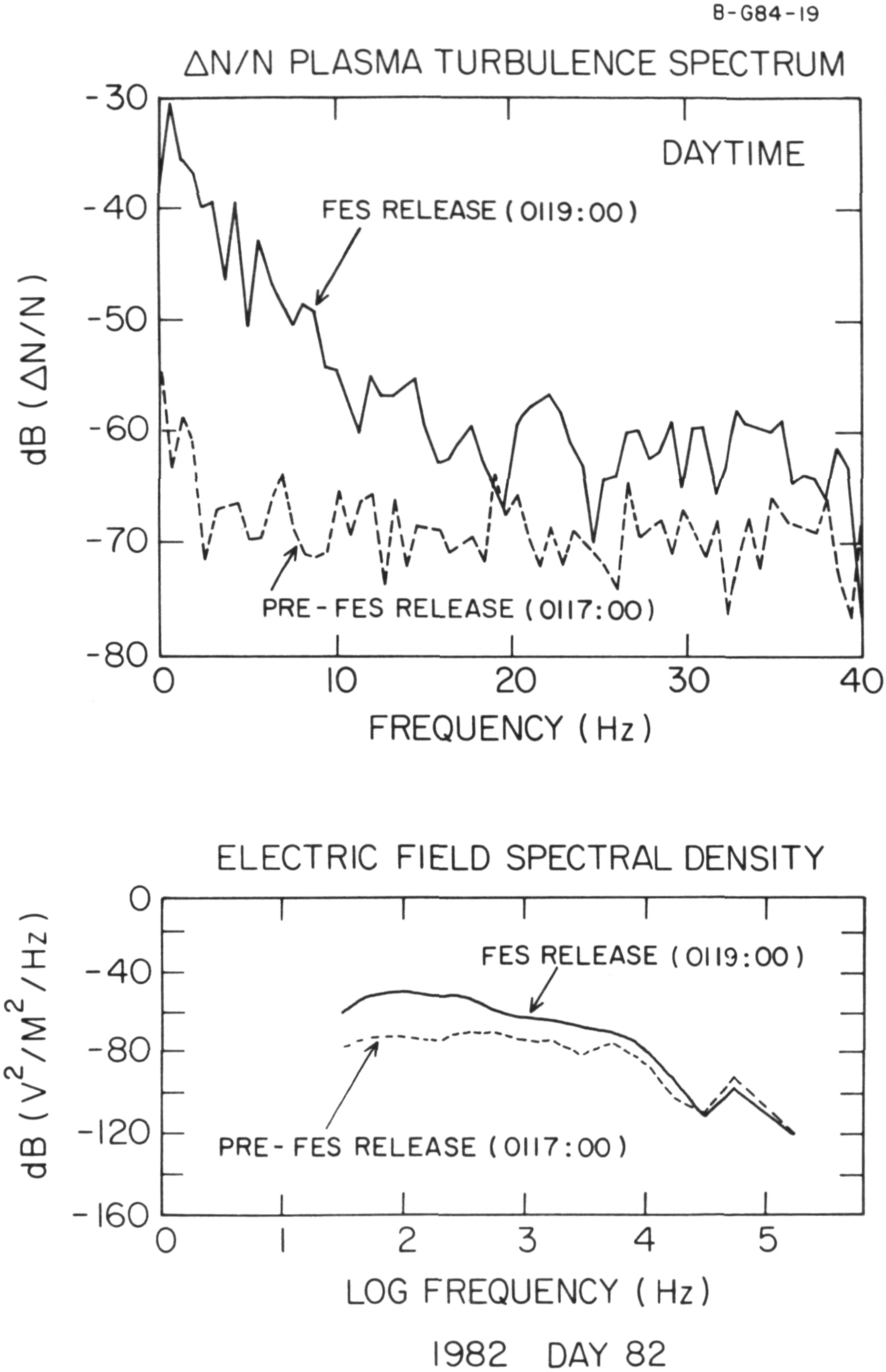

B-G84-19
ΔN/N PLASMA TURBULENCE SPECTRUM
DAYTIME
FES RELEASE (0119:00)
PRE-FES RELEASE (0117:00)
dB (ΔN/N)
-30
-40
-50
-60
-70
-80
0
10
20
30
40
FREQUENCY (Hz)
ELECTRIC FIELD SPECTRAL DENSITY
FES RELEASE (0119:00)
PRE-FES RELEASE (0117:00)
dB (V²/M²/Hz)
0
-40
-80
-120
-160
0
1
2
3
4
5
LOG FREQUENCY (Hz)
1982 DAY 82

Figure 5

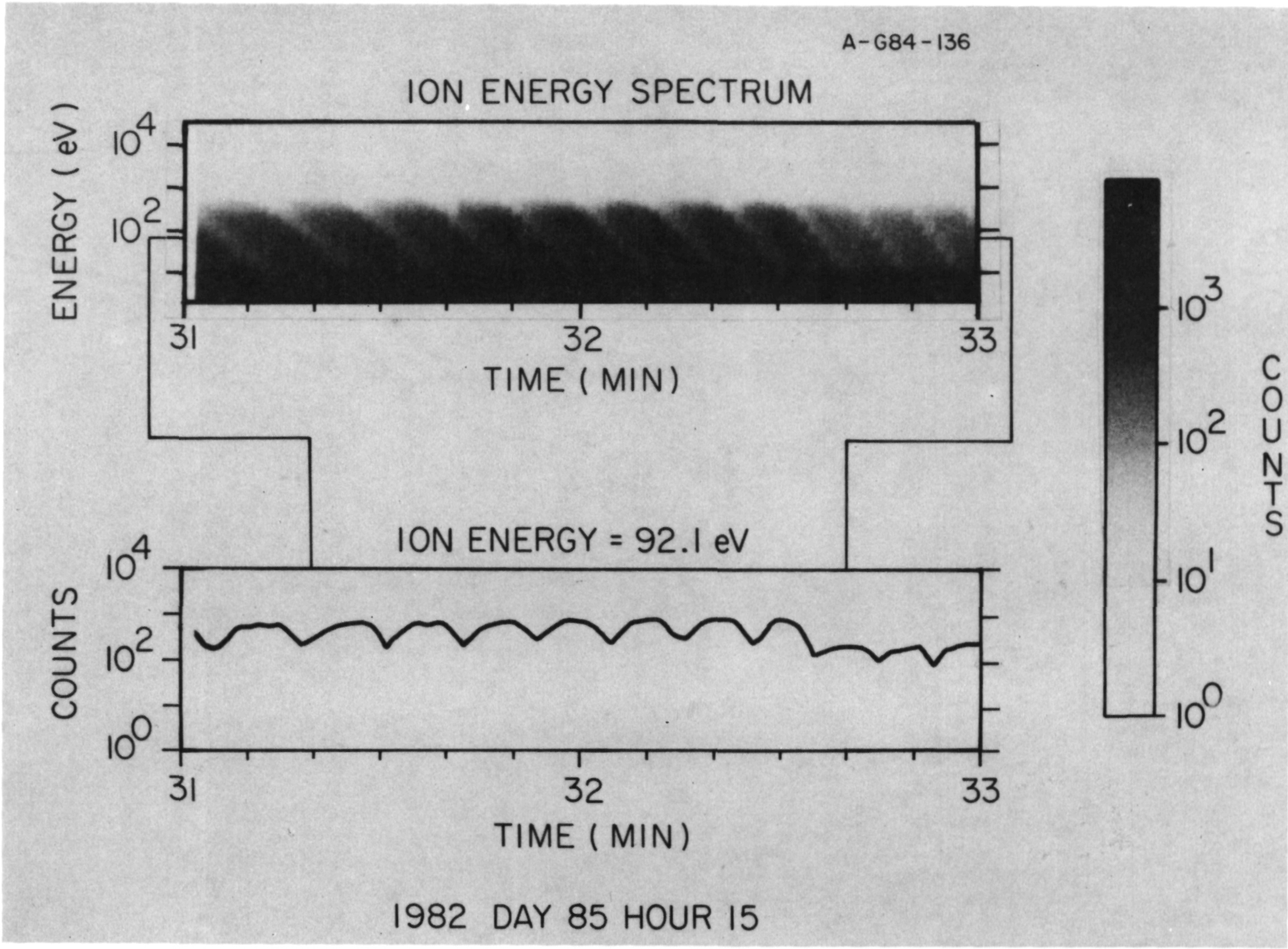

A-G84-136
ION ENERGY SPECTRUM
ENERGY (eV)
10^4
10^2
31
32
33
TIME (MIN)
ION ENERGY = 92.1 eV
COUNTS
10^4
10^2
10^0
31
32
33
TIME (MIN)
10^3
10^2
10^1
10^0
COUNTS
1982 DAY 85 HOUR 15

Figure 6a

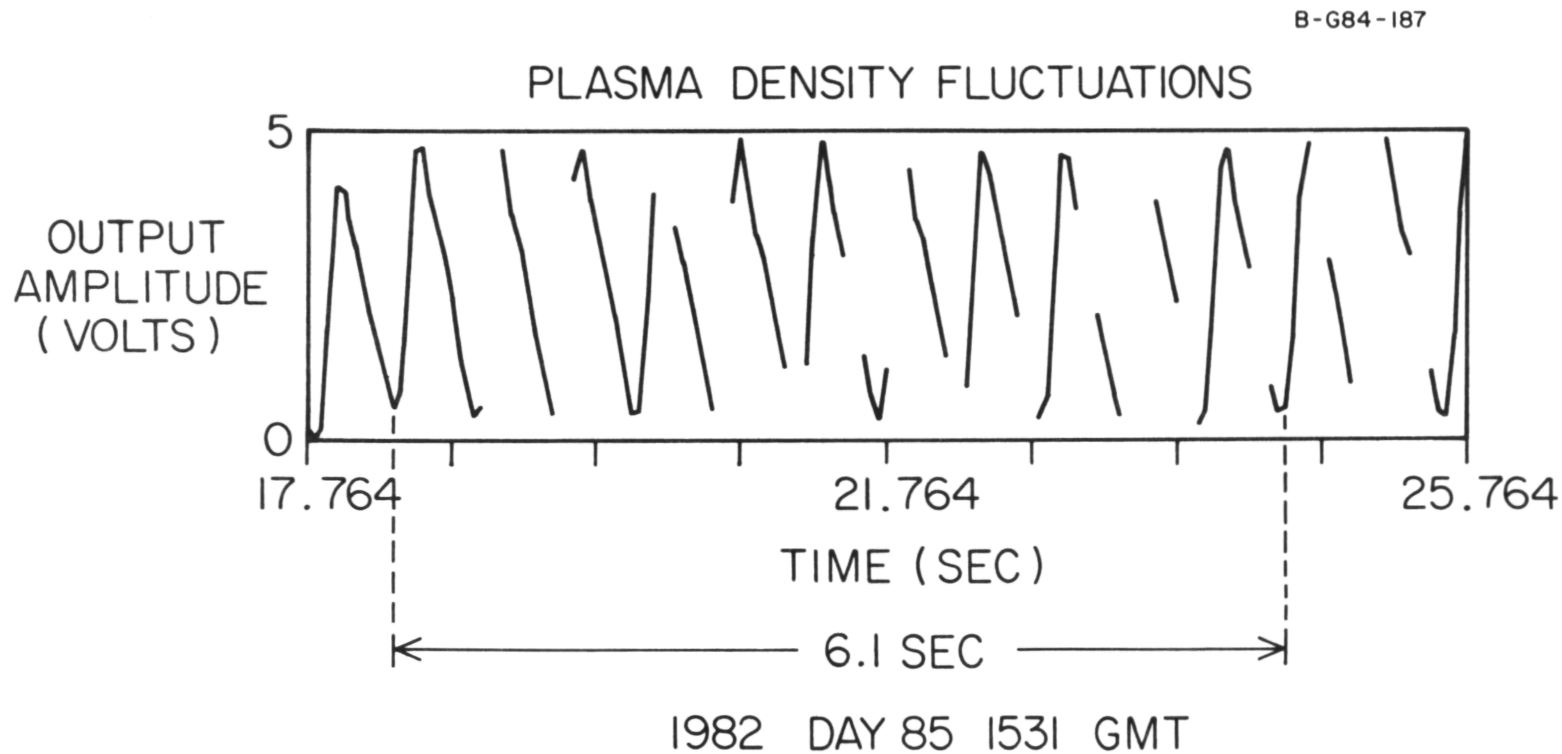

B-G84-187
PLASMA DENSITY FLUCTUATIONS
OUTPUT AMPLITUDE (VOLTS)
5
0
17.764
21.764
25.764
TIME (SEC)
6.1 SEC
1982 DAY 85 1531 GMT

Figure 6b

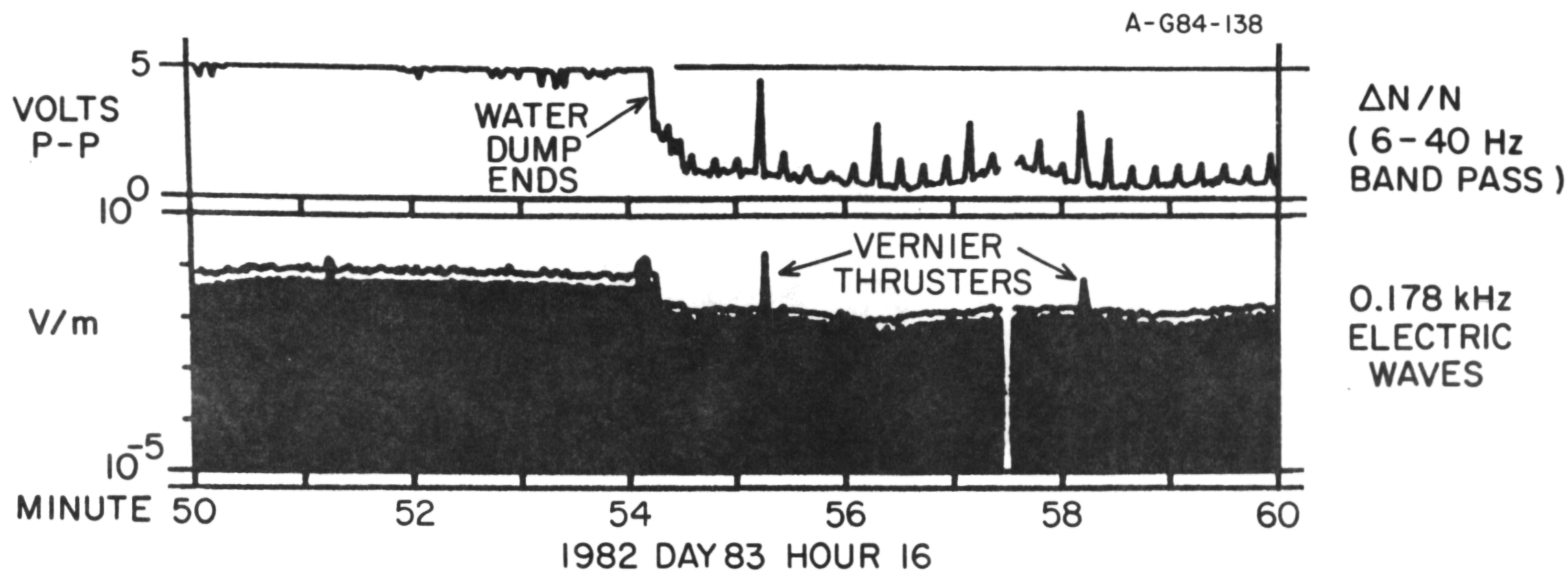

A-G84-138
5
VOLTS
P-P
10^0
WATER
DUMP
ENDS
ΔN/N
(6-40 Hz
BAND PASS)
VERNIER
THRUSTERS
V/m
0.178 kHz
ELECTRIC
WAVES
10^{-5}
MINUTE 50
52
54
56
58
60
1982 DAY 83 HOUR 16

Figure 7

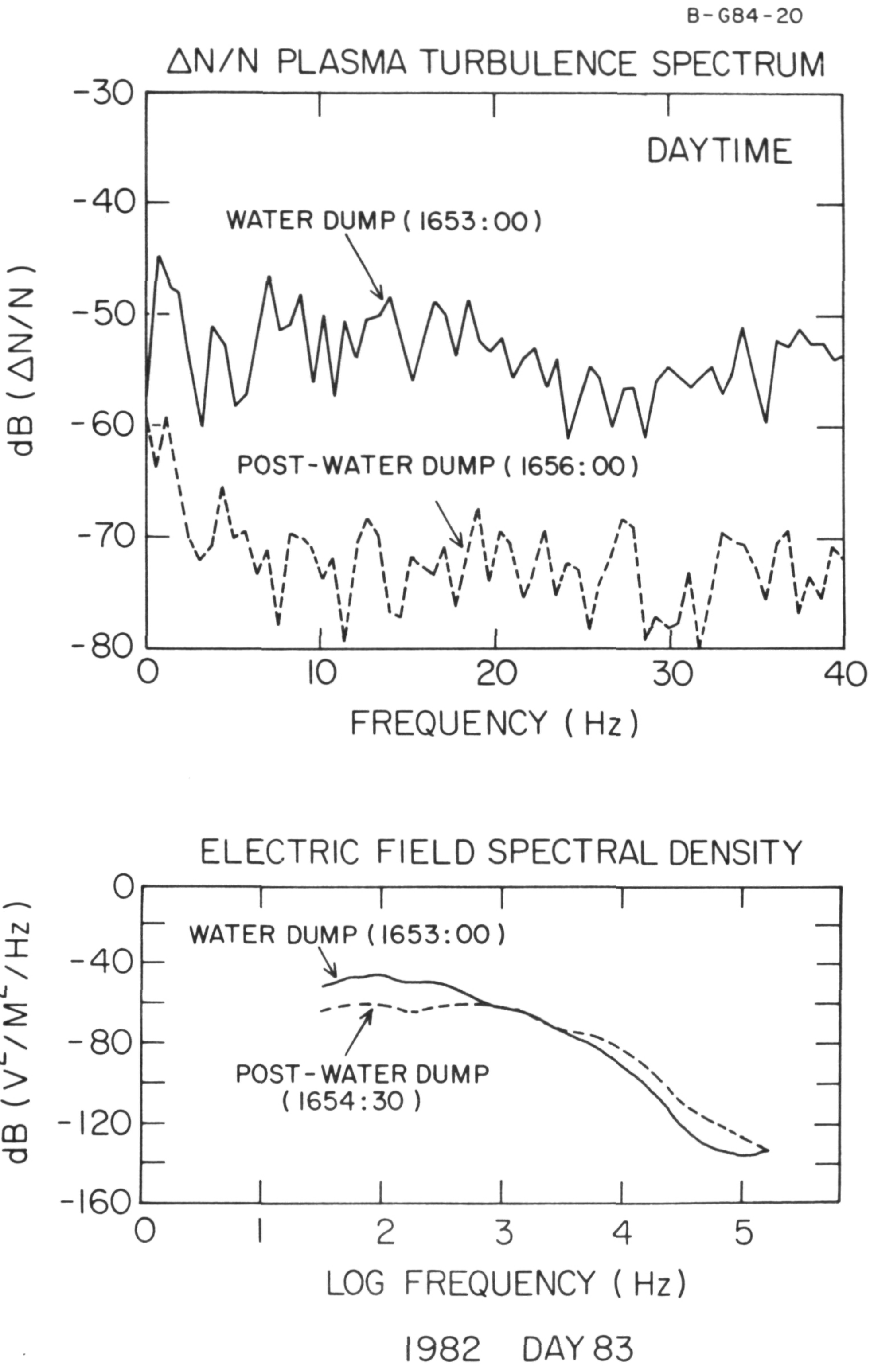

B-G84-20
ΔN/N PLASMA TURBULENCE SPECTRUM
DAYTIME
WATER DUMP (1653:00)
POST-WATER DUMP (1656:00)
dB (ΔN/N)
-30
-40
-50
-60
-70
-80
0
10
20
30
40
FREQUENCY (Hz)
ELECTRIC FIELD SPECTRAL DENSITY
WATER DUMP (1653:00)
POST-WATER DUMP
(1654:30)
dB (V²/M²/Hz)
0
-40
-80
-120
-160
0
1
2
3
4
5
LOG FREQUENCY (Hz)
1982 DAY 83

Figure 8

C-G84-123

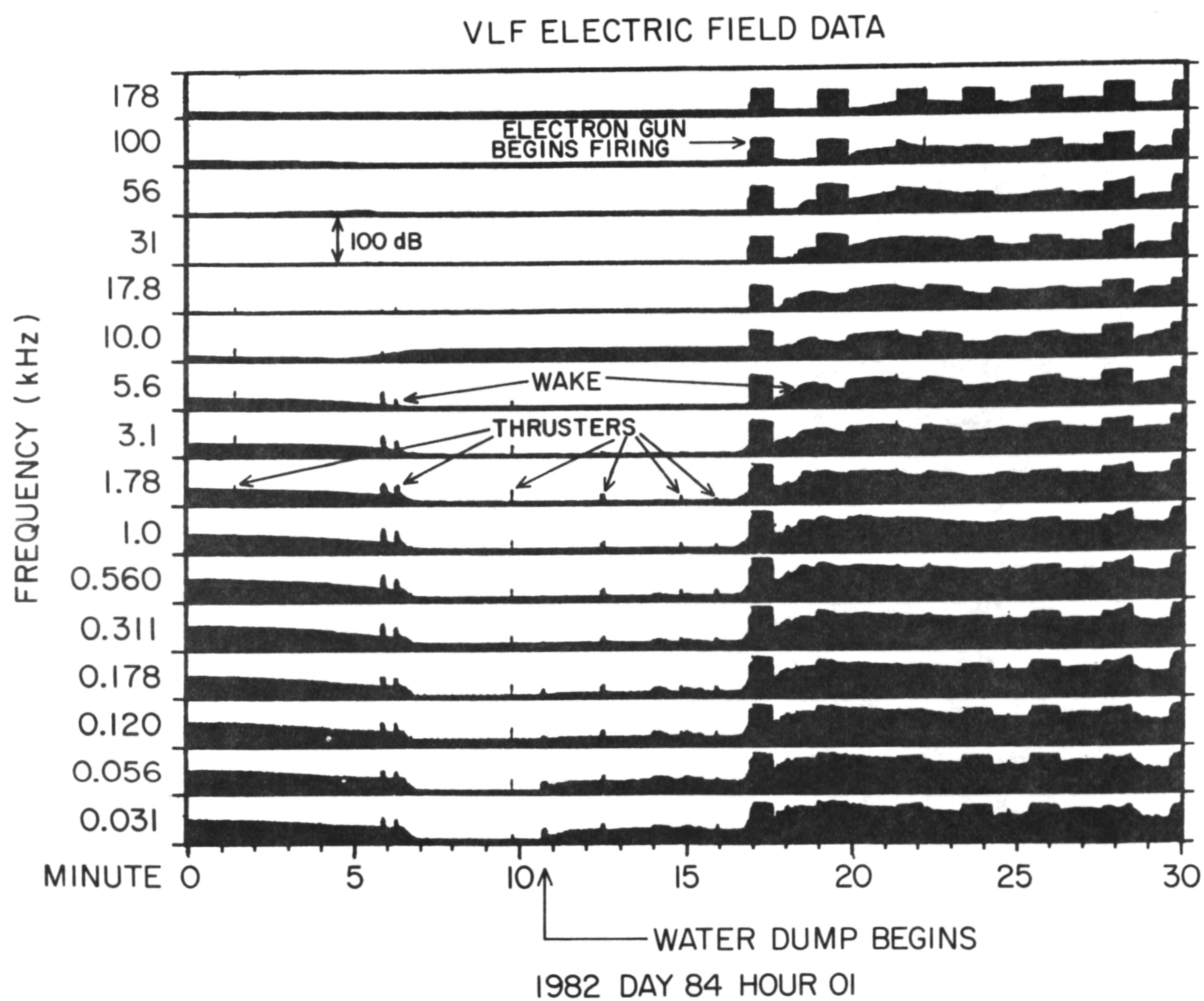


Figure 9

C-G84-124

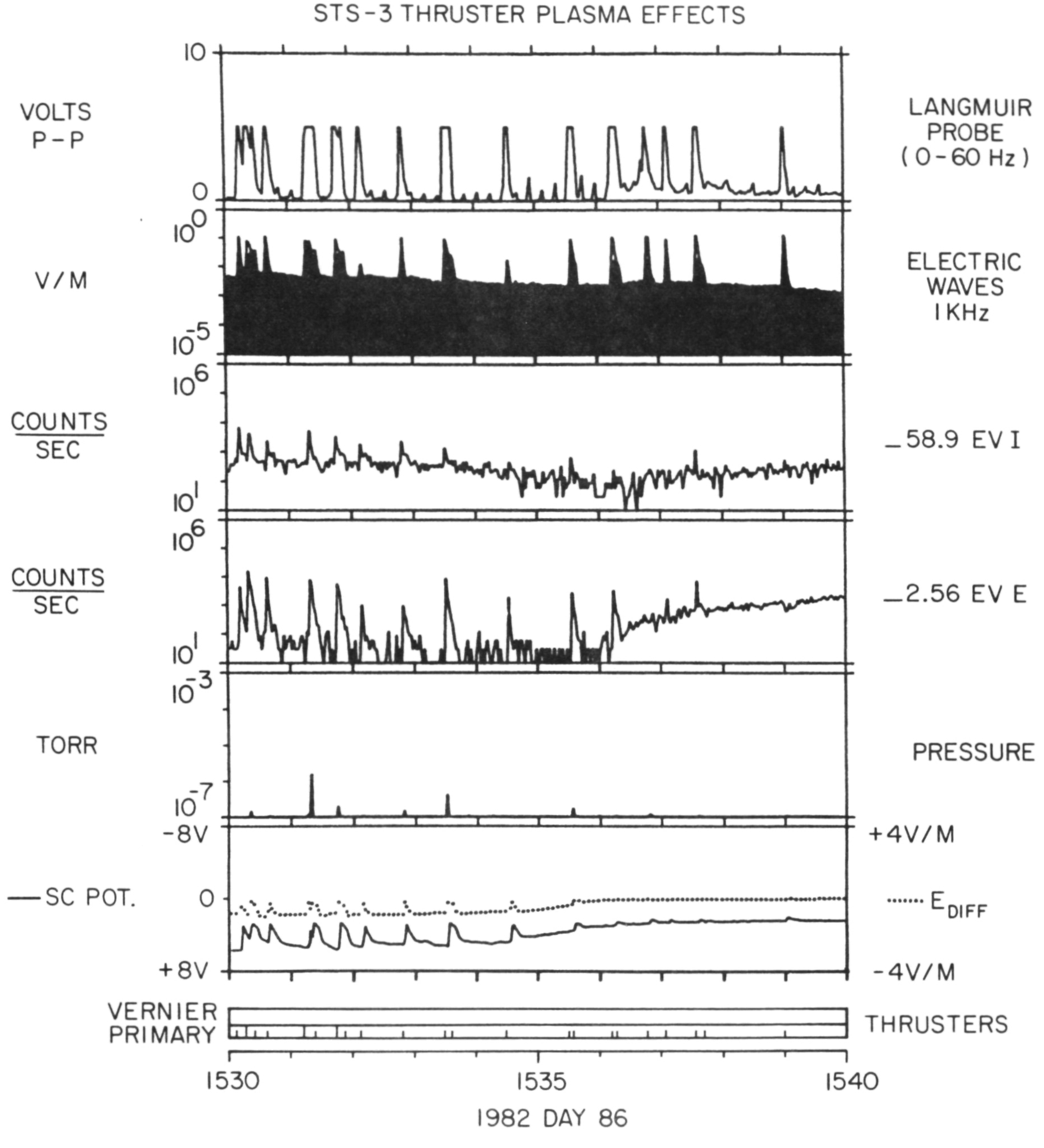
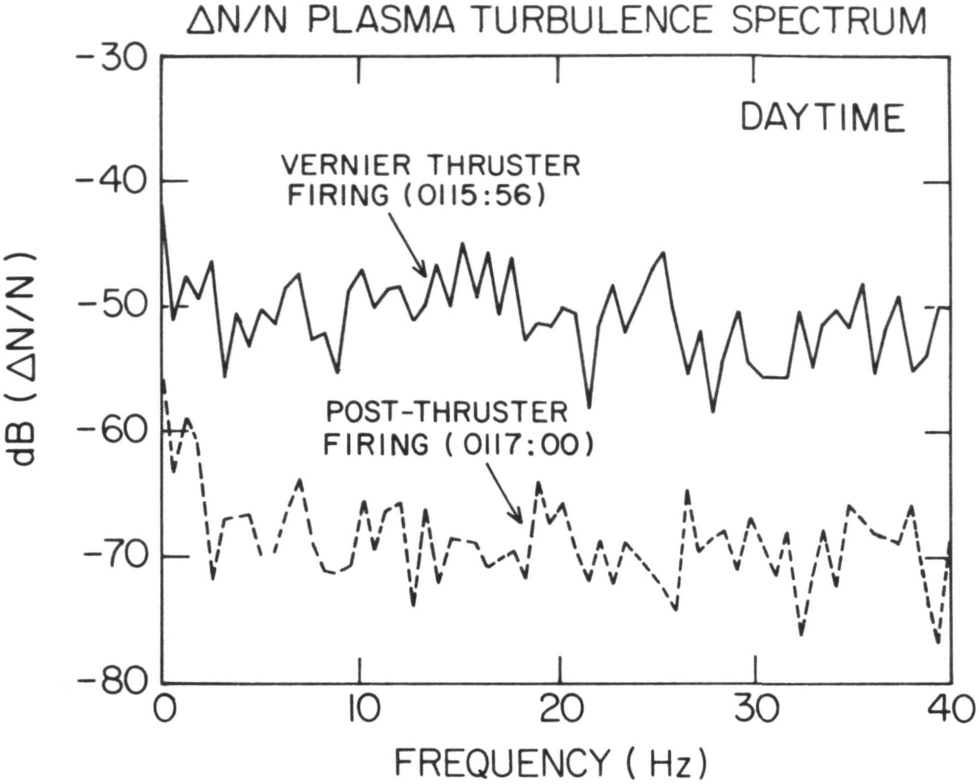
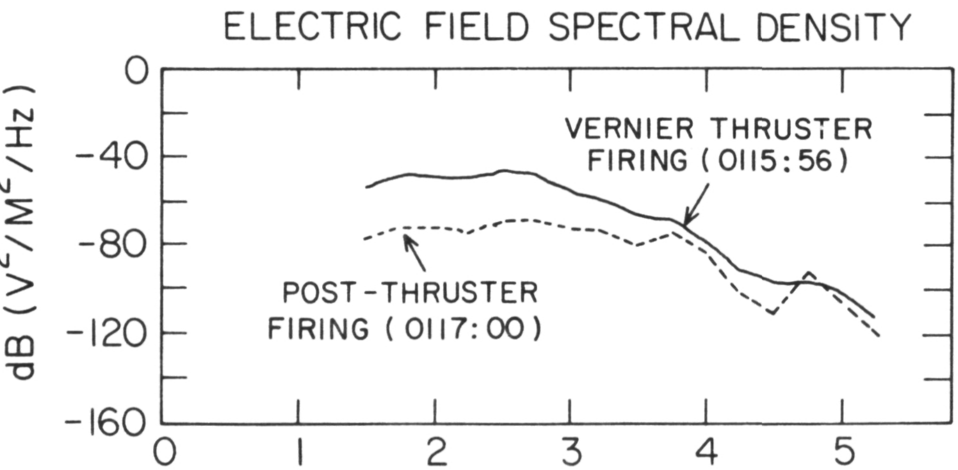


Figure 10

B-G84-21





1982 DAY 82

Figure 11