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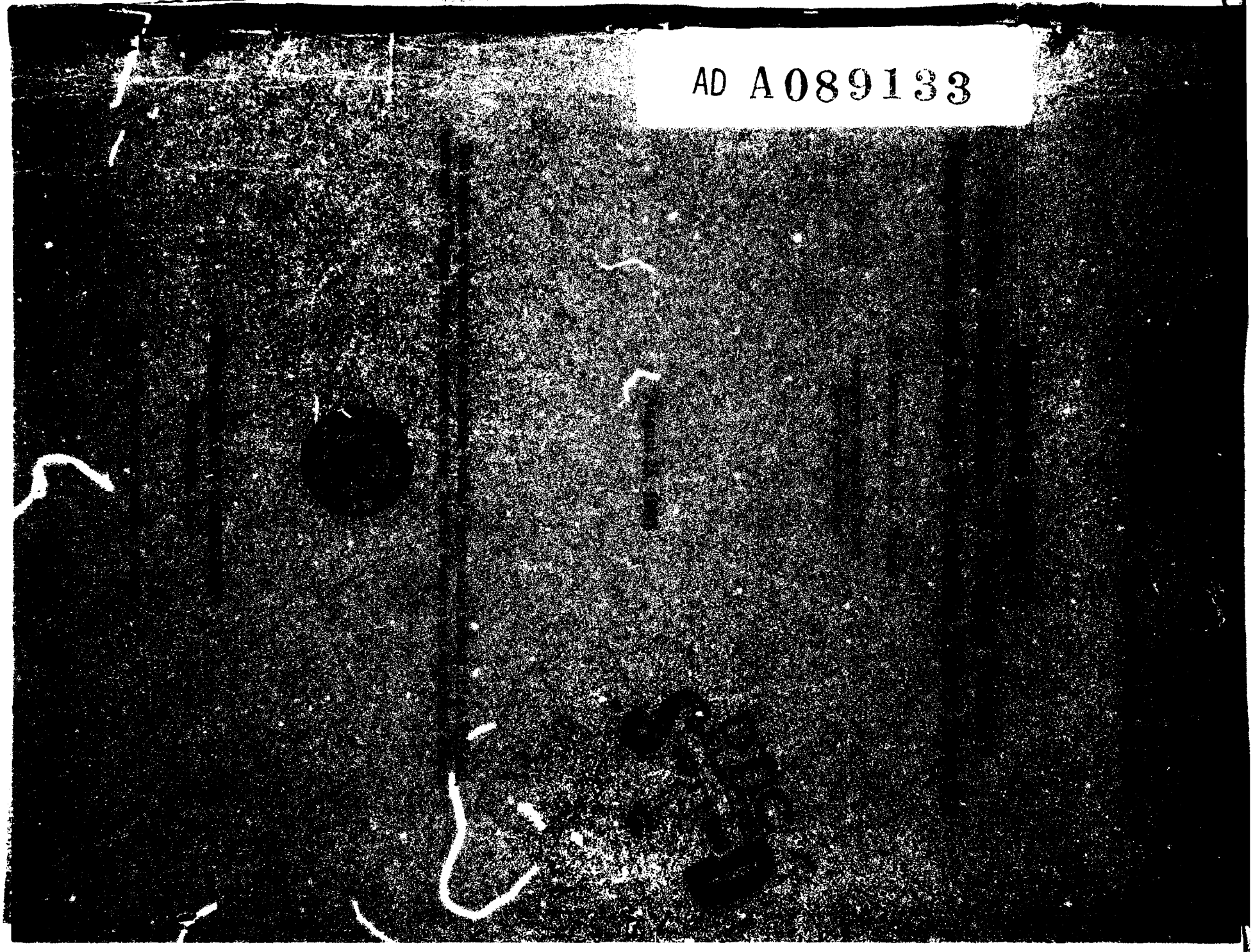

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The NRL pulsed plasma probe experiment was successfully flown on each of the two PLUMEX rockets during July 1979. The experiment provided direct measurements of absolute density N_e, temperature T_e and density fluctuation power spectra with a maximum Nyquist frequency of 1 KHz (1 meter resolution at a 1 km/sec rocket velocity). In the first operation, a number of major depletions ($\Delta N_e/N_e \leq 90\%$) were distributed throughout the F-region, from its bottomside gradient centered near 260 km,

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20. Abstract (Continued)

through the F-peak, to a topside altitude of 500 km. The F-peak was at 375 km, with N_e^{max} = 1.3 (10^6) cm^{-3} (± 10%). The electron energy distribution was characterized by T_e = 1350 (± 250)°K with no obvious signatures of energy redistribution in and around the depletions. The most intense "in situ" irregularities occurred on the bottomside ledge where gradient scale lengths were found to vary between 2 and 25 km. The power spectral density in this region of intense irregularities on the bottomside was dominated by a $k^{(-2.5)}$ power law over the intermediate wavelength domain k = 2π/1 km to k = 2π/2.5 m. This result supports the role of the collisional Rayleigh-Taylor instability in generating intermediate wavelength irregularities during the occurrence of equatorial spread-F.

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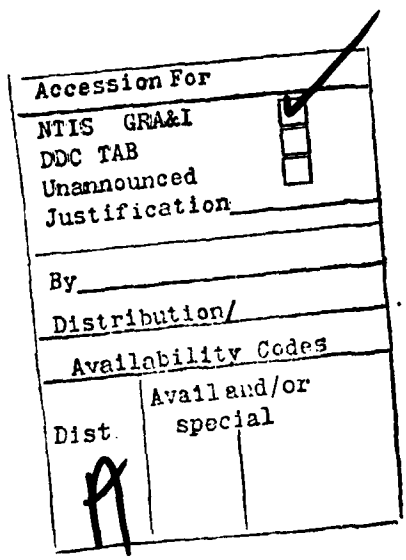

EQUATORIAL SPREAD F: "IN SITU" MEASUREMENTS OF ELECTRON DENSITY TEMPERATURE AND DENSITY FLUCTUATION POWER SPECTRA

I. INTRODUCTION

The DNA/PLUMEX rocket payloads launched into the equatorial ionosphere during the July 1979 campaign carried a plasma diagnostics complement that included a quadrupole ion mass spectrometer, a pair of pulsed plasma probes, vector electric field sensors and a four-frequency beacon. The pair of pulsed plasma probes not only provided simultaneous measurements of electron density N_e, temperature T_e, and density fluctuation power spectra $P_n(k)$, but also provided the capability for a running measurement of relative variations in mean ion mass $\langle M_i \rangle$.

The measurements of N_e and T_e form the basic information on the laminar condition of the ionosphere, allowing for the determination of the ionospheric plasma response to varying geophysical conditions (solar and magnetic activity, winds, gravity waves, etc.) and the detection of triggering mechanisms (e.g., steep density gradients in N_e) for ionospheric irregularities.

The measurements of $\delta N_e (\rightarrow P_n(k))$ yield important test information for signal channel models as well as candidate instability mechanisms (e.g., collisional drift modes, $\bar{E} \times \bar{B}$ and Rayleigh-Taylor) which might be active in the ionospheric plasma.

In this paper we describe the experimental technique, payload configuration, launch scenerios and present additional experimental results which complement companion papers[1,2].

Manuscript submitted June 13, 1980

II. TECHNICAL OVERVIEW

Introduction. The pulsed plasma probe technique (P^3 is the designated acronym) is a unique diagnostic tool capable of high spatial and temporal resolution of plasma parameters. The instrument is a Langmuir-type probe using a special electronic procedure for generating the current-voltage characteristic[3,4]. The result is greatly improved reliability and expanded versatility in Langmuir probe measurements. As a diagnostic tool, the P^3 technique reduces commonly found distortions in derived electron densities and energy distribution functions. A unique feature of the technique is its ability to measure simultaneously the electron temperature, density, and the density fluctuation power spectrum. Successful applications of the P^3 technique include not only rocket but also satellite [5,6] and laboratory beam-plasma studies[7] of turbulent charged-particle environments.

Figure 1 shows two types of probe operation. Figure 1(A) depicts a linear sawtooth sweep voltage which represents the conventional approach to Langmuir probe operation wherein some form of continuous voltage sweep is applied between voltage limits V_- and V_+. Fig. 1(B) shows the pulse-modulated sweep which has been utilized with P^3. The voltage pulses which follow the sawtooth envelope generate the probe's current-voltage characteristic. During the interpulse period, at constant voltage V_B, the collected probe current I_B provides a direct measure of variations in the probe-plasma system. The pulse duty-cycle is short so that the

probe rests at its baseline potential V_B for a period much longer than the pulse width. Fig. 2 shows pulse and baseline durations identified as τ_{on} and τ_B, respectively. So that sweep voltage transients will not affect the value of probe current, the probe current is sampled at the termination of subinterval τ_i within the sweep pulse and at the center of the baseline interval τ_B.

With τ_{on} much shorter than either τ_B or the time constant of the probe surface contamination layer[4], the pulse procedure will maintain the surface condition and associated voltage drop at a more nearly constant level than when using a continuous, slowly-varying sweep voltage. The resulting current-voltage characteristic can then be unfolded from the plasma density fluctuations (δI_B) so that the electron temperature and density are determined uniquely. In addition, the I_B-values provide the raw data from which density fluctuation power spectra are determined.

Payload configuration and P^3 characteristics. A pair of pulsed probes were diametrically extended from the forward end of the rocket payload (Fig. 3). The sensing elements constructed from tungsten wire, were isolated from their extension booms by coaxial guard electrodes driven at the same potential as the probes themselves. One of the probes, defined as the I-probe, operated with $V_B \tilde{\sim}$-1v, yielding net ion baseline current I_B^i. The other probe, defined as the E-probe, operated with $V_B \tilde{\sim}$ + 2v, yielding net electron baseline current I_B^e. Both probes generated

complete current-voltage characteristics in $\tau_s \gtrsim 400$ msec, yielding absolute values of N_e and T_e at an approximate 2.5 Hz rate. Maximum I_B sampling occurred at 2048 Hz, resulting in 0.5 meter spatial resolution for relative electron density fluctuations at a vehicle velocity of 1 km/sec.

Probe electrometers were set to operate over a dynamic range extending from $4(10^{-10})$ to 2.5 (10^{-4}) amperes, with automatic switching over 8 ranges maintaining 9 bit accuracy for all anticipated ionospheric conditions. The automatic ranging is best illustrated in Figure 4, an actual in-flight analog record of telemetry channel outputs for the probe currents and applied voltages, the roll magnetometer for magnetic aspect determinations, and pitch, yaw and roll monitors on the ACS jets. The data sample presented in Figure 4 was collected when the payload was 55 seconds into flight while the probe electrometers were being driven through a load resistor for calibration. The probes' operation alternated between a fixed-bias mode and a pulsed-sweep mode, with absolute currents determined by a simple algorithm which coupled the switching 0-5 v TM signal on PCM channel 26-1 with the sweep current range monitor on channel 27-1. The record format in Fig. 4 helped provide field-estimates of density profiles without distortions of magnetic aspect sensitivities and attitude control jets.

III. RESULTS

Density profiles and irregularity structures. By 9 P.M. (LT) on the night of the first rocket launch (PLUMEX I) the bottomside of the F-region had risen to an approximate

altitude of 400 km. The F-region then began a downward drift with a simultaneous onset of spread-F. The downward drifting and spread-F conditions continued, and when the bottomside F-layer had descended to an altitude below 300 km, the rocket was launched (12:31:30 UT on day 198; 00:31:30, 17 July 1979, LT).

Figure 5 displays the upleg measurements of relative electron density as presented by correlated ion- (I_B^i) and electron- saturation $I_e^i(V^+)$ currents. The ordinate has a linear scale for time-after-launch with altitude superimposed at 50 second increments. Because ion and electron saturation currents have significantly different sensitivities to velocity, sheath and magnetic field effects[8], variations in I_B^i and $I_e^i(V^+)$ not mutually corroborated were attributed to the various aspect sensitivities and excluded from Figure 5. This approach facilitated analysis, reduced computer time, and established credibility in the interpretation of the curves as relative electron density profiles.

The results in Figure 5 show that a number of major depletions ($\Delta N_e/N_e^o \lesssim 0.9$) were distributed throughout the F-region. Each of the large scale depletions (identified alphabetically) has its own distribution of irregularities, illustrated in Fig. 6 by the expanded view of regions C, D, H and I. It is clear that "C" is not a single narrow bite-out but a collection of rather large irregular structures

extending over a total altitude domain of about 12 km. (Vehicle velocity in region C was 2.4 km/sec.) To develop a quantitative view of irregularity fluctuations observed in the F-region, continuous linear detrends were executed throughout the entire upleg trajectory. The variations about those linear detrends were then plotted in Figure 5 as "Irregularity Intensity", with a maximum relative scale of $\pm$ 4. A fluctuation as great as $\pm$ 4 approximately represents a $\pm$ 80% fluctuation about the linear detrend. (Correlation of these results with macroscale gradients and Altair backscatter contours are discussed in a companion paper[1].

Absolute density and temperature. Absolute values of electron density and temperature were determined by conventional analyses of Langmuir probe characteristics[9] with appropriate care to eliminate perturbing effects of surface contamination[4], density fluctuations[3,10] and magnetic field effects[8]. Analysis of approximately 75 characteristics were executed over the F-layer from 340-560 km. In each case a conversion coefficient $a \equiv N_e\ [cm^{-3}]/I_e(V^+)$ was determined so that the $I_e(V^+)$ profile in Figure 5 could be directly scaled to absolute electron densities. This procedure yielded $a = (5.5 \pm 0.5)\ 10^{10}$ electrons $cm^{-3}A^{-1}$.

The upleg profile has been reconstructed in Figure 7 with relative and absolute electron density plotted as a function of altitude. The result shows the F-peak at 375 km, with a maximum density of 1.3 $(10^6)cm^{-3}$ ($\pm$ 10%).

Analysis of the retarding-field region of the same set of current-voltage characteristics yielded $T_e = (1350 \pm 250)^{o}K$, with no obvious signatures of electron energy redistribution in and around the depletions.

Intermediate wavelength power spectra. The pulsed probe data provided an excellent opportunity for comparison with the numerical simulations[11] of the collisional Rayleigh-Taylor (R-T) instability at intermediate wavelengths. Attention is focused on the bottomside F-layer gradient and region C, which is believed representative of the mid-phase development of the R-T process[1]. Typically, computer simulations employ several values for the zero-order gradient scale length

$$L = \left(\frac{1}{N_e^o} \frac{dN_e^o}{dy} \right)^{-1}$$

and initialize the code with some two-dimensional perturbation superimposed. In the work of Keskinen, et al.[11] L was selected at 5, 10 and 15 km and the perturbation took the form [12]

$$\frac{\delta N_e(x,y,t=0)}{N_e^o} = (1C^{-4}) \text{ Sin } (k_y\, y) \text{ Cos } (k_x\, x) + 2(10^{-6}) \text{ Sin } (2k_y\, y)$$

with k_x and k_y being the horizontal and vertical wavenumbers, respectively. Both k_x and k_y were set equal to $2\pi/960$ m in the simulation. In addition, the computation assumed that L was centered at 300 km.

Under actual conditions encountered in PLUMEX 1 (Fig 7), the bottomside F-layer gradient extended from 240 to 290 km. The question of gradient scale length can be studied in Figure 8 where it is shown that the bottomside gradient (encompassed in the 105-125 sec time frame) is not characterized by a single value of L. In region "C" (114s $\lesssim$ t $\lesssim$ 122s) L is seen to vary between 2 and 10 km, whereas adjacent domains (110s $\leq$ t $\leq$ 113s and 122s $\leq$ t < 126s) can be characterized by L = 25 km. We would suggest that the adjacent domains are representative of the zero-order gradient scale length and that L = 25 km would be a more appropriate value in the numerical simulation.

In any event, computer simulations[11] with L = 5, 10 and 15 km showed that linearly unstable modes saturate by non-linear generation of vertical modes. The results yield one-dimensional power laws (horizontal and vertical) that vary with a spectral index ($\equiv$ n in $P_{N_e} \propto k^{-n}$) between 2.0 and 2.5. To explore this result within the context of region "C", power spectral analyses were conducted over sliding intervals of 2.4 km. The results, presented in Figure 9, show that the dominant behavior is $k^{-2.5}$ over the range k = 2π/1km to k = 2π/2.5m. The $k^{-1.85}$ behavior at t = 116.001 sec is a result of the very sharp density gradient (see region "C" Fig. 6) encompassed by the domain of the spectral analysis.

In general we would conclude that our results support the numerical simulations of Keskinen, et al.[11]. We do

point out however that a spectral index variation from 2 to 2.5 is a rather broad domain. Further testing of this support can be achieved with an L = 25 km simulation and a downward drifting F-layer model that is more in keeping with the actual experimental conditions. The F-layer time-history can be important since unstable modes appear to require times in excess of 4,000 seconds to saturate...a time during which the F-layer encountered in PLUMEX I drifted downward in excess of 40 km.

IV. SUMMARY

In each of the two rocket operations (PLUMEX I & II) conducted at the Kwajalein Atoll during July 1979, the NRL pulsed plasma probe performed flawlessly. General results concerning coordinated rocket and radar measurements of small and large scale irregularities have been discussed in companion papers[1,2]. Complementary results developed here include:

(a) In PLUMEX I a number of major depletions ($\Delta N_e/N_e^o \lesssim 90\%$) were distributed throughout the F-region, from the bottom-side gradient centered near 260 km, through the F-peak, to a topside altitude of 500 km. The most intense "in situ" irregularities occurred on the bottomside ledge where gradient scale lengths were found to vary between 2 and 25 km. The power spectral density in this region of intense irregularities on the bottomside was dominated by a $k^{-2.5}$ power law over the intermediate wavelength domain $k = 2\pi/1\text{km}$ to $k = 2\pi/2.5\text{m}$. The experimental conditions were reasonably matched to the

numerical simulations of Keskinen et al.[11], and a comparison of the two resulted in general agreement.

(b) In PLUMEX I, the F-peak was at 375 km, with N_e^{max} = 1.3 (10^6) cm^{-3} ($\pm$ 10%). The electron energy distribution was characterized by T_e = (1350 $\pm$ 250)^oK with no obvious signatures of energy redistribution in and around the depletions.

ACKNOWLEDGMENTS

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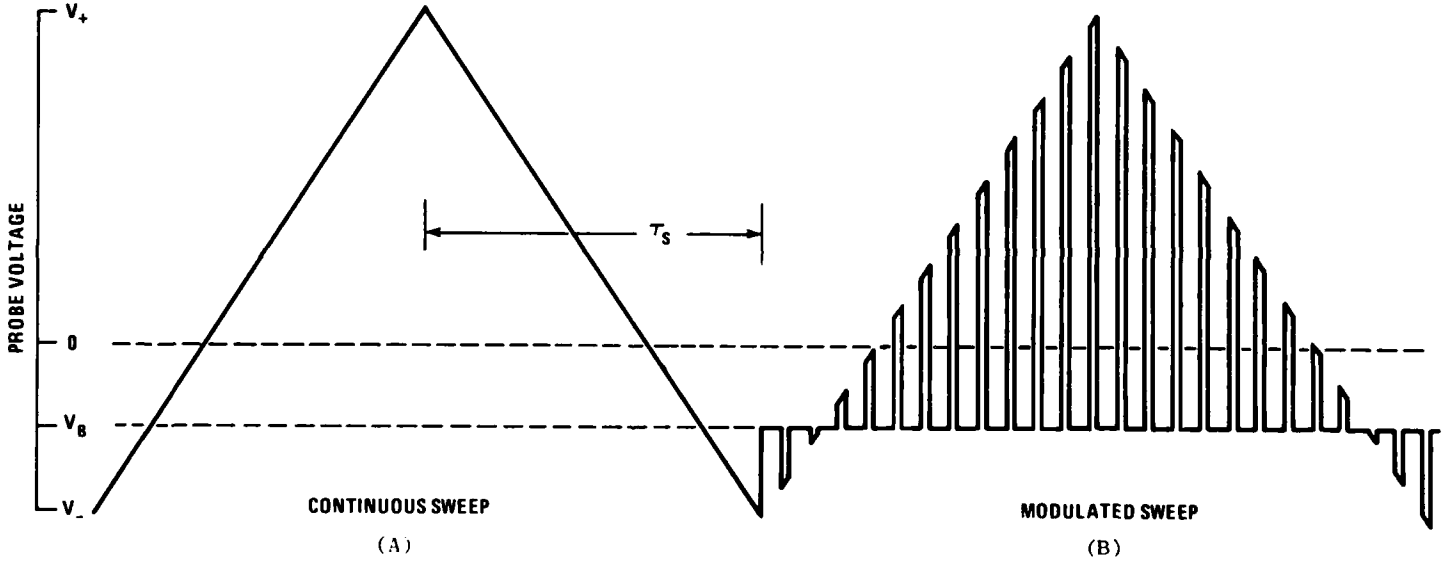

Fig. 1 — Continuous and pulsed modes of probe operation. (A) represents the conventional approach, while (B) shows the modulated sweep utilized in the P^3 technique.

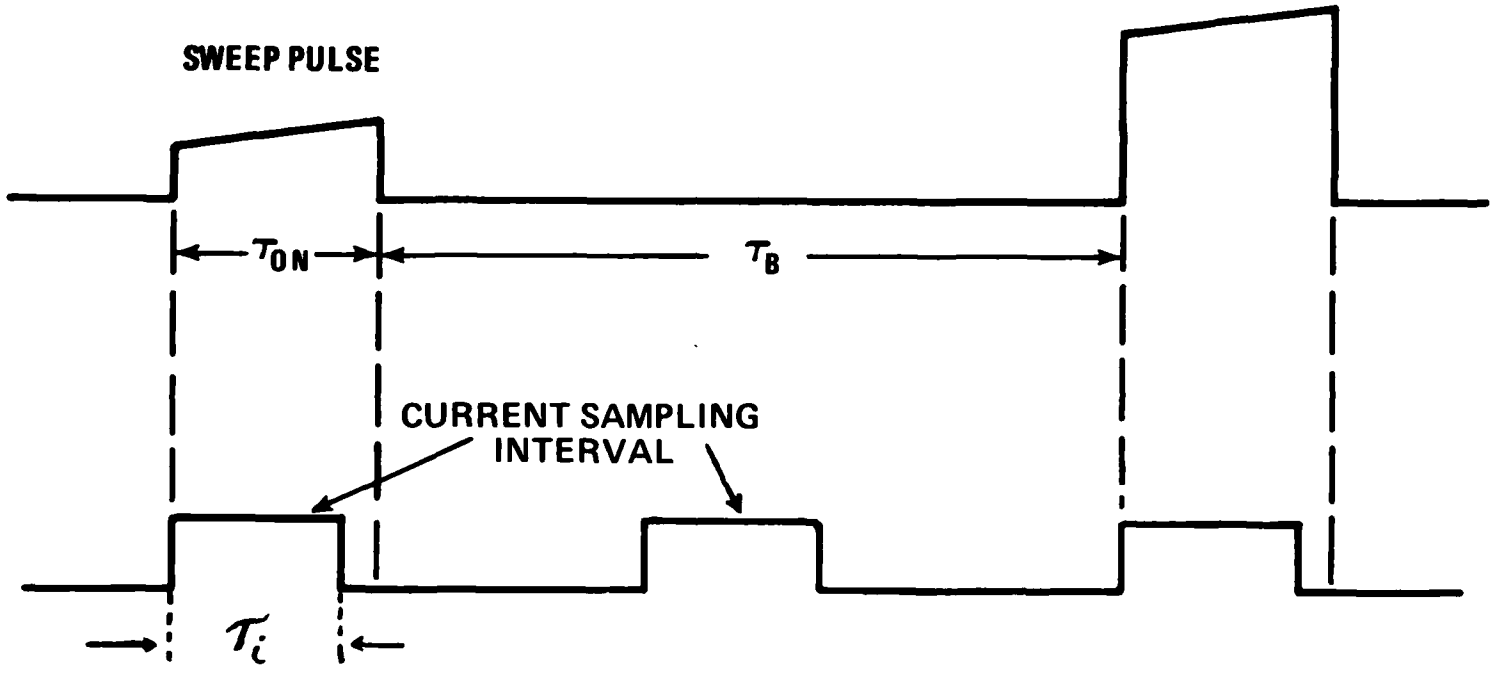

Fig. 2 — The sweep pulses (Fig. 1) shown on an expanded scale to illustrate the probe-current sampling intervals

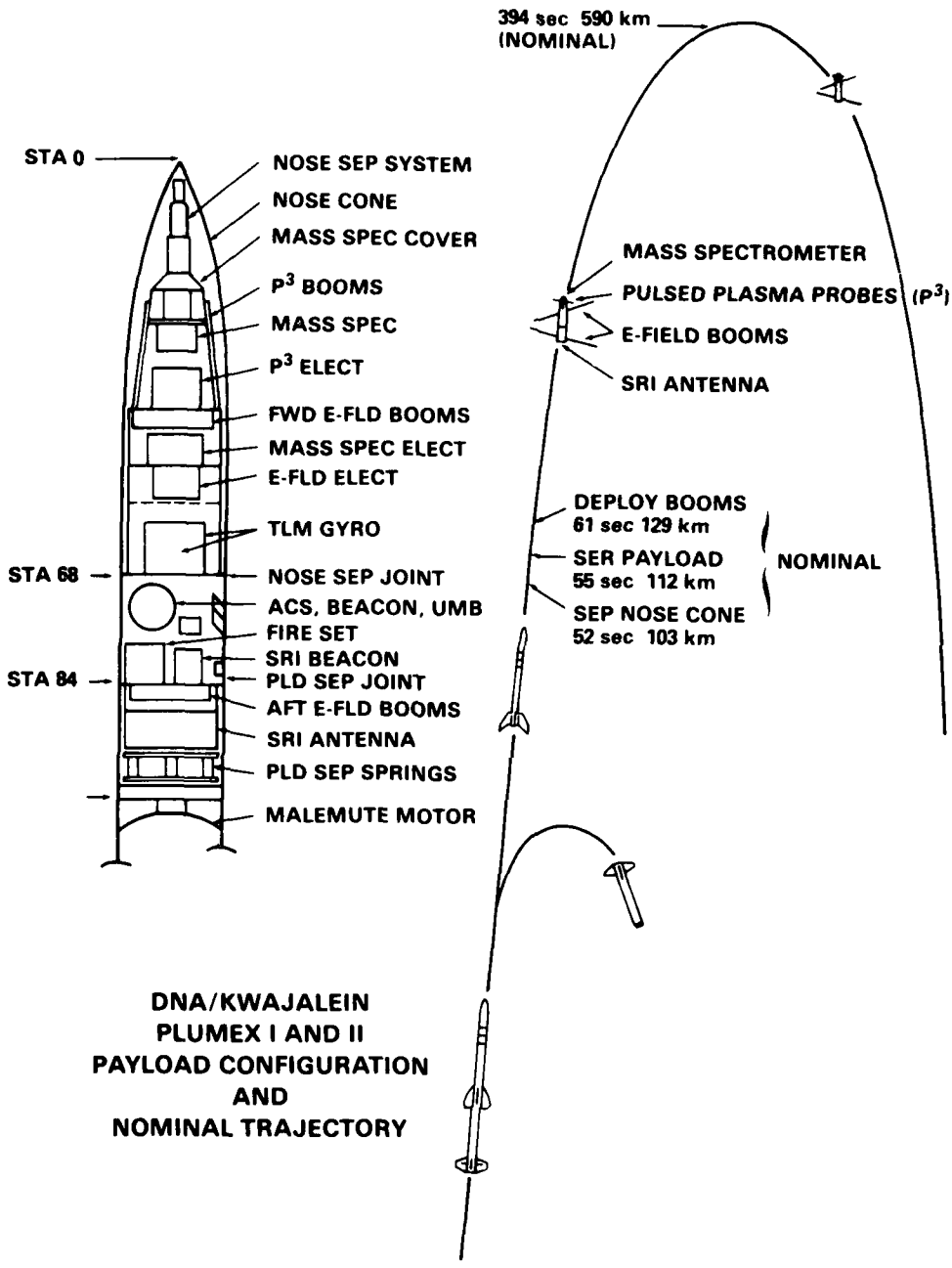

Fig. 3 — PLUMEX payload configuration and nominal trajectory. (This figure has been adapted from a Sandia report.)

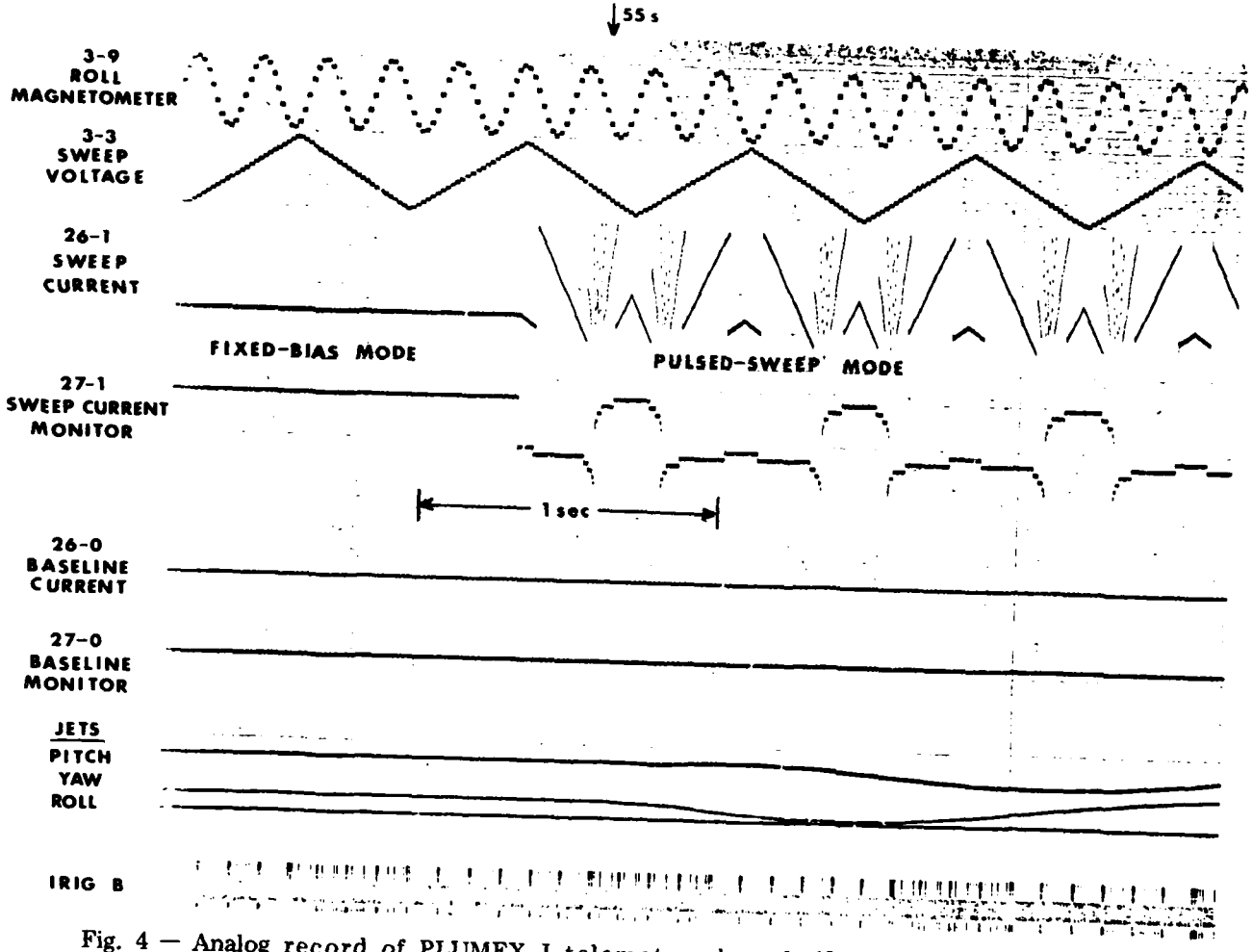

Fig. 4 — Analog record of PLUMEX I telemetry channels (3-9, 3-3, etc.) illustrating pulsed-plasma-probe outputs and relevant vehicle information (roll-magnetometer, attitude control jets and IRIG B timing). The probe electrometers (26-1) cover six decades of current in 8 automatic-switching ranges (26-1 shows automatic ranging, while 27-1 identifies each range through a simple algorithm). 9 bit accuracy is maintained throughout.

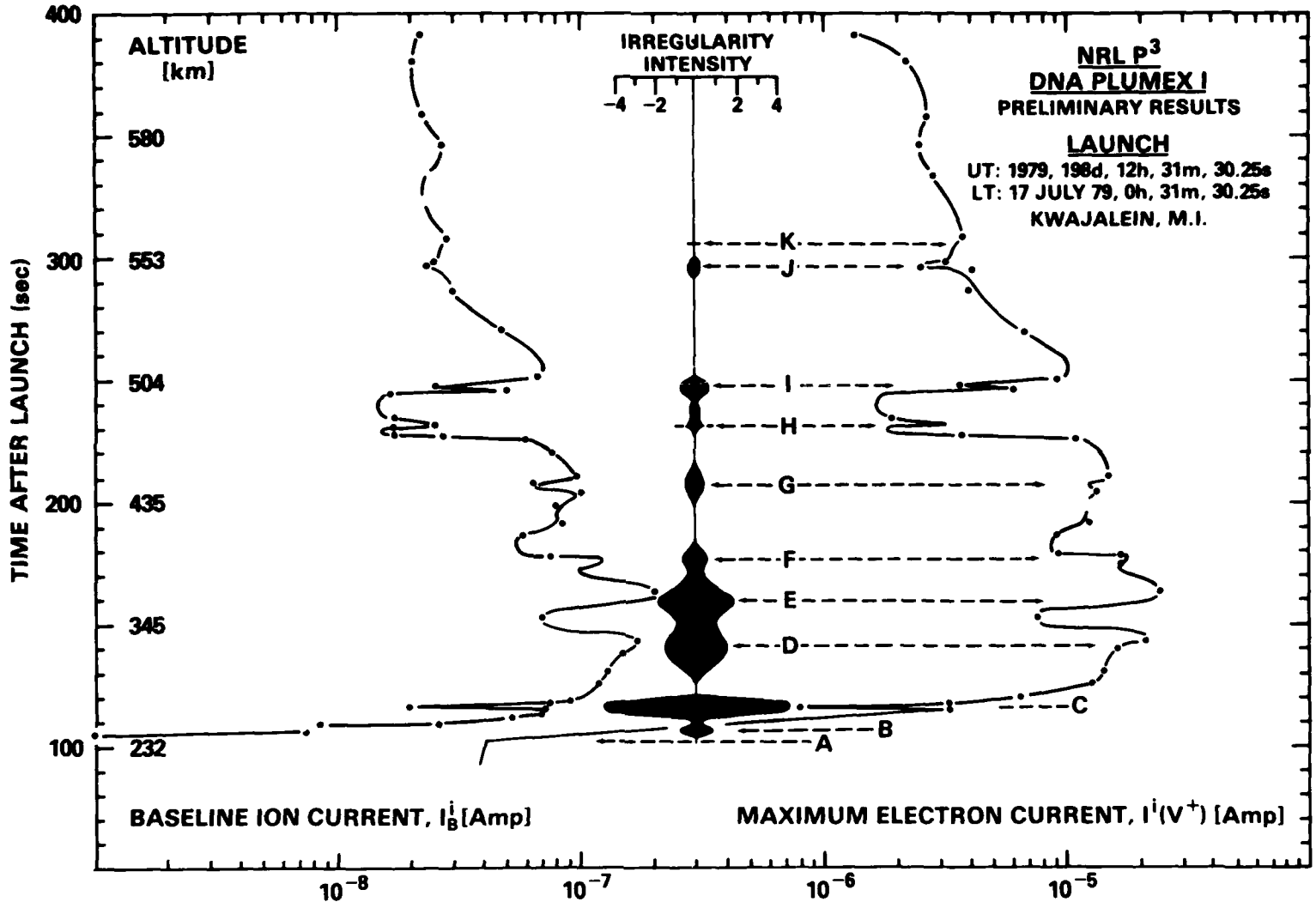

Fig. 5 — Relative electron density profile of macroscale features as measured simultaneously by ion and electron saturation probe currents collected on the upleg trajectory of PLUMEX I. The "irregularity intensity" provides a measure of smaller scale structure with a ± 4 intensity approximately equal to ± 80% fluctuations about a linear detrend.

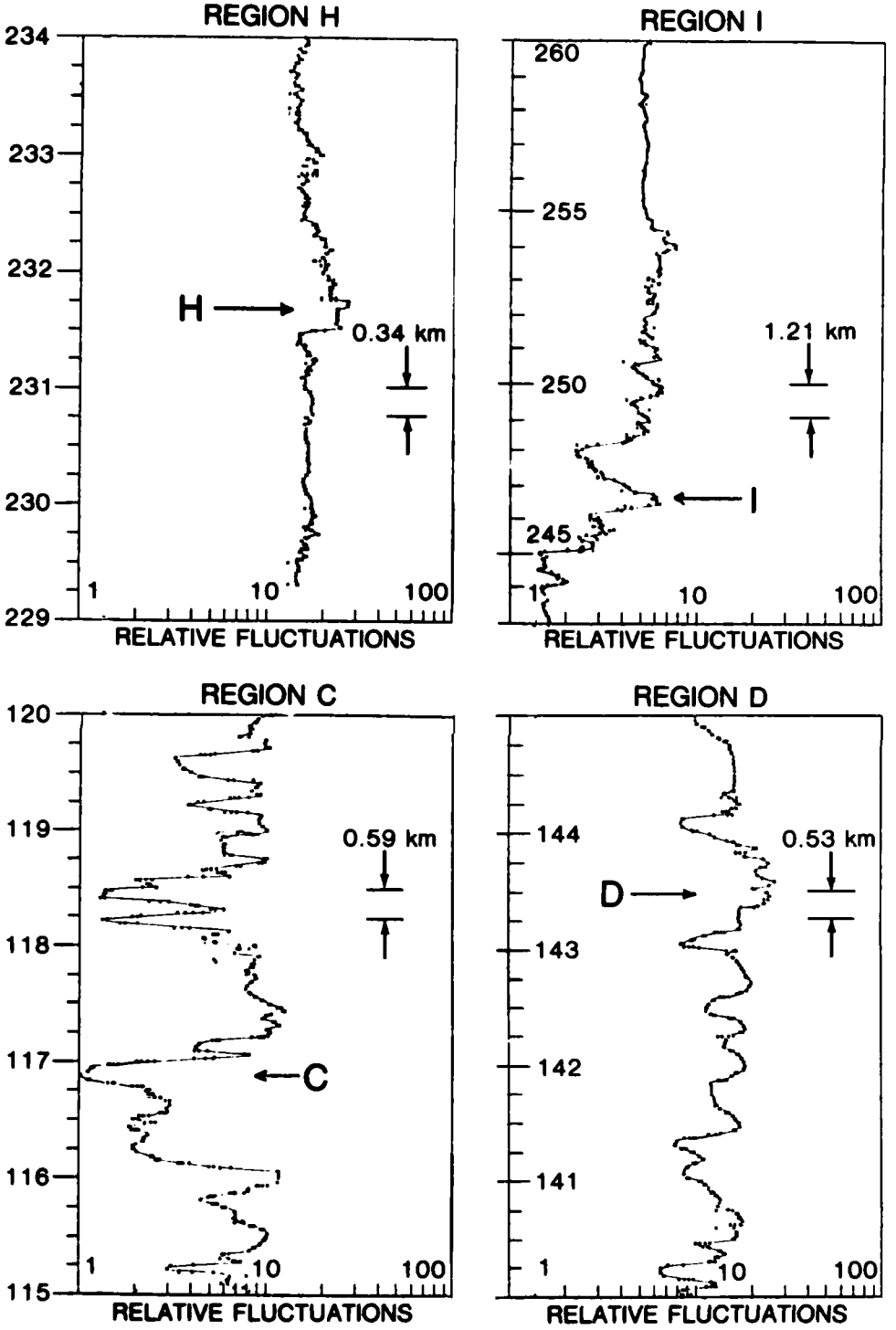

Fig. 6 — Expanded views of density fluctuations observed in regions C,D,H and I of Fig. 5

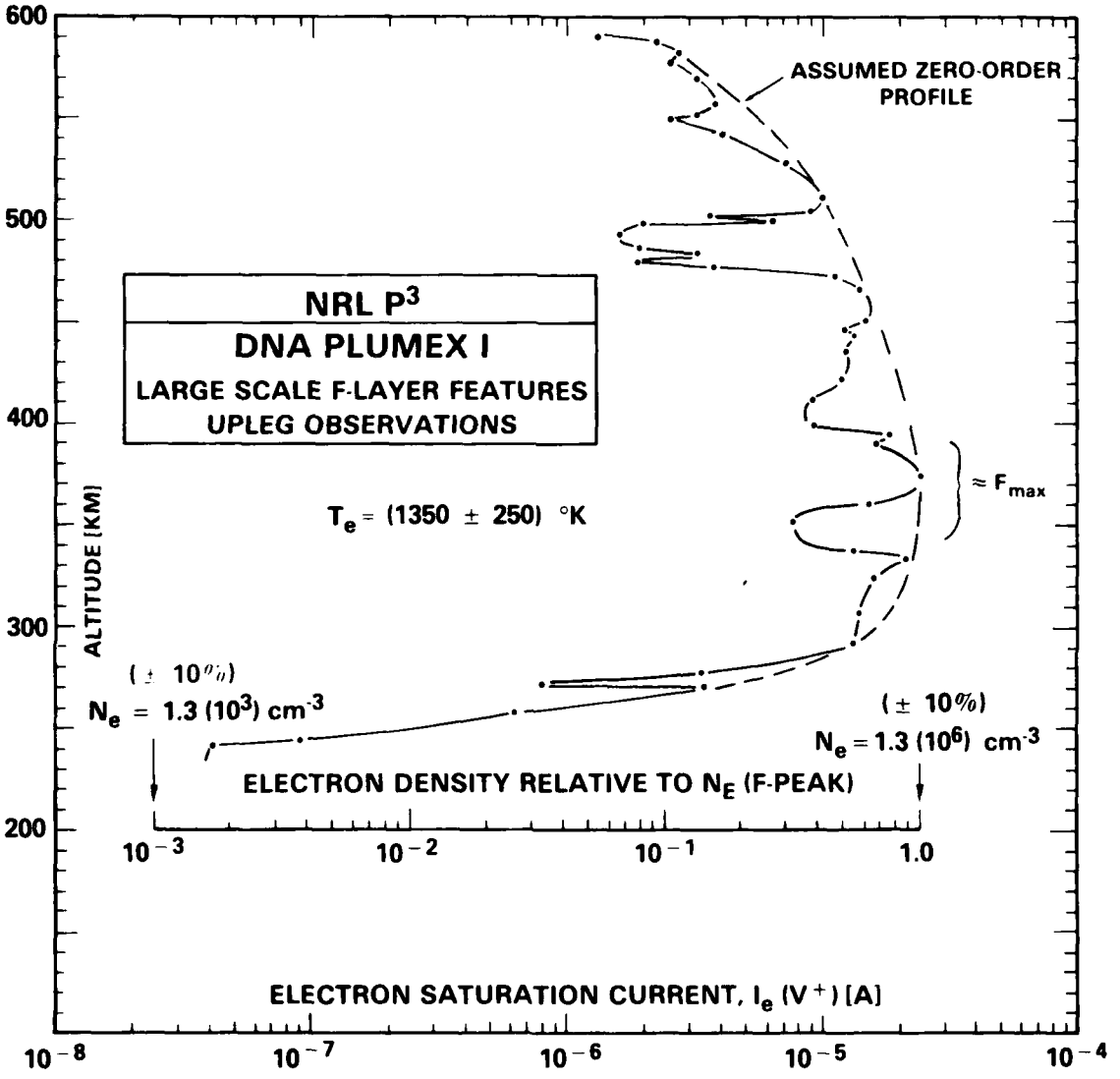

Fig. 7 — Relative and absolute profile of electron density (PLUMEX I upleg)

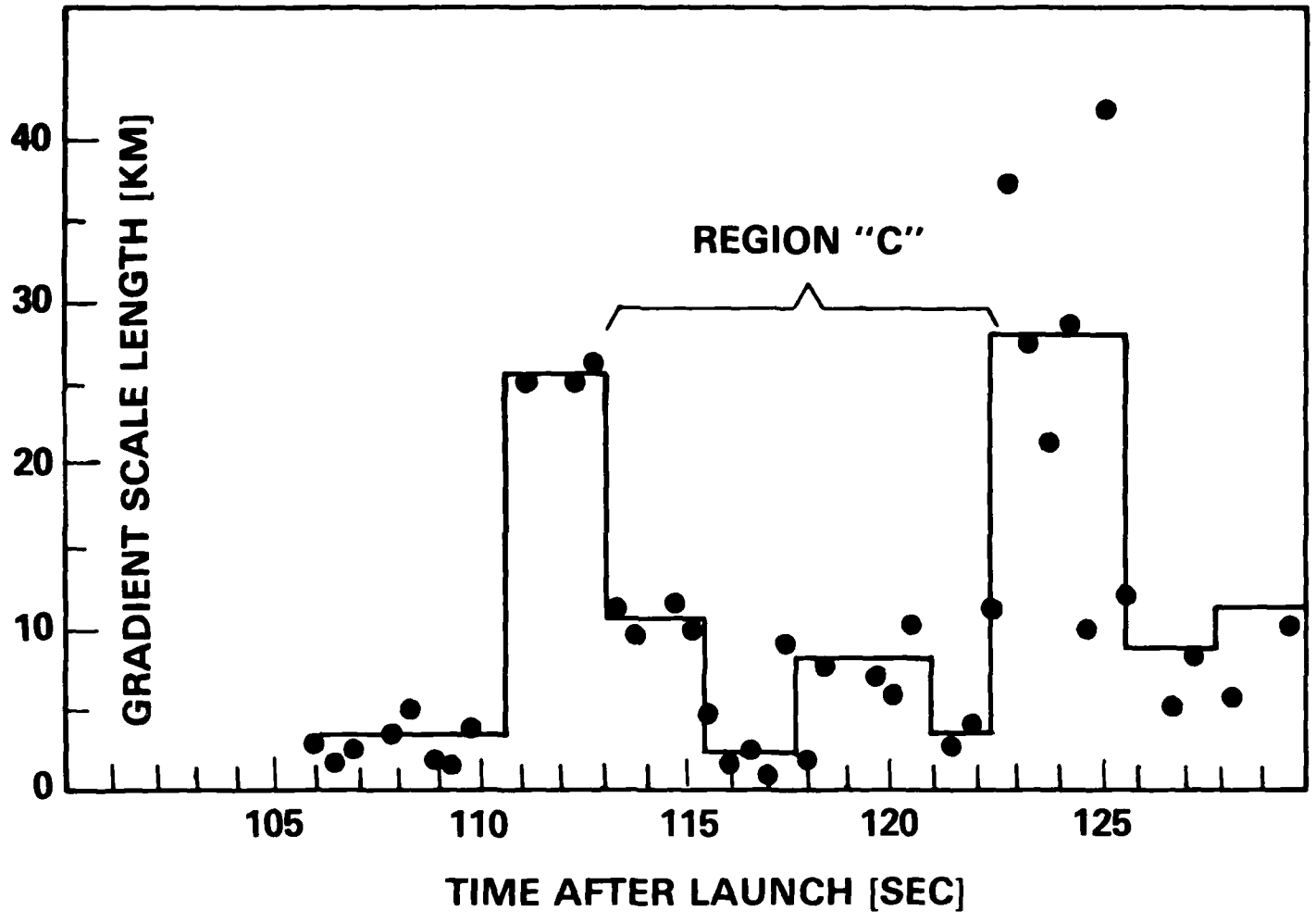

Fig. 8 — Gradient scale lengths $\left(L = \left[\frac{1}{N_e^o} \frac{dN_e^o}{dy} \right]^{-1} \right)$ on the bottomside gradient of the F-region layer shown in Figs. 5 and 6

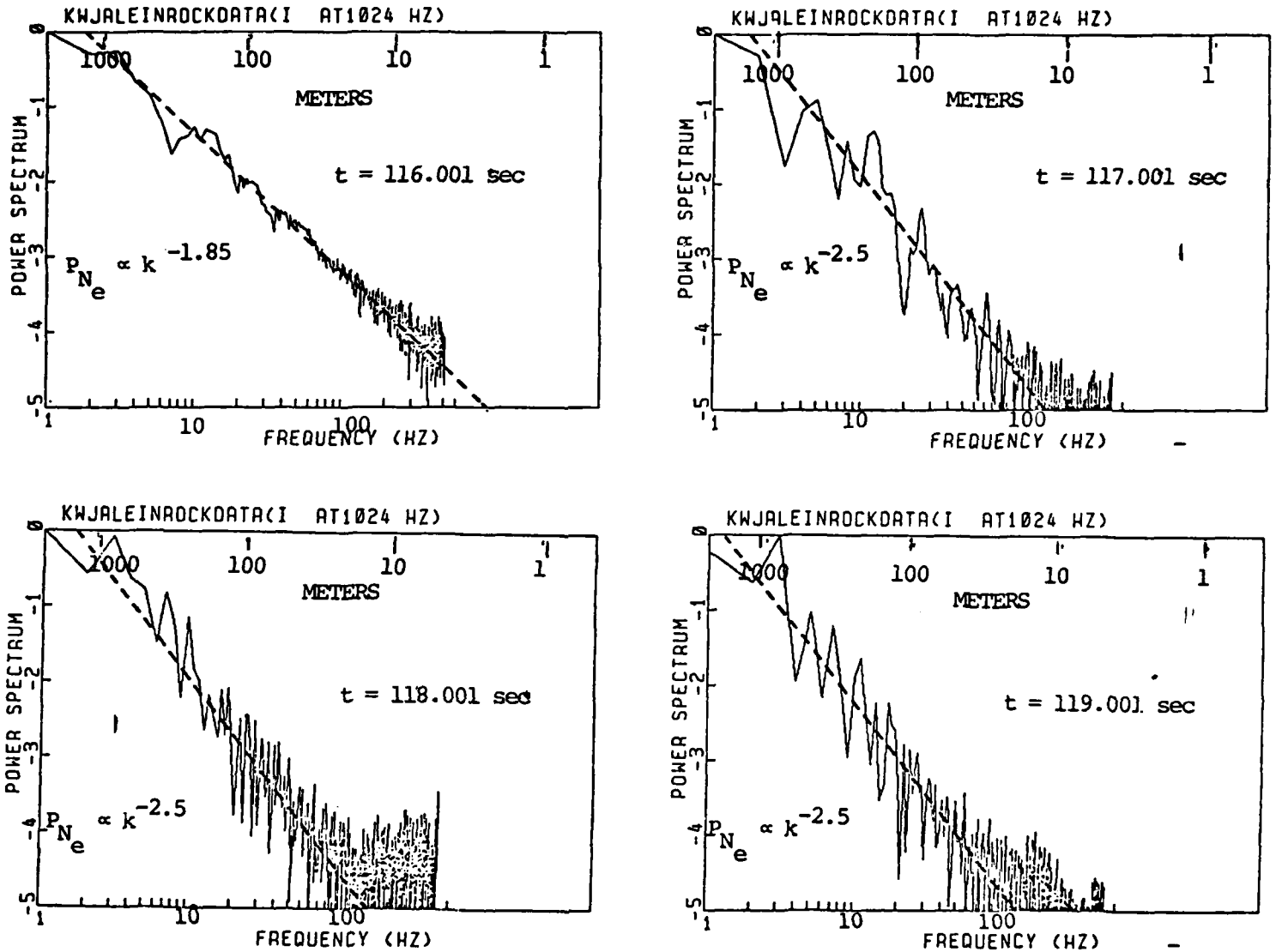

Fig. 9 — Power spectial analyses of density fluctuations in region "C" (Fig. 5)

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