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A NEW METHOD FOR IN-SITU ELECTRON TEMPERATURE DETERMINATIONS FROM PLASMA WAVE PHENOMENA

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A NEW METHOD FOR IN-SITU ELECTRON TEMPERATURE DETERMINATIONS FROM PLASMA WAVE PHENOMENA

by

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A discrepancy has been reported between the values of the electron temperature T_e deduced from satellite electrostatic probe measurements and ground based radar backscatter measurements [Hanson et al., 1969]. This discrepancy (radar backscatter temperature less than the probe temperature) is not present when the probe experiment is flown on a rocket to lower altitudes [Brace et al., 1969] but reappears when the rocket probe attains higher altitudes [Brace and McClure, 1971]. There is a need for an independent radio wave method for making in-situ T_e measurements in order to help resolve this problem. Several methods have been introduced which obtain T_e from the periodic amplitude structure often observed during the decay of the f_N and f_T plasma resonances stimulated by the ionospheric sounders on board the Alouette and ISIS satellites (f_N is the electron plasma frequency, $f_T = (f_N^2 + f_H^2)^{1/2}$ is the upper-hybrid frequency, where f_H is the electron cyclotron frequency) [Warnock et al., 1970] (Feldstein and Graff, personal communication, 1971). The main limitations of these methods are that extensive calculations are required and that the electron density scale height must be determined from the ionospheric sounder record (ionogram). This letter presents a new method of determining T_e from the satellite resonant phenomena. It is based on the "splitting" (observed at high latitudes) of the diffuse resonance which occurs at the frequency f_{D1} between f_H and $2f_H$ [Oya, 1970]. The advantage of this method over the other methods involving ionospheric resonances is the simplicity of the required calculations. There is, however, the limitation of plasma conditions where the f_{D1} resonance can be observed ($2 \lesssim f_N/f_H \lesssim 3$) and the limitation to mid-to-high latitudes where the "splitting" is observed.

The diffuse resonances observed on topside ionograms have been interpreted in terms of an electrostatic electron cyclotron harmonic wave instability together with nonlinear wave-wave and nonlinear wave-particle resonant interactions [Oya, 1971]. The instability in this interpretation results from a bi-Maxwellian electron velocity distribution function, with $(T_e)_\perp \gg (T_e)_\parallel$, which is created by the high-power sounder pulse; the observations indicate that this initial instability persists for no longer than $1.5\,\mathrm{msec}$ (($T_e)_\perp$ and $(T_e)_\parallel$ refer to the electron temperature corresponding to electron motion perpendicular and parallel to the ambient magnetic field vector $\vec{B}$). Fredricks (1971) has suggested that an instability due to a secondary peak in the electron velocity distribution function $f(v_\perp)$ may initiate the f_{D1} resonances ($v_\perp$ is the component of the electron velocity perpendicular to $\vec{B}$). This model, however, does not explain the observed variation of f_{D1} as the plasma parameter f_N/f_H changes.

The splitting of the f_{D1} resonance in high latitudes (see Figure 1a) is here interpreted in terms of a Doppler effect caused by the motion of the satellite. The energy contained in the $100\mu\,\mathrm{sec}$ sounder pulse propagates in all directions (see Figure 1b, time t_1), and some of this energy gives rise to a plasma instability. Since energy propagates in all directions, some wave components experience negligible Doppler shift; thus the center portion of the resonance is "filled in" during the short time delay portion of the f_{D1} resonance (t_1 of Figure 1a). Due to cyclotron and Landau damping, only the energy propagating nearly perpendicular to $\vec{B}$ can reach great distances from the satellite [Tataronis and Crawford, 1966]. As this energy is absorbed into the medium, a turbulent region is produced, a nonlinear wave-wave resonant interaction is set up, and plasma waves (including waves at the frequency f_{D1}) are re-radiated. Now,

however, only the energy propagating nearly perpendicular to $\vec{B}$ can return to the satellite, i.e., the energy traveling along the return path of the wave packet that produced the turbulent region. Thus, all the received energy at this time delay (t_2 of Figure 1) experiences a Doppler shift. The original wave packet continues to give up energy to the medium as it propagates in the direction perpendicular to $\vec{B}$ (creating a cloud of turbulence along the way) until it no longer contains sufficient energy to produce a turbulent plasma. This point in time (t_3 of Figure 1) corresponds to the longest duration portion of the f_{D1} resonance. Since the group velocity v_g for the f_{D1} waves is of the order of 100 m/msec, the distance to the final turbulent region is approximately 100 $(t_3/2)$m when t_3 is measured in msec. At greater distances there is no generation of f_{D1} waves, due to the lack of turbulence, and no signals are received at the corresponding delay times (such as t_4 in Figure 1).

Since the observations indicate that the original instability initiated by the sounder pulse in the vicinity of the satellite persists for no longer than 1.5 msec, and that the sounder pulse does not produce an instability beyond the distance $v_g(t_3/2)$ of Figure 1b (typically 300 m), it will be assumed that after a delay time of several milliseconds, e.g., t_2 of Figure 1a, that the electrons in the propagation region between the sounder receiver and the source region for the f_{D1} waves have a Maxwellian distribution in $v_\perp$. Then the Bernstein (1958) dispersion equation for electrostatic waves propagating perpendicular to $\vec{B}$ can be used; it is convenient to represent this equation in the form of the curves of Figure 2 where k is the absolute value of the propagation vector $\vec{k}$ and $R = [\kappa(T_e)_\perp/m(2\pi f_H)^2]^{1/2}$. The wave number k can be determined from the observed Doppler

shift of the f_{D1} resonance since each portion of the resonance is shifted by $(1/2\pi)\,\vec{k}\cdot\vec{V}_{sat} = (1/2\pi)\,k(V_{sat})_\perp$ for the Bernstein mode, where $(V_{sat})_\perp$ is the component of the satellite velocity V_{sat} perpendicular to $\vec{B}$. The frequency difference Δf between the two components of the f_{D1} resonance is just twice this value, thus $(T_e)_\perp$ can be expressed in terms of kR as follows:

$$(T_e)_\perp = \left(\frac{m}{\kappa}\right)\left(\frac{2\,(V_{sat})_\perp\,f_H}{\Delta f}\right)^2 (kR)^2. \tag{1}$$

The quantity kR can be obtained from Figure 2 (after the center frequency f_{D1}, f_N, and f_H have been scaled from the ionogram), $(V_{sat})_\perp$ can be obtained from the satellite orbital information, and Δf is obtained from the ionogram.

Alouette II diffuse resonances were scaled from the conventional ionogram format using a linear interpolation between frequency markers and applying frequency corrections for the non-linear frequency sweep rate of the Alouette II sounder [Benson, 1970]. A frequency correction of -10 kHz was applied to the center frequency f_{D1} (and to other resonances that did not reveal the frequency spectrum of the transmitted pulse) in order to compensate for the -10 kHz offset of the receiver with respect to the transmitter [Benson, 1969]; a frequency correction of -6 ±2 kHz was also applied to the scaled frequencies in order to compensate for the positive offset of the Alouette II transmitter [Benson, 1972]. The sharp upper frequency cut-off of each Doppler shifted component of the f_{D1} resonance was scaled in order to obtain Δf; these cut-offs correspond to the receivers 3 dB points. The effect of the rotating earth was considered in the determination of $(V_{sat})_\perp$. A value for $(T_e)_\perp$ was then obtained from (1).

Only data corresponding to times when the Alouette II electrostatic probe experiment was in operation were considered. The results are presented in Figures 3 and 4 for data recorded at the Ottawa and Winkfield telemetry

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stations. The electron temperature values obtained from the f_{D1} resonance $(T_e)_{f_{D1}}$ data are consistently below the values obtained from the probe experiment $(T_e)_{probe}$ in the Ottawa region (e.g., the average value of $(T_e)_{probe}/(T_e)_{f_{D1}}$ in Figure 4a is 1.32 with a standard deviation from the mean $\sigma/\sqrt{n} = 0.04$), whereas the values are in agreement in the Winkfield region (e.g., the average value of $(T_e)_{probe}/(T_e)_{f_{D1}}$ in Figure 4b is 1.02 with a standard deviation from the mean of 0.04). The result, i.e., $(T_e)_{f_{D1}} \leqslant (T_e)_{probe}$ supports the assumption that the artificially stimulated $(T_e)_\perp$ value is not maintained in the propagation region after a time delay of a few milliseconds since $(T_e)_{f_{D1}}$ corresponds to $(T_e)_\perp$ whereas $(T_e)_{probe}$ is not considered to be sensitive to direction.

The temperature discrepancy observed near Ottawa, but not near Winkfield, appears to be of geophysical rather than instrumental origin since two independent in-situ methods for determining T_e from the same satellite are involved. This conclusion supports the recent experiments of Brace et al. (1971), where simultaneous rocket and satellite measurements were found to agree, and Brace and McClure (1971) which suggest a geophysical cause for the discrepancy. The present observations are consistent with a recent comparison by Taylor and Wren (1970) of electron temperatures obtained from the Explorer 31 Langmuir plate experiment and radar backscatter observations in the Winkfield region; they found a reasonable agreement between the two methods.

Since the diffuse resonance is mainly dependent on the electrons of lowest energy (it is due to a collective phenomena in the plasma which is not very dependent on the electrons at the high energy end of the energy distribution function), as is the radar backscatter signal (Hoegy, 1971), the present observations

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support one of the suggestions made by Hoegy (1971) — namely, that the discrepancy may be due to a departure of the low energy ionospheric electrons from a Maxwellian distribution.

Acknowledgements

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noneFigure Captions

Figure 1   Example of the splitting of the f_{D1} resonance (a) and a sketch of the

model proposed to explain the observations (b).   The sketch shows

four "snap shots" of the medium in the vicinity of the satellite at

times t_1, t_2, t_3, and t_4 after the transmission of the sounder pulse.

These times are also identified on the data insert in (a); the time t_3

corresponds to 6 msec.   The f_{D1} resonance in (a) was taken from an

Alouette 2 Ottawa ionogram recorded at 21:43:50 UT on pass 1775

(27 April 1966).

Figure 2   Dispersion curves for the Bernstein mode, i.e., propagation per-

pendicular to $\vec{B}$, in the frequency domain of the f_{D1} resonance.

Figure 3   Comparison of simultaneous in-situ electron temperature measure-

ments using the Alouette 2 diffuse resonance data (solid points) and

the Alouette 2 electrostatic probe data (open circles) for two passes

over Ottawa (a and b) and one pass over Winkfield (c).   The corres-

ponding values for the electron density N (as obtained from the plasma

resonance data) and the satellite altitude z are given at the top of the

figure.   The data, in all three cases, were obtained between 23 and

26 April 1966 and between 16 and 17 hours local time (ionogram times

between 20:49:46 to 20:52:13 UT from OTT pass 1739 in (a), 21:25:13

to 21:26:48 UT from OTT pass 1763 in (b) and, 16:34:21 to 16:35:55 UT

from WNK pass 1725 in (c)).

Figure 4   Similar electron temperature comparison (as in Figure 3) for several

passes through a small region of space near Ottawa (a) and a similar

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region near Winkfield (b). The data points correspond to the time when the f_{D1} resonance was recorded (this time is usually between 6 and 8 seconds after the printed ionogram time). The geographic dimensions of the data regions are as follows: Ottawa (a) 32.4 to 38.7°N latitude, 66.2 to 85.5°W longitude, 510 to 538 km; Winkfield (b) 48.6 to 54.8°N latitude, 17.0°E to 1.8°W longitude, 511 to 534 km. Three of the data point pairs from Figure 3(a and b) are included in (a) of the present figure; the four data point pairs from Figure 3(c) are included in (b) of the present figure.

FREQUENCY⟶

f_{D1}

TIME DELAY

$-t_1$

$-t_2$

$-t_3$

$-t_4$

(a)

t_1

Turbulent Wave
Region Packet

Satellite

t_2

t_3

$\overrightarrow{V_{sat}}$

B

t_4

$-\dfrac{V_g t_4}{2}$ $-\dfrac{V_g t_3}{2}$ $-\dfrac{V_g t_2}{2}$ $-\dfrac{V_g t_1}{2}$ 0 $\dfrac{V_g t_1}{2}$ $\dfrac{V_g t_2}{2}$ $\dfrac{V_g t_3}{2}$ $\dfrac{V_g t_4}{2}$
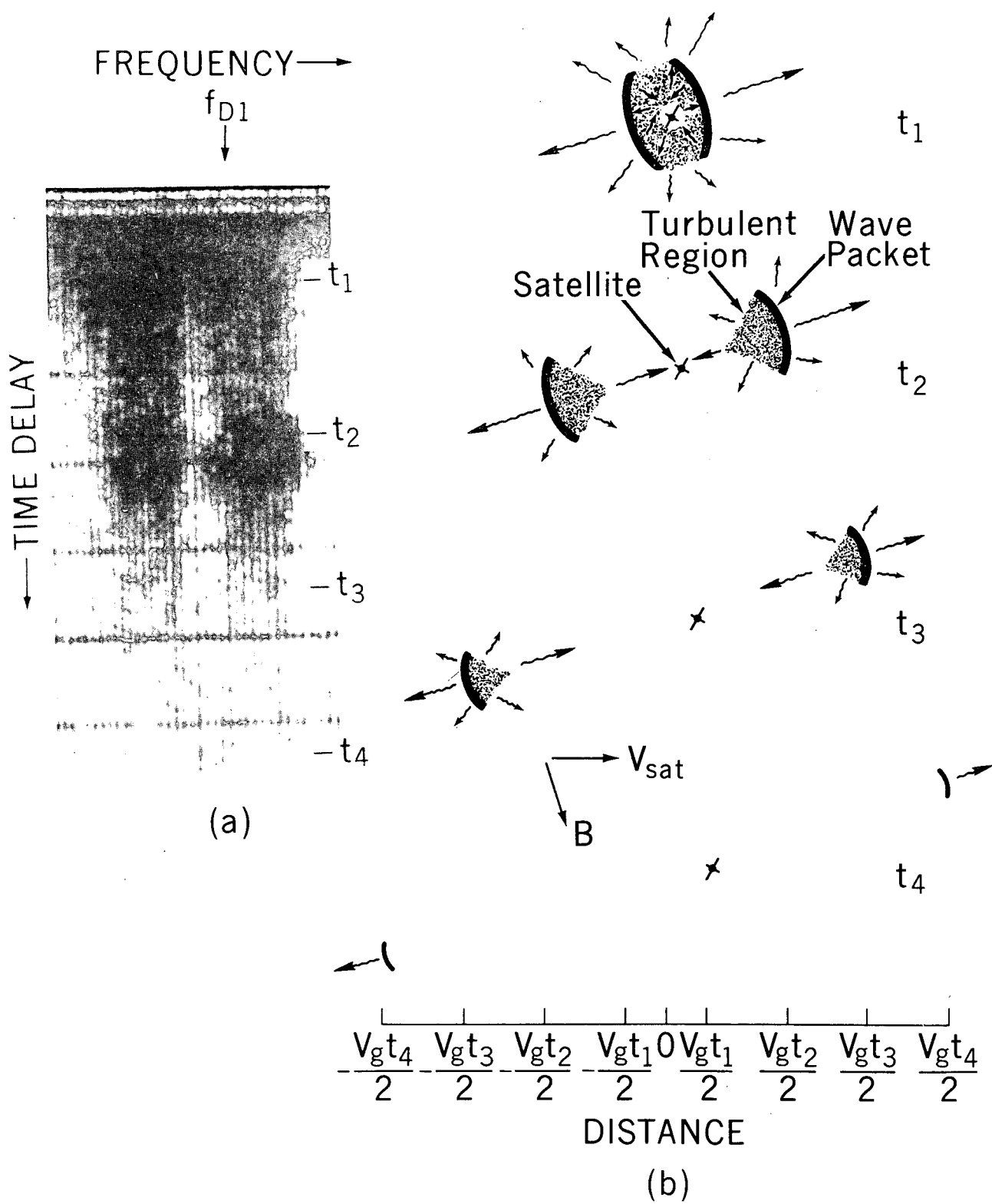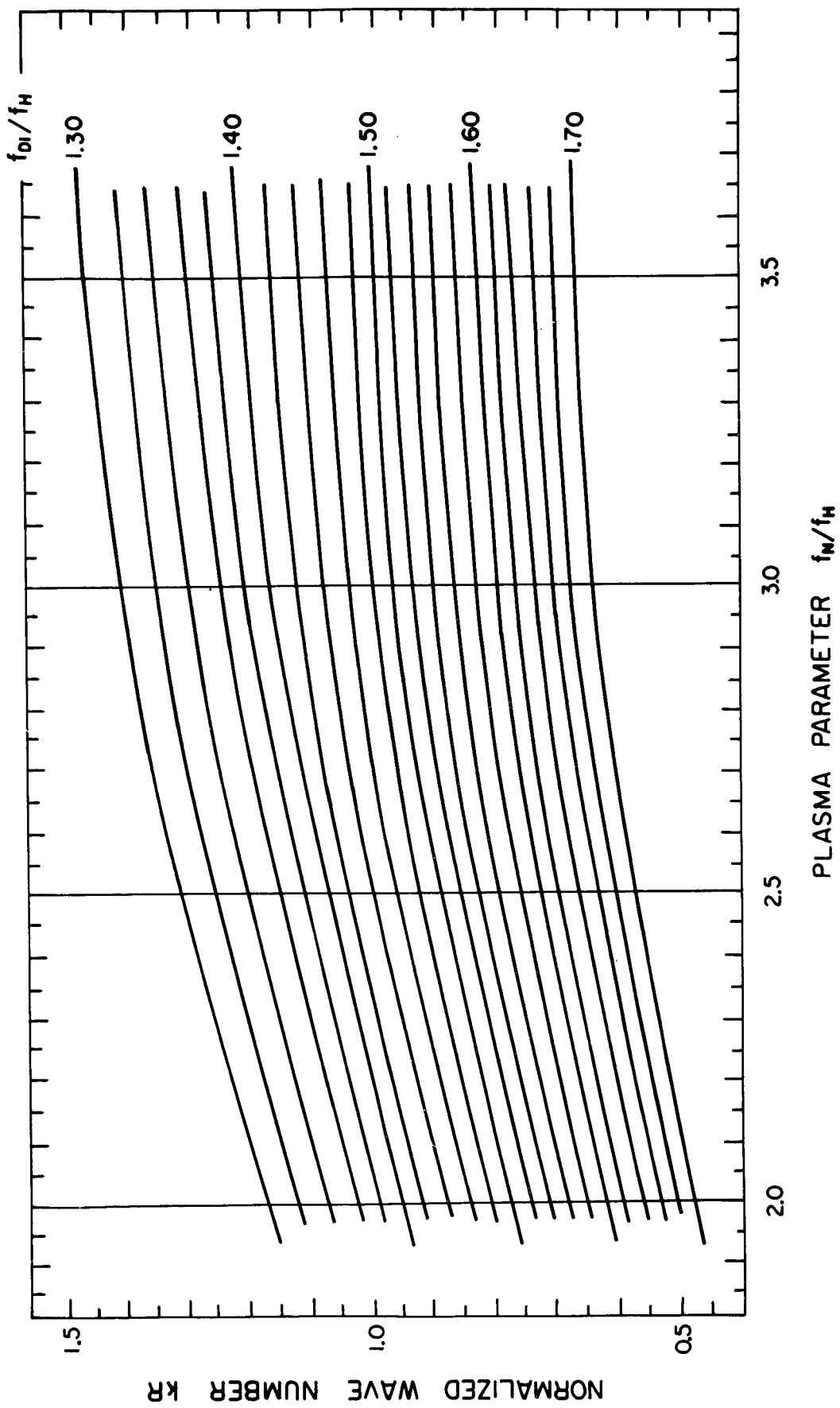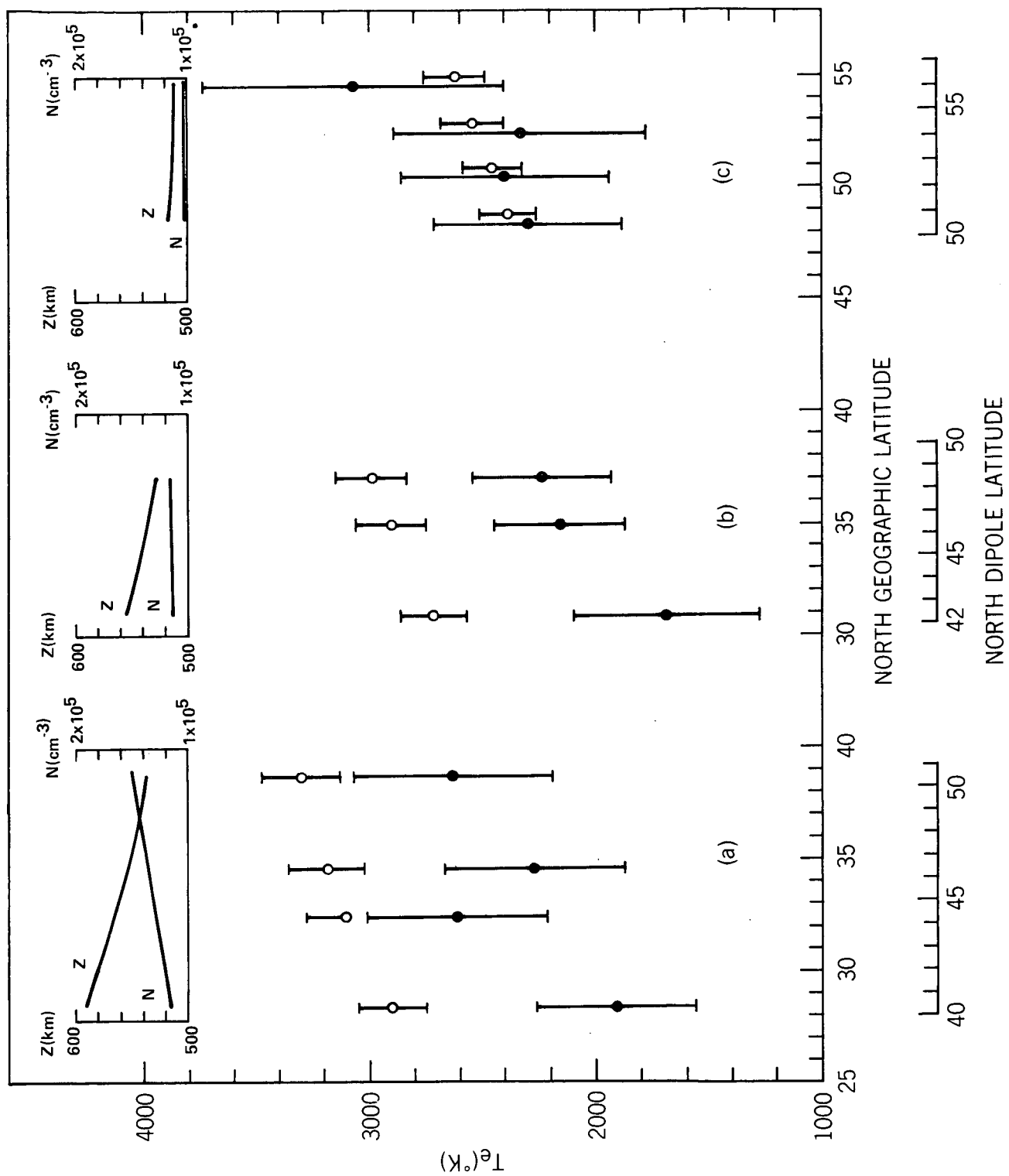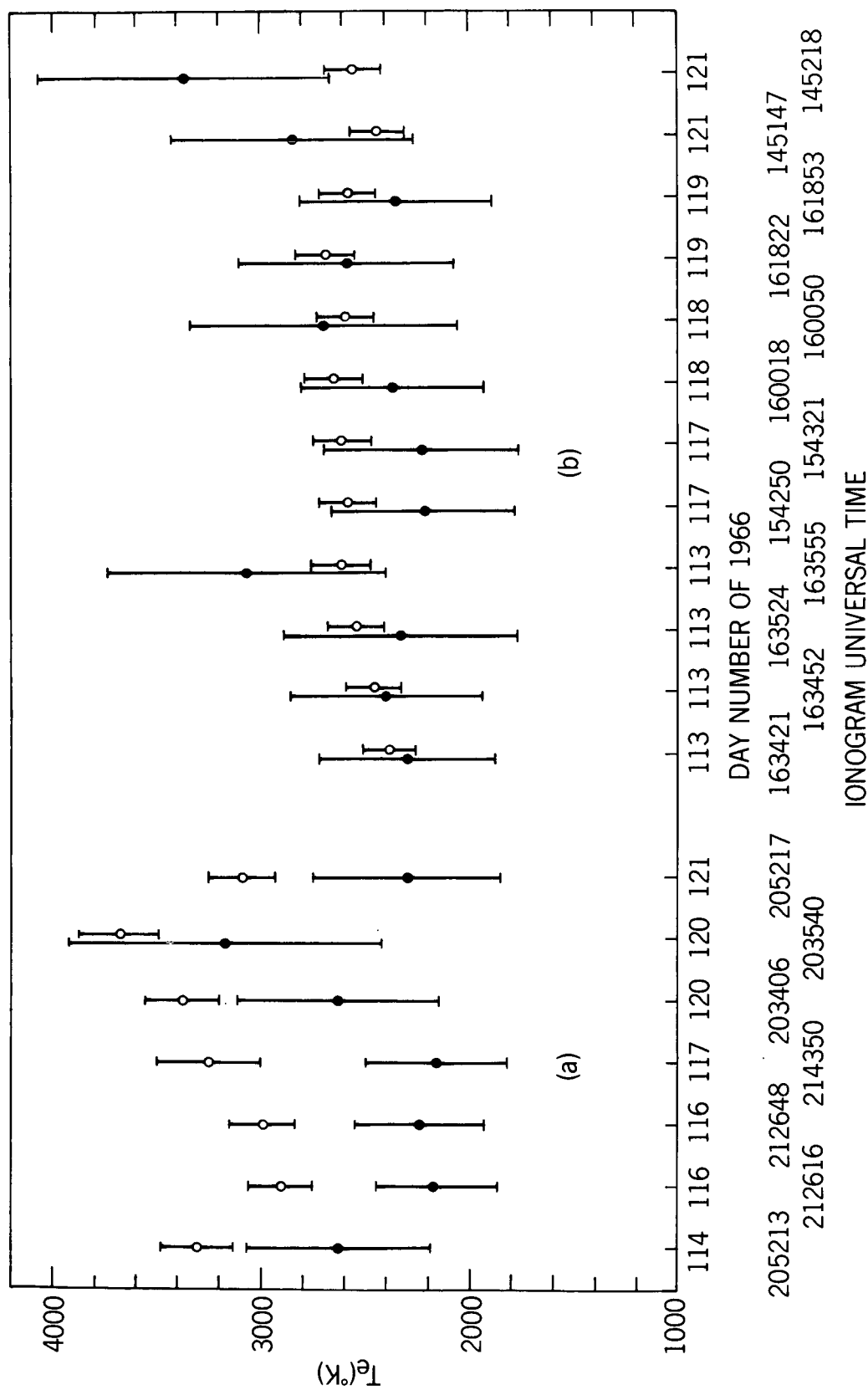
DISTANCE

(b)

Figure 1

Figure 2

Figure 3

Figure 4