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FINAL REPORT
IONOSPHERE/MICROWAVE BEAM INTERACTION STUDY

September 1977

WILLIAM MARSH RICE UNIVERSITY
Houston, Texas



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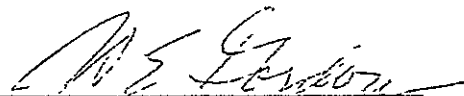
September 1977

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ABSTRACT

A Solar Power Satellite (SPS) microwave power density of 20 mW/cm^2 is confirmed as the level where nonlinear interactions may occur in the ionosphere, particularly at 100 km altitude. Radio wave heating at 100 km at this level can be produced in a test program outlined and the effects observed. A crucial element of the test program is a set of diagnostic measurements to assure that the frequency scaling used in the test is understood and that the results of the test can be extended to the SPS frequency.

The limited test conducted in June 1977 at the Arecibo Observatory produced negative results for radio wave heating of an underdense ionosphere, the condition to be encountered by an SPS system. The results are consistent with available theory. Overdense heating produced striations in the ionosphere easily detected nearly 700 km away by a small radar located to satisfy the predicted aspect sensitivity of the targets, as well as by an incoherent backscatter radar at Arecibo. These observations contain new results supporting some theories and casting doubt on others.

An assessment of the radio frequency interference problem from striations shows that under some conditions it might be severe, but this can be established in the test program proposed. The effects of thermal self-focusing originally thought to be a potentially serious source of radio frequency interference are shown to be limited severely geographically. The aspect sensitivity of field-aligned striations, regardless of how they are produced, makes interference-free regions above magnetic latitude about 60° .

A test program is proposed to simulate the interaction of the SPS beam with the ionosphere, to measure the effects of the interaction on the ionosphere and on communication and navigation systems, and to interpret the results.

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1. RESULTS

1.1 NONLINEAR INTERACTION (See Section 3.1, 3.2)

Theoretical studies confirm the prediction of Meltz that a 5 GW Solar Power Satellite (SPS) with power densities of 20 mW/cm^2 will heat the ionosphere's D, E and F regions sufficiently to excite nonlinear effects. The same and higher levels of radio wave heating can be introduced into the ionosphere by high frequency (HF) waves and the effects observed (see Section 5).

1.2 LIMITED TEST PROGRAM (See Section 4)

A limited test using the existing equipment at Arecibo at HF, 430 MHz and S-band for radio wave heating of the underdense ionosphere produced no striations over Arecibo that could be detected with a sensitive radar at Guadeloupe. As a check of the operating conditions, the radar easily detected striations over Arecibo when the heater frequency matched the plasma frequency of the ionosphere, a condition that will not be satisfied by the SPS system (Section 4). The results are consistent with currently accepted theory (Section 4.5).

1.3 COMMUNICATION AND NAVIGATION EFFECTS (See Section 3.4, 5.3)

Studies show that if striations are produced by the SPS system, radio frequency interference will be increased substantially in patterns that are predictable. Interference-free regions for ground-to-ground communication links exist at magnetic latitudes above 60° or 70° depending on the height of the striations. New England is in an interference-free region for striations above 250 km. Effects at lower altitudes are likely to be similar to sporadic-E effects except that they are permanent (Section 3.4). The effects produced by thermal self-focusing are limited for a 5 GW SPS system to angles of 5° or less between the SPS beam and the magnetic field lines. This limits the striations produced by thermal self-focusing to a narrow area extending from Miami, Florida to Brownsville, Texas. The radio frequency interference from this source will be mostly north-south across the Gulf of Mexico.

1.4 TEST PROGRAM (See Section 5, particularly 5.9)

An HF heater to equal or exceed the SPS radio wave heating (Section 5.1) can be built and operated in the next two years (Section 5.8) at an estimated cost of \$4 million (Section 5.7). A crucial part of the test program is a series of diagnostic observations to insure that the results can be scaled to S-band (Section 5.2, and 5.4). The test program should be conducted in the vicinity of the Arecibo Observatory (Section 5.6, 5.9).

2. RECOMMENDATIONS

- 2.1 An HF heater should be designed, built and operated to reproduce and exceed the radio wave heating of the ionosphere by the 5 GW SPS system.
- 2.2 The heating effects should be mapped and measured by an incoherent scatter radar, by photometers and by ionosondes so that the scaling from HF to S-band can be made with confidence.
- 2.3 The effect of the ionospheric heating on communication and navigation systems should be measured directly.
- 2.4 The heater should be located in the vicinity of the Arecibo Observatory to take advantage of the existing diagnostic capabilities and to minimize the cost of the program.
- 2.5 Theoretical and experimental investigations should be continued into the physics and phenomena of nonlinear wave-plasma interactions, plasma turbulence, and the ionospheric processes associated with substantial local heating.

3. ANALYSIS OF SPS BEAM/IONOSPHERE INTERACTION

Electromagnetic waves propagating through a plasma are reflected when the wave frequency equals the local plasma frequency f_{pe} , given by

$$f_{pe} = 9 \sqrt{n} \quad (3.1)$$

where n is electron density in electrons per meter cubed. The maximum plasma density thus defines a critical frequency, or penetration frequency, which for the ionosphere is usually found at the peak of the F region with typical values of 3 to 10 MHz, depending on time of day. Because microwave frequencies are much greater than ionospheric plasma frequencies, most of the radio wave energy passes through the ionosphere. The remainder goes into underdense ionospheric heating.

Ionosphere-microwave beam interactions can be divided into two general categories: resistive heating effects and self-focusing instabilities. The results of resistive heating by radio waves on ionospheric temperatures, electron densities, and airglow emissions have been investigated in detail by Perkins and Roble (Appendix 1) using numerical ionospheric models and heat balance codes. Independent theoretical derivations of self-focusing of radio waves in the ionosphere are given by Perkins and Valeo (1974), Abramovich (1977), and Cragin *et al.* (1977). These theories are summarized and interpreted in terms of resultant physical effects for underdense ionospheric heating.

3.1 RADIO WAVE HEATING OF THE IONOSPHERE

(from Perkins and Roble, Appendix 1)

The volume heat source Q resulting from collisional (ohmic) heating of a plasma is given by

$$Q = \frac{E_o^2}{8\pi} \frac{f_{pe}^2}{f_o^2} (\nu_{ei} + \nu_{en}) \quad (3.2)$$

where E_o is the peak electric field amplitude, f_o is the radio wave operating frequency, and ν_{ei} and ν_{en} are the

electron-ion and electron-neutral momentum transfer collision frequencies, respectively. The collision frequencies are functions of temperature and must be self-consistently determined in any reasonable theory.

Because ohmic heating scales as the inverse square of frequency, test programs designed to produce heating effects comparable to a solar power satellite microwave beam are scaled to lower frequencies, and thus lower transmitted powers. Two restrictions on a scaled experiment are: (1) the ionosphere must remain underdense, and (2) nonlinear resonant plasma instabilities should be avoided. These parametric instabilities represent a strong heat input mechanism which will not effect microwave transmissions. These two conditions are generally satisfied if we require that the radio wave frequency be at least twice the critical frequency of the ionosphere. Because of differing plasma conditions, the results of underdense ionospheric heating are analysed separately for the different ionospheric regions.

In the lower ionosphere, at altitudes near 100 km, the electron heating is controlled by a local balance between electron heating and electron loss processes. At these altitudes thermal conduction is unimportant. A 1 MW underdense heating experiment from an assumed antenna of 300 meters diameter at Arecibo produces heating effects of 100 km comparable to the SPS microwave beam. The most dramatic heating effects occur in the E region, where thermal runaway occurs. The electron temperature will increase from 200°K to approximately 1000°K and the electron density will increase by a factor of about three.

At F-region heights thermal conduction plays a dominant role in the heat balance equations. The key scaling parameter then corresponds to energy deposited along a magnetic flux tube per unit time. Evaluated for 300 km altitude, this parameter equals 2.8 km for the SPS and 0.84 km for Arecibo and $f_o = 15$ MHz. Thus it would take a 3 MW transmitter at 15 MHz, or a 2 MW transmitter at 10 MHz, to simulate the effects of the SPS accurately. However, a 10 MHz heating experiment could operate only at night, when the ionospheric plasma frequency was low. Although the length of heating along a magnetic field line for the Arecibo experiment (~ 21 km) is much greater than the corresponding value of the SPS microwave heating (~ 5.6 km), both cases fulfill the essential condition

that this scale be small compared to the size of the ionosphere. F-region electron temperatures are predicted to increase by 200-500°K along magnetic field lines passing through the radio wave beam with enhanced airglow emission also excited.

3.2 THERMAL RUNAWAY

Strong radio wave heating of the ionosphere is capable of inducing a thermal runaway in the D and E regions (Holway and Meltz, 1973). Thermal runaway can occur because the electron-neutral collision frequency ν_{en} increases with increasing electron temperature. As a result, as the electrons get hotter, the heat input Q becomes larger. In addition, the rotational excitation of N_2 and O_2 , which Holway and Meltz used as the principal energy loss mechanism, actually decreases with increasing electron temperature. In the Perkins and Roble work significant improvements have been made to the original Holway and Meltz study by including energy loss through vibrational excitation of N_2 and O_2 , as well as energy loss resulting from $O(^3P)$ excitation. The monotonic rise of electron temperature predicted by the original theory is stopped by vibrational energy losses, which increase rapidly for electron temperatures above 1000°K. These vibrational excitations then can lead to observable airglow emissions.

The time scale for electron heating and cooling associated with a thermal runaway is a sensitive function of altitude, equal to 2.5×10^{-3} sec at 100 km and 1×10^{-1} sec at 120 km. Threshold for achieving thermal runaway at 100 km is just satisfied in the center of the beam for a 15 MHz, 1 MW Arecibo underdense heating experiment. Scaling to microwave frequencies, this corresponds to an effective SPS power density of approximately 20 mW/cm². To assure that thermal runaway will occur in the experimental test program, a 2 or 3 MW Arecibo heating experiment is essential.

3.3 THERMAL SELF-FOCUSING

As an electromagnetic wave propagates through a plasma small natural density fluctuations cause a variation in the index of refraction of the medium, resulting in a slight focusing and defocusing of the wave. The electric

field intensity increases as the incident wave refracts into regions of comparatively underdense plasma. Ohmic heating then generates a thermal pressure which drives plasma from these focused regions, amplifying the initial perturbation. This process is shown schematically in Figure 3.1. The self-focusing instability continues until hydrodynamic equilibrium is reached.

Thermal self-focusing does not have an absolute threshold in the usual sense. The focusing process organizes the plasma into large-scale field-aligned irregularities or striations. The threshold for creating these striations depends directly on the striation width $\lambda_{\perp}$. As the electric field intensity of the incident radio wave increases, the resulting striations become narrower. The threshold field is given by

$$P_{th} \approx (7.2 \times 10^{21}) T_e^5 f_o^2 f_c^{-6} \lambda_{\perp}^{-4} \cos^2 \theta, \quad (3.3)$$

where T_e is the electron temperature (in °K), f_c is the critical ionospheric frequency, and θ is the angle between the plane orthogonal to the incident wave propagation and the magnetic field. For typical values of the SPS microwave beam, $T_e = 1200^\circ\text{K}$, $f_o = 2.45 \text{ GHz}$, and $f_c = 8 \text{ MHz}$, then

$$P_{th} \approx (4.1 \times 10^{14}) \lambda_{\perp}^{-4} \cos^2 \theta. \quad (3.4)$$

For Arecibo, $\theta = 50^\circ$, so that

$$P_{th} \approx (1.7 \times 10^{14}) \lambda_{\perp}^{-4}. \quad (3.5)$$

For $P(\text{SPS}) = 20 \text{ mW/cm}^2$, $\lambda_{\perp} \approx 960 \text{ meters}$;

$P(\text{SPS}) = 200 \text{ mW/cm}^2$, $\lambda_{\perp} \approx 540 \text{ meters}$.

For $\theta = 89^\circ$, $P_{th} \approx (1.25 \times 10^{11}) \lambda_{\perp}^{-4}$ and

$P(\text{SPS}) = 20 \text{ mW/cm}^2$, $\lambda_{\perp} \approx 158 \text{ meters}$;

200 mW/cm^2 , $\lambda_{\perp} \approx 112 \text{ meters}$.

The spatial amplification for self-focusing is $\exp(\sqrt{\lambda-1} D)$, where $D = k_{\perp}^2 L / 2k_0$, or $D \approx 3.8 \times 10^4 / \lambda_{\perp}^2$ for $f_0 = 2.45$ GHz and $L \approx 100$ km, the ionospheric scale height. Then there is only small spatial amplification for $\lambda_{\perp} > 200$ meters. Using this approximation, for an incident power density of 20 mW/cm^2 , now self-focusing can occur for $\theta > 88.4^\circ$; for 200 mW/cm^2 , we have 84.9° . This limits the interference problem due to thermal self-focusing to SPS beam angles nearly parallel to the magnetic field lines.

Theoretically then thermal self-focusing will be excited for microwave power densities comparable to those of the SPS beam and should be experimentally studied. Also, it is not well known what additional plasma phenomena accompany self-focusing radio waves in the ionosphere.

Using this theory, what results are expected from the Arecibo interim test? Defining threshold by the criteria for adequate spatial gain we require that $D > 1$. Then the threshold powers for Arecibo are:

$$\begin{aligned} P(\text{S-band: } 2380 \text{ MHz}) &= 104 \text{ mW/cm}^2 \\ P(430 \text{ MHz}) &= 10 \text{ mW/cm}^2 \\ \text{and } P(\text{HF: } 8 \text{ MHz}) &= 1.3 \times 10^{-6} \text{ mW/cm}^2, \end{aligned}$$

compared to transmitted power densities of the limited test program,

$$\begin{aligned} P(\text{S-band}) &= 1 \text{ mW/cm}^2 \\ P(430 \text{ MHz}) &= .35 \text{ mW/cm}^2 \\ \text{and } P(\text{HF}) &= 2.3 \times 10^{-6} \text{ mW/cm}^2. \end{aligned}$$

Clearly then no self-focusing is expected for S-band or 430 MHz radio waves. On the other hand, the HF power density is just above threshold so that some effect might have been produced although no echoes were observed in Guadeloupe.

In addition to the above conditions, another restriction must be imposed on the incident radio wave. If the spatial gain condition were relaxed, the threshold striation width would become larger, and thus easier to maintain. However, the striation width cannot become any longer than the radio wave beamwidth. At 250 km the S-band beamwidth is approximately 200 meters, the 430 MHz beamwidth is approximately 600 meters, and the HF beamwidth is approximately 30 km.

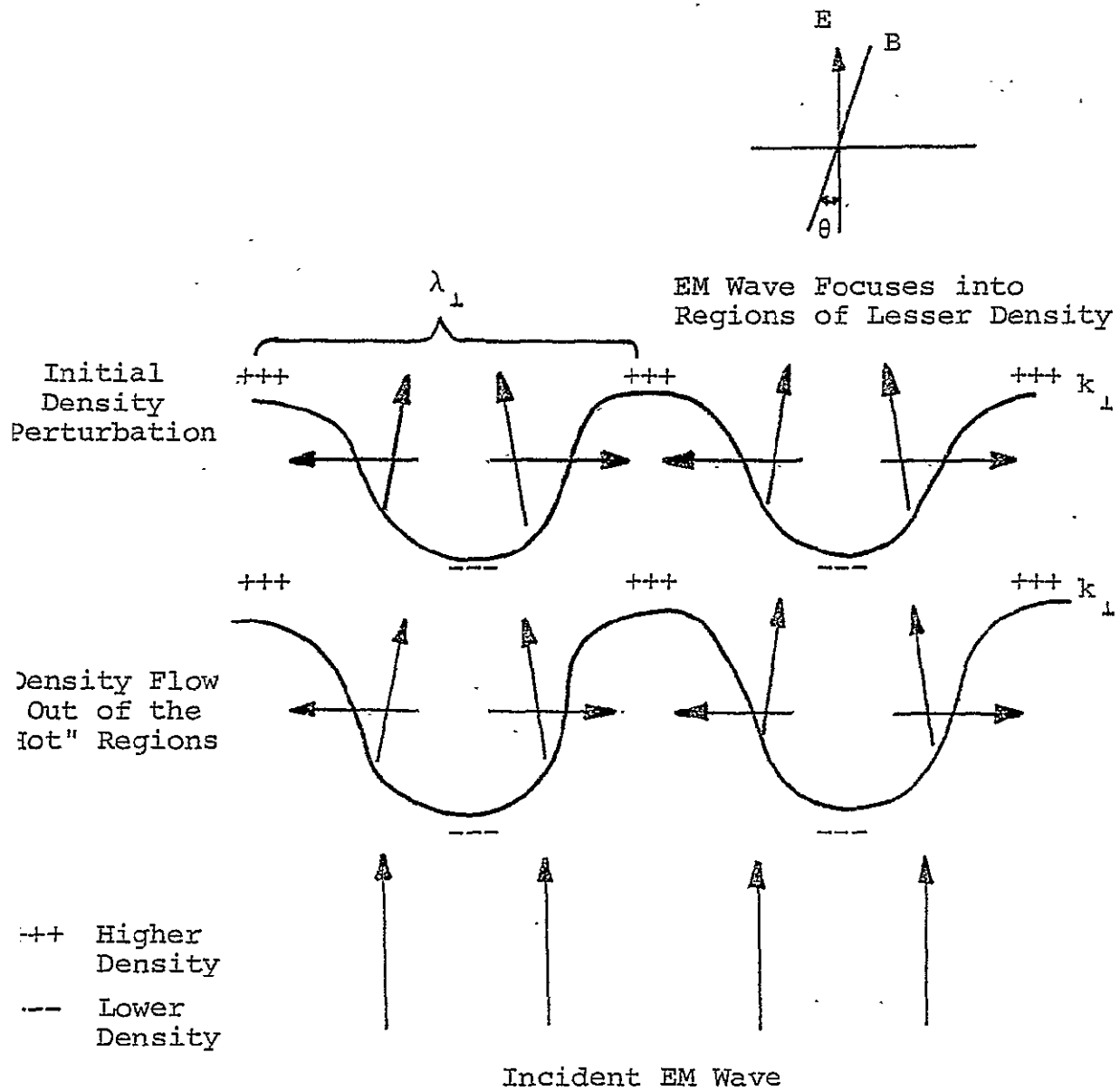


FIGURE 3.1 Thermal Self-Focusing

3.4 EFFECTS ON COMMUNICATION AND NAVIGATION SYSTEMS

"Assess the effects on existing communication and navigation systems if the microwave beam exceeds the power density limits for nonlinear interactions with the ionosphere."

The assessment depends on the production in the ionosphere above about 110 km altitude of striations that scatter radio waves, and on irregularities inserted into the earth-ionosphere waveguide below about 110 km that propagate low frequency waves. Whether the striations are produced by nonlinear interactions or by linear interactions (e.g., ohmic heating) makes little difference. Striations will scatter radio waves regardless of their production mechanism. Above about 110 km the striations have a shape and an orientation that limits their effectiveness as scatterers and the geographic region in which they provide ground-to-ground links. The effects of the striations and of the imperfections in the waveguide are considered separately in the following.

Striations in the lower E region

If produced, striations in the E region (around 100 km altitude) will act like natural sporadic-E clouds and scatter isotropically radio waves in the frequency range 2 to perhaps 200 MHz and perhaps higher. As with sporadic E, TV signals for example would be received from stations up to about 2000 km distant provided the scatterers are near the mid-path or at least visible to both transmitter and receiver. As with sporadic E, the signal scattered decreases rapidly with increasing frequency. Channel 2 at the low end of the VHF TV-band is most often seen by this mechanism and usually as an interfering, rather than useful, signal.

Striations above 110 km altitude

If produced, striations in the ionosphere above about 110 km will be elongated along the earth's magnetic field and the scattering will be very aspect sensitive. The shape of the striations is the result of the high conductivity along the field line compared to that across the field line. The striation may have an excess or a deficit of electrons compared with ambient.

The scattering cross-section for the striations over Platteville, although produced by anomalous absorption associated with plasma instabilities, suggests a frequency dependence that should apply to striations produced by other means. The scattering cross-section decreases relatively slowly (less than 10 db) from 40 MHz to 90 MHz, drops an additional 20 db by 157 MHz and then slowly (less than 10 db) to 435 MHz. An attempt to observe the backscatter at 1300 MHz was unsuccessful. This behavior is shown in Figure 3.2 taken from Minkoff (1974).

The aspect sensitivity is best described by thinking of specular reflection (angle of incidence equals angle of reflection) from a line segment where the line is along the magnetic field and the length of the segment determines the angle about the specular direction in which significant signal is observed. Note that the angle of incidence is fixed by the direction of the arriving wave normal and the direction of the magnetic field, but that the angle of reflection is satisfied by a cone with axis on the field line and half angle equal to the angle of incidence. An illustration of the intersection of these cones with the earth's surface is shown in Figure 3.3. Thus a transmitter located anywhere along the contour 96° (angle of incidence, 6° from normal to the field line) will be received by field-aligned scatter at 230 km over Platteville anywhere along the contour 84° (angle of reflection, 6° from normal to the field line). The reception sites will be in a zone along contour 84° with the width of the zone decreasing with increasing frequency because the length of the line segment (the striation size along the field), although fixed in physical length, is longer when measured in wavelengths at the higher frequencies. Since the scattering is occurring from heights around 230 km, the point-to-point path lengths on the ground may be as long as 2500 km. The scattering is described in detail by Fialer (1974) and by Stathacopoulos and Barry (1974).

The signals received are scattered not by a single striation but by many striations. They therefore introduce noise into the communication channel. The observed bandwidths for the Platteville experiments were a few kilohertz and this is consistent with the multipath effects associated with the volume of scatterers contributing to the received signals. The narrow band (few kilohertz) character of the scatter process makes it of limited use for communication purposes and establishes it as a possible source of inter-

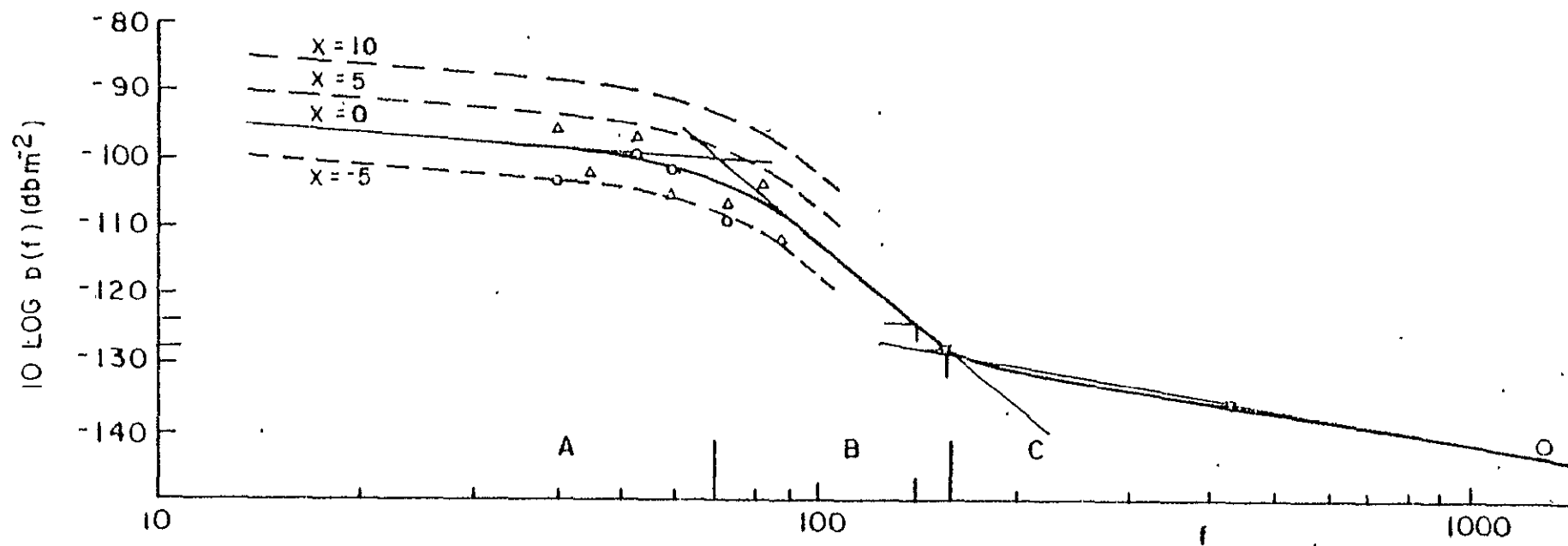


FIGURE 3.2 Observed backscatter coefficient as function of frequency (Minkoff 1974).

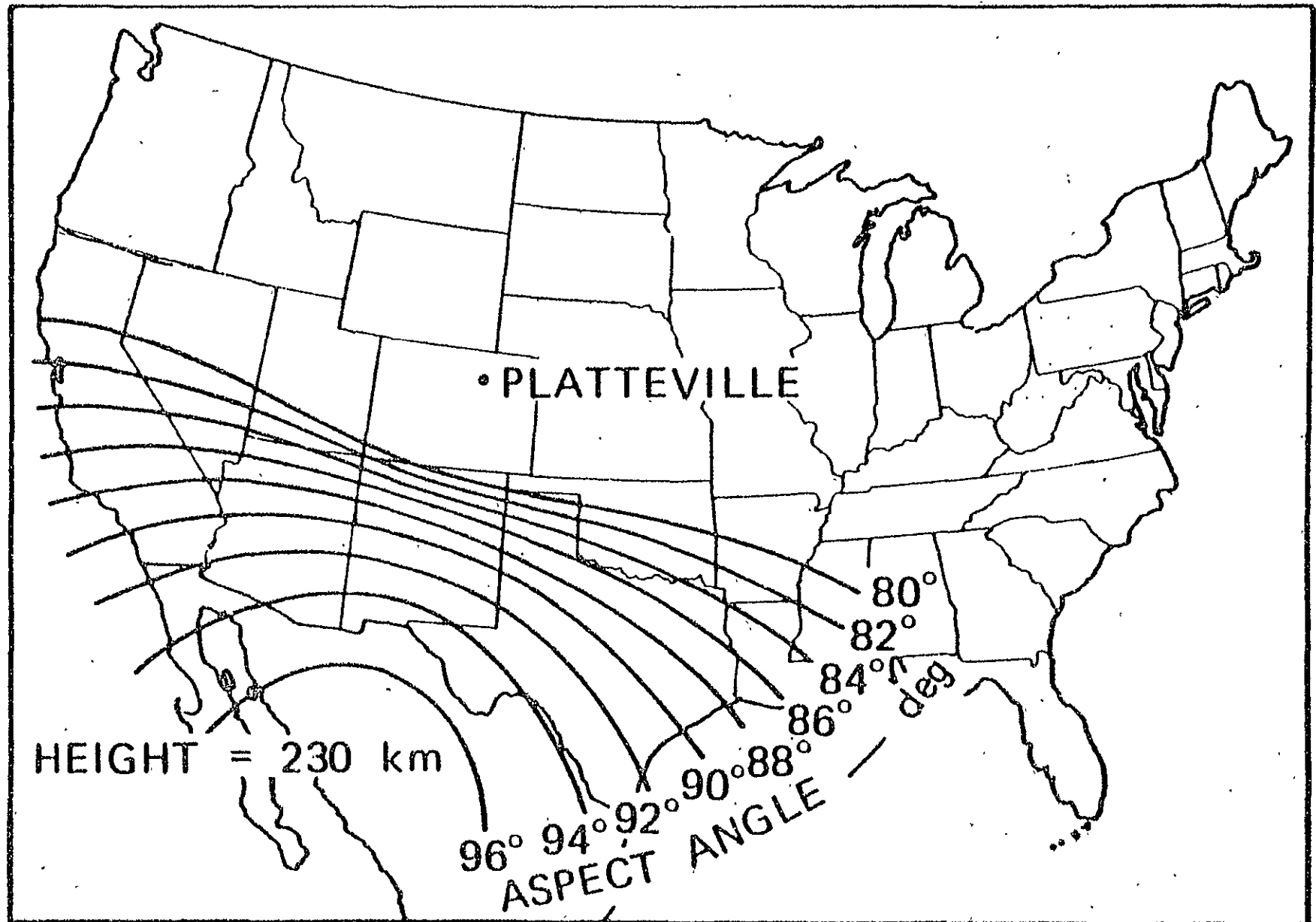


FIGURE 3.3

Contours of the earth intersection of rays originating at a point 250 km above Platteville and meeting the geomagnetic field at the angle indicated (Fialer 1974).

ference for broad-band transmissions (e.g., TV, FM radio). The interference region, of course, is subject to the limits imposed by the aspect sensitivity.

Finally, since the scattering is field-aligned, there will be a region of the earth free of interference because the dip angle (the angle the field makes with local horizontal) of the magnetic field is large enough that any signals transmitted from the ground and scattered in the ionosphere do not return to earth but are scattered into space. In this case the cone described above on which the scattered signals may be received does not intersect the earth. The maximum dip angle, $I_{\max}$, which will provide ground-to-ground communication links via scattering from field-aligned striations at an altitude h for an earth of radius r is

$$I_{\max} = \sin^{-1} \frac{r}{r+h} \quad (3.6)$$

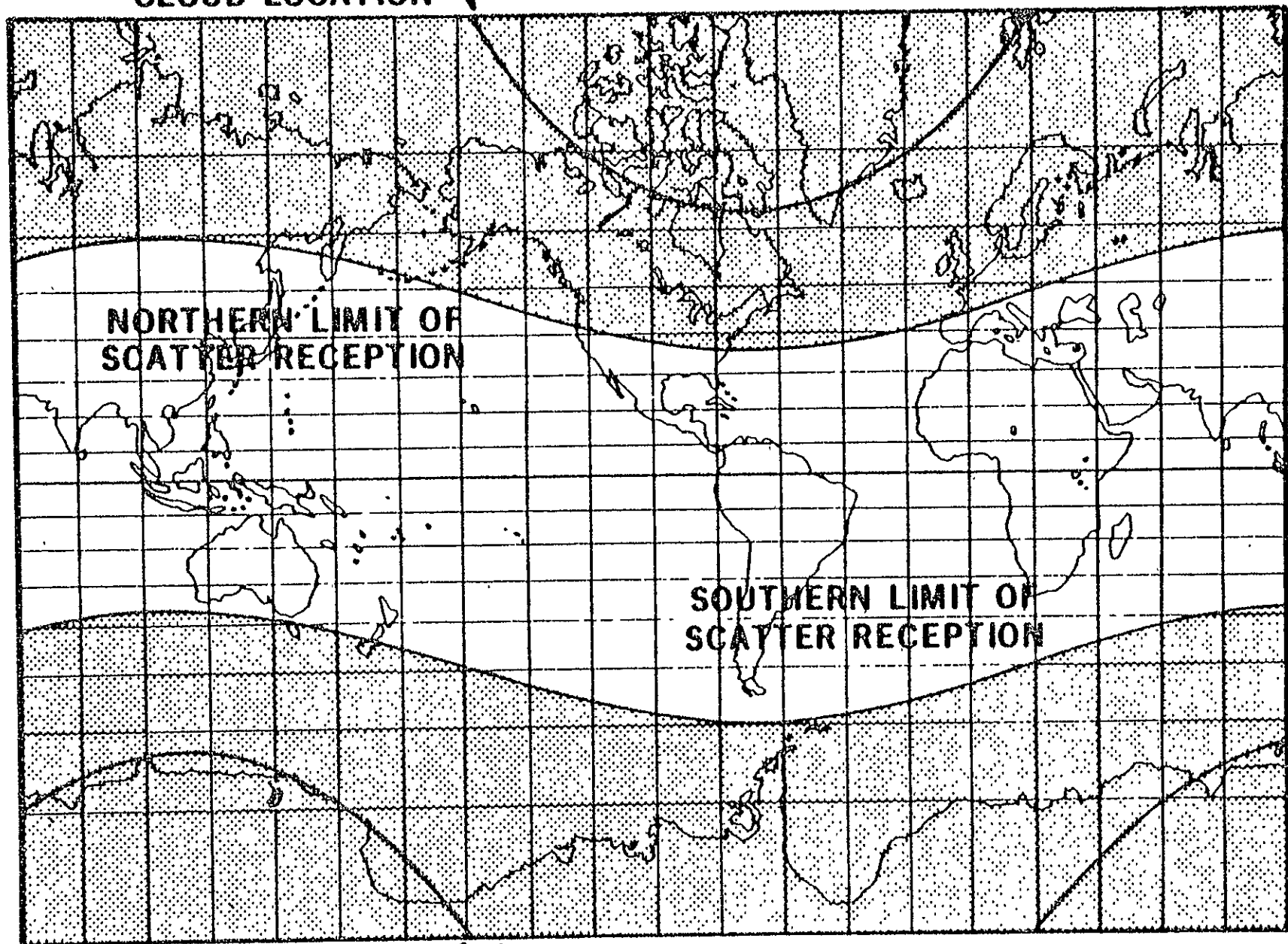
The dip angle I is related to the magnetic latitude λ by

$$\tan \lambda = \frac{1}{2} \tan I \quad (3.7)$$

so that for scatterers at 200 or 250 km, $I_{\max}$ is $77^{\circ}1$ or $75^{\circ}6$ and λ is $65^{\circ}3$ or $62^{\circ}8$. Figure 3.4 shows the regions of the earth (shaded) that are free of interference from field-aligned scatterers at 250 km altitude for ground-to-ground links. Note that it includes the northern U.S.A., including all of New England. The lines on the figure defining the limits of reception are lines of constant magnetic latitude.

A 5 GW SPS system will produce striations only when the angle between the SPS beam and the magnetic field is less than about 5° (Section 3.2). This limits striations produced by this mechanism to low latitudes (roughly a line from Miami, Florida to Brownsville, Texas) and the radio frequency interference will be mostly between stations north and south of the Gulf of Mexico and between stations south of the Gulf of Mexico.

**NORTHERN LIMIT OF USEFUL
CLOUD LOCATION**



**SOUTHERN LIMIT OF
USEFUL CLOUD LOCATION**

FIGURE 3.4 Region in which field-aligned scatter from 250 km altitude can reach the ground.

Earth-ionosphere waveguide

SPS heating of the D region (50-100 km altitude) will produce imperfections in the earth-ionosphere waveguide that will affect navigation systems (e.g., Omega, LORAN C) and any systems in the frequency bands 10 KHz and 100 KHz. The imperfections will essentially cast shadows down the guide and these shadows will introduce errors into the navigation systems. The errors should be measured both in magnitude and in the geographic regions affected by an imperfection. If the errors are stable in time and location as measured in the test program, a means of applying corrections should be available.

4. LIMITED TEST PROGRAM

"Perform a limited test program at the Arecibo facility using existing equipment. In particular the tests should be performed at S-band, using the maximum power and power density available at the facility. The test results should be compared with theoretical predictions as given in Task A."

4.1 SUMMARY OF LIMITED TEST OPERATION AND RESULTS

A limited test program was conducted between 2-15 June 1977 using the existing ionospheric heating facilities at the Arecibo Observatory and a portable radar placed to observe at normal incidence to the earth's magnetic field lines any field-aligned irregularities of electron density produced over Arecibo. The Arecibo Observatory is operated by Cornell University with the support of the National Science Foundation. The portable radar was provided and operated by the Aeronomy Laboratory of NOAA at Tarare near Point-à-Pitre on the French island of Guadeloupe made available by the Institut de Physique du Globe in Paris.

The results are that the available transmitters (HF, 430 MHz, 2380 MHz) and the 1000-foot antenna produced no striations that could be detected at Guadeloupe where the minimum detectable cross-section was 10^{-3} meters squared (10^{-3}m^2). The radio wave heating of the ionosphere for the available transmitters is about 1% for HF, 40% for 430 MHz, and 5% for 2380 MHz of the ohmic heating that the proposed 5 GW SPS system will produce. The horizontal dimensions of the heated ionosphere are 25 km at HF, 0.7 km at 430 MHz and 0.2 km at 2380 MHz. The latter two are less than the predicted scale size to produce thermal self-focusing instabilities and the power densities are less than the critical power densities predicted for thermal self-focusing instabilities. The negative results are consistent with the theoretical predictions.

As a check of the system strong echoes (cross-sections up to the order of 10^3m^2) from striations over Arecibo were observed at Guadeloupe when the Arecibo heating frequency was equal to the plasma frequency at some height in the ionosphere. In this case the striations are the result of instabilities based on resonances between the natural plasma frequency and the heater frequency, a problem that will not be encountered with the SPS.

The results are detailed below followed by a description of the experimental arrangements and the interaction volume.

4.2 RESULTS

Heating by HF waves above the critical frequency

Result.

Radio wave heating by HF waves above the critical frequency of the ionosphere (the maximum plasma frequency of the ionosphere) at a heating level of 1% of the ohmic heating predicted for a 5 GW SPS system did not produce field-aligned striations with radar cross-sections of 10^{-3}m^2 or more. The scattering volume is approximately 10^{13}m^3 for this case so the scattering cross-section per unit volume is less than $10^{-16}\text{m}^2/\text{m}^3$.

When the heating frequency is more than twice the local plasma frequency there are no known resonance effects. This condition was achieved on two days, 8 and 13 June. On 9 June the heating frequency determined by the operating conditions of the transmitter was well above the critical frequency but not above twice the critical frequency. The signals are averaged over the times given in Table 4.1 to improve the sensitivity of the measurement. The column headings are defined and the sources of the entries are given below.

The critical frequencies are read from ionosondes located at the Observatory and 10 km north of the Observatory.

Power density calculation.

The power density P_D at 250 km is calculated from the usual expressions,

$$P_D(r) = \frac{P_T G \alpha_a}{4\pi h^2} \quad (4.1)$$

where P_T is the transmitter power (60 to 100 kilowatts),

G is the antenna gain (160 at 7 MHz, 220 at 8 MHz, and 290 at 9 MHz),

TABLE 4.1

Date 1977	Time AST	Heating Frequency MHz	Critical Frequency MHz	Power Density at 250 km, mW/cm ²	Ohmic Heating as a Fraction of 5 GW SPS Heating	Cross-section Observed at Guadeloupe is less than m ²
08 June	0310-15	9.37	3.6	2.3×10^{-6}	0.8%	2.1×10^{-3}
	0316-27	9.37	3.5	2.6×10^{-6}	1.0%	2.8×10^{-3}
	0329-51	9.37	3.4	2.6×10^{-6}	1.0%	3.7×10^{-3}
	0415-37	9.37	3.3	3.0×10^{-6}	1.1%	3.0×10^{-3}
	0438-0500	9.37	3.1	3.0×10^{-6}	1.1%	4.0×10^{-3}
09 June	0320-0417	7.80	4.3-4.1	2.2×10^{-6}	1.0%	1.4×10^{-3}
	0455-0532	6.58	3.9-4.2	1.4×10^{-6}	0.9%	1.0×10^{-3}
13 June	0309-37	7.80	3.7	2.9×10^{-6}	1.3%	2.2×10^{-3}
	0343-0451	6.875	3.3	1.4×10^{-6}	0.9%	0.7×10^{-3}

α_a (taken as 1 for night observations) is the fraction of the power that is transmitted through the atmosphere, $(1-\alpha_a)$ is the radio wave attenuation by the atmosphere, and

h is the altitude.

Frequency scaling of ohmic heating.

The scaling of the ohmic heating from the operating frequency of the experiment to the SPS frequency is derived from the expression for ohmic heating of a plasma,

$$Q = \frac{E_o^2}{8\pi} \frac{f_p^2}{f^2} (\nu_{ei} + \nu_{en}) \quad (4.2)$$

$$\text{or} \quad Q \propto P_D / f^2 \quad (4.3)$$

where E_o is the peak value of the electric field of the heating wave,

f and f_p are the operating frequency and the plasma frequency, and

ν_{ei} and ν_{en} are the collision frequencies of the electrons with the ions and with the neutrals,

so that the ratio of ohmic heating produced by the test wave, Q , and the 2450 MHz wave of the SPS is

$$\frac{Q}{Q_{SPS}} = \frac{P_D}{P_{DSPS}} \frac{f_{SPS}^2}{f^2} \quad (4.4)$$

and the power density of the SPS is taken as 20 mW/cm².

Guadeloupe radar sensitivity.

The limit on the cross-section σ observed at Guadeloupe is calculated from the radar equation and the expression for the minimum detectable power of the receiver. The ratio of these is the signal-to-noise (S/N), the quantity observed at Guadeloupe.

$$S = \frac{\alpha_c P_T G}{4\pi r^2} \cdot \sigma \cdot \frac{\alpha_c A}{4\pi r^2} \quad (4.5)$$

$$N = kTB/n \quad (4.6)$$

where α_c is the factor representing the transmission line loss taken as 0.67,

P_T is the transmitter power 1.44×10^4 watts,

G is the antenna gain, 420 and

A is the antenna collecting area 1200 m^2 for an array of 4×40 half-wave dipoles above ground,

r is the slant range to the target (660 km) from the radar on Guadeloupe to the ionosphere directly above the Arecibo Observatory,

k is Boltzman's constant 1.38×10^{-23} ,

T is the system temperature, $T_r + \alpha_c T_s$ where the receiver temperature $T_R = 1000^\circ$ and the sky temperature is 6000° , and

B is the bandwidth of the receiver, 4000 Hz for a transmitted pulse length of 200 μs and n is a coherent integration factor that helps the sensitivity. Values of n used in the observations range from 1 to 4.

The observational conditions and results are summarized in Table 4.1.

Heating by 430 MHz waves

Radio wave heating of the ionosphere by 430 MHz waves at a heating level equal to 40% of the ohmic heating predicted for a 5 GW SPS system and in a volume with horizontal dimensions of 1 km or less rather than the 5 km of the SPS system did not produce field-aligned striations with radar cross-sections of 10^{-3} m^2 or more. The scattering volume is approximately 10^{11} m^3 for this case, so the scattering cross-section per unit volume is less than $10^{-14} \text{ m}^2/\text{m}^3$.

The Arecibo transmitter at 430 MHz operates only in a pulsed mode, but will produce pulses as long as 10 ms. The thermal time constant at 250 km altitude is about 2 ms. The 10-ms pulse, therefore, brings the ionospheric plasma into a "steady-state" during the pulse. The observational conditions and the results are summarized in Table 4.2 using column headings defined for Table 4.1.

Heating by S-band waves (2380 MHz)

Radio wave heating of the ionosphere by 2380 MHz waves at a heating level equal to 5% of the ohmic heating predicted for a 5 GW SPS system and in a volume with horizontal dimensions of 0.2 km rather than the 5 km of the SPS system did not produce field-aligned striations with radar cross-sections of 10^{-3}m^2 or more.

The Arecibo transmitter operated in a continuous wave mode; the power is fed into the 300-meter dish but only 200 meters are illuminated. The resulting beam is a cylinder of diameter 200 meters at the heights of interest. The observational conditions and the results are summarized in Table 4.3, using column headings defined for Table 4.1. The scattering volume is approximately 10^{10}m^3 for this case, so the scattering cross-section per unit volume is less than $10^{-13}\text{m}^2/\text{m}^3$.

4.3 EXPERIMENTAL ARRANGEMENTS

Arecibo

HF facility.

The HF transmitter built by the Office of Telecommunication Sciences of the Department of Commerce is connected through six-inch coax-line to a log-periodic antenna feed mounted above the 300-meter dish. The transmitter produces up to 140 KW of power at frequencies from 4 to 12 MHz and beams it vertically in either ordinary or extraordinary modes of polarization with antenna gains estimated at 160 for 7 MHz, 220 for 8 MHz, and 290 for 9 MHz. The gain increases more rapidly than frequency-squared because the blockage of the aperture by the feed support structure and cables decreases with increasing frequency.

TABLE 4.2

Date 1977	Time AST	Heating Frequency/ Pulse Length	Critical Frequency MHz	Power Density at 250 km, mW/cm ²	Ohmic Heating as a Fraction of 5 GW SPS Heating	Cross-section Observed at Guadeloupe is less than m ²
13 June	1301-43	430 MHz/ 10 ms	6.5-6.6	0.35	40%	4.0×10^{-3}
14 June	1827-1908	430 MHz/ 10 ms	9.5-9.0	0.35	40%	1.8×10^{-3}

TABLE 4.3

Date 1977	Time AST	Heating Frequency MHz	Critical Frequency MHz	Power Density at 250 km, mW/cm ²	Ohmic Heating as a Fraction of 5 GW SPS Heating	Cross-section Observed at Guadeloupe is less than m ²
12 June	1044-1115	2380	5.5-5.8	1	5%	10^{-3}
13 June	1046-1115	2380	5.3-5.8	1	5%	10^{-3}

The HF waves are refracted by the ionosphere when the wave frequency is near or less than the critical frequency, but for frequencies well above the critical frequency the refraction effects are negligible for our purposes.

The HF beamwidth is about 8° at half-power points and this corresponds to horizontal dimensions of 30 kilometers for the heated volume at an altitude of 240 km. The vertical dimension of the heated volume is about 10 kilometers centered near the peak of the electron density profile.

430 MHz facility.

The 430 MHz transmitter operates in a pulsed mode with peak powers of 2 megawatts. A waveguide connects the transmitter through movable joints to a line feed designed to correct for the aberration of the spherical reflector. The antenna gain is 10^6 , the beamwidth is 0.2° , and the beam can be pointed anywhere in a 40° cone with vertical axis. For our purposes the beam was pointed almost vertically. The zenith angle was 4° (limited by the physical presence of the HF feed), the azimuth angle was magnetic north (353°). The transmitter was operated in a long (10 msec) pulse mode. The thermal time constant of the ionospheric plasma is about 2 ms. During the long pulse the plasma was heated and almost reached a steady-state value. The diagnostic observations at Arecibo and Guadeloupe were examined with proper allowance for heating of the plasma during the long pulse and the relaxation of the plasma during the interpulse period.

S-band facility.

The S-band transmitter operates in a continuous-wave mode with power up to 500 kW. The frequency used was 2380 MHz. The transmitted power is delivered to a line-feed to correct for spherical aberration. Two hundred meters of the 300-meter dish are illuminated. The heights of interest are in the near-field of the antenna where the beam is a cylinder of diameter 200 meters. The beam was pointed almost vertically. The zenith angle was 5° , the azimuth angle 112.5° (the direction toward Guadeloupe).

Guadeloupe

Site.

Guadeloupe was selected as the site to observe any striations produced over Arecibo because the geometry is right, i.e., at Guadeloupe the radar sees striations at normal incidence to their long axes. Any striations in the ionosphere above about 110 km that occur naturally or are produced artificially will be elongated along the direction of the earth's magnetic field simply because the magnetic field constrains the charged particles to spiral about the field lines and it is therefore easier for electrons to travel along the lines than across them. An elongated target of charged particles will have a scattering coefficient that varies with the aspect angle with which it is observed and the coefficient maximizes when the striation is viewed in backscatter at normal incidence to the long axis. This was well mapped in the Platteville experiments (Radio Science 9, November 1974). If striations are produced in the ionosphere over Arecibo they will be elongated along the magnetic field line and observed in backscatter anywhere in the plane perpendicular to that field line. Since the field line direction changes slowly with height one picks a height where striations may be expected and generates the plane perpendicular to the field line at that height. The map of Figure 4.1.a has lines representing the intersections with the earth of the planes perpendicular to the field lines at 110, 220 and 330 km over Arecibo. For striations at heights from 220 to 250 km Guadeloupe is a good location. The site near Pointe-à-Pitre has a line-of-sight perpendicular to the earth's magnetic field over Arecibo at a height of 230 km, as shown in Figure 4.1.b.

Radar operation.

The radar placed on Guadeloupe operated with the following parameters (nominal):

Frequency	50 MHz
Peak Power	15 kW
Pulse Lengths	20-200 ms
Interpulse Period	10 ms
Receiver Noise Temperature	1000°K
Estimated Sky-Noise	6000°K

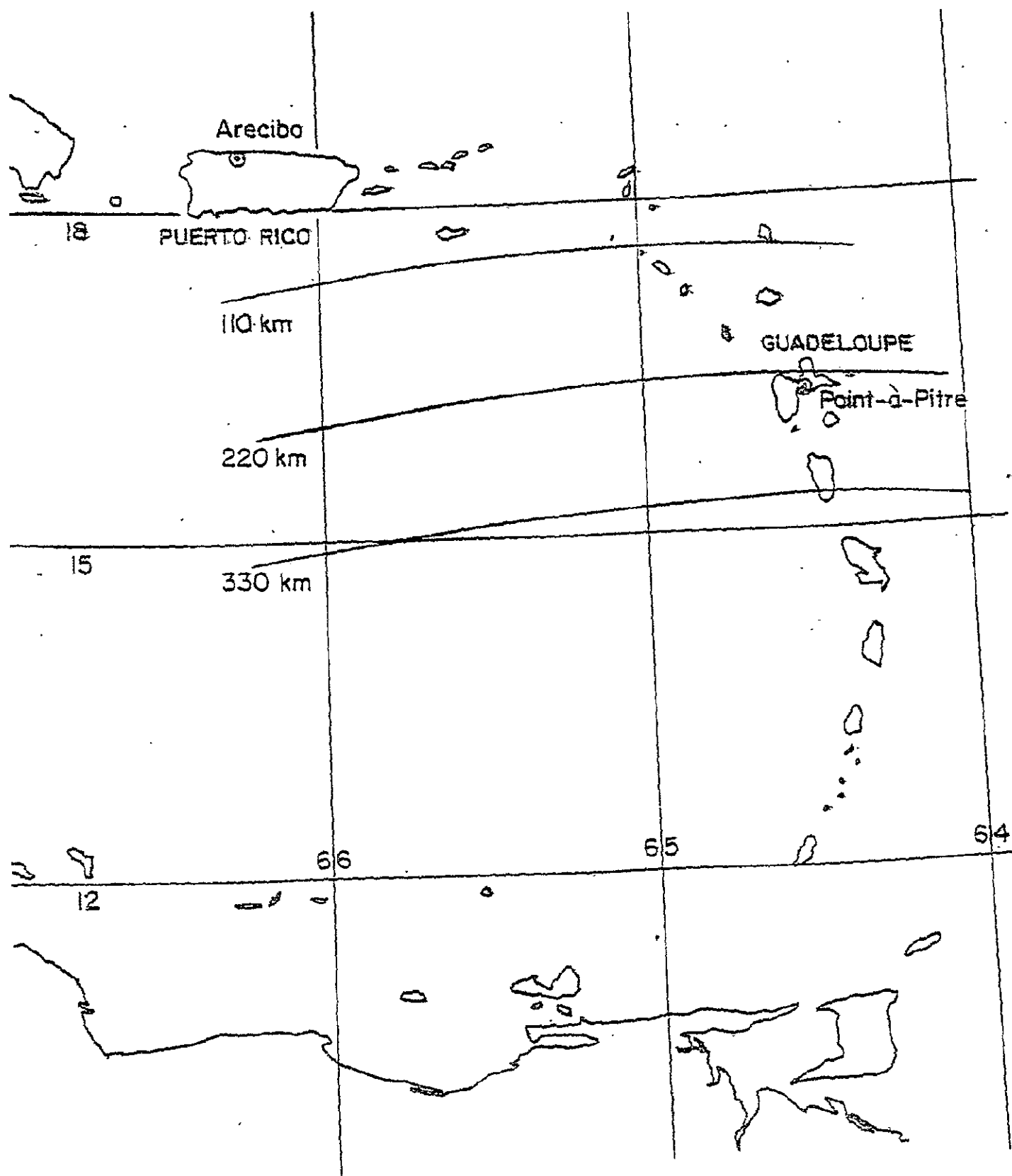


FIGURE 4.1.a Ground contours of normal incidence

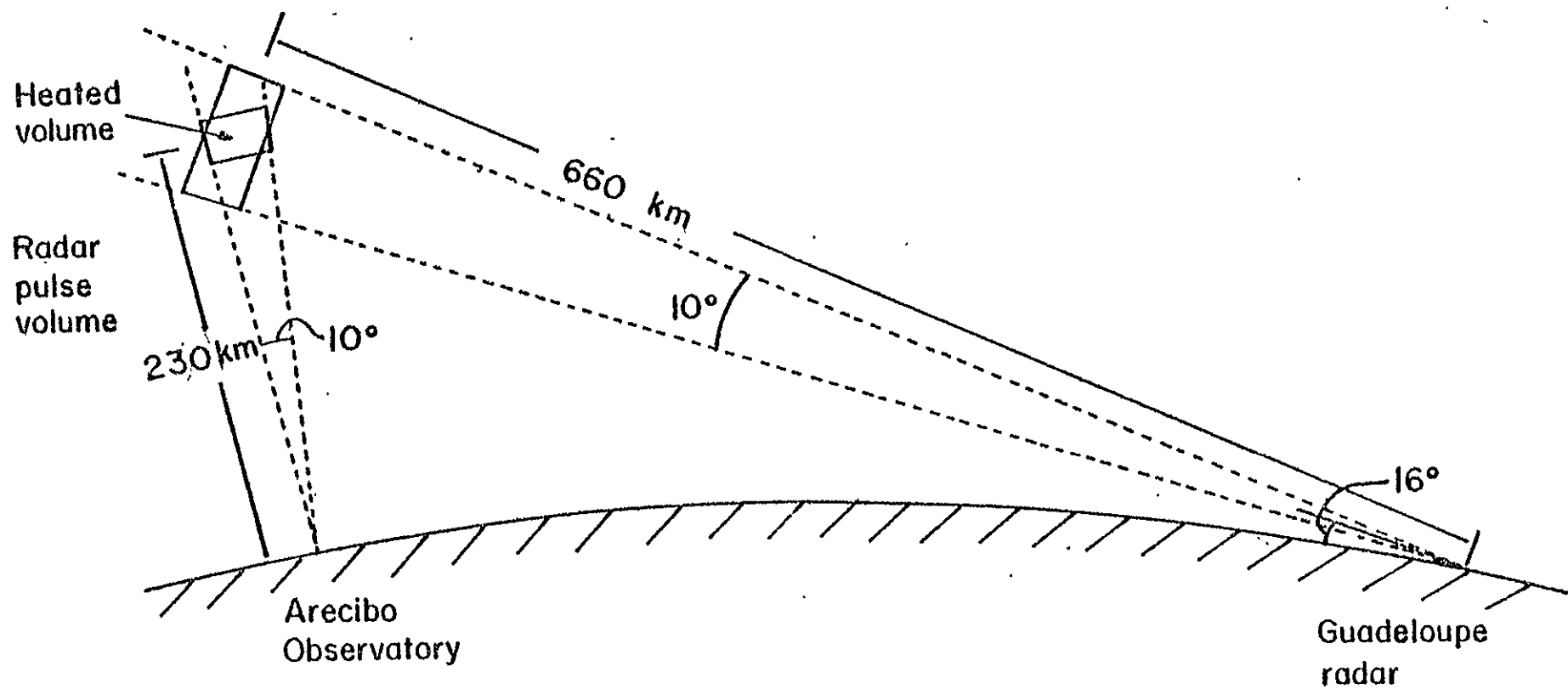


FIGURE 4.1.b Arecibo Guadeloupe Geometry

Antenna An array of 4 lines of 40 half-wave dipoles over the ground. The calculated parameters are:

Collecting area	=	1200 m ²
Antenna gain	=	420
Vertical beamwidth	=	10° (2-way)
Horizontal beamwidth	=	2° (2-way)
Elevation angle	=	16°
Azimuth angle	=	292°

Data.

The data are recorded on magnetic tape and in pictures of the A scope (range vs. intensity) and of the Doppler shifted spectrum of a target. For our purposes the signals at the ranges of interest were integrated over tens of minutes to improve the sensitivity of the measurement.

The system was checked by observing striations produced over Arecibo when the heating frequency matched the ionospheric plasma frequency. Field-aligned echoes over Arecibo with up to 30 db signal-to-noise ratios were observed at a slant range of 660 km from Guadeloupe. These echoes are from striations produced by instabilities tied to overdense heating.

4.4 THE INTERACTION REGION

The interaction region is defined by the intersection of the radar pulse volume and the modified volume. The modified volume is the extension by conduction and convection of the volume in which the energy is deposited.

Heated volume

Energy is deposited by ohmic heating in a volume that is defined by the heater beamwidth horizontally and by the variation of the electron density vertically. The horizontal dimensions are 30 km, 0.7 km and 0.2 km for the HF, 430 MHz and S-band heaters. The vertical dimensions are about 10 km for each (see Appendix 1). The heated volumes are essentially vertically over Arecibo. The 430 MHz heated volume is displaced northward by about

16 km at a height of 250 km; the S-band heated volume is displaced toward Guadeloupe by 21 km but these displacements leave the modified volume well within the radar field of view.

Modified volume

The energy deposited in the above volumes heats the electrons and they move along the magnetic field lines rather easily stretching out the heated volume along the field by a few tens of kilometers (see Appendix 1). The field lines over Arecibo are at an angle of 50° to the horizontal, and the heated volume is distorted along that direction.

The volume modified by the heating transmitters is, therefore, a cylinder of diameter .30, 0.7, or 0.2 km for HF, 430 MHz and S-band, of height about 10 km and the cylinder is stretched out or slid along the field line whose direction is 50° from horizontal in the N-S plane and the stretching adds about 10 km both up and down the field line. Figures 4.2 and 4.3 illustrate the modified volumes for the HF and S-band cases respectively.

Radar field of view

The radar observes a volume defined by the beam angles and the pulse length. Pulse lengths of 200 ms were used corresponding to a resolution length along the radar beam of 30 km. The horizontal beamwidth of 2° corresponds to a horizontal dimension of 22 km at 660 km range and the vertical beamwidth of 10° corresponds to a dimension normal to beam and in the vertical plane of 110 km. The beamwidths represent the angles between the points on the antenna pattern where the power is down by a factor of 0.7 from the power in the direction of the maximum (i.e., these are half-power beamwidths for the antenna pattern squared). The elevation angle of the beam at Guadeloupe is 16° , over Arecibo the elevation angle becomes 22° due to the curvature of the earth. The volume, therefore, is approximately a box centered at 230 km over Arecibo having dimensions 30 km along the line-of-sight (elevation angle 22° , azimuth 292°), and normal to the line-of-sight 110 km in the vertical plane and 22 km horizontally.

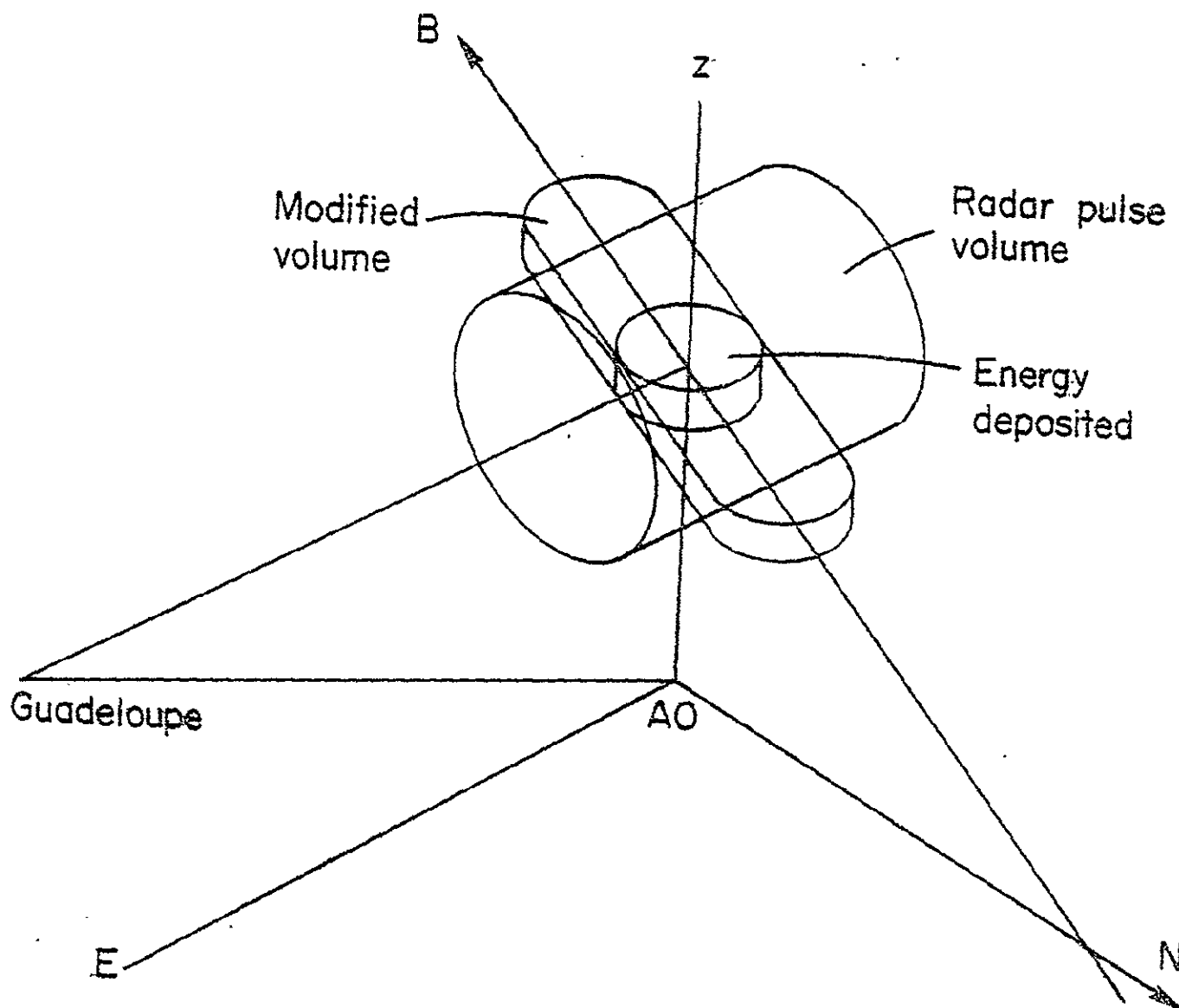


FIGURE 4.2 Intersection of Guadeloupe radar pulse volume and the Arecibo modified volume for HF.

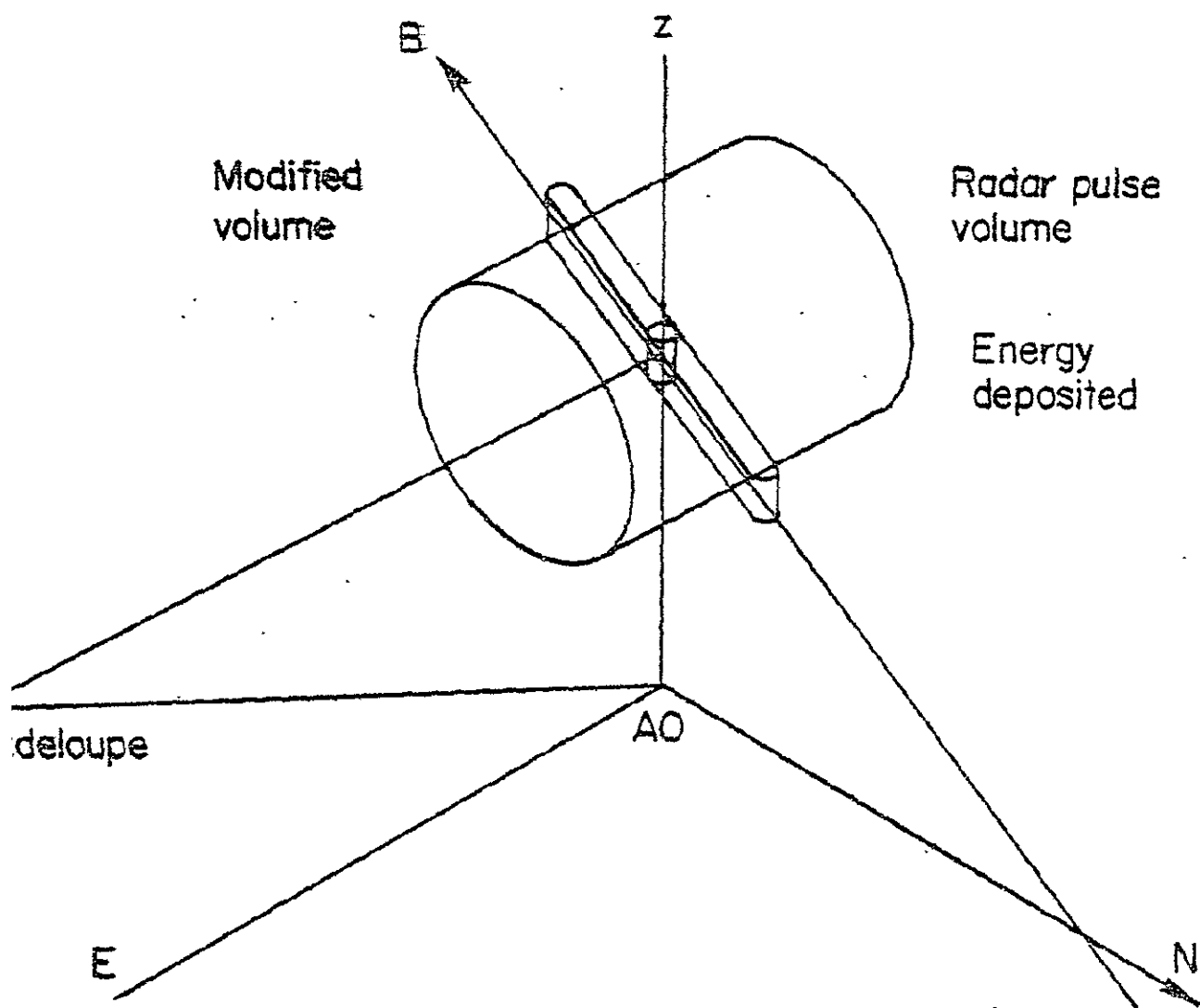


FIGURE 4.3 Intersection of Guadeloupe radar pulse volume and the Arecibo modified volume for S-band.

Scattering volume

The common portion of the modified volume and the observed volume is the scattering volume and has dimensions roughly 30 km, 0.7 km, 0.2 km (for HF, 430 MHz, S-band) in the direction of the radar beam, about 10 km vertically in the meridian plane (vertical plane containing the magnetic field line) and 22 km along the field line. The limits are set respectively by the heater beamwidth, by the heating efficiency (i.e., the electron density profile), and the azimuth beamwidth of the radar. The common volume in cubic kilometers is about 6.6×10^3 , 15.4, and 4.4 km³ for the HF, 430 MHz, and S-band cases.

The targets, striations, may have an aspect sensitivity that further restricts the volume since the elongated targets have a scattering coefficient that peaks at normal incidence for a backscatter radar (it peaks when the angle of incidence equals the angle of reflection for separated transmitter-receiver links).

4.5 COMPARISON OF EXPERIMENT AND THEORY

Part of the ionospheric modification experiment was devoted to attempts to produce field-aligned irregularities in the underdense ionosphere using the available S-band, 430 MHz and HF facilities. The principal diagnostic was a 50 MHz radar stationed in Guadeloupe, capable of receiving direct backscatter from 3 meter field-aligned irregularities over Arecibo. Such small scale features had been previously observed over Platteville for overdense heating of the ionosphere, and were believed to accompany thermal self-focusing striations. As predicted by theory, no signals were seen for underdense heating of the ionosphere by the subthreshold S-band and 430 MHz radio waves. Nor were echoes observed from HF underdense heating.

The overdense heating experiment produced some interesting results by itself. The accepted theory for the generation of the small-scale field-aligned irregularities (Perkins, 1974) required the parametric decay of the incident radio wave into electrostatic plasma oscillations. Parametric instabilities are known to be excited for ordinary mode (O mode) polarization of the radio wave, but not the extraordinary mode (X mode).

Nevertheless, small-scale features were observed by the Guadeloupe radar for both O and X mode HF radiation, with charges in range of the radar signal indicating that the transmitted polarizations were in fact different since O and X mode waves refract differently in the ionosphere...

The study of field-aligned irregularities in the overdense modified ionosphere was first undertaken by Thome (1974) using a circular HF phased array at Platteville. His results confirmed that these striations formed with power densities, scale sizes, and growth rates close to those predicted by Perkins and Valeo (1974). Development of a new diagnostic technique in conjunction with the recent ionospheric modification experiment has resulted in the first detailed observations of individual self-focused striations, as well as striation maps of the entire wave-plasma interaction region. These results, while in comparative agreement with theoretical predictions, suggest that additional plasma effects should also be considered.

Intense high-frequency electromagnetic radiation incident on the overdense ionospheric plasma is known to excite parametric instabilities, enhancing electron plasma oscillations observable by incoherent backscatter radar. These instabilities continue to be the subject of intense experimental study. Of importance here is the fact that the strength of the enhanced plasma waves directly depends on the local intensity of the pump electric field. In addition, because of frequency and wave number matching conditions for both the parametric wave-plasma interaction and the incoherent backscatter process, these enhanced waves are detected at only one specific altitude. As a result, systematic measurements of the enhanced plasma line, while sweeping the narrow backscatter radar beam across the interaction region, yield a two-dimensional cross-section characteristic of the local electric field intensity. The electric field striation maps thus generated show self-focusing spatial profiles and large-scale structuring of the illuminated plasma. Because the direction and rate of the radar movement are experimentally controlled, the cross-sectional dimensions of the striations are easily measured. Alternatively, if the radar is fixed, the striations follow a slow natural ($E \times B$) drift through the beam, allowing a detailed study of the small-scale structure within individual striations. Once the size is known striation velocities can be calculated from these drift measurements. The experimental configuration is shown in Figure 4.4.

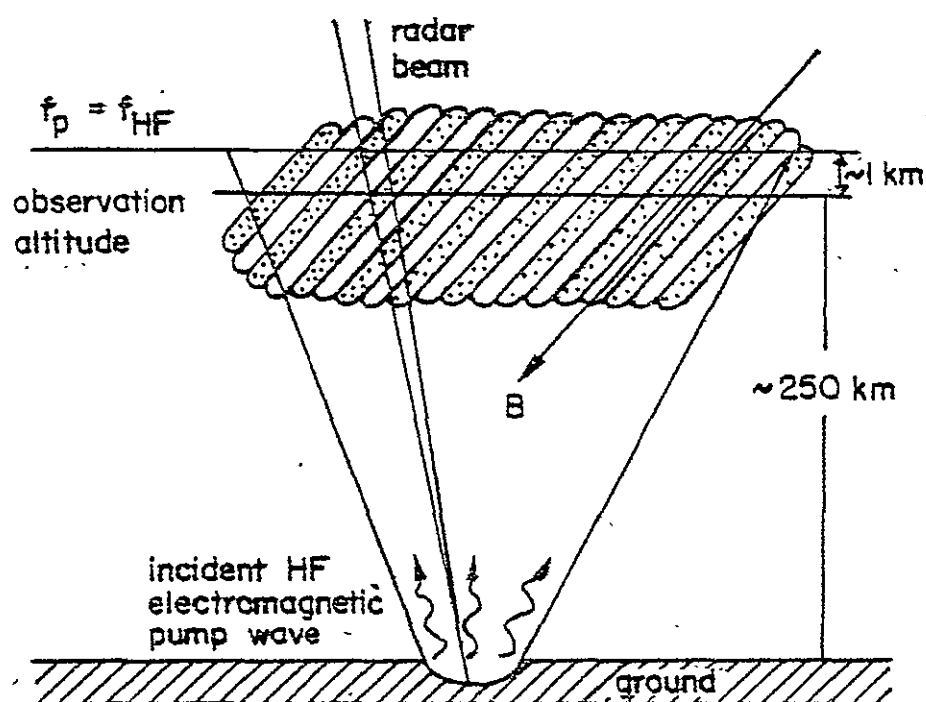


FIGURE 4.4 The experimental configuration for incoherent backscatter radar mapping of overdense self-focusing striations.

The incoherent backscatter radar operates at 430 MHz with a $1/6^\circ$ beamwidth, corresponding to approximately 730 meters at a typical interaction height of 250 km. The HF wave beamwidth is a function of the operating frequency, ranging from 7.2° at 7.8 MHz to 10.9° at 5.185 MHz, or 31.5 and 47.5 km respectively at 250 km altitude. The HF radiation, continuous wave with ordinary polarization, is fixed at vertical incidence, while the 430 MHz radar can be swept in zenith angle at a rate of up to $1.87^\circ/\text{minute}$, or 136 m/sec at 250 km. Plasma line intensities were measured over a 20 kHz filter bandwidth centered on the pump frequency, using a 500 μsec radar pulse and a pulse repetition period of 8500 μsec , as determined by a 6% transmitter duty cycle. The data rate is not continuous; data are accumulated in arrays of 1024 pulses, after which there appears a data gap of approximately 0.4 sec in which the array is recorded on magnetic tape and displayed real-time.

Results of the two basic observing strategies are shown in Figures 4.5 and 4.6. The first data correspond to the natural drift of striations through the fixed radar beam. This drift gives rise to a slow regular modulation of the measured plasma line intensities, with typical periods of 60 to 90 seconds. Similar fluctuations have been noted previously without interpretation. The second data set, taken immediately following the above drift measurements, shows a series of distinct striations observed by sweeping the radar beam north across the interaction region. Typical striation dimensions are measured to be approximately 1.2 km in the north-south magnetic meridian plane and 1.0 km in the east-west perpendicular plane. Striation velocities are of the order of 20 m/sec to the east and smaller than 15 m/sec in the north-south direction. North-south velocity measurements are complicated by a strong spatial dependence of the striation width.

These results now can be compared to overdense self-focusing theory. Accordingly,

$$P_{\text{th}} \approx (7.6 \times 10^{12}) T_e^5 L^{-1} f_o^{-1} f_c^{-2} \lambda_{\perp}^{-2} \cos^2 \theta . \quad (4.7)$$

Let $T_e = 1200^\circ\text{K}$, $f_o = f_c = 8 \text{ MHz}$, $L = 100 \text{ km}$, $\theta = 50^\circ$, and $P = 40 \mu\text{w}/\text{m}^2$ at the center of the HF beam. Then,

$$\lambda_{\perp} \approx 1.95 \text{ km} . \quad (4.8)$$

Beam fixed at 3.2° north

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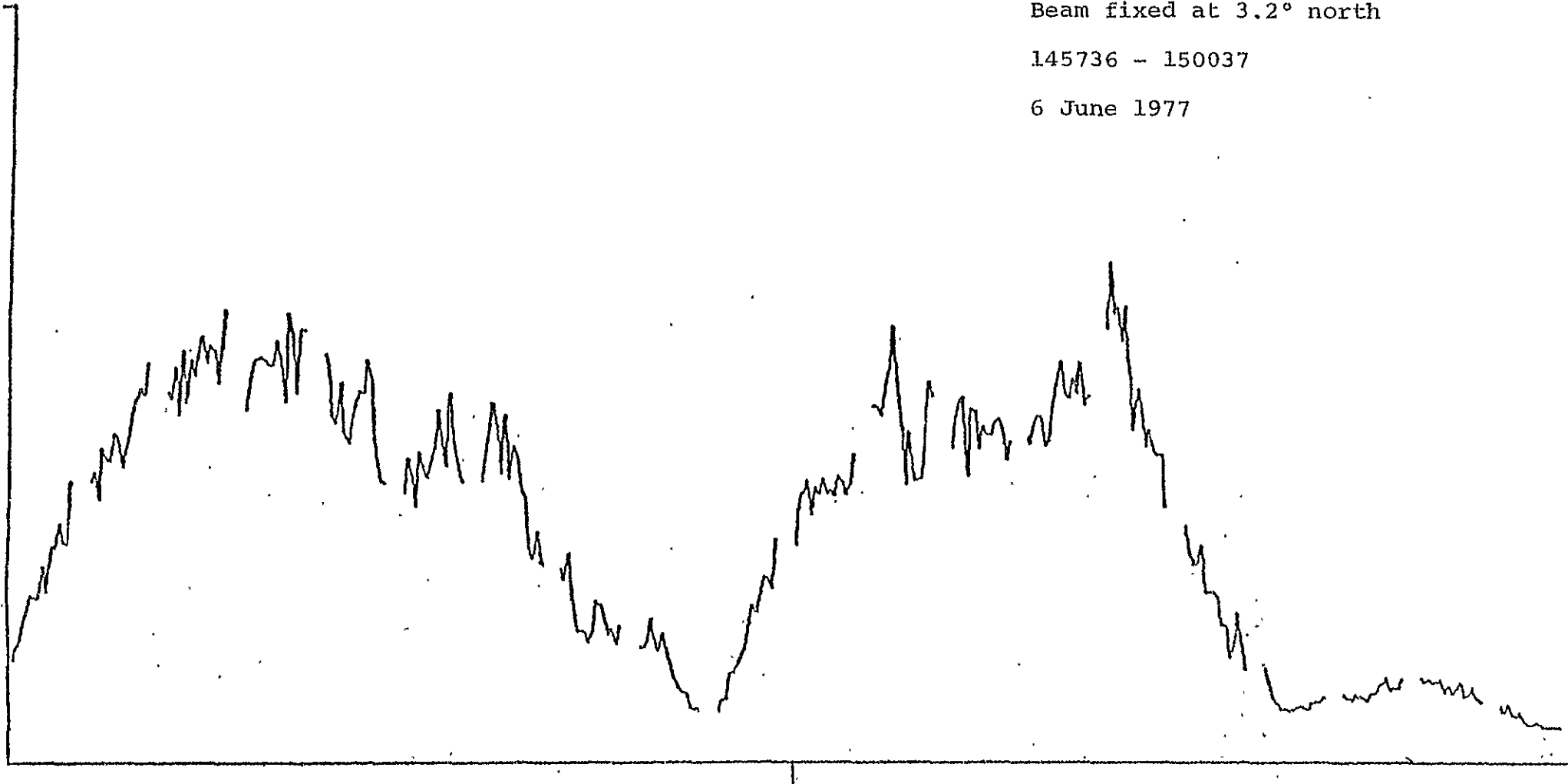


FIGURE 4.5 Natural striations drifting through the radar beam.

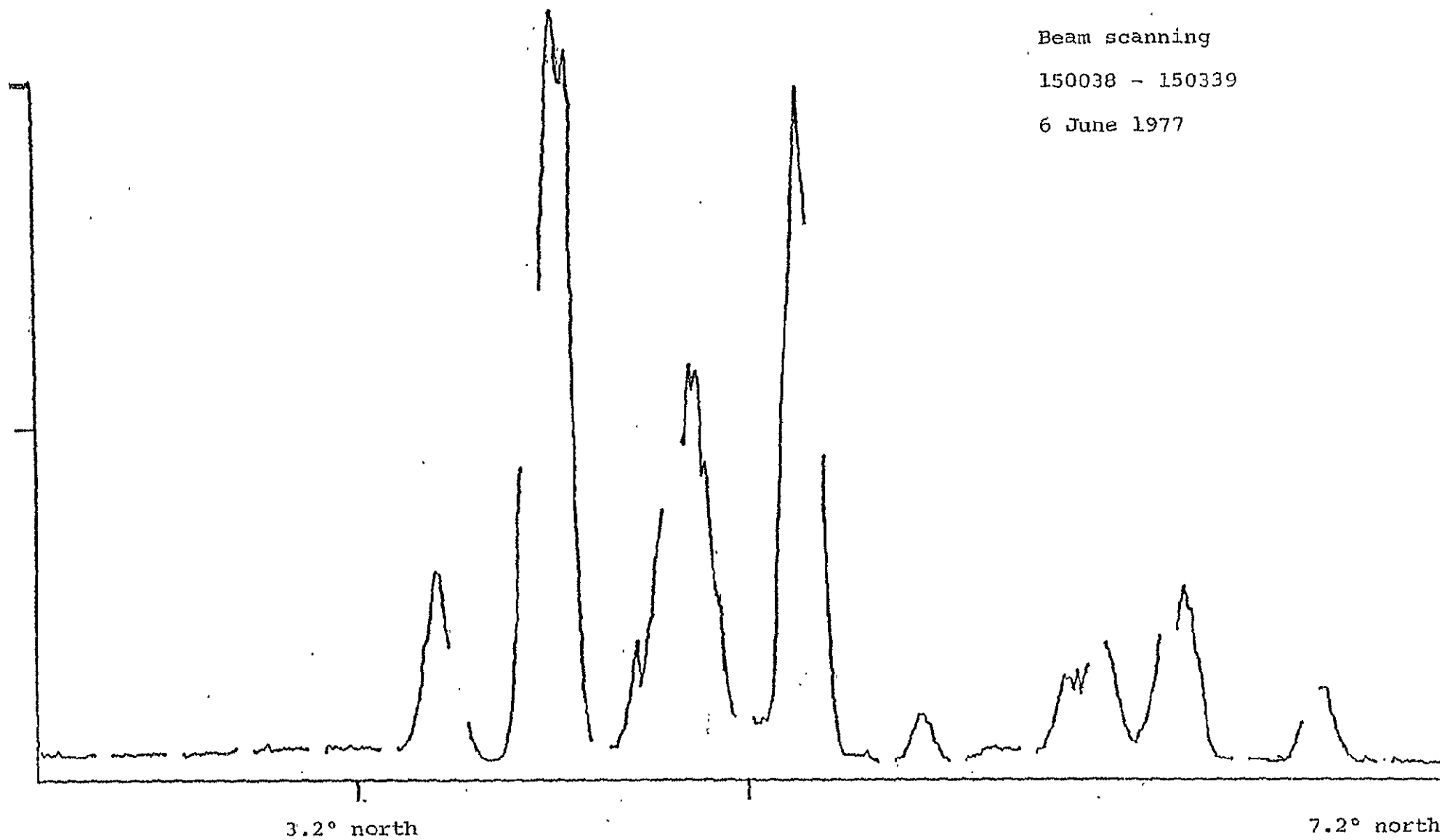


FIGURE 4.6 Radar beam sweeping through a series of striations.

Thus the striation width is, by definition, about 1 km at vertical incidence. The incident power density is a function of the angle from vertical incidence, since the transmitted power is not uniform over the beam, but can be represented by a gaussian distribution. In addition, the north-south sweeps also vary the value of θ . As a result, theoretical curves allowing for this variation of λ_1 can be computed. Figure 4.7 shows experimental data representing the width of striations (east-west and north-south components shown separately) versus their angle from vertical incidence. The solid curves are theoretical expectations accepting reasonable values for the striation width at the center of the beam. Despite the large scatter in the data, the theoretical curves approximate the data behavior fairly well.

An unexpected feature of the observations is the strong tendency for striations to appear in compact bunches, rather than occur uniformly distributed over the heated region. The fluctuations of signal strength during natural drifts of the striations through the radar beam suggest the presence of small scale irregularities such as those seen by the Guadeloupe radar. However, the diagnostic radar beam is too wide to directly resolve discrete striations of this size.

Although the present technique was developed for the observation of overdense self-focusing effects, a similar experimental program measuring the altitude changes of naturally enhanced plasma waves should work to make comparable observations of underdense self-focusing striations possible.

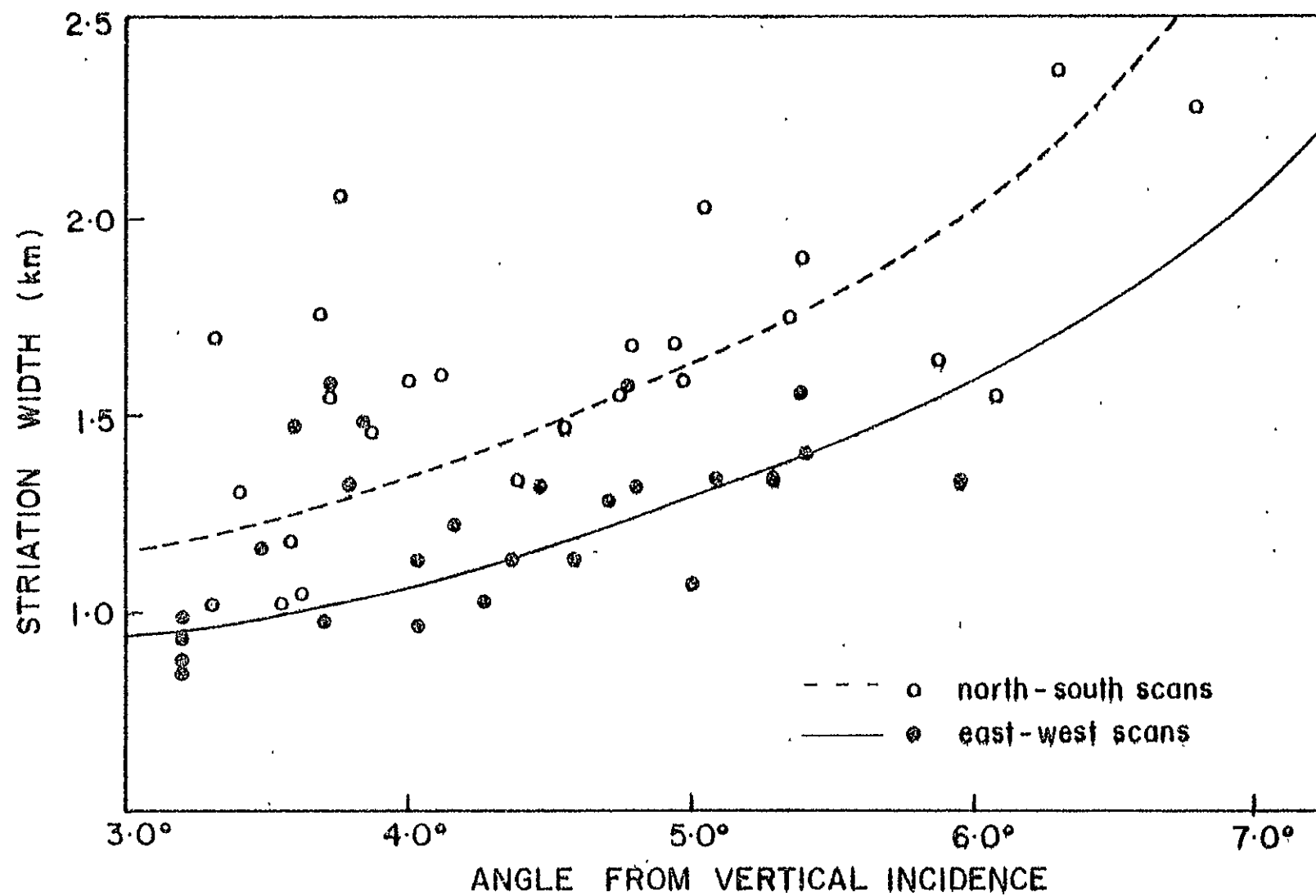


FIGURE 4.7 Variation of striation width as a function of power and θ - experiment and theory.

5. THE TEST PROGRAM

"Define a test program for detailed ground testing to fully determine the exact density levels at which the interactions occur, the extent of possible disruptions to navigation and communication systems, and any environmental impacts. This test program definition should include (1) measurement parameters, (2) evaluation of existing facilities at Arecibo and Platteville and the modifications needed at each of these sites to accommodate S-band testing at power densities up to 50 to 100 milliwatts/cm², (4) costing information for such a test program to fully determine the microwave beam ionospheric interactions, and (5) recommendations on the options given."

A test program is defined to simulate the interaction of the SPS beam with the ionosphere to measure the effects of the interaction and to interpret the results. The program includes (1) an HF heater capable of generating and delivering 15 MHz waves that produce more ohmic heating at all levels of the ionosphere than a 5 GW SPS and with a beam diameter that equals or exceeds the SPS beam diameter at all heights where it is critical, (2) diagnostics that map the changes in electron density and temperature and measure the intensity of any plasma instabilities produced, (3) field measurements to assess the effects on communications and navigation, (4) analysis and interpretation of the measurements, (5) associated studies, (6) a comparison of Arecibo and Platteville facilities, (7) budgetary estimates, (8) schedule, and (9) recommended test. Each of the nine elements of the test program is described below.

5.1 HF HEATER

A simulation of the SPS beam interaction with the ionosphere is necessary to keep the experiment manageable. The frequency scaling law for ohmic heating is known (Equation 4.4) and this provides a way of introducing the same quantity of heat into the medium from a source of a few megawatts rather than a few gigawatts. The scaling of the radio wave refraction in an ionized medium is also known and although this cannot be scaled in the experiment the proposed diagnostics permit the scaling to be made in the analysis and interpretation.

Heater frequency

The frequency scaling law for ohmic heating (Equation 4.4) shows that for the same heating ($Q = Q_{SPS}$) the test power density P that must be delivered to the ionosphere is

$$P_D = P_{DSPS} \frac{f^2}{f_{SPS}^2} \quad (5.1)$$

and this P_D is minimized for a given SPS system (P_{DSPS} and f_{SPS}) by making f as small as possible. A lower limit on the frequency is set by noting that one does not wish to excite any parametric instabilities in the ionospheric plasma in the test, for these are known to produce field-aligned striations. The SPS system frequency is far removed from the condition for parametric instabilities and the test frequency must, therefore, also be removed from that condition. To satisfy this condition one requires that the test frequency be at least twice the highest local plasma frequency, the critical frequency. Typical critical frequencies are 3 to 10 MHz depending on time of day and other factors.

We select 15 MHz as the nominal frequency that will satisfy the above conditions and permit operations for more than 50% of the time.

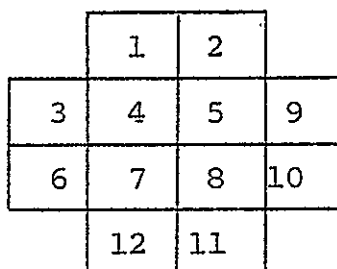
Power density

The 5 GW SPS system has typical power densities in the beam of 20-30 mW/cm². The contract calls for a test program with power densities equivalent to 50-100 mW/cm². Meltz (Space-Based Solar Power Conversion and Delivery Systems Study, Vol. III, Microwave Power Transmission Studies, Raytheon Co., March 1977) expects that non-linear effects may occur at 20 mW/cm² and above and recommends a test at these levels. Our studies (Section 3.2) show that thermal runaway in the E-region is likely to occur at 20 mW/cm². Perkins and Roble (Appendix 1) show that 20 mW/cm² will produce fractional changes of electron temperature of 30% or more in the ionospheric F-region. Although we have no firm prediction that this will result in an instability, the heating clearly needs to be produced and watched for instabilities.

Considering all of the inputs given above we use as criteria a test power density in excess of 25 mW/cm^2 at 300 km, 50 mW/cm^2 or more at 220 km and below, and in excess of 100 mW/cm^2 at 100 km.

Transmitter and antenna

The SPS beam contains about 98% of the power in a circle of 10 km diameter, and about 63% of the power in a circle of 5 km diameter. Since instabilities have a power threshold that must be exceeded to set them off, we concentrate on the 5 km diameter beam size where the SPS power densities are highest. The power density criteria given above can be produced in a circle of 5 km (or more) by transmitters with a power of 2.4 MW and an antenna of 12 modules, each consisting of an array of 16×16 crossed half-wave dipoles above a ground screen. The modules are arranged in the form of a cross as shown. Each module is fed 0.2 MW power.



Antenna Modules

For D and E region tests, modules 1 through 8 are excited producing the equivalent of 138 mW/cm^2 at 100 km in a beam just under 5 km diameter. The beam diameter is 5 km at 120 km increasing linearly with height. The equivalent power density is 50 mW/cm^2 at 166 km decreasing with height squared.

For F region studies all 12 modules are excited producing the equivalent of 61 mW/cm^2 at 200 km, 50 mW/cm^2 at 220 km, and 27 mW/cm^2 at 300 km in a beam size that is 5 km diameter at 160 km increasing linearly with height. The heater characteristics are summarized in Table 5.1.

TABLE 5.1

HF Heater

(Frequency 15 MHz; Wavelength 20 m;
Transmitter Power 2.4 MW)

		D and E Regions	F Region
Power		1.8 MW	2.4 MW
Number of Antenna Modules		8	12
Approximate Antenna Size (see Figure)		$24\lambda \times 24\lambda$ 480m $\times$ 480m	$32\lambda \times 32\lambda$ 640m $\times$ 640m
Equivalent SPS Power Density and Beam Diameter at Altitude of			
	80 km	216 mW/cm ² /3.3 km	
	100 km	138 mW/cm ² /4.2 km	
	120 km	96 mW/cm ² /5.0 km	
	160 km	50 mW/cm ² /6.7 km	96 mW/cm ² /5.0 km
	200 km		61 mW/cm ² /6.2 km
	220 km		50 mW/cm ² /6.9 km
	300 km		27 mW/cm ² /9.4 km

5.2 DIAGNOSTICS

To observe the interaction of the simulated SPS microwave beam with the ionosphere requires an incoherent scatter (IS) radar capable of mapping throughout the heated volume changes in electron temperature and electron density with spatial resolution of 0.5 km, temperature resolution of 5%, electron density resolution of 1% and time resolution better than a minute. The IS radar must be capable of detecting any plasma lines excited by the heater down to the level of the receiver noise for a receiver front end temperature of 100°K. Photometers to search for changes in the excitation of optical line radiation and ionosondes to follow the gross changes in the ionosphere are required.

5.3 FIELD MEASUREMENTS OF EFFECTS ON COMMUNICATION AND NAVIGATION SYSTEMS

To establish the effects, if any, on communication and navigation systems, we propose measurements at field sites chosen to emphasize the effects (see Section 3) associated with field-aligned striations and earth-ionosphere waveguide irregularities.

A 50 MHz radar of the type used successfully in the limited test on Guadeloupe (Section 4.3) is appropriate to look for field-aligned striations. Any radar that equals or exceeds in performance that used on Guadeloupe is acceptable and any site may be used that meets the aspect sensitivity requirements. Searches from two sites, however, are required. One to cover striations in the F region, the other to look for echoes in the E region. The E-region search should be conducted from a site where the aspect sensitivity from striations at 120 km is satisfied. A radar at this location should look for field-aligned echoes from 120 km and non-field-aligned echoes from lower heights.

To check for navigation problems, Loran-C and Omega receivers should be set up at fixed locations along the great circle from the navigation transmitter through the heater to look for changes in the system indicators with and without the heater operating.

The field measurements outlined here are first checks. If the results are negative then a wide range of possible problems are eliminated. If any of the results are positive the diagnostic observations must be analysed to assure a proper scaling to the SPS system. Additional field tests may be needed to define the scope of the difficulties.

5.4 ANALYSIS AND INTERPRETATION

The diagnostic measurements and the field measurements will be analysed to define the physical effects induced in the ionospheric plasma by the heater and relate them to the field measurements, either positive or negative.

Mapping of the electron temperature and density with and without the heater will yield plasma motions and scales, the intensities of any irregularities, the rates at which changes occur, and the time constants for achieving a new "steady-state."

While the scaling of the heating follows that of the SPS beam, the refraction is not scaled and the mapping will be crucial in establishing that the effects achieved in the simulation will also occur in the SPS beam.

Photometer observations will be useful indicators of both the usual thermal effects and the predicted thermal runaway in the D and E regions.

The interpretation will be based on the results of the field measurements in search of communication and navigation problems and on the analysis of the diagnostic data to define the areas that can be eliminated from further study, those that may have serious impact, and those that require additional testing.

5.5 ASSOCIATED STUDIES

Although theoretical plasma physics has been very successful at explaining ionospheric modification experimental measurements, it has been comparatively poor at predicting new results. The elegant mathematical techniques of linear plasma theory are relatively unprepared to explore the jungle of nonlinear phenomena found in experimental observations. As a result, there is a large inherent uncertainty in any discussion of future research

needs. The following section identifies several potentially important plasma effects which deserve further consideration.

Ponderomotive force

The ponderomotive force is a nonlinear plasma force deriving from the second order particle equation of motion, directly dependent on the gradient of the electric field strength. Although the ponderomotive force is generally much weaker than the ohmic heating thermal forces associated with the microwave beam, sharp gradients in electric field strength accompanying self-focused striations may introduce additional nonlinear effects. This gradient would be emphasized near the striation boundaries, suggesting that ponderomotive forces may produce irregularities on smaller scales than thermal self-focusing.

In the past instabilities driven by the ponderomotive force have been the most difficult plasma effects to theoretically anticipate. Because of the high power densities involved, nonlinear microwave-ionosphere interactions can generate completely unexpected plasma phenomena. For this reason, continued experimental and theoretical research of nonlinear plasma behavior is a necessity. To improve our understanding of self-focusing waves in plasmas, a self-consistent theory combining both thermal and ponderomotive forces needs to be developed.

Stimulated scatter

Self-focusing of the microwave beam, as discussed in Section 3.3, is a forward scattering mode of stimulated scatter driven by thermal forces. As such, only a small fraction of a percent of the incident radiation is actually absorbed or scattered away by the plasma. A much more serious problem would occur if the radiation suffered appreciable sidescatter or backscatter. In this case, a significant loss of transmission efficiency would result.

Stimulated scatter of electromagnetic radiation has been investigated as it applies to scatter from ion acoustic waves (stimulated Brillouin scatter) and electron plasma waves (stimulated Raman scatter). Fortunately, in both cases stimulated sidescatter and backscatter can be

neglected because of their much higher thresholds. Present theory states that these instabilities will be unimportant for the microwave power beam. However, as has been mentioned, theory is much better at explaining results than predicting observations. The possibility of additional stimulated scatter should not be forgotten, in case new studies significantly change our understanding of the scattering process.

Additional effects

The effect of microwave radiation on atypical ionospheric conditions needs to be studied. The amplification of existing ionospheric irregularities or an increased tendency for unusual ionospheric conditions represents a serious potential problem in ionosphere-microwave beam interactions. In addition, the possibility for generating or amplifying travelling ionospheric disturbances needs to be considered. All of the above effects can result in ionospheric irregularities over areas much larger than that intersected by the microwave beam.

Also, some basic physics questions remain unanswered. We have not discussed the possibility of radio frequency interference due to harmonic generation. The basic chemistry of the ionosphere could change drastically due to the large local input of thermal energy. Results from the most recent ionospheric modification experiment have left us without a viable explanation for the generation of small-scale field-aligned irregularities. We need to understand how plasma motions are affected by turbulent decay processes.

Parametric instabilities in the ionosphere have been suppressed successfully via frequency, phase, and amplitude modulation of the incident pump radiation. Although the spatial instabilities considered in this report differ considerably from parametric instabilities, continued research into the details of wave-plasma interactions offers interesting opportunities.

Laboratory plasma experiments

Detailed studies of intense ohmic heating effects in a plasma have been proposed based on ionospheric modification research. In all cases, these proposals have been developed around a frequency scaled experiment. That is, by lowering the operating frequency an equivalent amount of ohmic heating is achieved for much lower transmitter powers compared to the SPS microwave

system. Because the ionosphere is an excellent laboratory-without-walls for investigating large-scale plasma irregularities, the frequency scaled experiments offer promising research opportunities. However, additional experimental configurations were also considered.

A study was made of the feasibility for scaled laboratory studies of ionosphere-microwave interactions using Johnson Space Center's large thermal-vacuum test facility (Chamber A). An experiment was considered using microwave frequencies while scaling the radiated power and plasma density. Consequently a study was made to identify the principal problem areas for such an experimental program, the results of which appear in a report given in Appendix 2. The questions which arose out of this report were then studied, with the conclusion that a scaled laboratory experiment was not practical at this time.

Laboratory experiments at microwave frequencies lack adequate spatial amplification for self-focusing to occur. The theoretical condition for forward scattering requires $\lambda_{\perp} > \lambda_0/\epsilon$, ϵ small. In addition, the condition for spatial amplification can be expressed as $\lambda_{\perp} < N \lambda_0$, where N is the number of wavelengths $\lambda_{\perp}$ which go into the plasma scale length L , or $\lambda_{\perp} = L/N$. These restrictions then yield a relationship defining a key scaling factor,

$$\lambda_0/L \leq \epsilon^2. \quad (5.2)$$

Thus for microwave frequencies ($F_0 = 2.2$ GHz, $\lambda_0 = 13.6$ cm) and small angle scattering ($\epsilon = 10^{-1}$ is still fairly large angle scattering) the plasma scale length for self-focusing spatial amplification is $L \geq 13.6$ meters. This large dimension suggests that scaled laboratory experiments would be only minimally useful since the working plasma scale length of JSC's Chamber A is approximately 10 meters.

It is interesting to note that by increasing the operating frequency, the plasma scale length for self-focusing can be reduced. However, a test program using frequencies higher than those proposed for the SPS microwave beam is not necessary, since the equivalent phenomenon of beam filamentation has already been studied using high power densities and laser radiation. These results are not directly applicable to the study of ionosphere-microwave beam interactions.

Although laboratory experimentation does not appear promising for the investigation of thermal self-focusing instabilities, it continues to play an important role in the overall study of the ionosphere. Laboratory work provides valuable information on the ionospheric chemistry, collisional processes, and plasma instabilities, all of which are important if we hope to understand how the ionosphere behaves when strongly heated. Attention should be quickly given to any new laboratory research results which affect our present understanding of ionospheric processes.

5.6 COMPARISON OF ARECIBO AND PLATTEVILLE FACILITIES

The requirements for the test program can be listed under three main headings: the heater, the diagnostics, the field measurements. The general requirements for each item and the present availability at each site is indicated in the table below.

TABLE 5.2

		Availability at	
	<u>Requirement</u>	<u>Arecibo</u>	<u>Platteville</u>
<u>Heater</u>			
Transmitter (15 MHz)	2.4 MW	140 Kw	2.0 MW
15 MHz Antenna	~ 640m x 640m	None	None
Transmission Line	~ 6 km	None	~ 3 km
Site	120 acre flat rentable	Available	Available
<u>Diagnostics</u>			
Incoherent scatter radar	Equivalent AO	Available	None
Photometer		Available	Available
Ionosondes		Available	Available
<u>Field Measurements</u>			
Sites		Available	Available
Equipment		Available	Available

The advantage is with Platteville with respect to the heater and the value of the advantage is about \$2.5 million. The advantage is with Arecibo with respect to the diagnostics and the dollar value of the advantage is well in excess of \$10 million. Without attempting to price-out an IS radar at Platteville equivalent to Arecibo, one notes that the cost of the Arecibo facility was \$9 million in 1963.

There is no apparent advantage with respect to field measurements from the table but it should be noted that for a Platteville heater all of the interesting area is land and in the U.S.A. For an Arecibo heater much of the interesting area is sea with islands, few of which are U.S. territory.

The advantage with respect to cost is heavily in favor of Arecibo.

5.7 ESTIMATED BUDGET

The estimates tabulated below are based on inputs from Continental Electronics, the Aeronomy Laboratory of NOAA, L. M. LaLonde, and a proposal from Cornell University to the National Science Foundation for an HF Ionospheric Modification Facility dated November 1975 written by W. E. Gordon and L. M. LaLonde with the aid of AO staff members.

Heater in Place

Transmitter 15 MHz, 2.4 MW	\$1,000 K	
Antenna 12 modules, 16 x 16 crossed dipoles	750 K	
Transmission line and dividers	300 K	
Primary power 4000 kW	600 K	
Site development and transmitter shelter	300 K	
		\$2,950 K

<u>Field Sites and Equipment</u>	\$ 50 K	50 K
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Operations, Associated Studies and Analysis

Staff	\$ 600 K	
Site rentals, field expenses and travel	90 K	
Power	130 K	
Materials and supplies	180 K	
		1,000 K

TOTAL ESTIMATED COST		\$4,000 K
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BUDGET NOTES:

- (1) The transmitter estimate depends on securing 12 FRT-86 Navy units for modification. The units are presently available.
- (2) The antenna modules are 16 lines x 16 lines of 16 dipoles of the kind described by Balsley and Ecklund (1972).
- (3) The transmission lines are fabricated locally from standard irrigation pipes.
- (4) The equipment at the field sites will be on loan.

5.8 SCHEDULE

The schedule outlined in Table 5.3 calls for final design of the heater by early 1978, the procurement and installation of the heater by the end of 1978, tests in the first half of 1979 with the second half of 1979 reserved for further tests if warranted.

5.9 RECOMMENDATIONS

- (1) An HF heater should be designed, built and operated to reproduce and exceed the radio wave heating of the ionosphere of the 5 GW SPS system.
- (2) The heating effects should be mapped and measured by an incoherent scatter radar, by photometers and by ionosondes so that the scaling from HF to S-band can be made with confidence.
- (3) The effect of the ionospheric heating on communication and navigation systems should be measured directly.
- (4) The heater should be located in the vicinity of the Arecibo Observatory to take advantage of the existing diagnostic capabilities and to minimize the cost of the program.

TABLE 5.3

SCHEDULE

	Cal Year	1977	1978				1979			
	Quarters	4	1	2	3	4	1	2	3	4
<u>The Heater</u>										
Design		(1)	(1)							
Procure										
Install										
Operate										
Reserved for additional testing										(2)
<u>Field Measurements</u>										
Site negotiation										
Install equipment										
Operation										
<u>Operations, Associated Studies and Analysis</u>										
Associated studies		(1)	(1)							
Operations										
Analysis										

NOTES:

(1) Proposed work under contract being considered by NASA.

(2) Not included in budget.

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APPENDIX 1

IONOSPHERIC HEATING BY RADIOWAVES:
PREDICTIONS FOR ARECIBO AND THE SATELLITE POWER STATION

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ABSTRACT

The effect of resistive heating by radiowaves on ionospheric temperatures, electron densities, and airglow emissions is examined by using numerical ionospheric structure and heat balance codes. Two cases are studied: (1) a 3 GHz, 10 GW microwave beam from a proposed satellite power station and (2) 1 MW and 3 MW beams of 15 MHz radiowaves launched by the Arecibo antenna. By intent, these two cases have similar intensities and geometries of resistive heating. The most dramatic heating effects are predicted to occur in the E-region, where a thermal runaway will take place. The E-region electron temperature will increase from 200°K to roughly 1000°K, and the E-region electron density will increase by a factor of about three. In the F-region, where thermal conductivity plays an important role, temperature increases of 200-500°K will appear along magnetic field lines passing through the radiowave beams. Enhanced emissions in airglow and molecular infrared lines will also occur. Radiowave heating, when combined with the diagnostic capabilities of the Arecibo incoherent scatter radar, will generate new opportunities to measure the rates of atomic physics processes and neutral atmosphere temperatures and composition at D- and E-region altitudes.

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INTRODUCTION

Underdense ionospheric heating occurs when the earth's ionosphere is heated by a beam of high power radiowaves and most of the radiowave energy propagates through the ionosphere because the ionospheric plasma frequency remains well below the radiowave frequency. Two systems which have this property are considered in detail: (1) a satellite power station [Brown, 1973; Glasser, 1977] which transmits from geosynchronous orbit to ground a radiowave beam with a diameter of roughly 8 km and which has a power of 10^4 MW at a frequency of 3 GHz, and (2) an ionospheric heating facility using the Arecibo antenna and having a power of 1-3 MW with a frequency in the range of 5-30 MHz. Although the F-region heating of the ionosphere is generally overdense at the lower end of these frequency ranges, heating in the E-region is still underdense and, as is shown later, it is in the E-region that the most dramatic heating effects take place.

We examine the physics that occurs when a radiowave beam is incident on an underdense ionosphere. There are two general classes of resulting physical effects: resistive heating and self-focusing instabilities. This paper concentrates solely on the resistive heating effects. A subsequent paper will develop existing self-focusing theories [Perkins and Valeo, 1974] in the context of underdense ionospheric heating experiments.

We show that, in general, the heating effects of a satellite power station can be simulated by an appropriately scaled Arecibo heating

facility. In addition to enabling simulations that have engineering interest with regard to the satellite power station, underdense heating by the Arecibo heating facility provides a tool for performing active experiments in ionospheric heat balance, optical and infrared airglow kinetics, and diagnostics of the neutral atmosphere above about 80 km. These exciting possibilities derive from two facts: the radiowave-induced heating is as strong as the natural heating from the sun, and it can be temporally controlled, allowing measurements of time constants, coherent detection techniques, etc.

RADIOWAVE HEATING OF THE IONOSPHERIC PLASMA

Radiowaves propagating through the ionosphere are attenuated by electron-ion and electron-neutral collisions. The volume heat source Q which results from these processes is

$$Q = \frac{E_0^2}{8\pi} \frac{\nu_{pe}^2}{\nu^2} (\nu_{ei} + \nu_{en}) \quad (1)$$

where E_0 is the peak electric amplitude, ν_{pe} is the ionospheric plasma frequency, ν is the radiowave frequency, and ν_{ei} and ν_{en} are the electron-ion and electron-neutral momentum transfer collision frequencies, respectively. These collision frequencies are functions of temperature and they must be self-consistently determined in any code that is used to calculate ionospheric effects. The electric field E_0 is determined by the extent and power of the radiowave beam and must be evaluated for beams from both a satellite power station and a Arecibo heating facility.

Satellite Power Station. We assume that a satellite power station will beam to earth a radiowave that has a Gaussian shape such that 95% of the power is contained in a circle 8.6 km in diameter. Figure 1 portrays the geometry of radiowave propagation from geosynchronous orbit to earth. The power is assumed to be 10 GW and the radiowave frequency to be 3 GHz [Brown, 1973; Glasser, 1977]. The shape of the radiowave beam has a power flux given by

$$F = c_1 \exp(-r^2/r_0^2) \quad (2)$$

where $c_1 = 500 \text{ Wm}^{-2}$ and $r_0 = 2.5 \text{ km}$. The volume ionospheric heating rate associated with this flux is

$$Q = \frac{F v_{pe}^2}{c v^2} (v_{ei} + v_{en}) = f \epsilon_0 n_e (v_{ei} + v_{en}) \quad (3)$$

where

$$\epsilon_0 = \frac{4\pi e^2 F_0}{m \omega^2 c} = 2.95 \times 10^{-16} \text{ ergs},$$

$$F_0 = 10^6 \text{ ergs cm}^{-2} \text{ s}^{-1} = 1000 \text{ W/m}^2,$$

$$f = F/F_0 = 0.5 \exp(-r^2/r_0^2), \text{ and}$$

$$n_e = \text{electron number density.}$$

The altitude dependence of Q is determined by how the spatial variation of the beam is mapped into a height variation along the magnetic field line. We consider two arbitrary ground stations, in Boulder, Colorado, and Houston, Texas, whose collectors receive radiowave energy beamed from a satellite in geosynchronous orbit. The geometry giving the intersection of the radiowave beam with each ground station and geomagnetic field line is illustrated in Figure 1. The relevant parameters for Boulder are $D = 70^\circ$ and $\beta = 26.4^\circ$; for Houston they are $D = 49^\circ$ and $\beta = 9^\circ$.

From the geometry of Figure 1, the parameter f becomes

$$f = 0.5 \exp[-(z-z_0)^2/\ell^2] \quad (4)$$

where $\ell = r_0 \sin D / \sin \beta$, z is altitude and z_0 is the altitude at which the center of the radiowave beam intersects the geomagnetic field line. The value of ℓ is 5.6 km for Boulder and 15.9 km for Houston.

Arecibo Heating Facility. The resistive heating generated by an Arecibo heating facility can be calculated by assuming a beam pattern such as that illustrated in Figure 2 and represented by the formula

$$F = \frac{P}{\pi \theta_0^2 z^2} \exp(-\theta^2 / \theta_0^2) \quad (5)$$

where P is the heating power and z is the altitude. The angle $\theta_0 = 2\sqrt{2}/ka$, where a is the diameter of the antenna and k is the wave-number. Formula (5) assumes the effective area of the Arecibo antenna to be $A_{\text{eff}} = 0.5 A$, with A being the geometrical area, $A = \pi a^2 = 7 \times 10^4 \text{ m}^2$, and $a = 150 \text{ m}$. The volume heating rate due to radiowave heating by the Arecibo facility is

$$Q = f \epsilon_0 n_e (v_{\text{en}} + v_{\text{ei}}) \quad (6)$$

where $\epsilon_0 = 2.95 \times 10^{-16} \text{ ergs}$ and

$$f = 0.09 \left(\frac{PA}{7 \times 10^4 \text{ MW m}^2} \right) \left(\frac{200 \text{ km}}{z} \right)^2 \exp[-(z-z_0)^2 / \ell^2]$$

where PA denotes the power aperture product appropriate to the antenna and transmitter and z_0 is the altitude at which the radiowave beam intersects the geomagnetic field line. The length ℓ is given by

$$\ell = \frac{z_0^2 \theta_0}{\tan D} = 7 \text{ km} \left(\frac{z_0}{200 \text{ km}} \right) \left(\frac{30 \text{ MHz}}{\nu} \right) \quad (7)$$

where ν is the radiowave frequency and the value $D = 50^\circ$ has been used for Arecibo.

Scaling Analysis. From the heating relations derived above it can be seen that a 1 MW underdense ionospheric heating experiment at Arecibo can produce heating effects comparable to those from a satellite power station, especially at altitudes on the order of 100 km. In the E- and D-regions of the ionosphere, the electron heating is controlled by a local balance between electron heating and electron loss processes. Thermal conduction can be neglected at these altitudes. At 100 km, the Arecibo simulation gives $f = 0.36$, compared to $f = 0.50$ for the satellite power station, and with the frequency of the modifier chosen to be $\nu = 15 \text{ MHz}$, the spatial scale is $\ell = 7 \text{ km}$ for Arecibo and $\ell = 5.6 \text{ km}$ for the satellite power station beaming radiowave energy to Boulder.

At F-region heights, where thermal conduction plays the dominant role, the key scaling parameter is $f\ell$, which physically corresponds to the energy deposited on a magnetic flux tube per unit time. Using the expressions given above evaluated at 300 km, the satellite power station yields $f\ell = 2.8 \text{ km}$, and for the $\nu = 15 \text{ MHz}$ Arecibo simulation $f\ell = 0.84 \text{ km}$. Thus, the 1 MW Arecibo heating is roughly one-third as intense as that from the satellite power station. Hence it would take a 3 MW heater, or a 2 MHz heater at $\nu = 10 \text{ MHz}$, to simulate the effects of the satellite power station accurately. An underdense 10 MHz heating experiment will work only at night, when the ionospheric plasma frequencies are small

enough that refraction is not a problem. Even though the length of heating along a magnetic line for the Arecibo experiment ($\ell \approx 21$ km) is much greater than the value for the satellite power station ($\ell \approx 5.6$ km), both cases fulfill the essential condition - that this length be small compared to the size of the ionosphere. Finally, if one were able to use the full Arecibo aperture ($A_{\text{eff}} = A = 7.10^4$ m), the E-region heat input would double and F-region heating would increase by a factor of $\sqrt{2}$ [due to the factor θ_0 in (7)].

THERMAL RUNAWAY IN THE D- AND E-REGIONS

Holway and Meltz [1973] first showed that strong radiowave heating could induce a thermal runaway in the D- and E-regions. The reason for this thermal runaway is that the electron-neutron collision frequency ν_{en} increases with increasing electron temperature; the hotter the electrons get, the larger the volume heat source Q becomes [see (1)]. Moreover, the rotational excitation of N_2 and O_2 , which Holway and Meltz assumed to be the principal electron energy loss mechanism, actually decreases with increasing electron temperature thus contributing to the thermal runaway. We shall show in the following discussion that if the resistive radiowave heating is sufficiently large, this model has no steady-state solution to the electron heat balance equation and the electron temperature will monotonically increase in time.

But the Holway and Meltz model has only limited physics; it specifically neglects electron energy loss via vibrational excitation of N_2 and O_2 , as well as energy loss resulting from $O(^3P)$ excitation. The vibrational excitation processes provide an energy loss for electrons that increases rapidly as the electron temperature rises above 1000°K. Hence vibrational energy loss will stop the monotonic rise in electron temperature. In this nonlinear stage, the energy input through resistive heating will appear as vibrational excitation of N_2 and O_2 . The literature then suggests that the energy in the vibrational excitations will be resonantly exchanged to vibrational modes of CO_2 and H_2O , and radiated as 4.3 μ and 6.5 μ photons [Houghton, 1967; Kumer and James, 1974; Kumer,

1977a, 1977b]. Energy loss resulting from $O(^3P)$ excitations proceeds at all relevant electron temperatures and combines with rotational losses to determine the threshold for initiating the electron thermal runaway.

Let us now develop the equations which govern the electron thermal runaway. If we neglect thermal conduction, the electron energy equation becomes

$$\frac{3}{2} n_e \frac{dT_e}{dt} = \frac{F4\pi e^2}{mc\omega^2} n_e \nu_{en} \left(\frac{T_e}{T_n} \right) - \left[\nu^{(R)} \left(\frac{T_n}{T_e} \right)^{1/2} + \nu^{(0)} \right] n_e (T_e - T_n) \quad (8)$$

where T_e is the electron temperature in energy units, T_n is the neutral gas temperature, t is time, n_e is the electron density, e the electronic charge, m the mass of an electron, c the speed of light, ω the radiowave frequency, F the power flux, ν_{en} the electron-neutral collision frequency, $\nu^{(R)}$ the electron-rotational excitation energy loss frequency, and $\nu^{(0)}$ the oxygen fine structure energy loss frequency. According to data, when $n(O) \ll n(N_2)$ and $n(O_2)$, we can fit these quantities sufficiently well by the formulas [Massey et al., 1969; Hoegy, 1976].

$$\nu_{en} = 2.3 \times 10^{-9} \left[n(N_2) + n(O_2) \right] \left(\frac{T_n}{100} \right) s^{-1} \quad (9)$$

$$\nu^{(R)} = 3.4 \times 10^{-11} \left[n(N_2) + 2.3n(O_2) \right] \left(\frac{100}{T_n} \right)^{1/2} s^{-1} \quad (10)$$

$$\nu^{(0)} = 3.4 \times 10^{-10} n(O) \left(\frac{100}{T_n} \right) s^{-1} \quad (11)$$

These formulas give the collision frequencies that are appropriate when $T_e = T_n$. The explicit dependence of collision frequencies on electron temperature appears in (8), which one can cast into the nondimensional form

$$\frac{3}{2} \frac{dy}{d\tau} = \Lambda y - (y^{-1/2} + a)(y - 1) \quad (12)$$

where

$$\Lambda = \frac{F4\pi e^2 v_{en}}{cm\omega^2 v^{(R)} T_n} \quad (13)$$

$$a = \frac{v^{(0)}}{v^{(R)}} = \frac{10n(O)}{n(N_2) + 2.3n(O_2)} \left(\frac{100}{T_n} \right)^{1/2} \quad (14)$$

$$y = T_e / T_n \quad (15)$$

$$\tau = v^{(R)} t \quad (16)$$

Thermal runaway occurs when steady-state solution to (12) is not possible because of the high value of Λ . This condition can be evaluated by solving the two equations

$$\frac{d}{d\xi} \left(\frac{\Lambda \xi^3}{1+a\xi} - \xi^2 + 1 \right) = 0 \quad (17)$$

$$\frac{\Lambda \xi^2}{1+a\xi} - \xi^2 + 1 = 0 \quad (18)$$

where $\xi = y^{1/2}$. These conditions find the value of Λ_c for which the curve $\Lambda_c \xi^3 / (1+a\xi)$ is tangent to $\xi^2 - 1$. The solution is

$$\Lambda_c = \frac{2(a^2 + 1 + a\sqrt{a+3})^2}{4a^3 + (4a^2+3)\sqrt{a+3} + 9a} \quad (19)$$

which is shown in Figure 3.

The asymptotic formulas for Λ_c are

$$\Lambda_c = \begin{cases} a + \frac{1}{4a} & a \gg 1 \\ \frac{2}{3\sqrt{3}} (1 + a\sqrt{3}) & a \ll 1 \end{cases} \quad (20)$$

For standard abundances of the molecular species and $n(0) \ll n(N_2) + n(O_2)$ one can transform (13) and (14) into

$$\Lambda = 0.39 \left(\frac{T_n}{100} \right)^{1/2} \left(\frac{\text{PA}}{7 \times 10^4 \text{ MW-m}^2} \right) \left(\frac{100 \text{ km}}{z_0} \right)^2 \quad (21)$$

$$a = 6.8\eta_0 \left(\frac{100}{T_n} \right)^{1/2} \quad (22)$$

where

$$\eta_0 = \frac{n(0)}{n(N_2) + n(O_2)}$$

We have used (5) and (6), appropriate for the Arecibo experiment, to evaluate F appearing in (13).

The U.S. Standard Atmosphere, [NASA et al., 1976] has $\eta_0 = 0.043$ at 100 km yielding $a = .21$ for $T_n = 200^\circ\text{K}$. Hence these numbers suggest that a 1 MW Arecibo underdense heating experiment would be just on the margin of achieving a thermal runaway at 100 km and then only in the

center of the beam. At lower altitudes, where both z_0 and the atomic oxygen concentration are smaller, thermal runaway will occur. Above 100 km, the cooling of atomic oxygen prevents a large thermal runaway. Clearly, to assure that thermal runaway will occur, a 2 or 3 MW Arecibo heating experiment is essential.

The time scale for heating and cooling is essentially

$$\frac{1}{\nu(R)} = \begin{cases} 2.5 \times 10^{-3} \text{ s}; & z_0 = 100 \text{ km} \\ 10^{-1} \text{ s}; & z_0 = 120 \text{ km} \end{cases} \quad (23)$$

The rapid heating and cooling at 100 km suggest that a pulsed experiment might well suffice to get high peak powers and thus not be as demanding on the average power. For example, a 10 ms pulse on the 430 MHz Arecibo radar could achieve steady-state heating conditions and still satisfy the thermal conductivity requirements of (26). The problem of how to use the 430 MHz radar both as a heater and as a diagnostic tool can be solved by employing separate but neighboring frequencies.

In the collision-dominated regime, the Arecibo Thomson scatter spectrum is Lorentzian, $P(\omega) = (\text{const})/(\omega^2 + \gamma^2)$ where γ is the ambipolar diffusion rate

$$\gamma = \left(\frac{4\pi}{\lambda_R} \right)^2 \frac{T_e + T_i}{mv_{in}} \quad (24)$$

with λ_R being the radar wavelength. Since the heating time scales are

so rapid ($\sim 10^{-1}$ s) any measured change in γ will be due to T_e and not to T_i or v_{in} . Hence the values of γ before and after heating can be compared to deduce the electron temperature increases, assuming that in the absence of heating the electron temperature is equal to a known neutral temperature. A similar comparison of values of the total Thomson scatter cross section σ_T' would also reveal an electron thermal runaway, since $\sigma_T \propto (T_e + T_i)^{-1}$. The "after" measurement must be made within a few milliseconds of turning off the heating pulse before the temperature rise decays.

Let us now check our assumption that thermal conductivity is unimportant. The appropriate scaling experiment is to have the radiowave heating rate γ_H much larger than the thermal conductivity rate γ_c , based on the beam radius $\theta_0 z_0$.

$$\gamma_H = \frac{2F\omega_{pe}^2 v_{en}}{3cn_e T_e \omega^2} \gg \gamma_c = \frac{2.2T_e}{\theta_0^2 z_0^2 m v_{en}} \quad (25)$$

In nondimensional form, this equality becomes

$$\frac{\gamma_H}{\gamma_c} = \frac{1}{3.3\pi^2} \left(\frac{p_e^2 v_{en}^2 (T_n)}{T_n^2 v_c^2} \right) \gg 1 \quad (26)$$

In dimensional form it is

$$2 \times 10^4 \left(\frac{P}{1 \text{ MW}} \right) \left(\frac{15 \text{ MHz}}{\gamma} \right)^2 \left(\frac{v_{en}(T_n)}{3 \times 10^4 \text{ s}^{-1}} \right)^2 \gg 1 \quad (27)$$

where $v_{en} = 3 \times 10^4 \text{ s}^{-1}$ at an altitude of 100 km. Evidently, the neglect

of thermal conductivity is a good approximation everywhere in the E-region.

Our analysis has shown that an appreciable fraction of the energy given to the electrons in the D- and E-regions is given to N_2 vibrational states and is resonantly transferred to CO_2 , which then radiates 4.3μ photons [Kumer and James, 1974; Kumer, 1977a, 1977b]. Similarly, energy given to O_2 vibrational energy is transferred to H_2O , which radiates at 6.5μ [Houghton, 1967]. Since vibrational excitation is limiting a thermal runaway in the D- and E-regions, the efficiency for transforming absorbed radiowave energy into infrared photons must be high, probably exceeding 80%. The infrared radiation energy will be split roughly equally between 4.3μ CO_2 radiation and 6.5μ H_2O radiation. Therefore the amount of infrared radiation emitted can be estimated by computing the radiowave energy absorbed.

The attenuation length for the radiowave heating energy is defined by

$$-\frac{dF}{dz_0} = \frac{F}{\ell} = \frac{Fv_{pe}^2}{cv^2} v_{en} \quad (28)$$

which is readily solved for ℓ

$$\ell(z_0) = \frac{cv^2}{v_{en}v_{pe}^2} = 7.5 \text{ km} \left(\frac{10^5 \text{ cm}^{-3}}{n_e(z_0)} \right) \left(\frac{v}{15 \text{ MHz}} \right)^2 \exp \left(\frac{z_0 - 100 \text{ km}}{H} \right) \quad (29)$$

where the atmosphere scale height $H \approx 10 \text{ km}$ and we used $v_{en} = 10^5 \text{ s}^{-1}$ because it is appropriate to the 1000°K electron temperature occurring

in a thermal runaway. In the daytime E-region, $n_e \approx 10^5 \text{ cm}^{-3}$ and the total attenuation of the radiowave energy is roughly 10% for $\nu = 15 \text{ MHz}$. Obviously, with a lower frequency (5 MHz), the attenuation would almost complete. Hence, provided thermal runaway can be induced, roughly 100 kW to 1 MW of power can be radiated as infrared photons. The overall infrared radiative power is roughly 10^{-8} W/cm^2 -ster in the two bands having approximately 0.5 μ bandwidth. These radiances are comparable to the naturally occurring zenith radiance above 100 km and could be detected by a rocket-borne coherent detection instrument. Such an experiment would be an active way to test the theories of vibrational temperature and radiative transfer above 100 km. At night, the electron densities are roughly a factor of thirty lower, and the absorbed radiowave power is correspondingly less.

IONOSPHERIC MODEL

The numerical model that is used to calculate the E- and F-region ionospheric response to heating in the proposed satellite power station and Arecibo heating experiments is an extension of the model described by Roble [1975], Stolarski et al. [1975], and Roble et al. [1976]. Figure 1 of Roble et al. [1977] is a block diagram showing the physical processes within the current model. A list of the ion and neutral chemical reactions and the reaction rates used within the model is also given in Roble et al. [1977] and Roble and Rees [1977]. Most of the physical and chemical processes within the ionospheric model have been described in these earlier papers; therefore we will discuss here only the modifications and additions for this study. However, since the heating experiments primarily affect the thermal structure of the ionosphere, we will describe the processes involved in determining the ionospheric thermal balance in more detail.

The time-dependent coupled electron and ion energy equations within the model are solved simultaneously using the Newton iteration technique described by Hastings and Roble [1977] and Roble and Hastings [1977]. The electron heat sources include heating by fast photoelectrons in the daytime ionosphere, heat conduction from the magnetosphere, and resistive heating due to the absorption of radiowave energy beamed into the ionosphere as discussed in the second section of this paper. Roble [1975] has shown that the thermal structure in the daytime ionosphere below about 250 km is maintained primarily by heating due to photoelectrons

and above that altitude by thermal conduction from the magnetosphere. The effects of thermal conduction in the electron gas become important above about 200 km, whereas below that altitude the electron temperature is determined by a local balance of electron heating and cooling rates. The electron conductivity used in the analysis is given by Banks and Kockarts [1973] and Rees and Roble [1975].

The ion heat sources are Coulomb coupling with electrons, chemical reactions [Stolarksi et al., 1975], and heat conduction from the magnetosphere. The ions lose energy in collisions with neutrals through polarization interactions and resonance charge exchange interactions. The ion-neutral loss rates are described by Banks and Kockarts [1973] and are listed in Table 3 of Rees and Roble [1975]. Thermal conduction in the ion gas becomes important above about 300 km.

The electron loss processes include energy loss in Coulomb collisions with ions as well as elastic and inelastic collisions with the neutrals. The elastic loss rates are given by (22.69) through (22.72) in Banks and Kockarts [1973]. The inelastic loss rates include excitation of the fine structure levels of the ground state of atomic oxygen [(1) of Hoegy, 1976], excitation of atomic oxygen to the $O(^1D)$ level [(61) of Rees and Roble, 1975], excitation of the vibrational levels of molecular nitrogen [(22.75) of Banks and Kockarts, 1973], and the excitation of the vibrational levels of molecular oxygen [(62) of Rees and Roble, 1975]. We also consider the electron loss rates due to thermal electron excitation of molecular oxygen to the $O_2(a^1\Delta_g)$ and $O_2(b^1\Sigma_g)$ levels using the procedure given by Noxon [1970].

Various processes within the model have been examined in detail in a recent comparison of model predictions with data obtained simultaneously by the Atmospheric Explorer-C satellite and the incoherent scatter radar station at Millstone Hill, Massachusetts [Roble et al., 1977]. There was general agreement between model predictions and the satellite and incoherent scatter radar measurements of electron and ion temperatures, electron and ion densities, 6300 Å airglow emission rates, NO densities, and photoelectron spectra in the daytime ionosphere at the time of the satellite crossing over Millstone Hill. We use this same model to calculate the ionospheric response to radiowave heating from a satellite power station and from a Arecibo heating experiment, however, the simulation is for typical geomagnetic quiet conditions over an arbitrary midlatitude station.

To simulate the effects on the ionosphere from the satellite power station and Arecibo heating experiment we consider two types of ionospheric runs: steady state calculations in the midlatitude daytime ionosphere and diurnal calculations. In the daytime ionosphere the thermal and photochemical time constants are short, therefore the model is run to steady state [Roble et al., 1977]. For these calculations, the neutral atmospheric temperature and composition profiles are specified by the OGO-6 empirical model [Hedin et al., 1974], the Hinteregger [1976] solar flux values are used, and typical daytime electron and ion heat fluxes and plasma flow from the magnetosphere are specified. These are the only values that are specified and the model is then run to steady state with all interactive processes being calculated self-consistently. The radiowave heating due to the satellite power station

and Arecibo heating facility are superimposed upon the normal daytime processes in this background ionosphere and the model is run to steady state. The differences between the two calculations give the ionospheric perturbations due to radiowave heating.

For the diurnal variation, a calculation similar to those given by Roble [1975], Roble et al. [1976], and Roble et al. [1977] is performed for conditions typical in the geomagnetic quiet midlatitude ionosphere. The calculation is then repeated with the radiowave heating superimposed.

The electron temperatures in the D- and lower E-regions of the ionosphere are calculated on the basis of a local energy balance between electron heating and cooling rates. The neutral atmospheric temperature profile and number density profiles of atmospheric constituents within this region are obtained from the U.S. Standard Atmosphere [NASA et al., 1976].

IONOSPHERIC RESPONSE TO RADIOWAVE HEATING BY THE
SATELLITE POWER STATION

The satellite power station will beam 3 GHz, 10 GW radiowave energy from a geosynchronous orbit over the equator to a ground station somewhere in the United States as shown in Figure 1. For our calculations, we arbitrarily consider two stations that collect the radiowave beam: Boulder, Colorado, and Houston, Texas. Although the two stations are geographically close, the radiowave beam intersects the geomagnetic field lines over them at different angles. As discussed in the second section, this results in a different ionospheric heating rate over each station. The geomagnetic dip angle D is 70° for Boulder and 49° for Houston. From the geometry given in Figure 2 the angle β between the radiowave beam and the geomagnetic field line is 26.4° for Boulder and 9° for Houston. The resulting values for the parameter l , given by (4), are 5.6 and 15.9 km for Boulder and Houston, respectively.

The electron temperature response to the satellite power station radiowave heating calculated for the ionosphere over Boulder is shown in Figure 4. The ionospheric model calculates properties along individual geomagnetic field lines; therefore this figure is constructed using the results from several model runs. The peak radiowave heating occurs where the center of the beam intersects a geomagnetic field line. The radiowave heating distribution at this interaction is given by (3) and it is superimposed upon the normal daytime ionospheric heating rates. The daytime ionospheric temperatures calculated outside of the microwave beam are indicated by the horizontal contour lines.

Below about 150 km, the electron temperature is determined by a balance between the local electron heating and cooling rates within the ionosphere. In the undisturbed daytime ionosphere the electron temperature is nearly equal to the neutral gas temperature below about 120 km. The radiowave heating raises the electron temperature to a peak of about 950°K throughout the D- and E-region of the ionosphere, causing a significant perturbation in the ambient ionospheric electron temperature along the radiowave beam. Above about 150 km, thermal conduction in the electron gas becomes important. Even though the bulk of the radiowave heating takes place at the beam's intersection of the geomagnetic field line, thermal conduction in the electron gas redistributes this energy upward and it couples with the normal downward-directed heat flow from the magnetosphere in the daytime ionosphere. The two energy flows combine to increase the electron temperature along the geomagnetic field line. The maximum F-region temperatures occur along the geomagnetic field line that intersects the radiowave beam near the F_2 peak. The region of enhanced electron temperature in the topside ionosphere follows the geomagnetic field line, whereas in the region below about 150 km it occurs along the radiowave beam.

The calculated electron temperature response in the ionosphere over Houston is shown in Figure 5. The angle between the radiowave beam and the geomagnetic field line over Houston is 9° and, as a result, the F-region electron heating along a given geomagnetic field line that intersects the radiowave beam is greater over Houston than over Boulder. The calculated electron temperature is also greater over Houston than over

Boulder. However, the ionospheric area that is affected is smaller; over Houston the radiowave beam heats a narrow region more intensely. Below about 150 km, on the other hand, the calculated electron temperature is similar in magnitude to the previous calculations, indicating local heating and cooling along the radiowave beam throughout the D- and E-regions.

Maximum electron heating occurs when the radiowave beam is parallel to the geomagnetic field line. The calculated electron temperature for this limiting case is shown in Figure 6, as are the calculated electron and ion temperature profiles for the undisturbed ionosphere. In the topside ionosphere the calculated electron temperature is approximately 4000°K along the geomagnetic field line that is coincident with the center of the radiowave beam. The electron temperature decreases toward both edges of the radiowave beam. Below about 150 km, the calculated electron temperature is similar to that in the previous two cases.

The electron energy loss rates corresponding to the undisturbed daytime ionosphere and to the case of maximum heating from the satellite power station (Figure 6), in which the radiowave beam is parallel to the geomagnetic field line, are shown in Figures 7a and 7b, respectively. In the undisturbed daytime ionosphere, the maximum electron energy loss above about 200 km is due to Coulomb collisions with ions. Below about 200 km, excitation of the vibrational levels of molecular nitrogen and molecular oxygen, the excitation of the ground levels of atomic oxygen, and the excitation of the rotational states of molecular nitrogen are all important processes in electron energy loss. For comparison, the

total neutral gas heating rate is shown as the dashed curve in Figure 7a. In addition to the electron loss processes, the neutral gas heating consists of components due to ion chemistry [Stolarski et al., 1975] and to heating from the photodissociation of molecular oxygen in the Schumann-Runge continuum [Roble, 1975].

The electron loss rate corresponding to the case of maximum radio-wave heating when the satellite power station radiowave beam is parallel to the geomagnetic field line is shown in Figure 7b. Above about 300 km, the major electron loss process is Coulomb collisions with electrons and the excitation of atomic oxygen to the $O(^1D)$ level. Below 300 km, the excitation of the molecular nitrogen vibrational levels becomes important. The rate of electron loss due to the excitation of the ground levels of atomic oxygen is most important between about 100 and 150 km. Finally, below 100 km the excitation of the vibrational and rotational levels of molecular nitrogen and molecular oxygen are the dominant electron energy loss processes. These results indicate that the electron thermal runaway of the type discussed by Holway and Meltz [1973] and Meltz et al. [1974] occurs below 100 km and that above that altitude thermal runaway can still occur but it is restrained by electron energy loss due to the excitation of the ground levels of atomic oxygen as discussed in the third section of this paper. The radiowave energy input to the ambient plasma in the ionospheric D- and E-regions is ultimately transferred to the neutral gas through collisions.

Within the ionospheric F-region the radiowave heating produces enhanced airglow emission rates. Part of the atomic oxygen excited to

the $O(^1D)$ level radiates as 6300 Å radiation and part is quenched by collision with molecular nitrogen and molecular oxygen. The calculated 6300 Å volume emission rates in both the undisturbed daytime ionosphere and the maximum heating case are shown in Figure 8. The solid curve is the total 6300 Å volume emission rate calculated in the daytime ionosphere. The components include excitation of $O(^1D)$ due to photodissociation of molecular oxygen in the Schumann-Runge continuum, excitation due to photoelectron impact, excitation due to dissociative recombination of O_2^+ , and thermal electron impact. The various excitation mechanisms, the excitation cross sections, chemical reaction rates, and quenching and radiative coefficients used in the analysis have been discussed in detail by Roble et al. [1976]. The 6300 Å volume emission rate peaks at 240 km and has a calculated dayglow intensity of 4.14 KR. The excitation component includes 1280 R due to Schumann-Runge photodissociation, 1624 R due to photoelectron impact, 1191 R due to dissociative recombination, and 45 R due to thermal electron impact. The calculated 6300 Å volume emission rate for the maximum heating case is the dashed curve in Figure 8. The height of the 6300 Å volume emission peak is near 260 km, with a total intensity of 13.1 KR. Almost all of the enhanced 6300 Å airglow intensity in the daytime ionosphere is due to the impact of the hot ambient electrons on atomic oxygen along the radiowave beam. The dashed curves in Figure 8 give the calculated 6300 Å volume emission rate along various geomagnetic field lines for the Boulder case shown in Figure 4. The curves are for field lines where the radiowave beam intersects the geomagnetic field at 200, 250,

and 350 km. The calculated 6300 Å intensities along these field lines are 4.41, 5.73, and 4.34 KR, respectively.

The electron energy that excites molecular nitrogen vibrational states in the lower ionosphere is resonantly transferred to CO₂, which then radiates 4.3 μ photons [Kumer and James, 1974; Kumer, 1977a, 1977b]. Similarly, energy given to molecular oxygen vibrational energy is transferred to H₂O, which radiates at 6.5 μ. Hence, most of the radiowave energy that is transferred into the vibrational states of N₂ and O₂ is radiated to space as infrared photons. We have not done a detailed radiative transfer calculation to examine the magnitude of the enhanced 4.3 μ and 6.5 μ radiations; however, it is anticipated that the enhanced radiation is small compared to the black body spectrum radiated by the earth. Locally, however, the enhanced volume emissivity may be comparable to natural levels.

The electron density profiles calculated for the undisturbed daytime ionosphere and for the maximum heating case are shown in Figure 9. Below about 200 km, the electron density in the radiowave beam is enhanced by a factor of two, primarily because of the decreased reaction rate for dissociative recombination of the dominant molecular ions in the lower ionosphere. The neutral and ion chemical reactions and reaction rates that are used in the model are given in Table 1 of Roble *et al.* [1977]. The F₂ peak electron density decreases slightly; however, above the F₂ peak the electron density increases because of thermal expansion in the topside ionosphere. Even though the electron temperature enhancement is large, the change in electron density in the F-region is relatively

small [Schunk and Walker, 1969]. The electron density profile was calculated three hours after the initiation of the radiowave heating and the response at the top of the ionosphere is time-dependent. However, it is unlikely that heating along any given field line will occur very long, since typical daytime ionospheric electric fields [Kirchhoff and Carpenter, 1976] will cause the geomagnetic field tube to drift out of the beam and be replaced by another undisturbed geomagnetic field tube.

Within the high electron temperature region of the radiowave beam the vibrational levels of molecular nitrogen are excited by thermal electron impact [Newton et al., 1974]. The increased vibrational temperature of molecular nitrogen results in an increased $O^+ + N_2 \rightarrow NO^+ + N$ reaction rate [McFarland et al., 1973], which in turn causes a decrease in the F-region electron densities [Newton and Walker, 1975]. Our calculations have not included this process, which could result in lower F_2 peak electron densities than those calculated in Figure 9.

The satellite power station will beam radiowave energy into the ionosphere during the day and night. To determine the diurnal ionospheric response to this heating, the diurnal ionospheric properties are calculated for a case in which there is no radiowave heating and compared to a case in which the radiowave heating is superimposed. We consider the maximum heating case when the radiowave beam is parallel to the geomagnetic field line. The diurnal variations in electron temperature and density, calculated over a typical midlatitude ionospheric station, are shown in Figures 10a and 11a, respectively. The electron density increases rapidly after sunrise and reaches a maximum

of 10^6 cm^{-3} at 260 km near 1400 LT. The electron density in the F-region decreases thereafter, reaching minimum values just before sunrise. Below the F_2 peak the electron density decreases to nighttime values rapidly after sunset. The bulge in the electron density near 1300 LT is due to an enhanced downward flow of O^+ from the magnetosphere that is arbitrarily assumed in the calculation.

The diurnal variation of the calculated electron temperature shows an inverse relationship with electron density in the daytime ionosphere. The enhanced electron temperatures in the topside ionosphere in the morning and evening hours are due to the enhanced heat flow rates from the magnetosphere that are assumed in the calculation. The diurnal variation of the ionosphere is typical of midlatitude ionospheric conditions. We have not attempted to model a specific day, as described by Roble [1975], Roble et al. [1976], and Roble et al. [1977], but merely calculate some typical ionospheric variation from which the effects of the radiowave heating by the satellite power station can be evaluated.

As discussed in the second section, the radiowave heating of the ambient plasma is proportional to the electron density and electron-neutral collision frequency. The calculated diurnal variation of the radiowave heating for the case when the radiowave beam is parallel to the geomagnetic field line is shown in Figure 12. The radiowave heating of the ambient plasma has a diurnal variation that is similar to the diurnal variation of electron density. Maximum heating occurs in the lower D- and E-regions where the electron-neutral collision frequency is high. At F-region heights maximum heating occurs in the daytime ionosphere.

The calculated diurnal variations of electron temperature and density when the satellite power station radiowave beam is parallel to the geomagnetic field line over the ionospheric station are shown in Figures 10b and 11b, respectively. The calculated electron temperature is considerably enhanced from typical ionospheric conditions, and below about 300 km the diurnal variation is small. The electron temperature variation reflects not only variations in the electron heating rate due to radiowave heating but also variations in the topside heat flow rate in the electron gas that is assumed from the magnetosphere. The calculated electron temperature due to the radiowave heating is relatively constant throughout the day because the electron heating rates and electron loss rates both depend upon the electron density and electron neutral collision frequency in the same manner.

The calculated diurnal variation in electron density for the case when the radiowave beam is heating the ionosphere is shown in Figure 11b. The electron density at the F_2 peak is slightly lower than in the case of no radiowave heating; however, in the topside ionosphere the plasma density has increased. This is primarily due to thermal expansion in the topside ionosphere in response to the enhanced electron temperatures. The high electron temperatures also give rise to enhanced 6300 Å airglow emission rates throughout the day.

IONOSPHERIC RESPONSE TO RADIOWAVE HEATING BY THE
PROPOSED ARECIBO HEATING EXPERIMENT

As discussed in the second section of this paper, the ionospheric heating rates of a 3 GHz, 10 GW radiowave beam from a satellite power station can be closely simulated by a 15 MHz, 3 MW heating experiment from a ground-based station. In this section, we present calculations of the ionospheric response to various heating experiments from an assumed ground-based station at Arecibo. The ionospheric calculations are similar to those described in the previous section; however, the geometry is modified to simulate a heating experiment from a ground-based station. The assumed beam shape, power flux, and ionospheric volume heating rate associated with a 15 MHz, 3 MW heating experiment have been described in the second section.

The calculated ionospheric electron temperature response to a 15 MHz, 3 MW heating experiment is shown in Figure 13. Below about 150 km, the ground-based radiowave beam heats the electrons locally to high temperatures. In the D-region the ambient electron temperature within the beam is raised by an order of magnitude from ambient background electron temperatures. The calculated electron temperatures in the E-region are slightly lower than D-region temperatures, and above about 150 km, thermal conduction along the geomagnetic field line causes the major heating response to occur in the direction along the field line rather than along the beam. Since the volume heating rate is proportional to the electron density and electron-ion and electron-neutral collision frequencies, the peak heating within the F-region

occurs near the F_2 peak and decreases with altitude in the topside ionosphere. Within the F-region the calculated electron temperatures for the ionospheric heating experiment are similar to those calculated for the satellite power station. In the D-region, however, the ground-based heating experiment causes a considerably larger perturbation in the ambient electron temperature than the satellite power station radiowave beam. The large perturbation could be used to probe D-region processes, as is proposed in the discussion section.

A similar calculation is made for a 15 MHz, 1 MW heating experiment, and the results are shown in Figure 14. The calculated temperature response is smaller than in the previous case; however, the temperature pattern is similar. For comparison with the satellite power station ionospheric effects, the 15 MHz, 3 MW heating experiment produces similar effects at F-region altitudes whereas the 15 MHz, 1 MW heating experiment produces similar effects in the D- and E-regions. The calculated electron temperature for the maximum heating case, when the 15 MHz, 3 MW radiowave beam on Arecibo is directed along the geomagnetic field line, is shown in Figure 6. The calculated F-region temperature is similar to the maximum heating produced by the satellite power station; however, the D- and E-region ionospheric temperatures are greater. The calculated electron energy loss rates for this maximum heating experiment are shown in Figure 7c. In the F-region the electron energy loss rates are similar to the loss rates calculated for the satellite power station. In the D- and E-regions of the ionosphere the major energy loss processes are the excitation of the vibrational states

of molecular oxygen and molecular nitrogen followed by the excitation of the rotational levels of the same molecules. This is just the opposite of the loss rate sequence for the satellite power station because the vibrational excitation loss rates increase rapidly with temperature and the 15 MHz, 3 MW heating experiment produces greater electron temperatures in the D- and E-regions than the satellite power station. The increased vibrational excitation loss rates will also give rise to increased 4.3 μ and 6.5 μ radiation because of the efficient exchange of vibrational energy between molecular nitrogen and carbon dioxide and molecular oxygen and water vapor in the region below about 100 km. The high electron temperatures also excite the $O_2(a^1\Delta_g)$ and $O_2(b^1\Sigma_g)$ levels by thermal electron impact, thus giving rise to enhanced airglow emissions at 1.27 μ and 8644 Å, respectively [Noxon, 1970, 1975]. In the F-region the quenching of $O(^1D)$ by O_2 results in an enhanced $O_2(b^1\Sigma_g)$ emission of about 100 R which could be detected from the ground at night. The 15 MHz, 3 MW Arecibo heating experiment transfers enough radiowave energy to the ambient plasma to double the neutral gas heating rate within the radiowave beam from its value under typical daytime conditions.

The calculated electron density response to heating by the 15 MHz, 3 MW Arecibo heating experiment is shown in Figure 15. Below about 150 km, the molecular ions O_2^+ and NO^+ are the dominant ions. The O_2^+ ion dissociative recombination rate used in the calculation varies as $T_e^{-0.7}$ for $T_e < 1000^\circ K$ and $T_e^{-0.55}$ for $T_e > 1000^\circ K$. The NO^+ ion dissociative recombination rate varies as $T_e^{-1.0}$ for $T_e > 1000^\circ K$ and $T_e^{-0.85}$ for

$T_e < 1000^\circ\text{K}$. Both reaction rates are given in Table 1 of Roble et al. [1977], along with other important temperature-dependent rate coefficients involved in the O_2^+ and NO^+ chemistry. The increased electron temperature in the D- and E-region results in an increase in the electron density that is 2.5 times greater in the vicinity of the radiowave beam than in the region outside the beam. There is a slight decrease in the electron density in the vicinity of the F_2 peak, with an increase above the peak. This effect is due to thermal expansion in the topside ionosphere and it is time-dependent. The calculations shown in Figure 15 are for conditions three hours after the radiowave heating was imposed. It is unlikely that the field tube would remain longer in the radiowave beam because the ambient electric field should replace field tubes within the beam at a more rapid rate. The region of enhanced electron density in the topside ionosphere is along the geomagnetic field line in the same direction as the region of enhanced electron temperature.

The Arecibo radiowave heating experiment produces the largest electron temperature perturbations in the ionospheric D- and E-regions. The electron temperature in these regions is a strong function of the radiowave heating power as shown in Figure 16. In the D-region, the electron temperature increases almost linearly with the heating power until about 2.5 MW, when the losses due to vibrational excitation of molecular oxygen and molecular nitrogen become dominant and change the slope of the electron temperature curve. In the D-region the atomic oxygen number density is small so that the major loss rates are due to rotational and vibrational excitation of molecular oxygen and nitrogen. Above about 90 km,

the loss due to the excitation of the fine structure levels of atomic oxygen also become important. This condition is shown in Figure 16, where it is seen that the slope of the electron temperature curves with respect to radiowave heating power is less for altitudes above 90 km. than for altitudes below that.

DISCUSSION

The previous sections have shown that the satellite power station radiowave beam perturbs the ionospheric properties from normal background values and that these effects can be simulated by an Arecibo heating facility. A 15 MHz, 3 MW Arecibo heating facility produces effects at F-region heights similar to those produced by a satellite power station. The heating and ionospheric response for both experiments depend upon the angle between the radiowave beam and the geomagnetic field line. Within the E-region the ionospheric temperature response is about two times greater for the Arecibo heating experiment than for the satellite power station. The effects are comparable at D- and E-region heights if the power of the Arecibo heating experiment is reduced to 1 MW. Thermal runaway occurs in the D-region because the main loss processes at low thermal energies is the electron impact excitation of rotational states of N_2 and O_2 . The thermal runaway, however, is limited at high temperatures by the electron impact excitation of the vibrational levels of N_2 and O_2 . Within the E-region electron cooling due to the excitation of the fine structure of atomic oxygen also limits thermal runaway. It should be possible to use the measured D- and E-region electron densities and temperatures to infer the atomic oxygen density in the altitude region above about 90 km.

Airglow measurements should also prove to be a diagnostic measure of aeronomic processes in the high temperature region. Enhancements in the volume emission rate of $O_2(a^1\Delta_g)$ and $O_2(b^1\Sigma_g)$ radiation at 1.27μ and

8644 Å could be detected in addition to the enhanced 6300 Å emission at F-region heights. The infrared volume emission rates at 4.3 μ due to CO₂ emission and at 6.5 μ due to H₂O emissions within the radiowave beam could be detected locally from space. Measurements of the doppler width of the 6300 Å airglow emission line with a Fabry-Perot interferometer can be used to determine the neutral gas temperature at F-region heights. Similarly measurements of the rotation bands of O₂(b¹Σ_g) can be used to determine the neutral gas temperature in the D-region and the doppler width of the atomic oxygen green line gives the neutral gas temperature near 97 km.

Finally, the D- and E-region electron density and temperature variations can be used to derive information on reaction rates of various aeronomic processes, such as the recombination rates.

Our calculations show plasma density enhancements along the geomagnetic field line in the topside ionosphere over the ionospheric region heated by the radiowave beam. These enhancements would presumably extend along the geomagnetic field tube toward the conjugate hemisphere and perhaps interfere with natural processes occurring within the plasmasphere.

Evidently, the most dramatic changes caused by a satellite power station occur in the ionospheric D- and E-regions where thermal runaway occurs. To induce the same effect at Arecibo, a heater with a power aperture product $PA > 7 \times 10^4 \text{ MW m}^2$ is required. (We have assumed $A_{\text{eff}} = 0.5A$.) Therefore an underdense heating experiment at a frequency $\nu = 15 \text{ MHz}$, 2 MW of radiated power, and efficient use of the Arecibo dish should simulate the ionospheric heating aspects of a satellite

power station. But we should clearly point out that any facility which falls short of these specifications will fail to produce the thermal runaway and hence will not simulate the satellite power station. And, because the electron temperature will remain low, no interesting molecular airglow lines will be excited that can be used for analyzing D- and E-region dynamical, chemical, and aeronomical effects.

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FIGURE CAPTIONS

- Fig. 1. a) Geometry of the satellite power station beam with respect to the earth's magnetic field $\vec{B}$, which has a dip angle D . The angle θ is the latitude and β is the angle between the microwave beam and the earth's magnetic field.
- b) Diagram determining the altitude extent of the heating along a magnetic field line which passes through the center of the microwave beam.

Fig. 2. Geometry of an underdense radiowave heating experiment. The altitude interval l over which the radiowave beam intersects a given magnetic field line is small in comparison with the size of the ionosphere itself. The solid curve represents a projection of the heating rate per unit volume along the magnetic field line onto the vertical direction, and ΔT_e is a schematic representation of the temperature change along the magnetic field line. Specifically, lines A and B connect a particular temperature change ΔT_e with the spatial location where that temperature change occurred. Note that thermal conductivity produces temperature changes well outside the radiowave heating beam. Also sketched is the altitude resolution Δh appropriate to a photometer line of sight.

Fig. 3. Relation between the critical values of Λ [see (30), where it is denoted by Λ_c] and a [see (31)] at which thermal runaway occurs. The formula for Λ_c is (28).

Fig. 4. Contours of calculated electron temperature ($^{\circ}\text{K}$) over Boulder for radiowave heating by the satellite power station. The long dashed lines give the radiowave beam direction and the light solid lines indicate the geomagnetic field direction.

Fig. 5. Same as Figure 4, except for heating over Houston.

Fig. 6. Vertical profiles of electron temperature ($^{\circ}\text{K}$) calculated for the case where the radiowave beam is parallel to the geomagnetic field line giving maximum electron heating. The solid curves give the calculated electron and ion temperatures in the undisturbed daytime ionosphere. The dashed curve is the calculated electron temperature due to maximum heating by the satellite power station, and the long-and-short-dashed curve is the electron temperature due to maximum heating by the 15 MHz, 3 MW Arecibo heating experiment. The daytime neutral gas temperature profile is labeled T_n and the dashed T_i curve is the calculated ion temperature for both the satellite power station and the Arecibo heating experiment.

Fig. 7. Calculated vertical profiles of the total neutral gas heating rate (dashed curve, total-n), $\text{eVcm}^{-3}\text{s}^{-1}$, the total electron loss rate in collisions with neutrals (solid curve, total-e), and various electron loss components. The curve labels indicate electron loss rates; N_{2E} , O_{2E} , and O_E are due to elastic collisions with N_2 , O_2 , and O , respectively; N_{2R} and O_{2R} are due to excitation of rotational structure of N_2 and O_2 ; N_{2V} and O_{2V} are due to excitation of vibrational levels of O_2 and

N_2 ; $O(^3P)$ and $O(^1D)$ are due to excitation of atomic oxygen fine structure and atomic oxygen to the 1D level. $O_2(b^1\Sigma_g)$ and $O_2(a^1\Delta_g)$ are due to excitation of O_2 to the $^1\Sigma_g$ and $^1\Delta_g$ levels by electron impact, and e-i indicates electron-ion Coulomb collisions. The cases are (a) loss rates in undisturbed daytime ionosphere, (b) maximum heating by the satellite power station, and (c) maximum heating by the 15 MHz, 3 MW Arecibo heating experiment.

Fig. 8. The calculated vertical profile of the 6300 Å volume emission rate (photons $cm^{-3}s^{-1}$). The solid curve is the volume emission rate in the undisturbed daytime ionosphere, and the long- and short-dashed curve is the emission rate calculated for maximum heating by the satellite power station. The dashed curves are volume emission rates calculated over Boulder along geomagnetic field lines that intersect the radiowave beam at 200, 250, and 350 km, respectively.

Fig. 9. Calculated vertical profiles of electron density (cm^{-3}). The solid curve is the electron density calculated in the undisturbed daytime ionosphere and the dashed curve is the electron density curve determined three hours after the maximum radiowave heating due to the satellite power station is turned on.

Fig. 10. Contours of the diurnal variation of electron temperature ($^{\circ}K$) calculated (a) in the undisturbed daytime ionosphere, and (b) with the maximum heating rate of the satellite power station superimposed.

- Fig. 11. Contours of the diurnal variation of electron density (cm^{-3}) calculated (a) in the undisturbed daytime ionosphere, and (b) with the maximum heating rate of the satellite power station superimposed.
- Fig. 12. Diurnal variation of electron heating rate [$\log_{10}(Q_e, \text{ergs cm}^{-3}\text{s}^{-1})$] in the case of maximum radiowave heating by the satellite power station.
- Fig. 13. Contours of calculated daytime electron temperature ($^{\circ}\text{K}$) over Arecibo in response to the 15 MHz, 3 MW ionospheric heating experiment. The solid lines with arrows are geomagnetic field lines. The heating experiment beam is indicated by the diverging solid lines.
- Fig. 14. Same as Figure 13, except for a 15 MHz, 1 MW heating experiment.
- Fig. 15. Same as Figure 13, except electron density (cm^{-3}) for the 15 MHz, 3 MW heating experiment.
- Fig. 16. Relationship between electron temperature and heating power for an Arecibo heating experiment at various altitudes in the D- and E-regions.

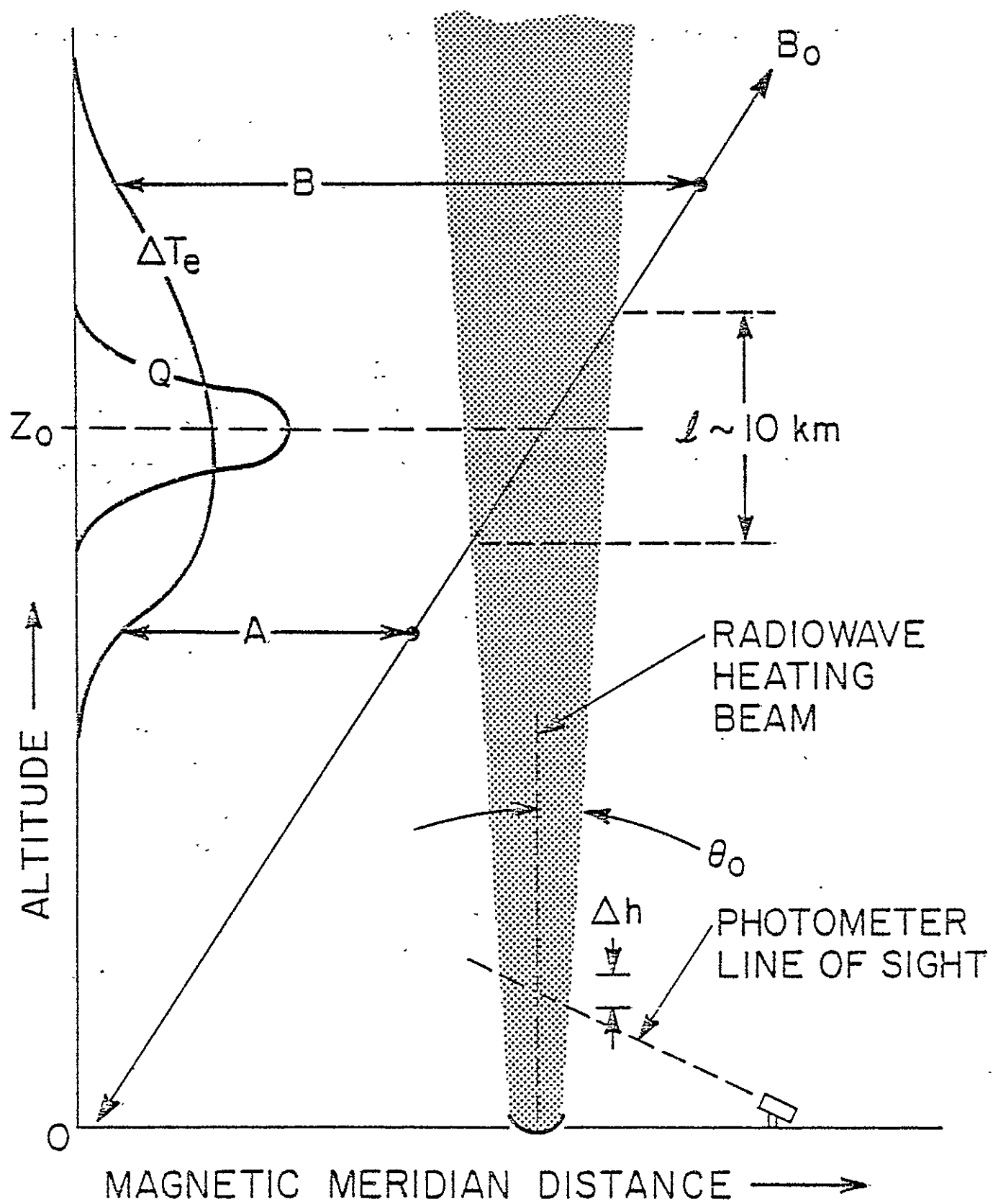


Fig. 2

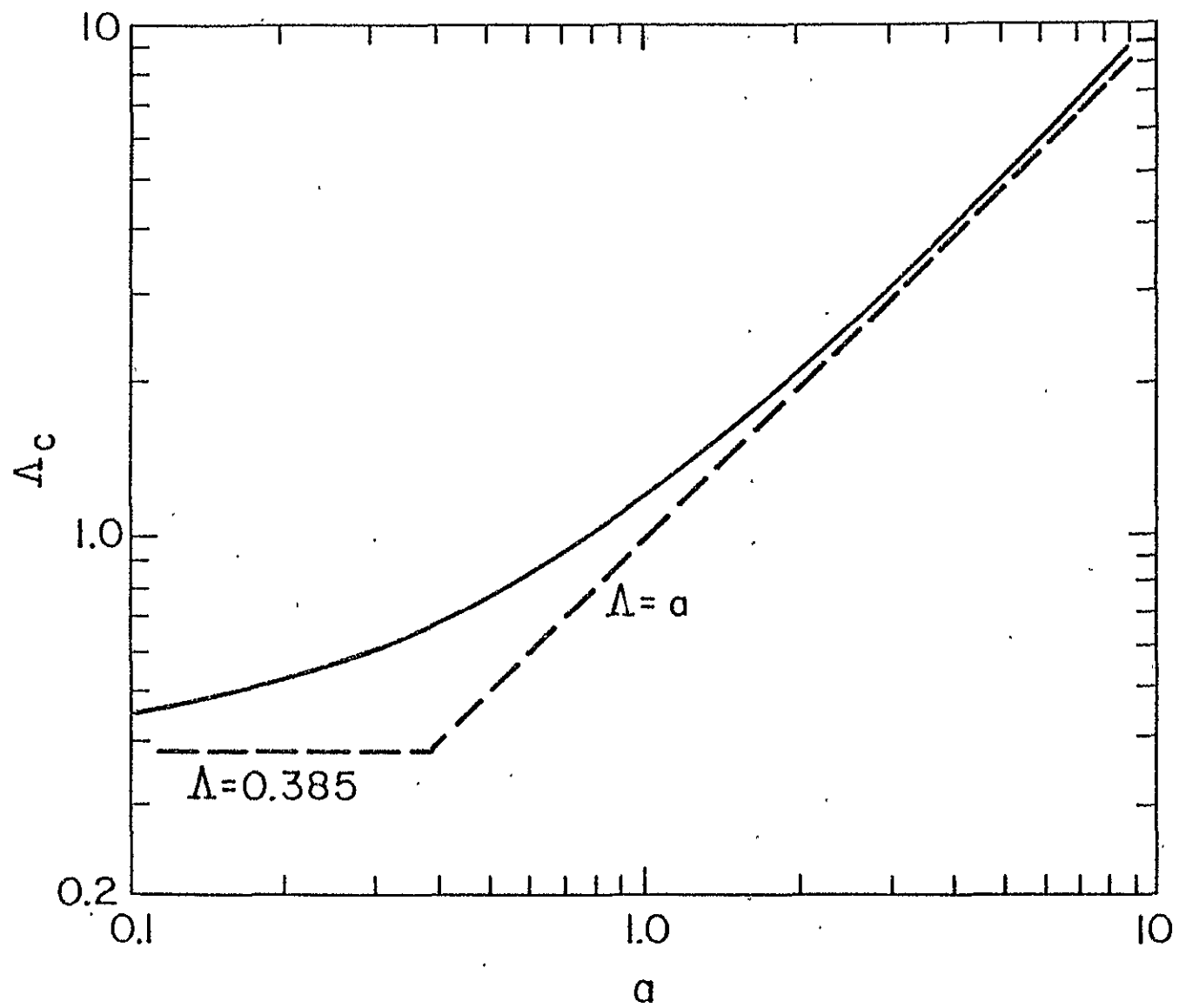


Fig. 3

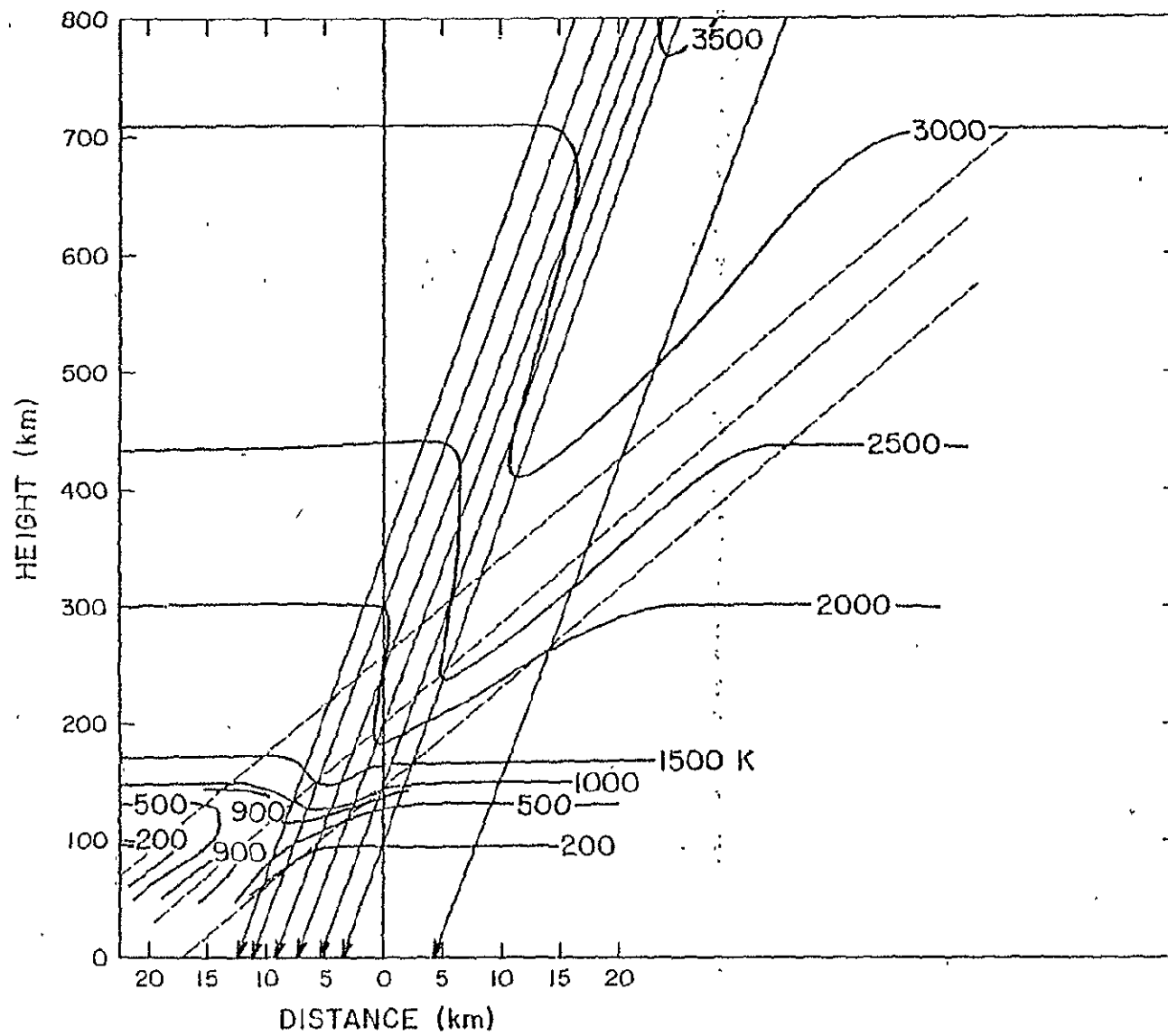


Fig. 4

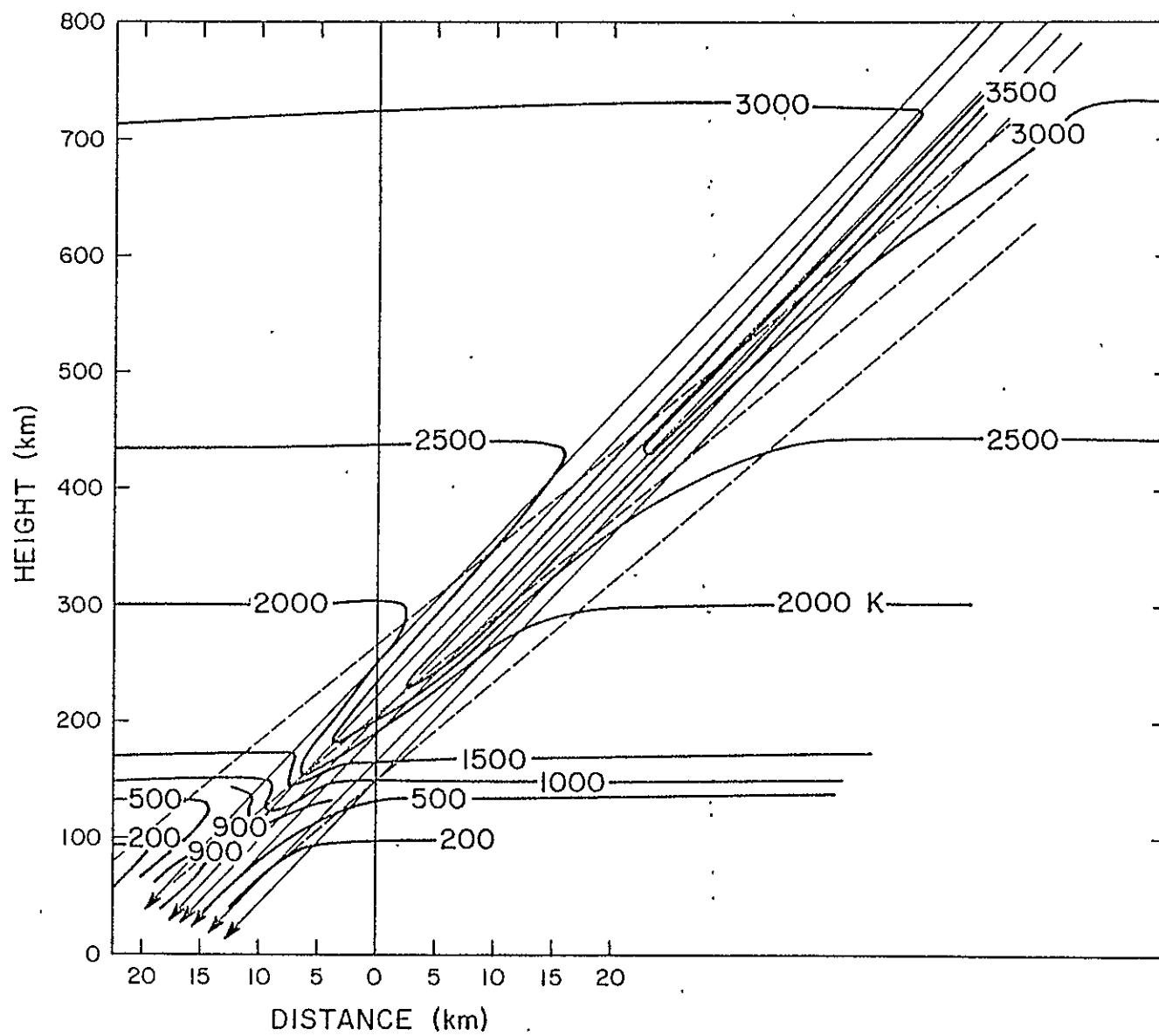


Fig. 5

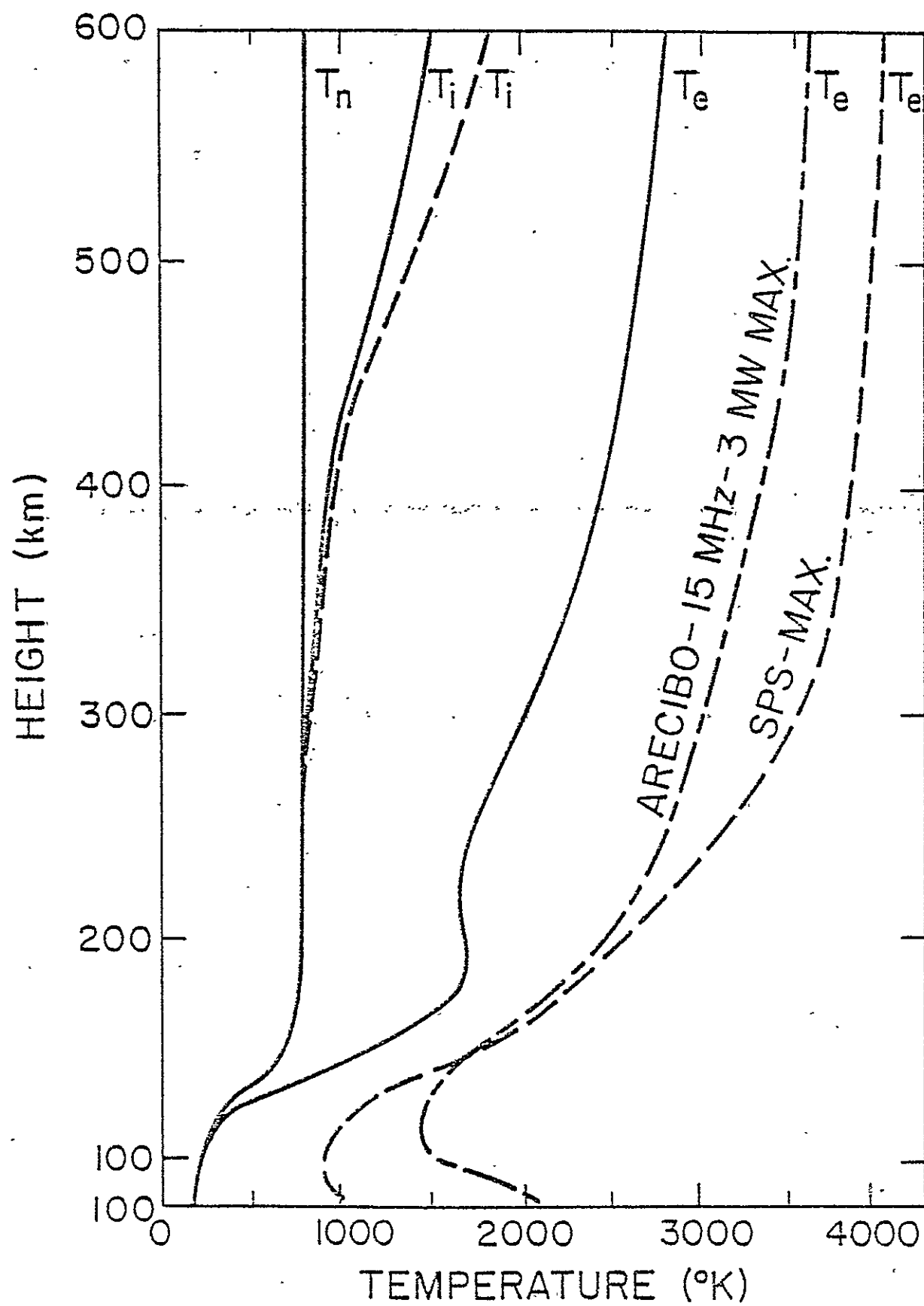


Fig. 6

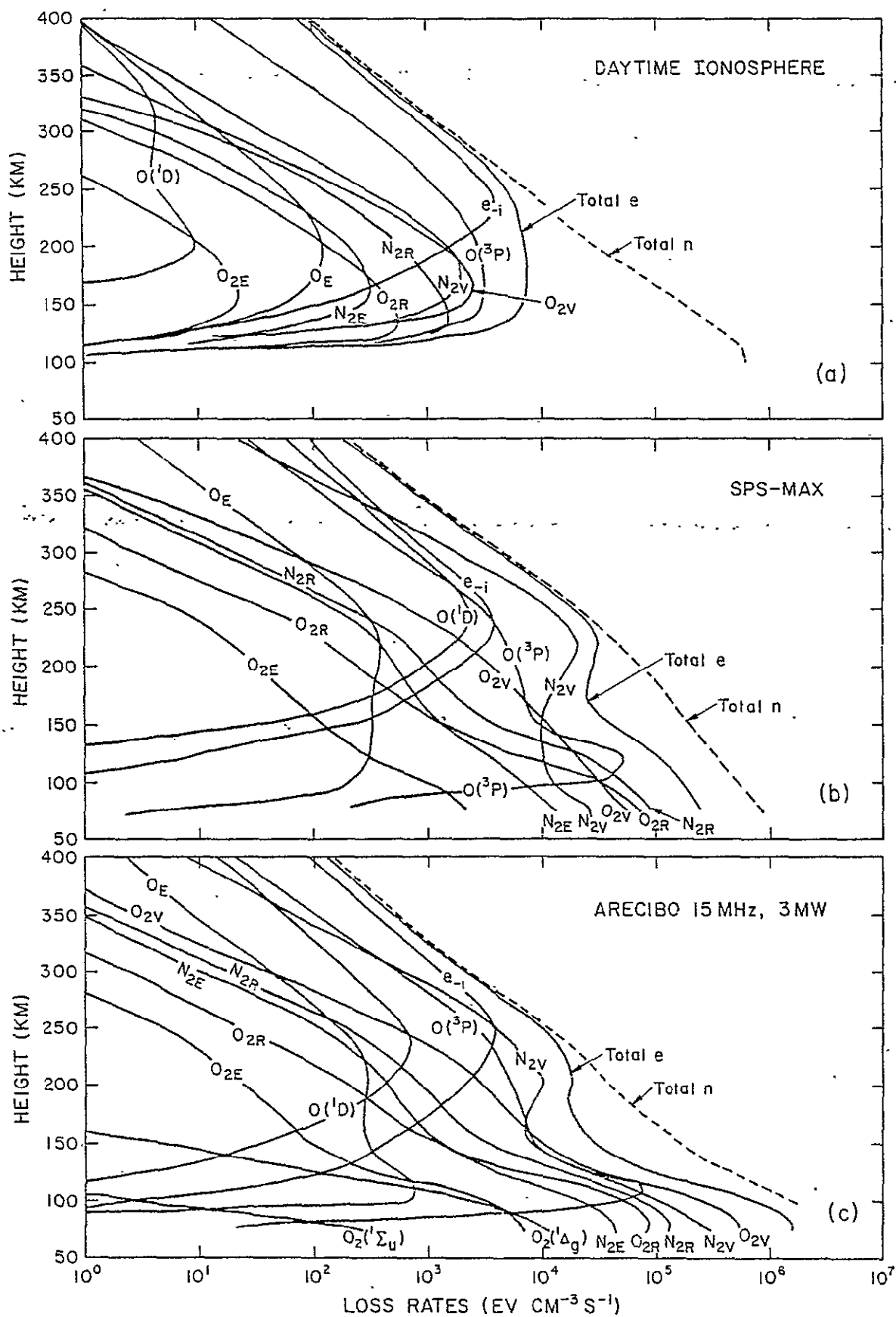


Fig. 7

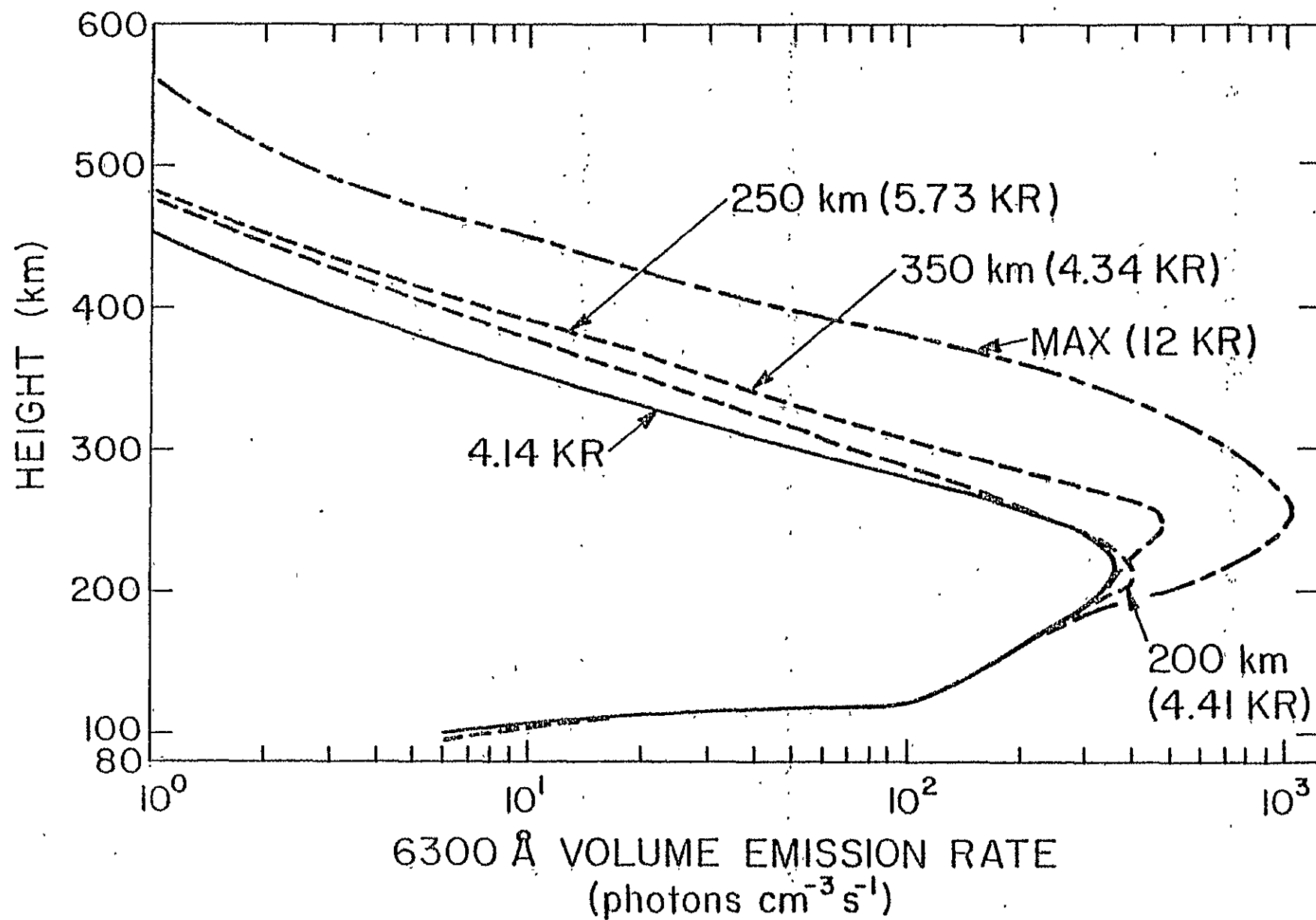


Fig. 8

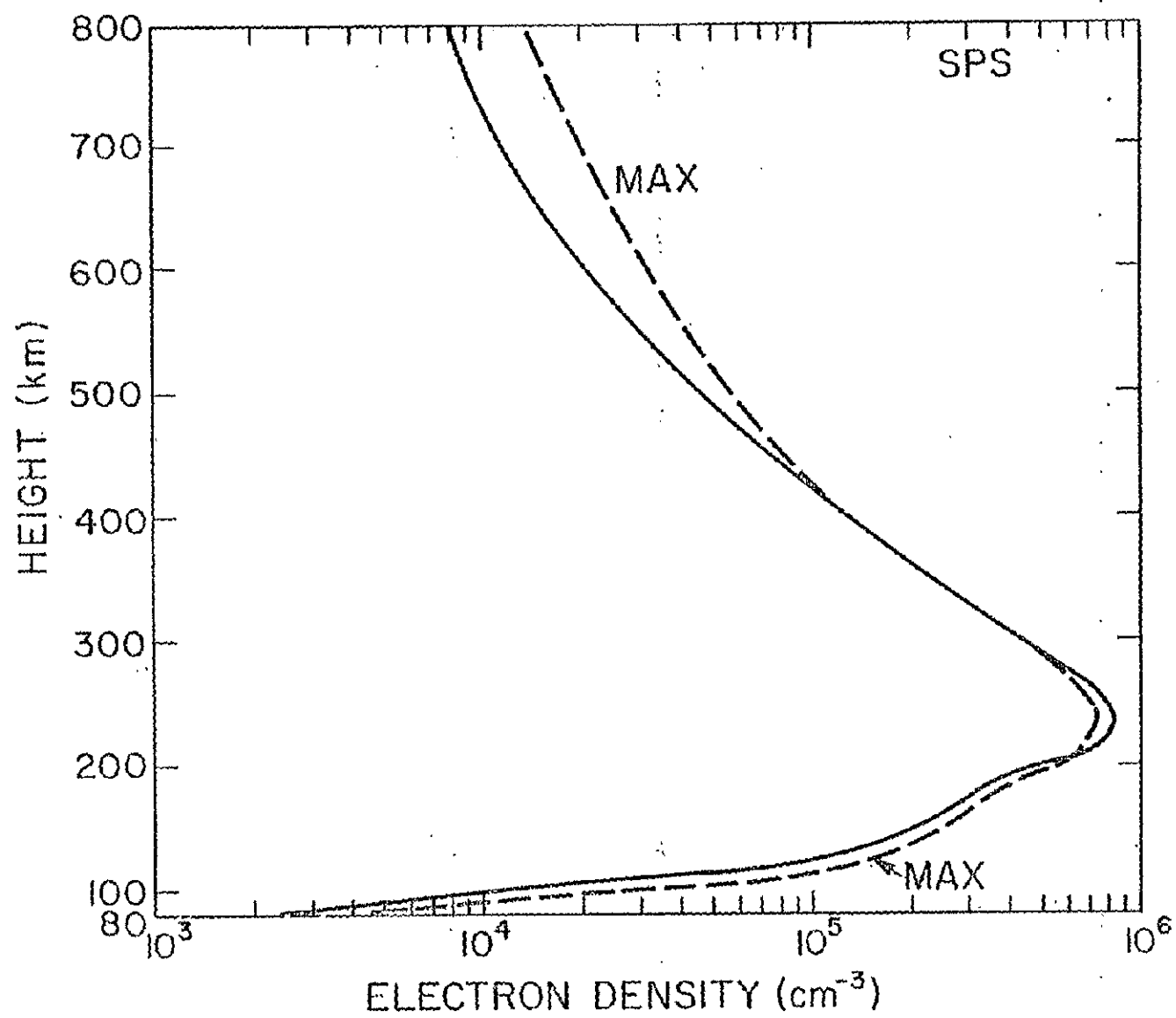


Fig. 9

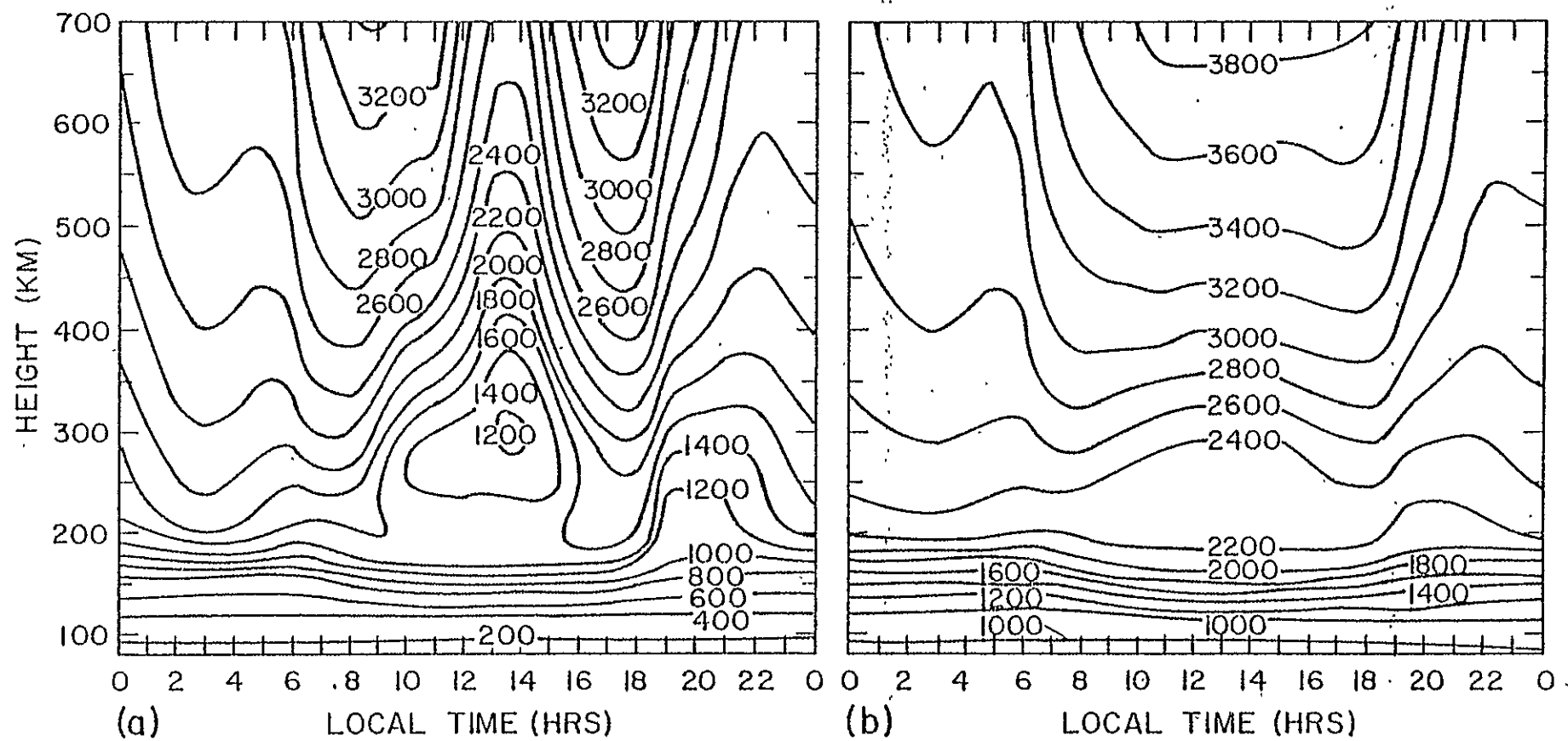


Fig. 10

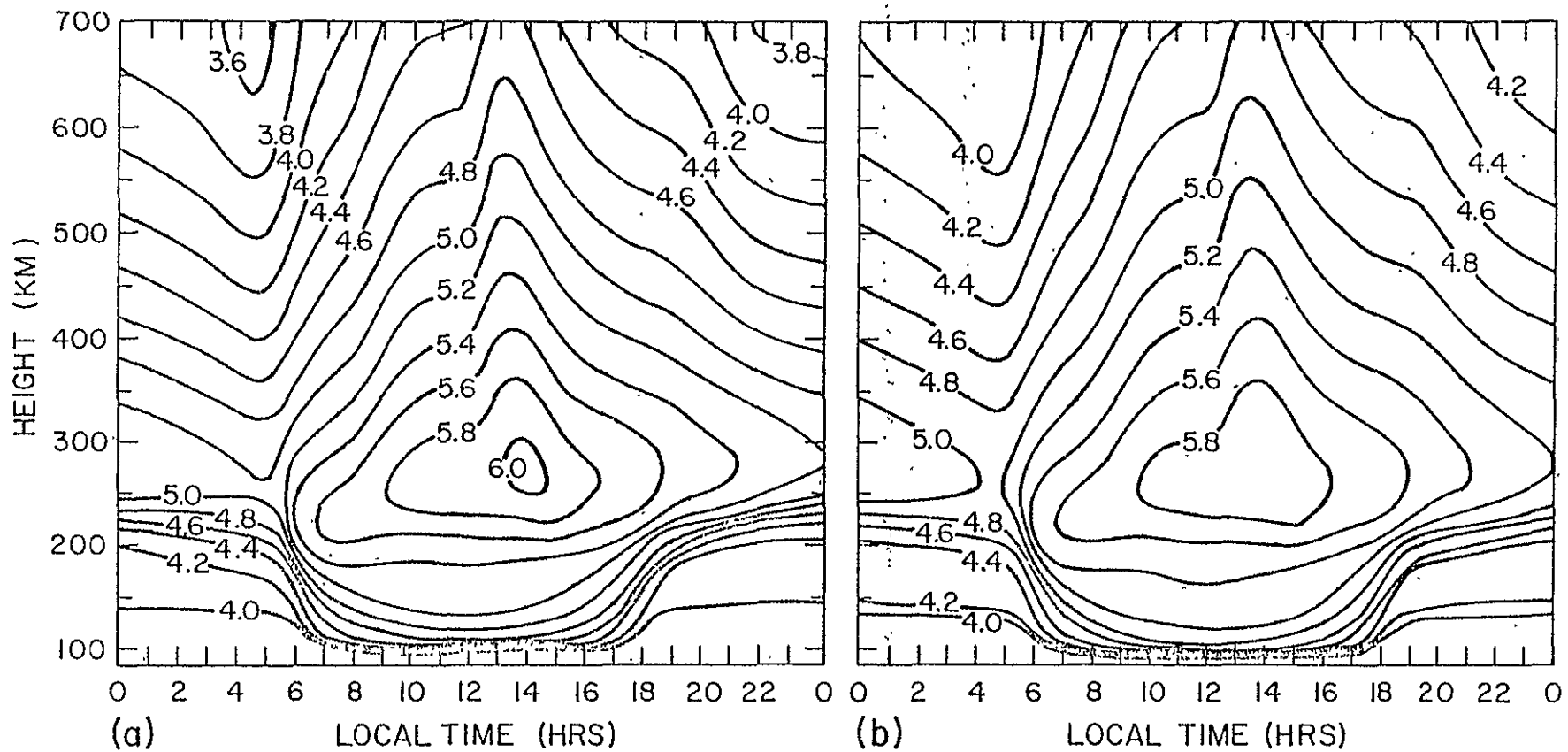


Fig. 11

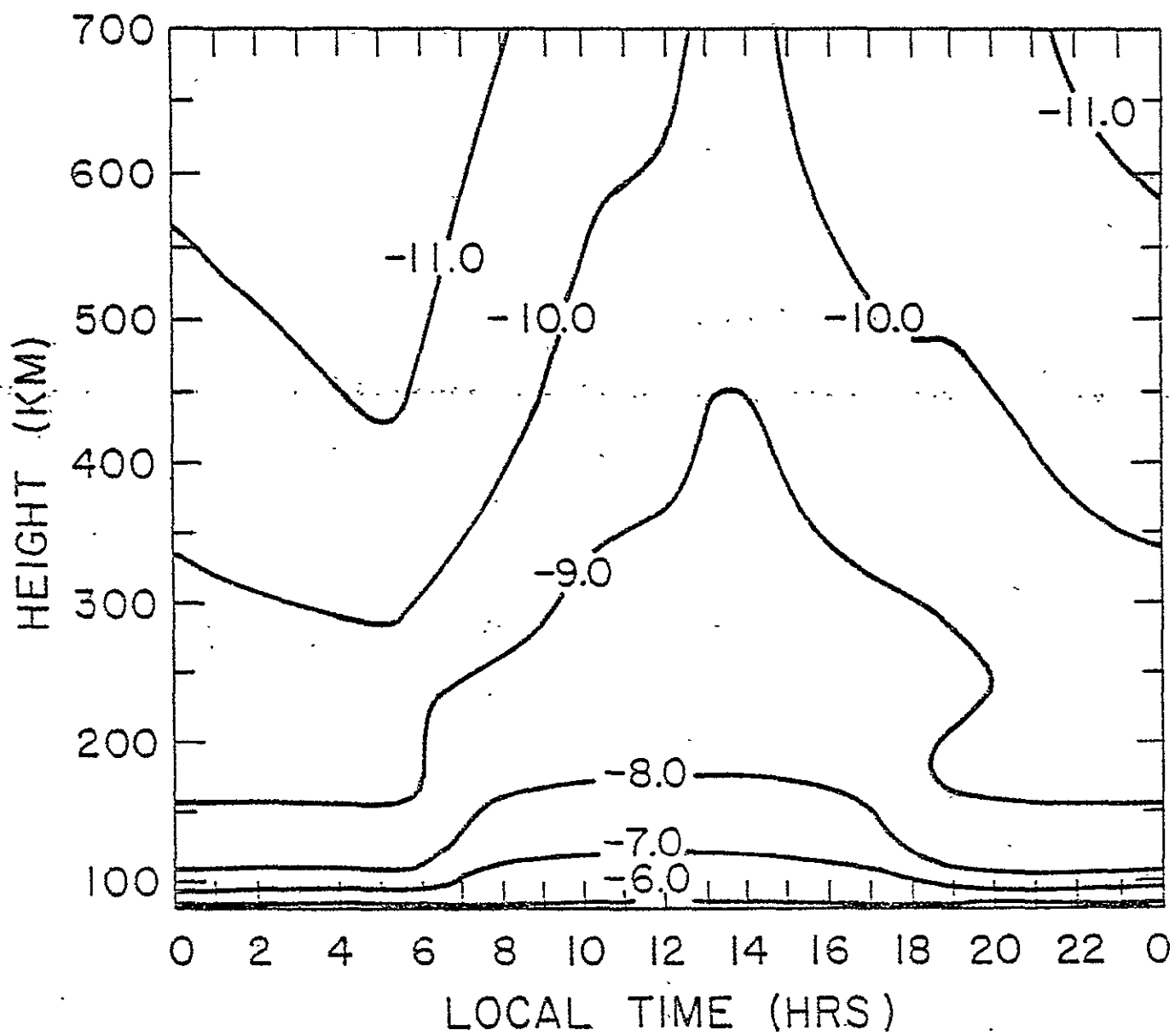


Fig. 12

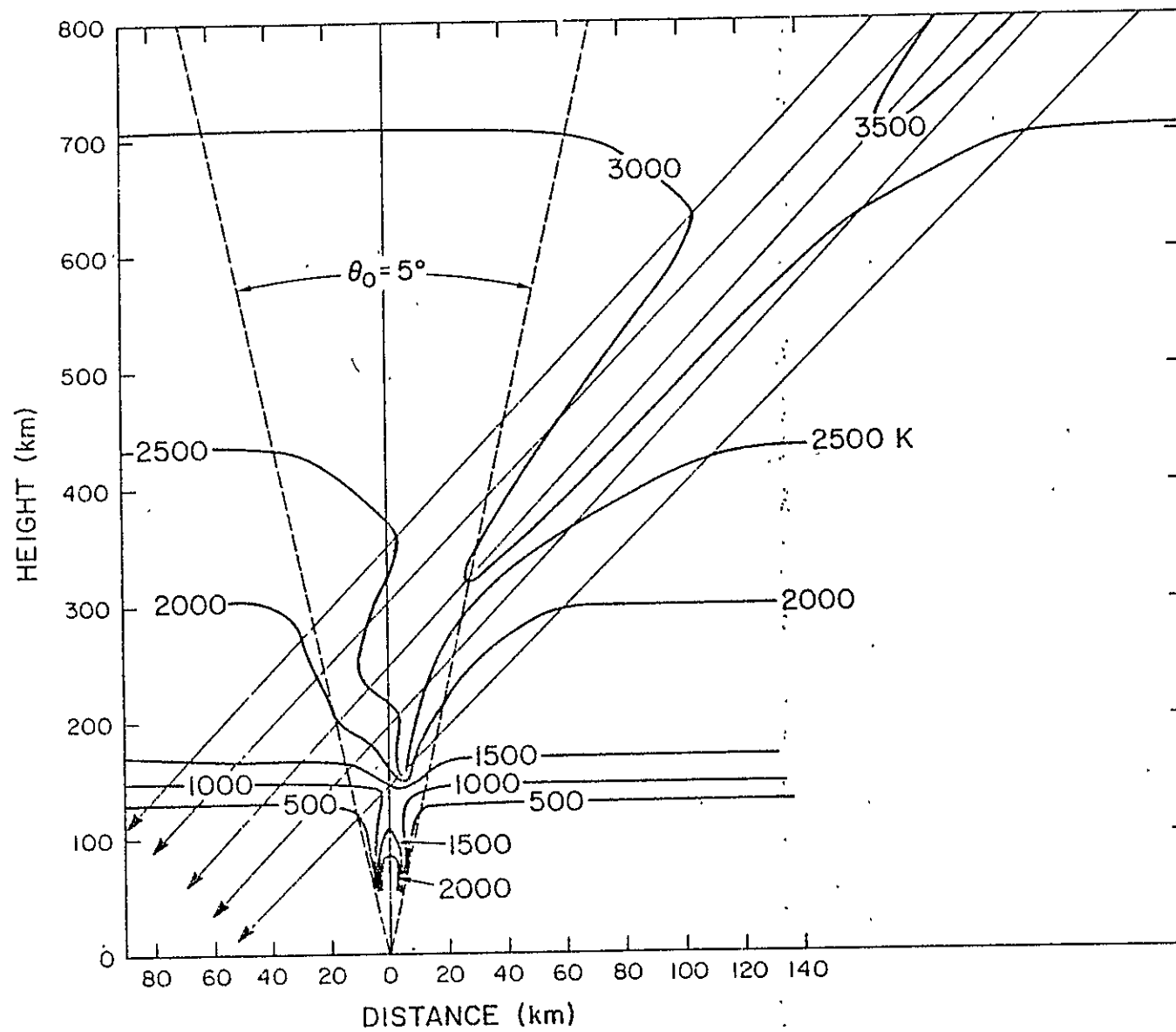


Fig. 13

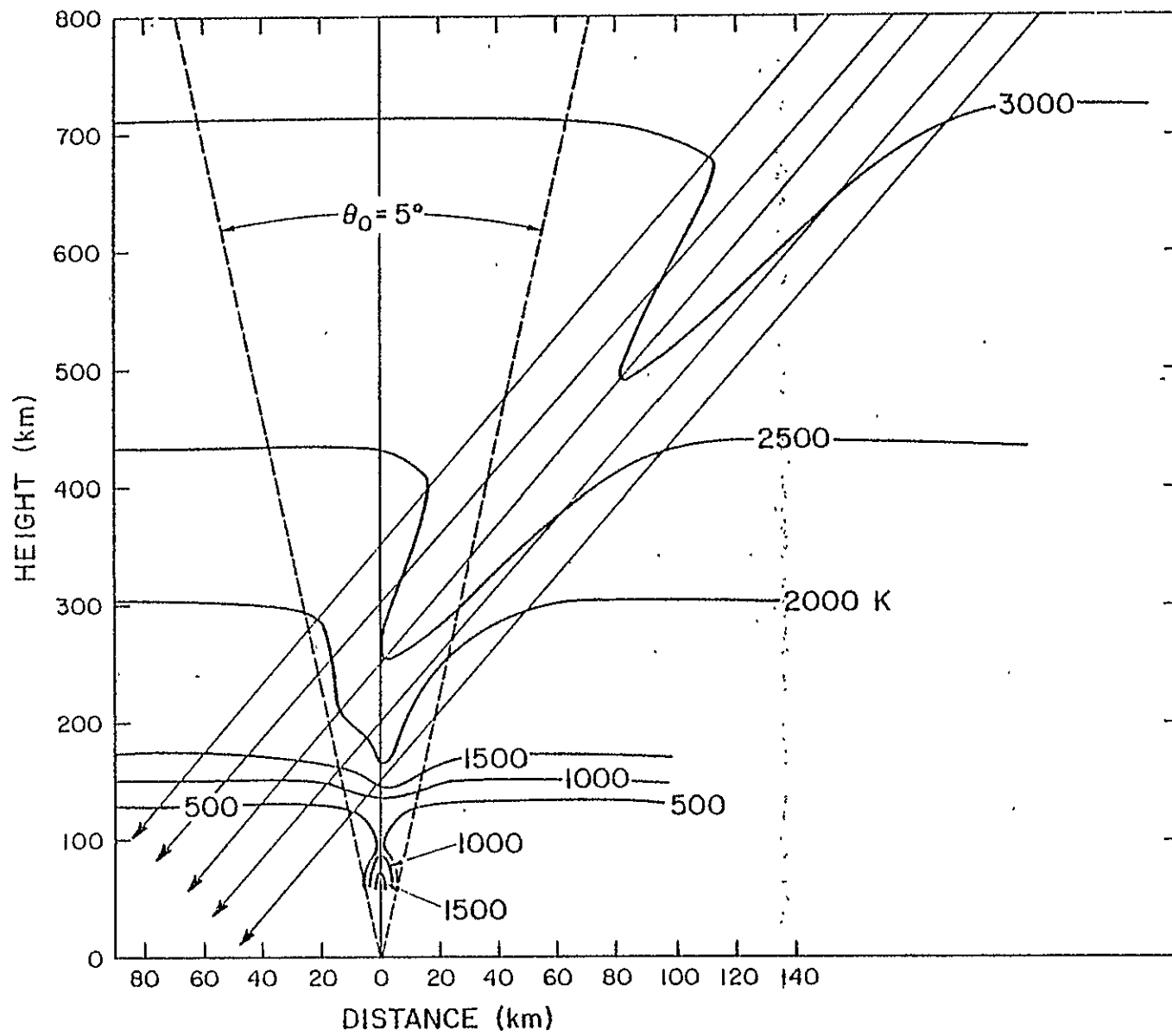


Fig. 14

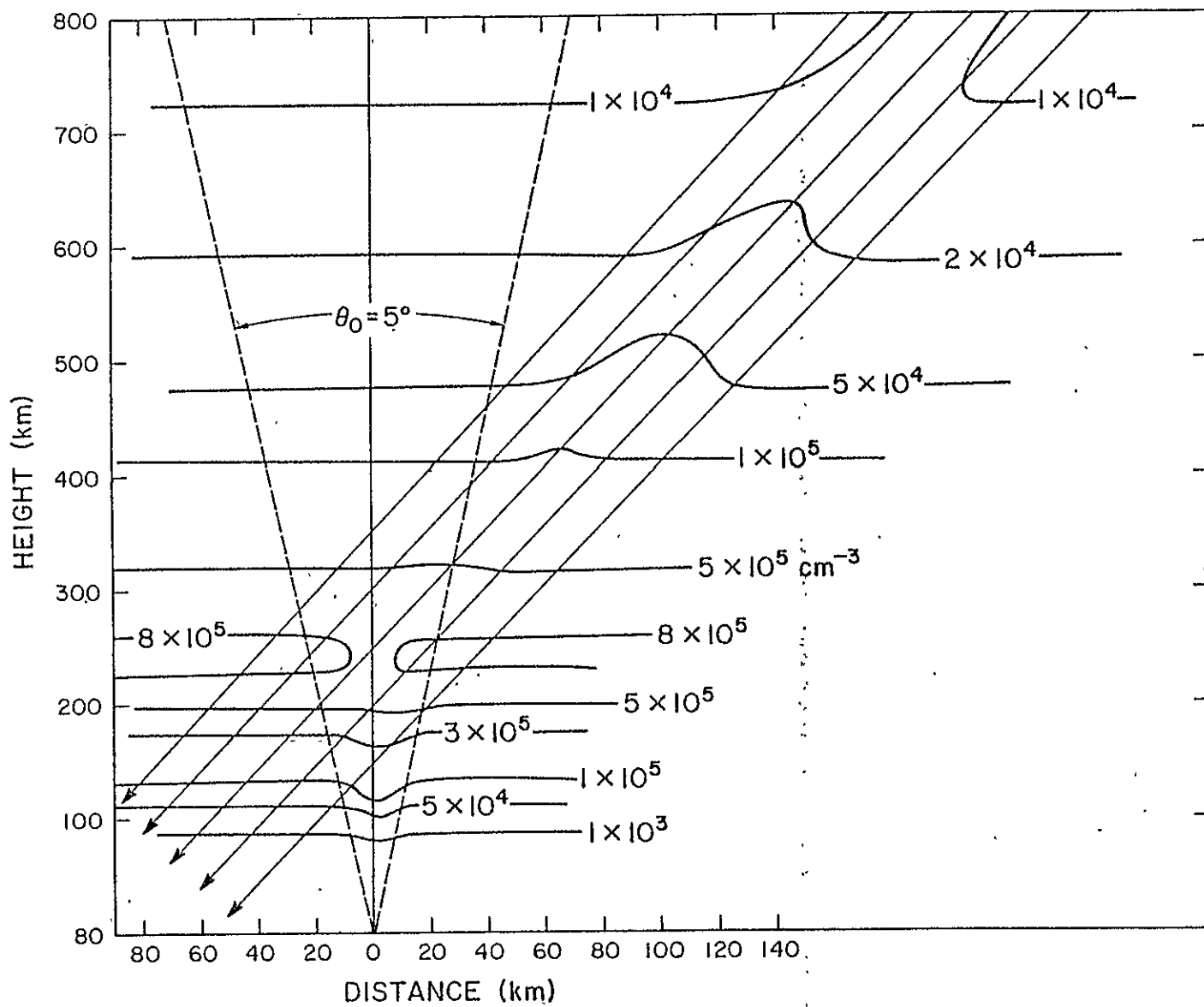


Fig. 15

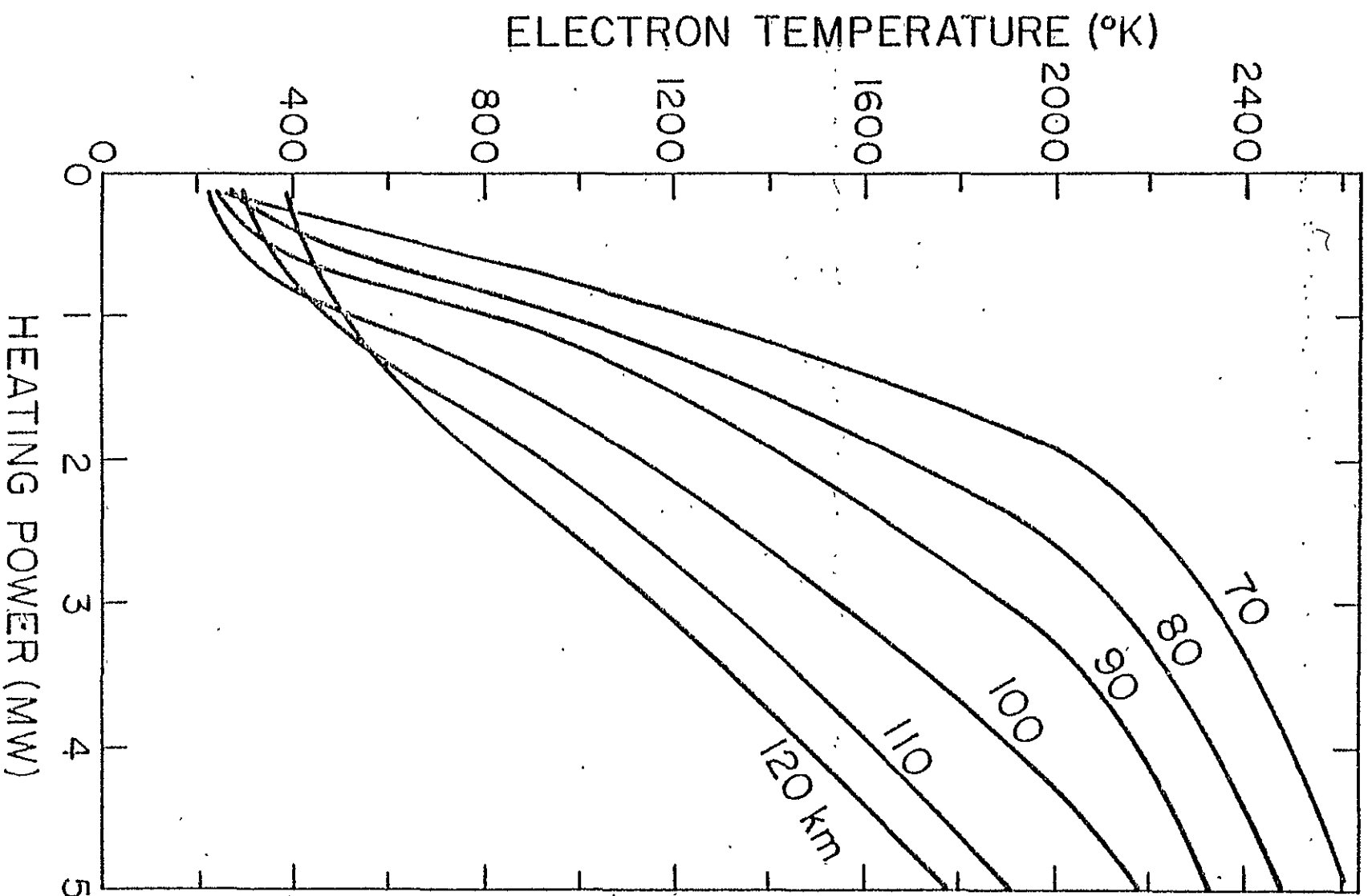


Fig. 16

APPENDIX 2

IONOSPHERE-MICROWAVE INTERACTION SUBGROUP

O. Garriott, W. E. Gordon, L. Duncan

The purpose of this subgroup was to discuss the possibility for scaled laboratory studies of ionosphere-microwave interactions, in particular thermal self-focusing instabilities. The JSC Chamber A facility is well-suited to the large scale sizes of these interactions and we need to determine if the other plasma parameters can be scaled appropriately.

The transmitter system was proposed to be a microwave horn producing a beam incident on the laboratory plasma. The fact that this is not a plane wave, as assumed in the theory, needs to be considered. To avoid a standing wave configuration in the plasma, and thus to avoid plasma density striations unrelated to self-focusing, the microwave radiation should be absorbed after passing across the chamber. The question arose as to whether absorbing material exists which can be put into a vacuum environment.

In a later conversation it was suggested that, under the proper geometry, microwave reflection could be tolerated. However, if microwave absorption can be achieved in a vacuum, it is the better solution because it suppresses the unwanted standing waves.

We understand that a plasma generator could produce a large plasma, as required for Chamber A. Other methods, such

as using an electron beam, could produce plasma instabilities much stronger than the self-focusing mechanism.

The question of plasma diagnostics was not addressed. In the general discussion group, Langmuir probes were the most commonly mentioned density diagnostic. Light and radio wave scattering are other possibilities. The usefulness of each method is determined by its sensitivity, which then must be related to the $\Delta n/n$ of the density striations. The time scales and saturation levels of these density fluctuations has not been discussed.

Although close attention has been given to the perpendicular scale size of the density striations ($\lambda_{\perp}$), we have not considered the effects of finite parallel scale sizes, limited by the laboratory dimensions.

It was suggested that we might try parametric excitation in an overdense plasma (a situation much closer to previous work in the ionosphere) as a means of building confidence in our laboratory technique.

The major problem in producing thermal self-focusing instabilities in a plasma laboratory is the scaling of the plasma parameters.

We assume a threshold power of $P_{th} \sim 1 \text{ kw/m}^2$ as a reasonable laboratory microwave transmitter output. A beam diameter of 3-5 meters is in keeping with the chamber dimensions. So as to produce several striations within the plasma,

we require $\lambda_{\perp} \leq 2m$ (striation width = $\lambda_{\perp}/2$). To avoid parametric interactions, $f_o^2 \geq 5 f_{\text{critical}}^2$, where f_o is the operating frequency and f_{critical} is the plasma critical frequency.

$$\text{Using } \lambda_{\perp}^4 \approx (6 \times 10^{22}) f_o^2 \cos^2 \theta f_{\text{crit}}^{-4} P_{\text{th}}^{-1}$$

yields $f_{\text{crit}} \sim 4 \text{ GHz}$ [$n_{\text{crit}} \sim 2 \times 10^{11}$], neglecting θ term;

$$f_{\text{crit}} \sim .075 \text{ GHz} [n_{\text{crit}} \sim 7 \times 10^7], \theta = 89^\circ;$$

$$f_{\text{crit}} \sim 1.8 \text{ GHz} [n_{\text{crit}} \sim 4 \times 10^{10}], \theta = 65^\circ \sim \text{vertical incidence for Chamber A.}$$

We understand a plasma density of 10^{10} electrons/cm³ is difficult to obtain.

A question was raised in the general group discussion concerning the T_e dependence of $\lambda_{\perp}$. This dependence, working through the electron collision frequency, does not appear in the expression given above because of an ionospheric-like plasma approximation. With explicit T_e dependence included,

$$\lambda_{\perp}^4 \approx (3.44 \times 10^{21}) T_e^5 \cos^2 \theta f_o^2 f_{\text{crit}}^{-6} P_{\text{th}}^{-1}.$$

The plasma density and T_e are related through the electron mean free path, which is limited by the condition

$$\lambda_{\text{mfp}} \ll \text{chamber dimensions.}$$

For reasonable values of T_e , this expression reduces to the previous equation.

One possibility now being explored is allowing neutrals to act as the primary source of electron collisions, replacing electron-ion collisions. Then,

$$\lambda_{\perp}^4 \approx (3 \times 10^{28}) \cos^2 \theta f_o^2 f_{\text{crit}}^{-2} (T_e/n_n^2) P_{\text{th}}^{-1}.$$

To maintain low conductivity across field lines, we require

$$v_{\text{en}} \ll f_{\text{ce}} \quad (\text{collision frequency} \ll \text{gyrofrequency}).$$

$$\left. \begin{array}{l} \text{For } f_o^2 \sim 5 f_{\text{crit}}^2 \\ T_e \sim 10^3 \text{ }^\circ\text{K} \\ \lambda_{\perp} \sim 2 \text{ m} \\ \theta \sim 65^\circ \end{array} \right\} \begin{array}{l} \text{then } n_n \sim 4.1 \times 10^{13} \\ v_{\text{en}} \sim 2.7 \times 10^5 \text{ (} f_{\text{ce}} \sim 10^6 \text{)} \end{array}$$

Notice that f_{ce} can be increased by using an applied field. This capability also was suggested by the beam-plasma subgroup. It is probably advantageous to maintain an ionospheric-like condition that $f_{\text{pe}}/f_{\text{ce}} \approx 4$. This approach appears promising, but additional thinking is required.

In order to determine if Chamber A is well suited for use in studying thermal self-focusing instabilities, we need to answer the following questions:

1) Transmitter

- (a) What are the amplitude variations in the near field?
- (b) Can absorbing material be used in a vacuum?
- (c) Are there hardware problems with the microwave system in a vacuum?

2) Plasma production

What n_n , n_e , T_e , L (scale height) are readily produced?

3) Plasma diagnostics

- (a) What are the operating characteristics of a Langmuir probe?
- (b) Can we use microwave, radio wave, or laser scattering?
- (c) What other diagnostics might be effective?

4) Theoretical studies

- (a) What is the saturation prediction for $\Delta n/n$?
- (b) What is the effect of electron-neutral collisions?
- (c) What is the effect of finite $\parallel$ dimensions to the striations?

5) What are the amplitude and shape of applied B-fields?

6) What is necessary for parametric excitation? (i.e., repeat questions 1-5)

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