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IONOSPHERIC HEATING ANALYSIS

William Marsh Rice University

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IONOSPHERIC HEATING ANALYSIS

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FOREWORD

Portions of the work described in this report were performed in collaboration with the staff of the Arecibo Observatory operated by Cornell University at Arecibo, Puerto Rico, and their support is gratefull acknowledged. The report was prepared by the principal investigator, but also includes the contribution of the project scientists H. C. Carlson and Robert L. Showen, and graduate students Ivan J. Kantor and Luiz Dias.

This technical report has been reviewed and is approved.

Joseph J. Simons
For Vincent J. Coyne
RADC Project Engineer

Fred C. Wilson
RADC Contract Engineer

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13. ABSTRACT

The high frequency radio heating of the ionosphere running from May 1-20, 1972 has produced some surprising observational evidence of enhancements associated with the extraordinary mode of the heating radiowave (previously all other enhancements have been excited by the ordinary mode), enhanced gyro lines, and of ionospheric "holes" burned by the heating transmitter. While each of these surprises is still tentative, being based on superficial examination of the data as it was collected, they add new interests to people concerned with the plasma physics of the experiments.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ionosphere						
Electron Density						
Wave Propagation						
Plasma Temperature						
Ionospheric Heating						
Plasma Instabilities						

IONOSPHERIC HEATING ANALYSIS

SUMMARY

The high frequency radio heating of the ionosphere running from May 1-20 has produced some surprising observational evidence of enhancements associated with the extraordinary mode of the heating radiowave (previously all other enhancements have been excited by the ordinary mode), enhanced gyro lines, and of ionospheric "holes" burned by the heating transmitter. While each of these surprises is still tentative, being based on superficial examination of the data as it was collected, they add new interests to people concerned with the plasma physics of the experiments.

The possibility of extraordinary mode enhancements of plasma lines was recently suggested by Fejer based on Bernstein waves in the plasma. The data will be examined carefully in the light of this suggestion and the experiments altered to test the predicted bands where enhancements should occur (between the multiples of the electron gyrofrequency) and where they should be forbidden (at and near the multiples of the gyrofrequency).

In the search for spectral features there has been discovered evidence for weak but measurable lines induced by the HF radio waves (O-mode) at the electron gyrofrequency and at twice the gyrofrequency. These observations are being carefully reduced and the theory of gyroline enhancements is being examined. The HF waves producing the enhancement are five or more times the local gyrofrequency.

The ionospheric "holes" are seen as extra traces on the ionograms and can be checked against electron density profiles made with the heater on and off. The extra traces on the ionograms are seen to fatten and merge, giving the appearance of spread-F, a phenomenon rarely seen above Arecibo but a regular feature of the Boulder heating experiment.

The anomalous heating that produces large enhancements in the intensity of the plasma line continues to attract major attention. The details of this work are reported separately in a report (Kantor's doctoral thesis).

TEMPERATURE EFFECTS OF THE ARECIBO HEATING EXPERIMENT

The heating is produced by deposition of energy from a 100 KW HF transmitter tunable from 5 to 10 MHz. The heating is measured by an incoherent backscatter radar with a frequency of 430 MHz.

The results presented here are from ordinary mode HF transmission. The O-mode wave bends to the north a few degrees, and the diagnostic radar was roughly pointed at the center of the heated volume (the heating beamwidth is about 10°).

Rise and fall times of the electron temperature are fast compared to the integration time (5 min) of the measurements. (Thermal relaxation times $\tau = (G\nu)^{-1}$ of tens of seconds are expected.)

At night, the electron temperature typically raises by ΔT_e = 200-300°K (occasionally up to 400°K). The ion temperature possibly shows an increase up to 1/3 ΔT_e . In daytime, the ΔT_e (when observable) is much smaller. All of the temperature increases can readily be explained by the standard deviative absorption theory.

The results of an ON/OFF experiment for both penetrating and reflecting conditions are shown in Figure 1. When the HF wave is closely matched but penetrating, as shown in the left-hand cube, heating of ≈ 100°K was observed throughout the F-layer. When the wave was reflecting, heating of 200°K was produced but only below the reflection altitude.

An experiment where the HF transmitter was cycled from OFF/HALF/FULL power gave the results shown in the next two figures. T_e and T_i are presented vs altitude in Figure 2 averaged separately for the three power settings. Notice that ΔT_e(50 KW) is slightly more than half ΔT_e

(100 KW). The ΔT_i may or may not be significant. In Figure 3 are presented T_e and T_i integrated in altitude and presented along with the HF power. The T_e tracks remarkably well with the HF power, while the T_i behavior is ambiguous.

In Figure 4 are plotted contours of T_e for an experiment where the HF wave was reflected. After 23:32 the ionosphere resumes its ambient temperature of 850-950°K. ΔT_e up to 400°K just below the reflection altitude are shown.

The results of a zenith angle scanning in two directions are shown in Figure 5. An increase of 140°K in T_e is measured in the northerly direction at a distance consistent with ray tracing. The increase in a westerly direction is quite small.

OBSERVATION OF ELECTRON CYCLOTRON LINES ENHANCED BY HF RADIO WAVES

The experiments performed at Arecibo using a 100 KW transmitter tunable between 5 and 12 MHz as a heater to excite artificially the ionosphere (Carlson et al., 1972) produced many new results, e.g., HF enhanced ion plasma fluctuations and HF enhanced plasma lines. In searching different portions of the spectrum of the 430 MHz back-scatter echo, it was found that under certain conditions a new line, typically 2 kHz wide, and with a signal intensity up to 3.5 times the noise, appeared at times near the electron cyclotron frequency and at other times near twice the cyclotron frequency. The lines appeared infrequently, suggesting that stringent ionospheric and experimental conditions must be satisfied.

The experiment was performed at the Arecibo Observatory (NAIC), Arecibo, Puerto Rico. The heating transmitter used as an antenna a log-periodic feed mounted near the focus of the 1000-foot dish to produce the ordinary magnetoionic mode of polarization launched vertically and delivered sufficient incident power density into the ionospheric F-region to modify the local plasma. The diagnostics include photometers, ionosondes and the 430 MHz radar. This deals only with the radar results.

A computer controlled data taking program measured the returned power profile, which is recorded on magnetic tape and subsequently the spectrum is computed by means of a fast Fourier transform. A receiver filter of 125 kHz bandwidth is examined with a frequency resolution of 1.12 kHz. The received frequency is controlled by the computer and can be changed every radar interpulse period. Thus, one is able to look at different portions of the spectrum essentially simultaneously.

Figure 6 shows a typical returned spectrum when the heater is OFF and Figure 7 the same portion of the spectrum when the heater is ON. Note the big enhancement at the plasma line and the appearance of a new line at one or two times the electron cyclotron frequency. It is likely that the spectrum is quasi-symmetrical; the plasma lines have been observed to be nearly symmetrical with respect to the center of the spectrum; however, the weak new lines have not yet been detected in the lower part of the spectrum. At the next opportunity (October 1972) the search will be extended.

A close look in the vicinity of the line near the electron cyclotron frequency is shown in Figure 8, with the statistical fluctuation denoted by bars from an actual observation.

There is some evidence of a shift of the line frequency with time, suggesting changes in the height of the excited layer and other ionospheric parameters. Further analysis is underway.

The experiments were done in three steps in order to rule out any possible interference: (1) with the heater ON and the receivers connected to the antenna, to record the data; (2) with the heater ON and the receivers connected to a dummy load, to be sure that the signal was coming from the ionosphere; and (3) with the heater OFF and the receivers connected to the antenna, to be sure that the effect seen was produced by the artificial heating of the ionosphere. The lines were seen only in step (1), which is a decisive proof of their existence.

Observations were made at the following heater frequencies: 5.1, 5.425, 6.79, 8.195, 10.85 MHz, but the best results (higher signal-to-noise) were obtained for f_{HF} = 5.425 MHz and f_{HF} = 10.85 MHz. It is interesting to note that the last frequency is the double of the previous and this is almost 5 times the local electron cyclotron frequency at the height of reflection over Arecibo. A standard computer program computes the electron cyclotron frequency over Arecibo from POGO satellite coefficients (Cain, 1970).

The lines came from the height of reflection of the HF signal. The change in frequency with time could indicate a reflection from a different height and/or that the frequency of the line is proportional to some time varying parameter; however, at this stage no conclusion can be drawn.

HF ENHANCEMENTS OF INCOHERENT BACKSCATTER PLASMA LINES

Observations of enhancements of incoherent backscatter plasma lines excited by strong HF radio waves are reported. Among the features described are: spectral shape and correlation between features, power dependence, decay times, longer term fading rates, comparison between up and downshifted plasma lines.

Some experimental data of instabilities generated at plasma frequencies when a strong HF radio wave from 5-10 MHz is incident in the F-region in the ionosphere is shown. The data was obtained at the Arecibo Observatory facilities.

Figure 9 shows the schematic backscatter spectrum. At the radar frequency we have the usual ion line. The enhancement from HF radio wave could not be observed yet. At each side of it it is usual to observe two plasma line enhancements, up and downshifted at approximately the heater frequency. They usually have similar shape and their amplitude follows grossly with time. There is one enhancement at the HF frequency corresponding to the growing mode. Displaced by approximately an ion acoustic frequency, there is an enhancement corresponding to the parametric or decay instability, referred to here as the plasma line.

Figure 10 shows an example of a plasma line spectra. The peak intensity is 64,000°K, with a signal-to-noise ratio of 132, and is displaced by approximately 5 kHz as predicted by the parametric theory.

Figure 11 shows the peak of the plasma line measured at different HF power, in the range from 0 to 125 KW. The data was taken every 20 seconds. It shows a power dependence and there seems to be an hysteresis effect, but that cannot be separated from the natural time fluctuation.

Figure 12 shows the peak intensity of the plasma line with constant HF power. A Fourier analysis shows a strong harmonic component of a 35 second period. It can be seen that on occasions the intensity fluctuates more than an order of magnitude.

Figure 13 relates the peak signal at the plasma line (decay mode) and the peak signal at the HF (growing mode), for different HF powers. It shows a very strong correlation.

Measurements done of the decay time of the plasma line show time constants of the order of 700μs, which corresponds closely to electron ion collision frequency and Landau damping from photoelectrons.

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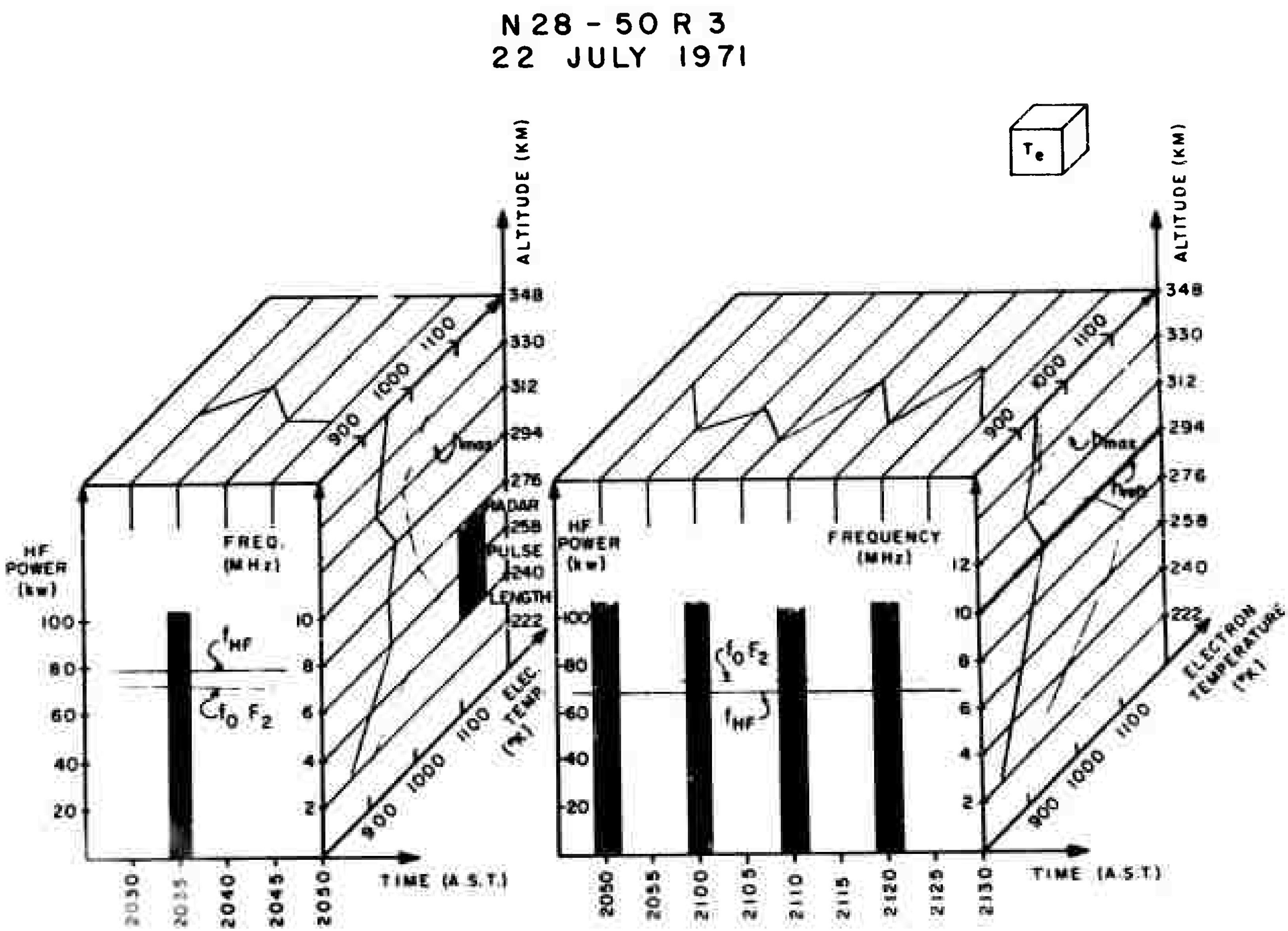
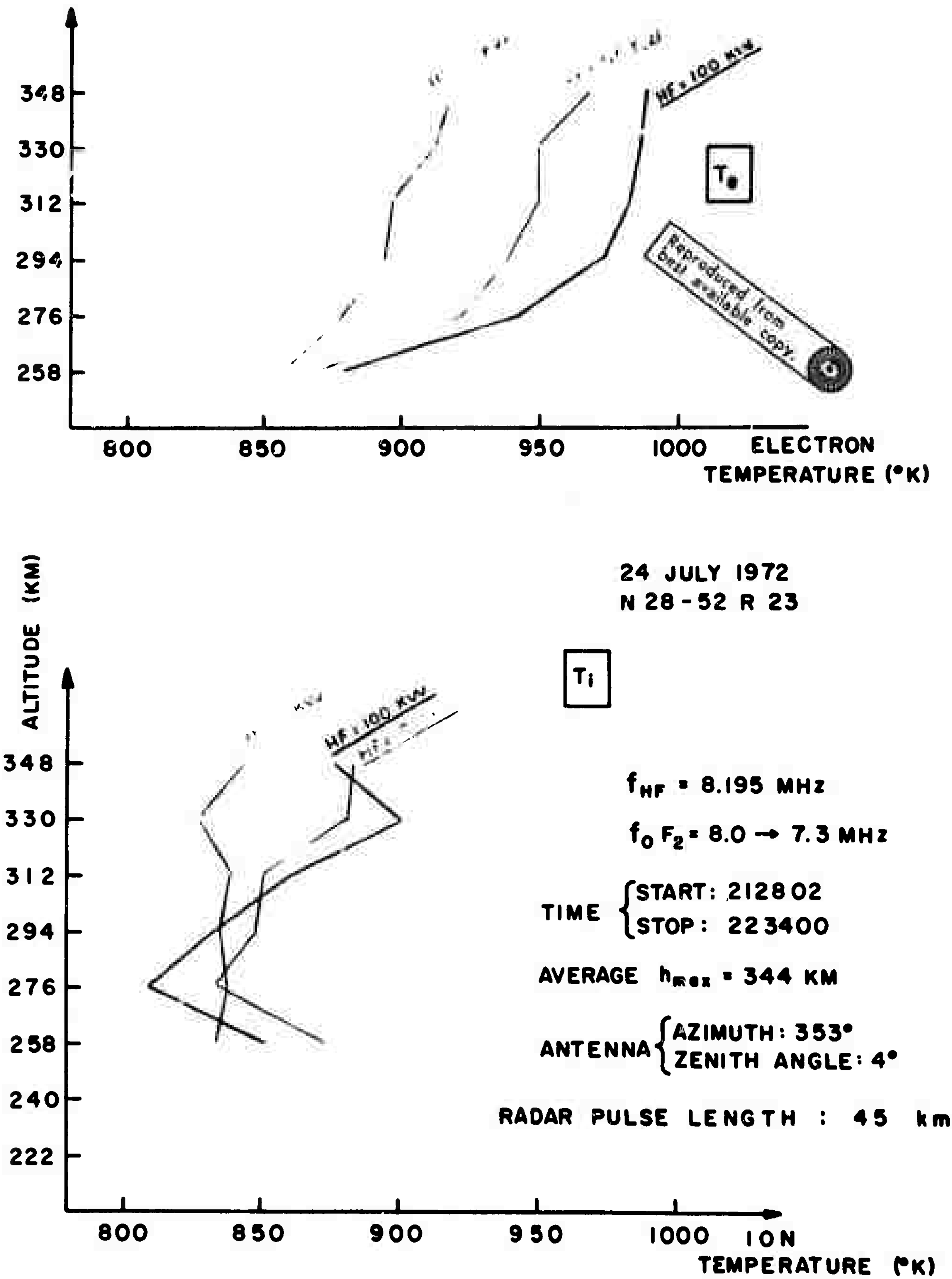
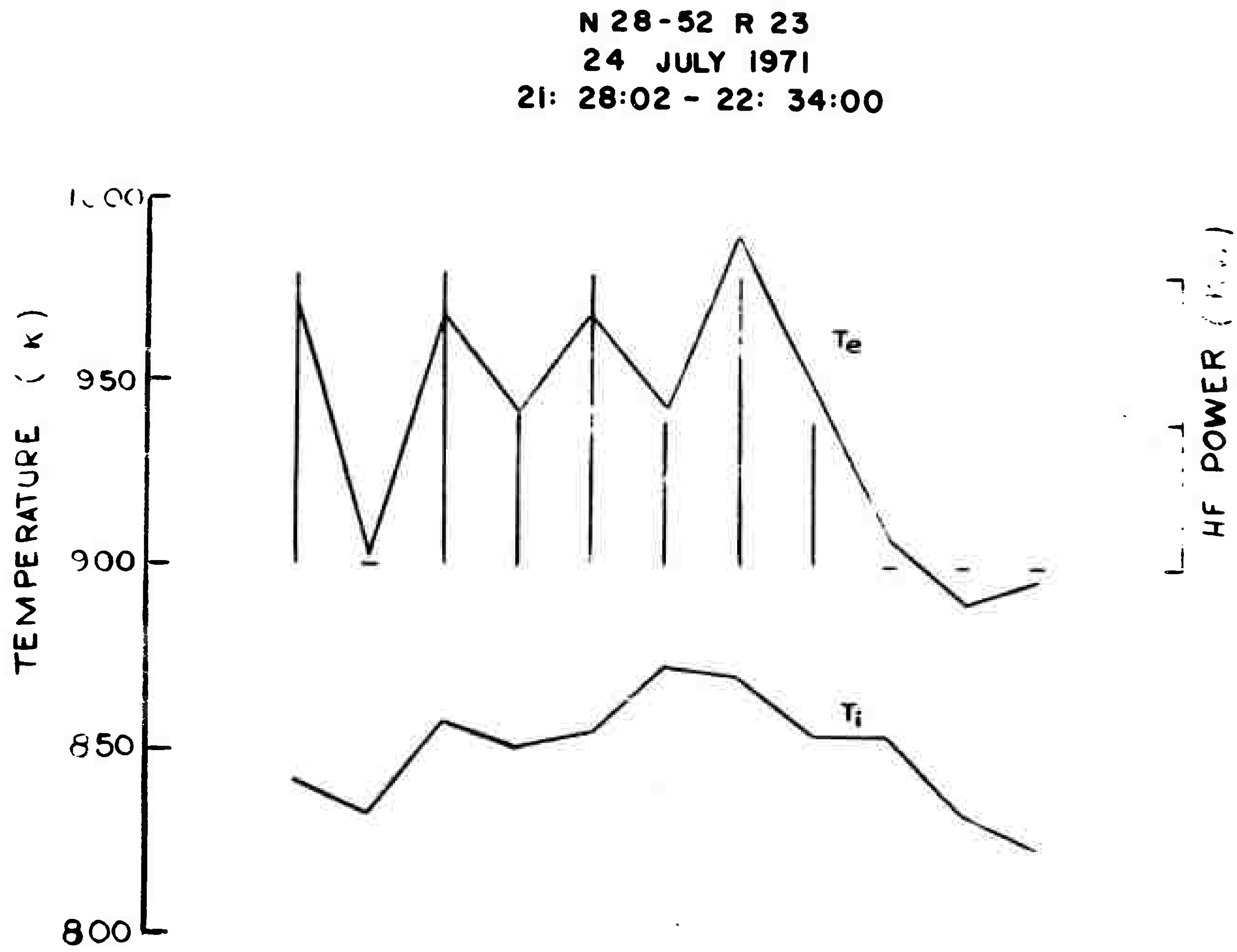

N28 - 50 R 3
22 JULY 1971
T_e
ALTITUDE (KM)
348
330
312
294
276
258
240
222
HF POWER (kw)
100
80
60
40
20
FREQ. (MHz)
FREQUENCY (MHz)
2
4
6
8
10
12
f_{HF}
$f_0 F_2$
h_{max}
RADAR PULSE LENGTH
ELEC TEMP (°K)
ELECTRON TEMPERATURE (°K)
900
1000
1100
TIME (A.S.T.)
2030
2035
2040
2045
2050
2055
2100
2105
2110
2115
2120
2125
2130

FIGURE 1



348
330
312
294
276
258
800
850
900
950
1000
ELECTRON TEMPERATURE (°K)
HF = 100 KW
Te
Reproduced from best available copy.
ALTITUDE (KM)
24 JULY 1972
N 28 - 52 R 23
Ti
HF = 100 KW
348
330
312
294
276
258
240
222
fHF = 8.195 MHz
fo F2 = 8.0 → 7.3 MHz
TIME START: 212802
STOP: 223400
AVERAGE hmax = 344 KM
ANTENNA AZIMUTH: 353°
ZENITH ANGLE: 4°
RADAR PULSE LENGTH : 45 km
800
850
900
950
1000
ION TEMPERATURE (°K)

FIGURE 2



N 28-52 R 23
24 JULY 1971
21: 28:02 - 22: 34:00
TEMPERATURE (K)
950
900
850
800
Te
Ti
HF POWER

FIGURE 3

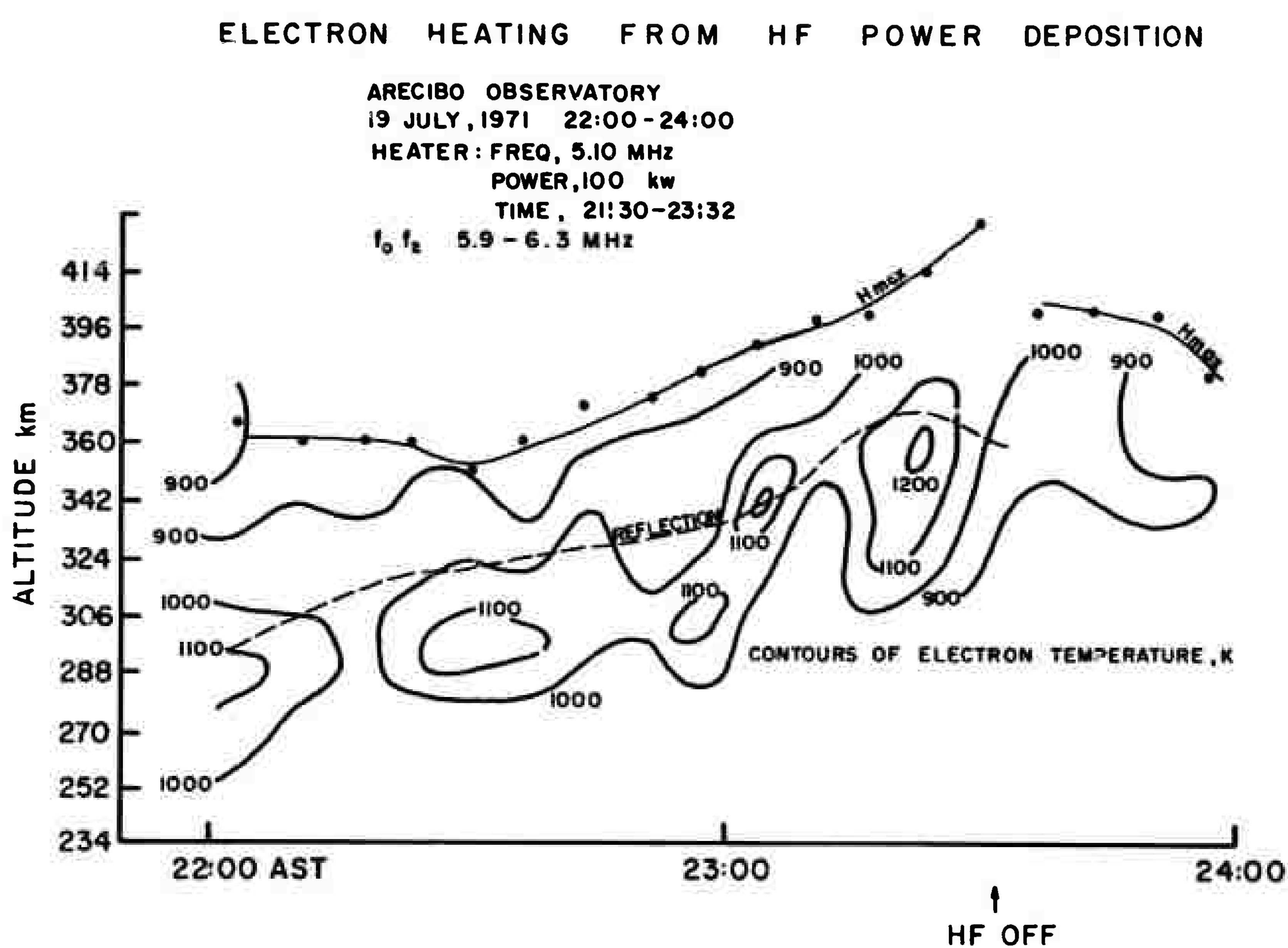

ELECTRON HEATING FROM HF POWER DEPOSITION
ARECIBO OBSERVATORY
19 JULY, 1971 22:00-24:00
HEATER: FREQ, 5.10 MHz
POWER, 100 kw
TIME, 21:30-23:32
f₀ f₂ 5.9 - 6.3 MHz
ALTITUDE km
414
396
378
360
342
324
306
288
270
252
234
22:00 AST
23:00
24:00
HF OFF
Hmax
REFLECTION
CONTOURS OF ELECTRON TEMPERATURE, K
900
1000
1100
1200

FIGURE 4

ΔTe Map

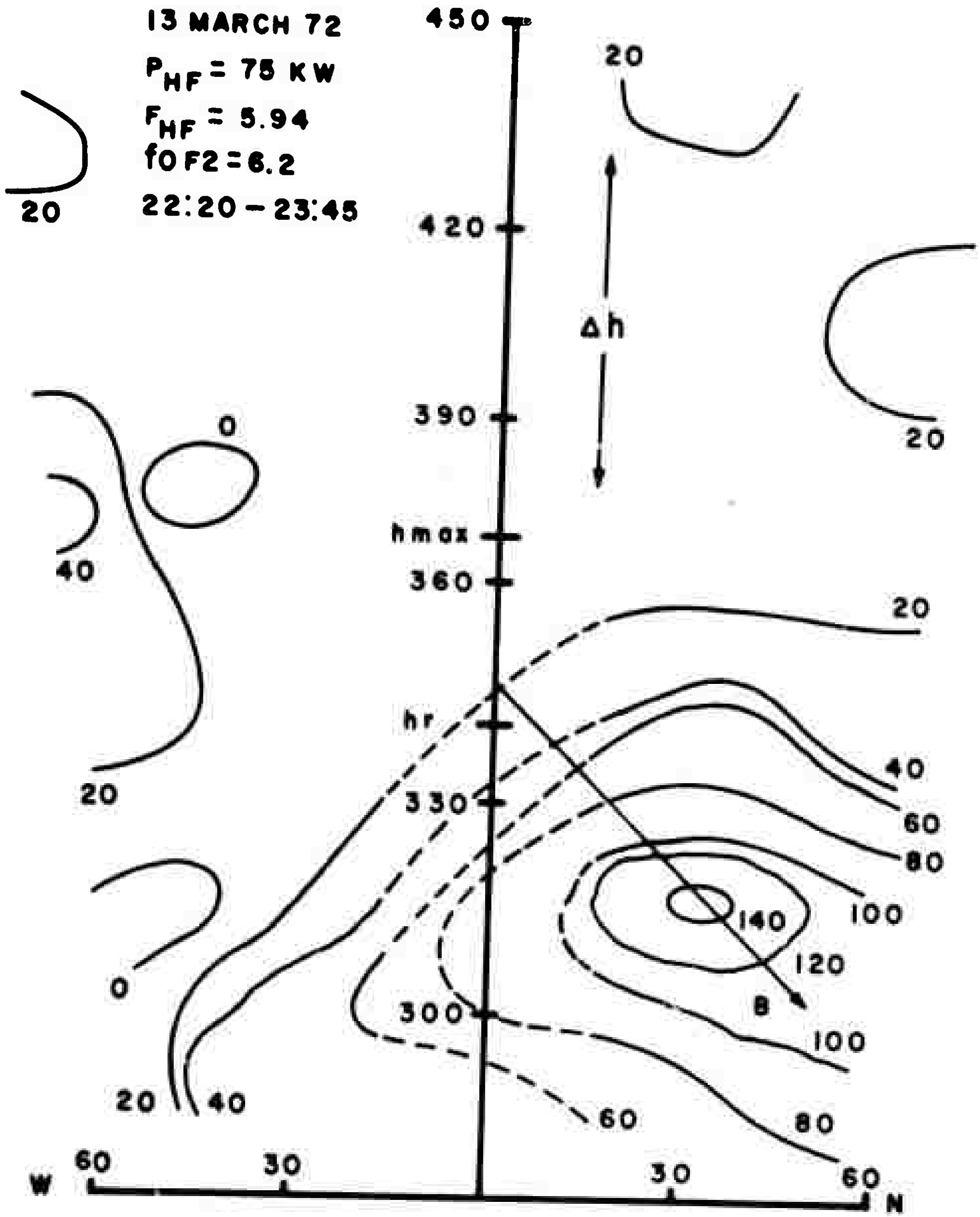


FIGURE 5

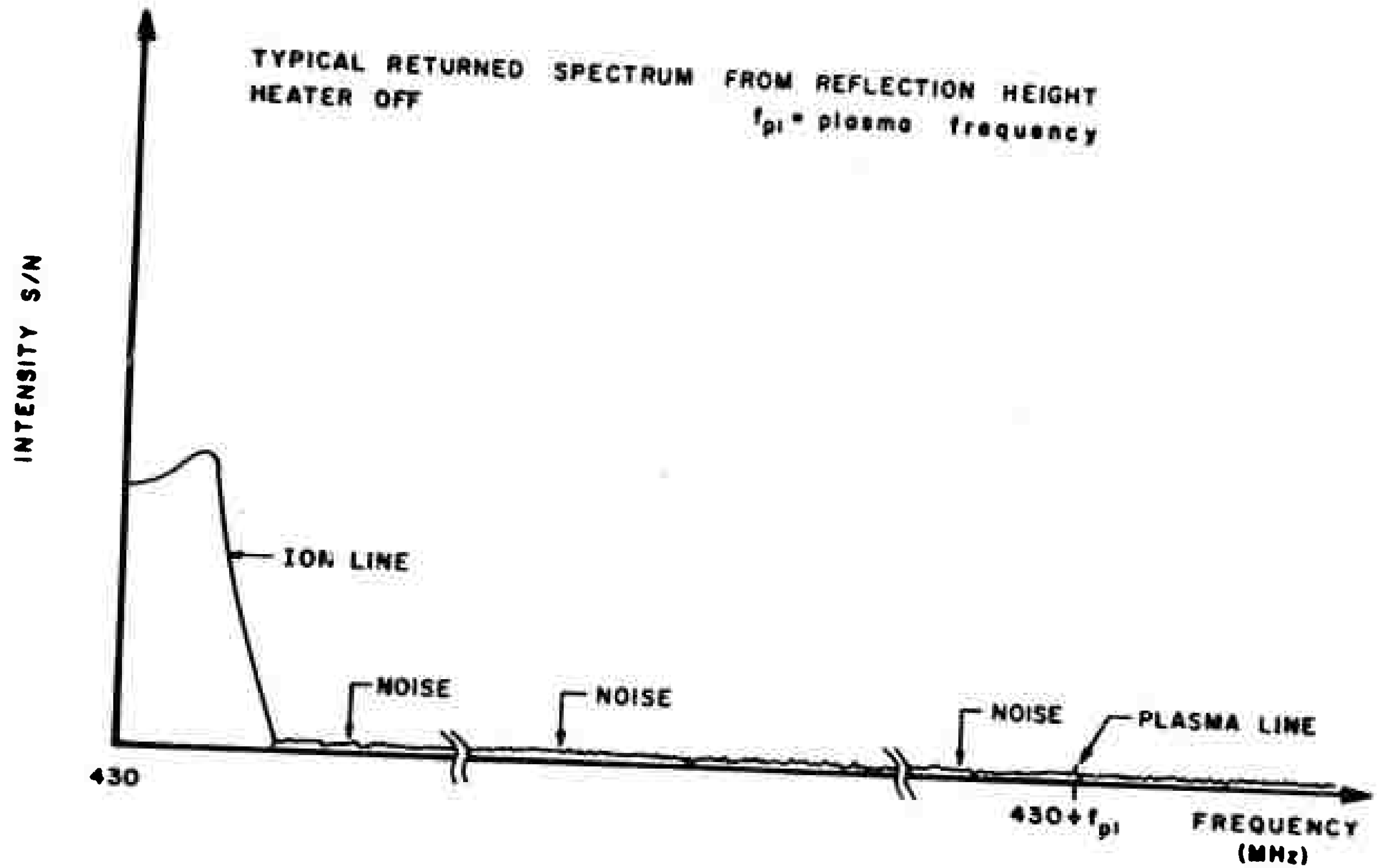

TYPICAL RETURNED SPECTRUM FROM REFLECTION HEIGHT
HEATER OFF
f_{pl} = plasma frequency
INTENSITY S/N
ION LINE
NOISE
NOISE
NOISE
PLASMA LINE
430
430 + f_{pl}
FREQUENCY (MHz)

FIGURE 6

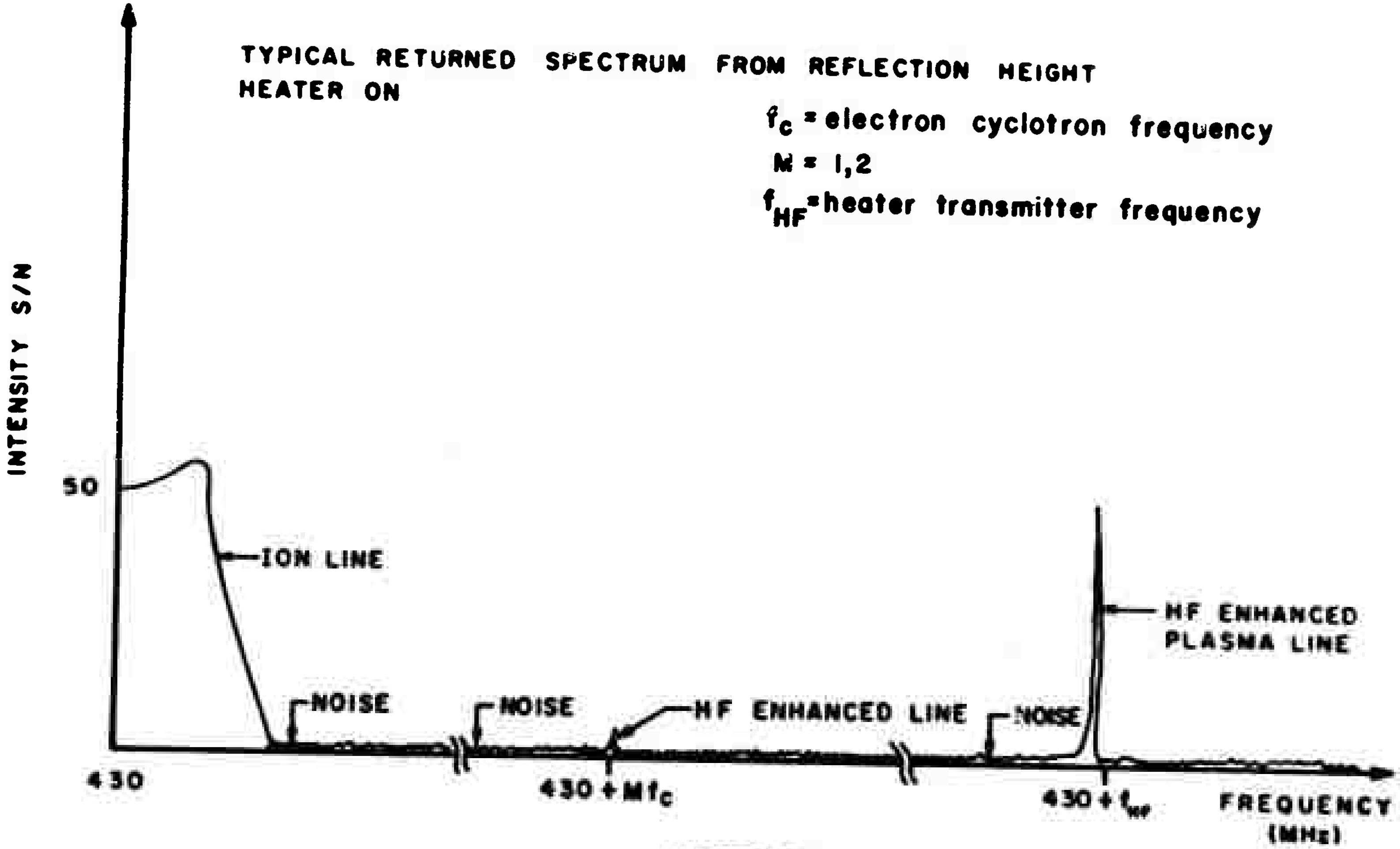

TYPICAL RETURNED SPECTRUM FROM REFLECTION HEIGHT
HEATER ON
f_c = electron cyclotron frequency
M = 1,2
f_{HF} = heater transmitter frequency
INTENSITY S/N
50
ION LINE
NOISE
NOISE
HF ENHANCED LINE
NOISE
HF ENHANCED PLASMA LINE
430
430 + Mf_c
430 + f_{HF}
FREQUENCY (MHz)

FIGURE 7

Frequency Spectrum Near Electron Cyclotron Frequency

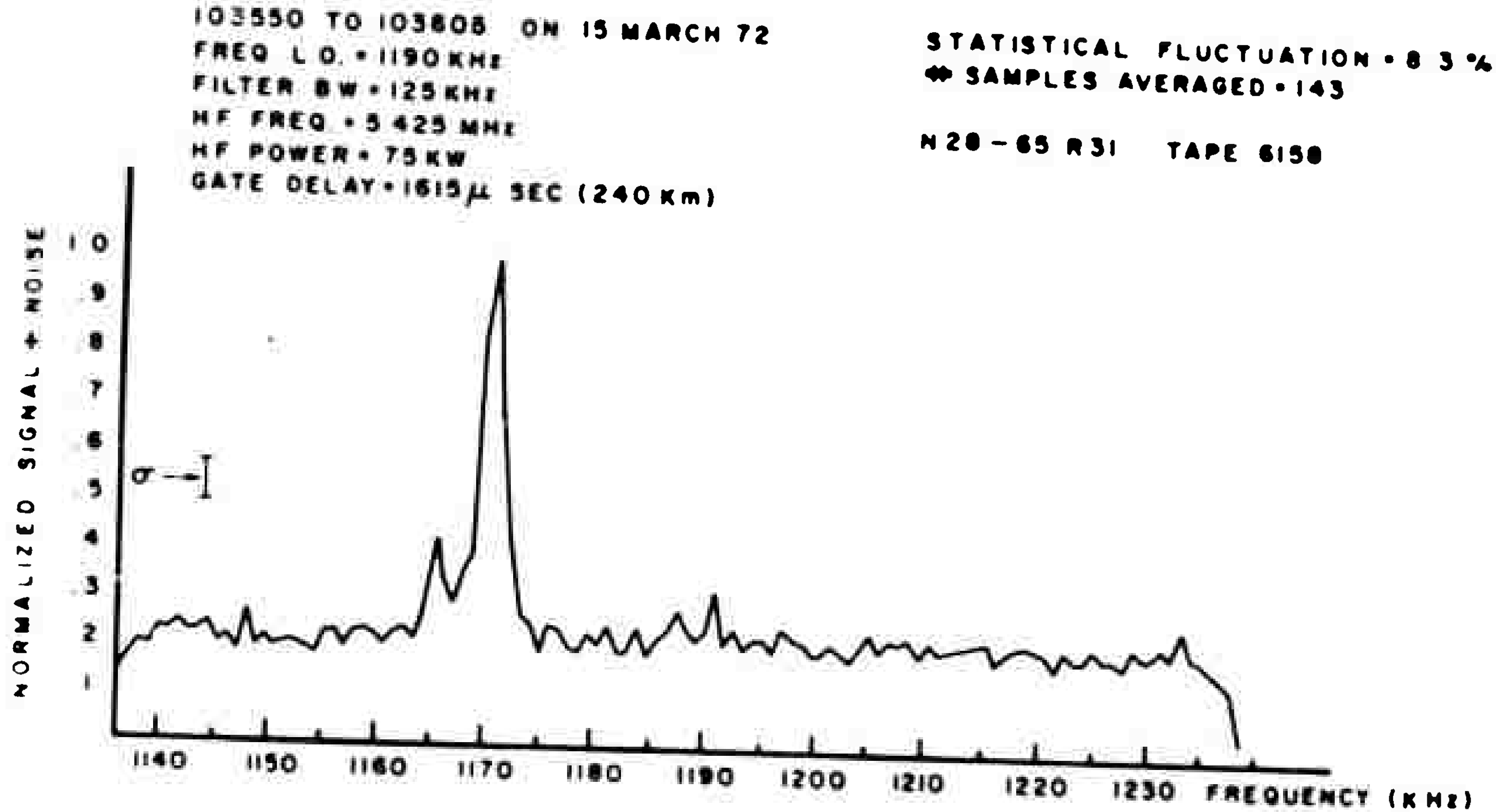


FIGURE 8

SCHEMATIC BACKSCATTER SPECTRUM DURING IONOSPHERIC HEATING

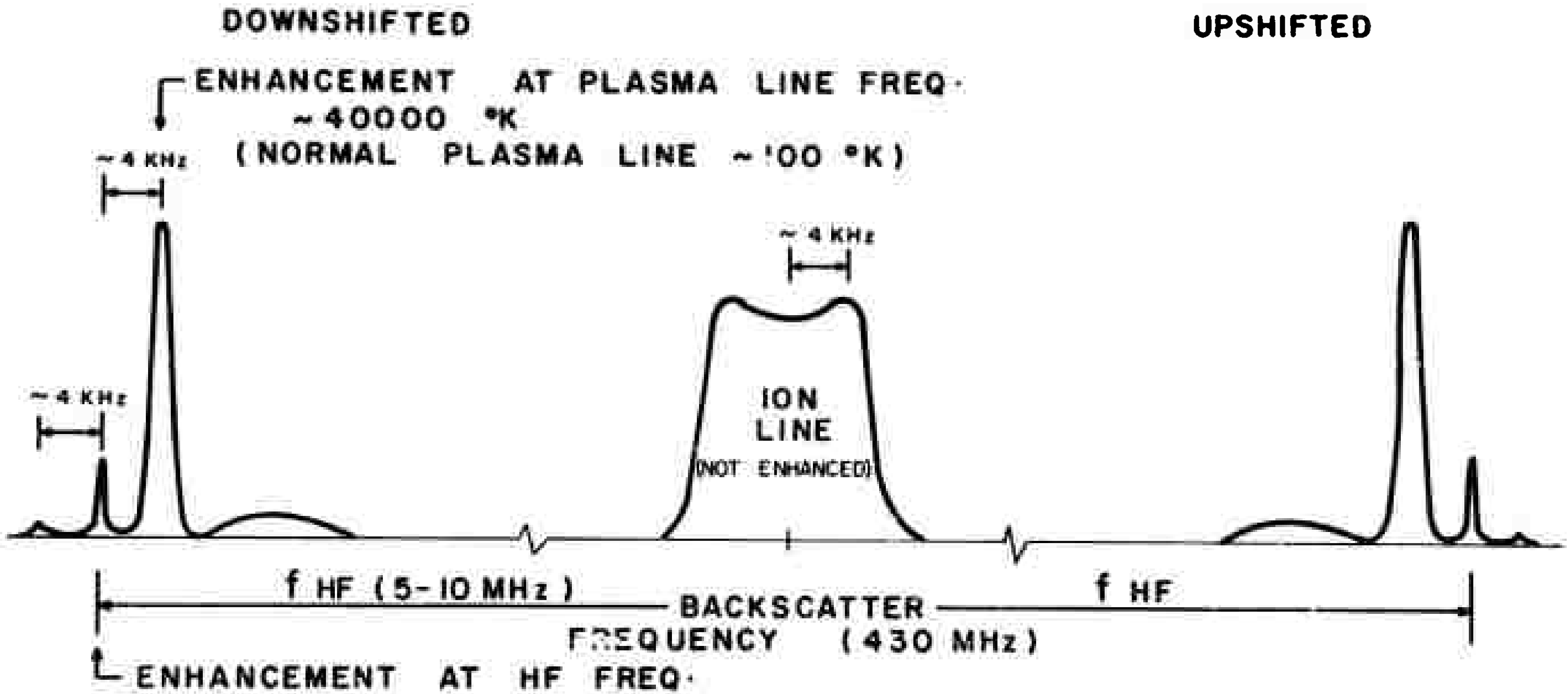


FIGURE 9

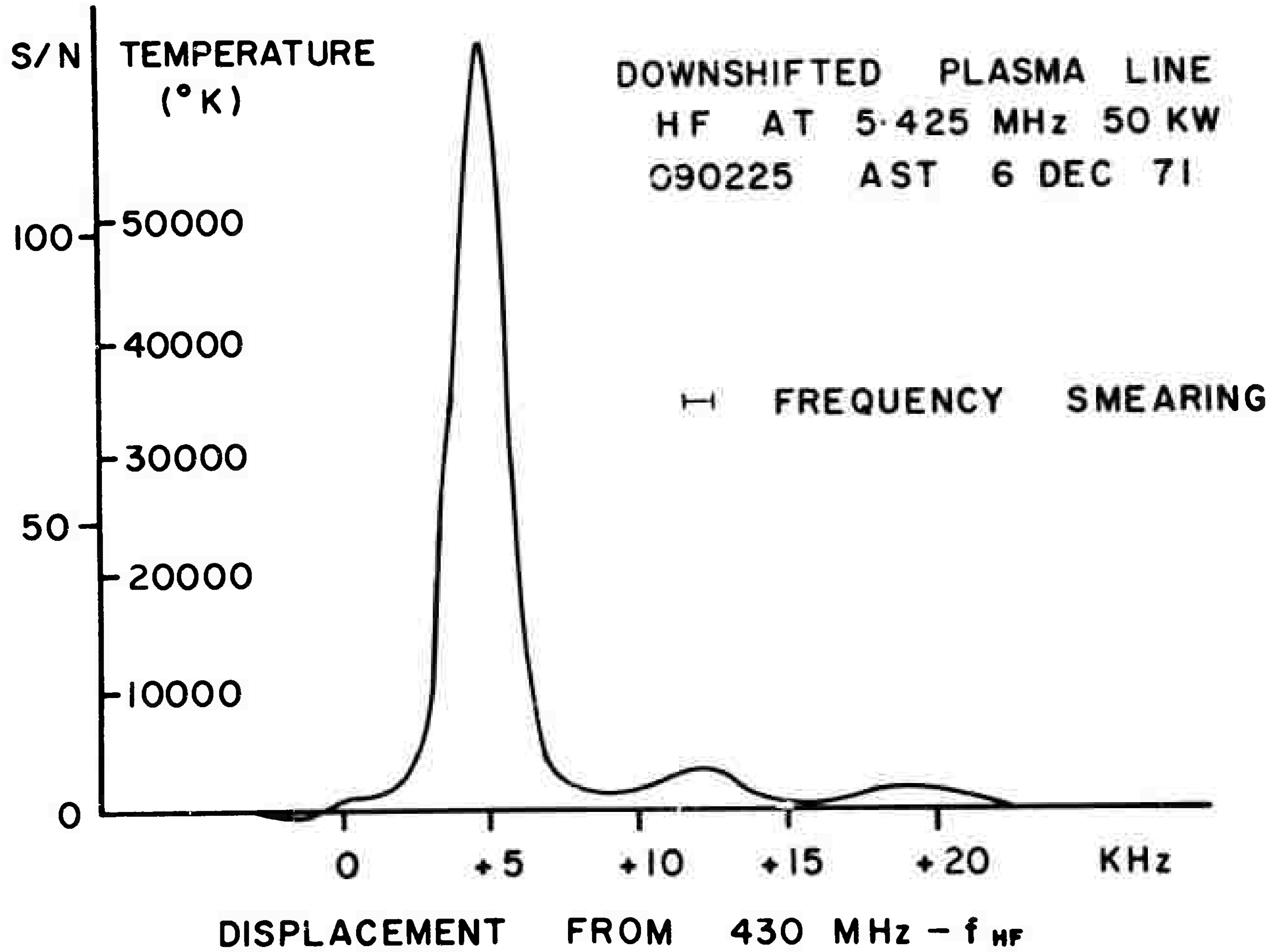
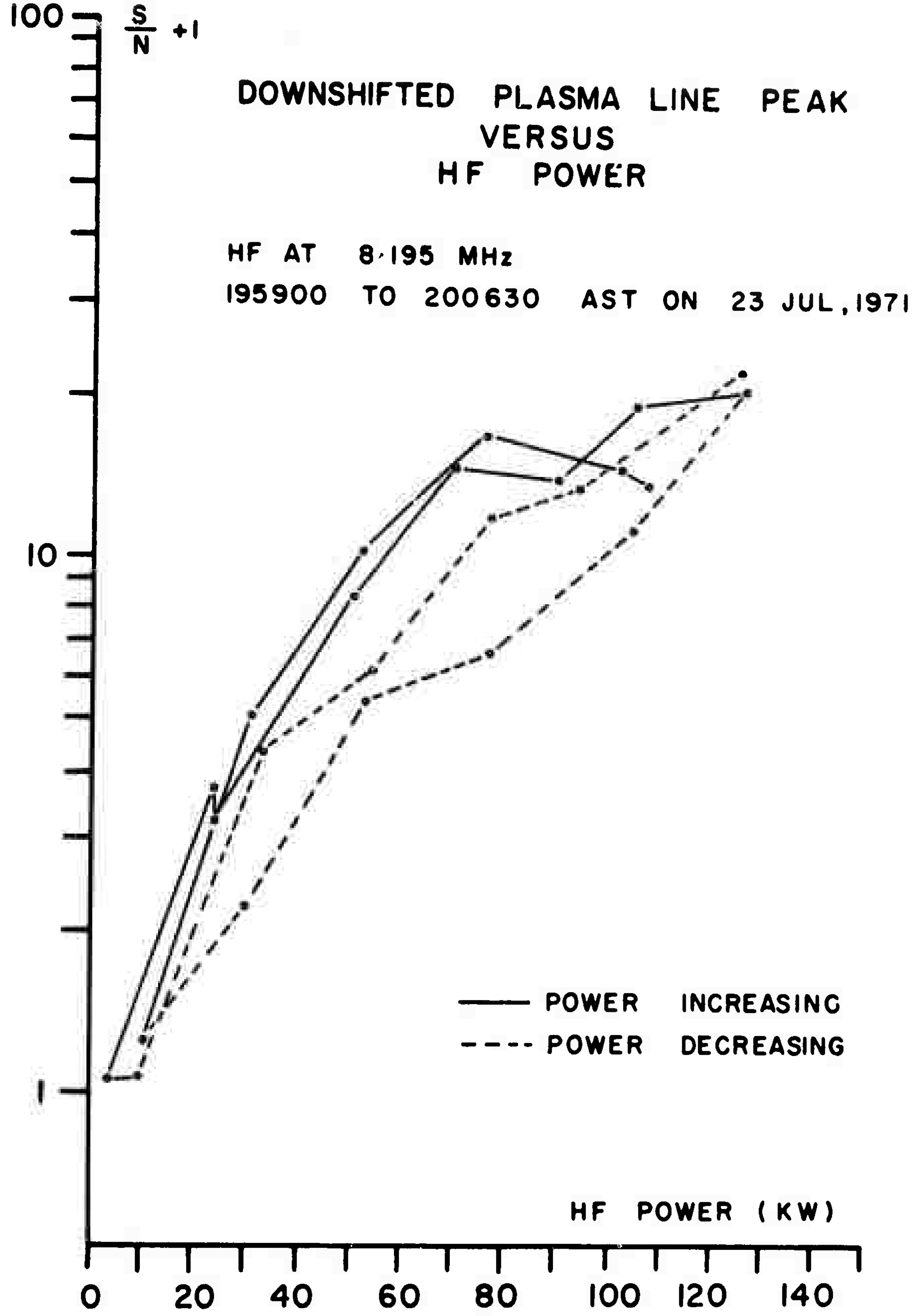

S/N
TEMPERATURE (°K)
100
50
0
50000
40000
30000
20000
10000
DOWNSHIFTED PLASMA LINE
HF AT 5·425 MHz 50 KW
090225 AST 6 DEC 71
FREQUENCY SMEARING
0
+5
+10
+15
+20
KHz
DISPLACEMENT FROM 430 MHz − f HF

FIGURE 10



100
10
1
$\frac{S}{N}+1$
DOWNSHIFTED PLASMA LINE PEAK
VERSUS
HF POWER
HF AT 8·195 MHz
195900 TO 200630 AST ON 23 JUL, 1971
POWER INCREASING
POWER DECREASING
HF POWER (KW)
0
20
40
60
80
100
120
140

FIGURE 11

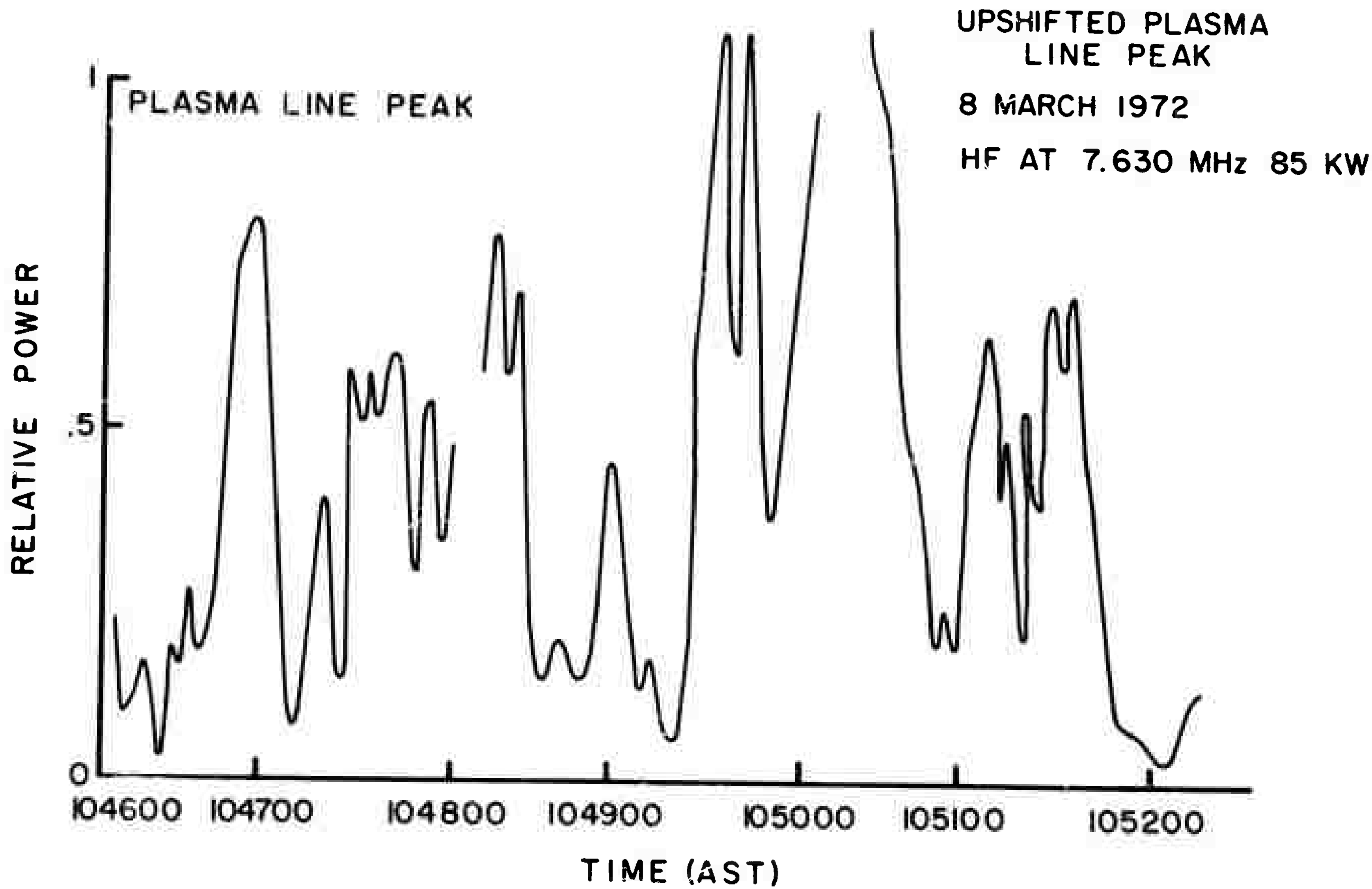

UPSHIFTED PLASMA LINE PEAK
8 MARCH 1972
HF AT 7.630 MHz 85 KW
PLASMA LINE PEAK
RELATIVE POWER
1
.5
0
104600
104700
104800
104900
105000
105100
105200
TIME (AST)

FIGURE 12

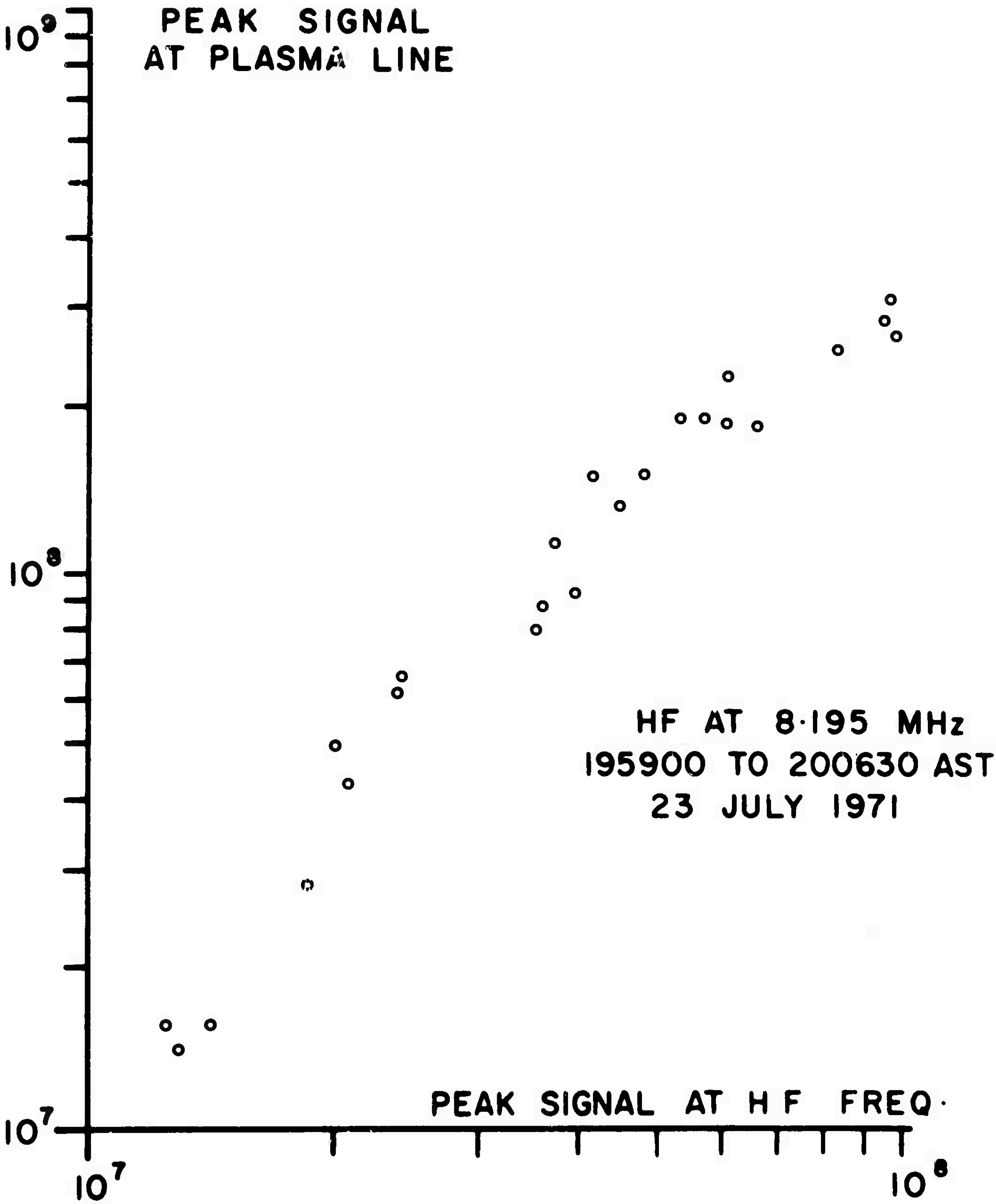

PEAK SIGNAL
AT PLASMA LINE
10⁹
10⁸
10⁷
HF AT 8·195 MHz
195900 TO 200630 AST
23 JULY 1971
PEAK SIGNAL AT H F FREQ.
10⁷
10⁸

FIGURE 13