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INTERPRETATION OF ATMOSPHERIC EMISSION SPECTRA NEAR 1-CM WAVELENGTH

Hoo-min David Toong

Research Laboratory of Electronics, M.I.T.

18 Blackstone Drive
Livingston, N.J.
201-WY2-2384

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The techniques of passive microwave meteorology were used to measure atmospheric water vapor densities and cloud water content at 1 cm wavelength. Theoretical and experimental values of surface water vapor density were found to have a high degree of correlation. Postulated and observed sky brightness temperatures differed by an average $3^{o}K$ throughout the frequency spectrum.

Emission spectra of the earth's atmosphere were observed during the summer of 1966 using a five-channel superheterodyne microwave radiometer fed from a single 20-db antenna feed horn. Measurements were made in the immediate region of the H_2O resonant line (22.235 GHz) at 19.0, 21.9, 22.235, 23.5, and 32.4 GHz. It was desired to obtain experimental observations during meteorological conditions involving clouds, rain, and frontal passage. In particular, the data of August 2-3, 1966, depicting the passage of a cold front over the Boston area, was selected for detailed scrutiny. Duration of this front was from 1330 to 0730 the next morning. Temperatures and relative humidities from Logan Airport, Hanscom Air Force Base, and from the radiometer site were recorded throughout the experiment. As a result a complete spectral and meteorological history of this particular front passage was recorded and charted.

To correlate these experimental observations with theory, modeling parameters were introduced. A standard atmospheric model was postulated with temperature being modeled linearly with height and both pressure and water vapor density decaying exponentially with height. Fifteen kilometers was chosen as an upper limit of consideration since nearly all atmospheric water vapor lies below this height. The atmosphere was stratified into 60 homogeneous layers, each of 250 meters thickness. Each layer was assumed isothermal. Theoretical sky brightness temperatures were then computed using:

$$T_A = \sum_{i=0}^{n} T_i (1-e^{-\alpha_i \Delta x_i}) e^{-\tau_{i-1}} \quad \text{and} \quad \tau_i = \sum_{j=0}^{i} \alpha_j x_j$$

where: T_A = temperature observed at ground level

T_i = average temperature of layer i

α_i = absorption coefficient for i^{th} layer

ΔX_i = path length of i^{th} layer

Using this model atmosphere as well as the equations for sky brightness temperature, theoretical emission spectra were generated. Figure 1 shows the consequences of water vapor alone in the absence of clouds. In this as well as in the other charts, smooth curves have been drawn connecting the five frequency points that were both calculated and observed.

Although clouds possess no special microwave resonance, they do have identifying spectral characteristics. To illustrate the properties of clouds, a value of 10.0 gm/m^3 surface water vapor density was chosen and the parameters of cloud thickness (Δ) and cloud liquid water density (L) for a cloud at a height of 1 km above the earth were allowed to vary. Figure 2 resulted. The dashed line spectrum represents the absence of clouds and is identical to the corresponding plot in Figure 1. Cloud opacities affect spectral plots around 1 cm wavelength by an increase in effective sky brightness temperatures as approximately the square of the frequency. The spectra of Figue 2 represent a few of the many theoretical spectra generated for matching purposes. Their correlation to some of the observed frontal spectra are presented in Figure 3. Experimental values, accurate to within $2^{o}K$, are solid while theoretical values are dashed.

In (1) of Figure 3 the experimental spectra shows a fairly sharp H_2O resonant peak with the presence of some clouds. A model cloud of thickness 1 km and liquid water density of 0.2 gm/m^3 at an altitude of 1 km was chosen. Surface water vapor density was 15.0 gm/m^3. Close agreement throughout the frequency range of interest was reached with maximum deviation reaching $5^{o}K$ at the low end. It is interesting to note that the experimental value of 14.98 gm/m^3 for surface water density is in close agreement with the model. Cloud opacity ranges from .008 to .0234 nepers across the frequency band and the cloud contributes a maximum of 13% to the total observed sky brightness temperature.

The model chosen for (2) was identical to that of (1) except that ρ_o was increased from 15.0 to 17.5 gm/m^3. Correlation is very good with a maximum of 4^oK difference at 19.0 GHz. However, the difference in theory and experiment indicates that the increase in spectral magnitude was actually due to both an increase in L and Δ as well as ρ_o.

Heavy cloud activity was indicated by the substantial level increase and shape alteration of the observed frequency spectrum in (3) . Theoretically, Δ was allowed to jump to 3 km and L increased to 0.6 gm/m^3. Also, ρ_o was increased to 20 gm/m^3 in fairly close agreement with the observed value of 19.0 gm/m^3. Again a close match was obtained with deviations up to 3^oK. Cloud contribution ranges from 55^oK or 39% of observed signal at 32.4 GHz to 20^oK or 25% of observed signal at 19.0 GHz.

During the recording of spectrum (4) , appreciable amounts of rain fell. Since the modeling parameters used did not take into account rain or scattering effects, no accurate correlation could have been generated. Instead of attempting to closely match the entire spectra, cloud parameters were increased until sky brightness temperatures at 32.4 GHz were nearly identical. This was done in order to determine how thick and how dense a cloud alone without rain would have to be to produce such a large opacity (~1.6 nepers) and such a high sky brightness temperature (280^oK). A cloud 5 km thick at a height of 3 km and density 2.8 gm/m^3 was found to give these results. Its opacity contributed from 50% to 85% of observed spectral temperatures. Of course such a super-cloud would not be expected to actually exist meteorologically, but it does show that scattering effects and rain are a large component of these saturated spectra. For the cloud used, an equivalent attenuation by just rain without clouds would correspond to 1.4 db/km or an equivalent rainfall rate of 5 mm/hr at 1 cm wavelength. This is a very substantial rain. Therefore, the experimental spectra indicates that a correct model for (4) must utilize some combination of heavy clouds and rain as well as scattering considerations.

In similar fashion, experimental spectra throughout the remainder of the front passage were correlated with theoretical spectra. By graphically displaying these correlations, there results a very good picture of the front as a function of time. Please consult Figure 4. Experimental parameters have also been supplied to provide more explicit comparison. It must be noted that the time scale in Figure 4 is not strictly linear. However, in the absence of wind speed and wind direction data, the scaling remains more a matter of choice. Of course, the discontinuities in atmospheric and cloud parameters that are pictured are only an approximation to the actual continuum situation. Nevertheless, a fairly lucid representation of what was quite possibly happening has been achieved. The high degree of correlation obtained between experimental surface water density data and theoretical spectra supports the accuracy of this model and the interpretation procedure. The theoretical model of Figure 4 resulting from the correlations of Figure 3 was found to agree in several major respects with the standard cold front passage found in the literature.

F I G U R E S

Figure 1: Theoretical Spectra Without Clouds showing effects of increasing surface water vapor density upon line shape. Resonant peak enhanced by higher densities.

Figure 2: The Effect Of Clouds. Increasing cloud opacity enhances higher frequencies over the resonant peak. Saturation levels are approached as L goes to 1.8 gm/m^3.

Figure 3: Experimental-Theoretical Correlations. Back lobes and effective beam width of antenna not considered. Large shields were erected to deflect ground radiation away from receiving antenna.

Figure 4: Front Model. History of frontal passage postulated from correlations of Figure 3 and also other spectra.

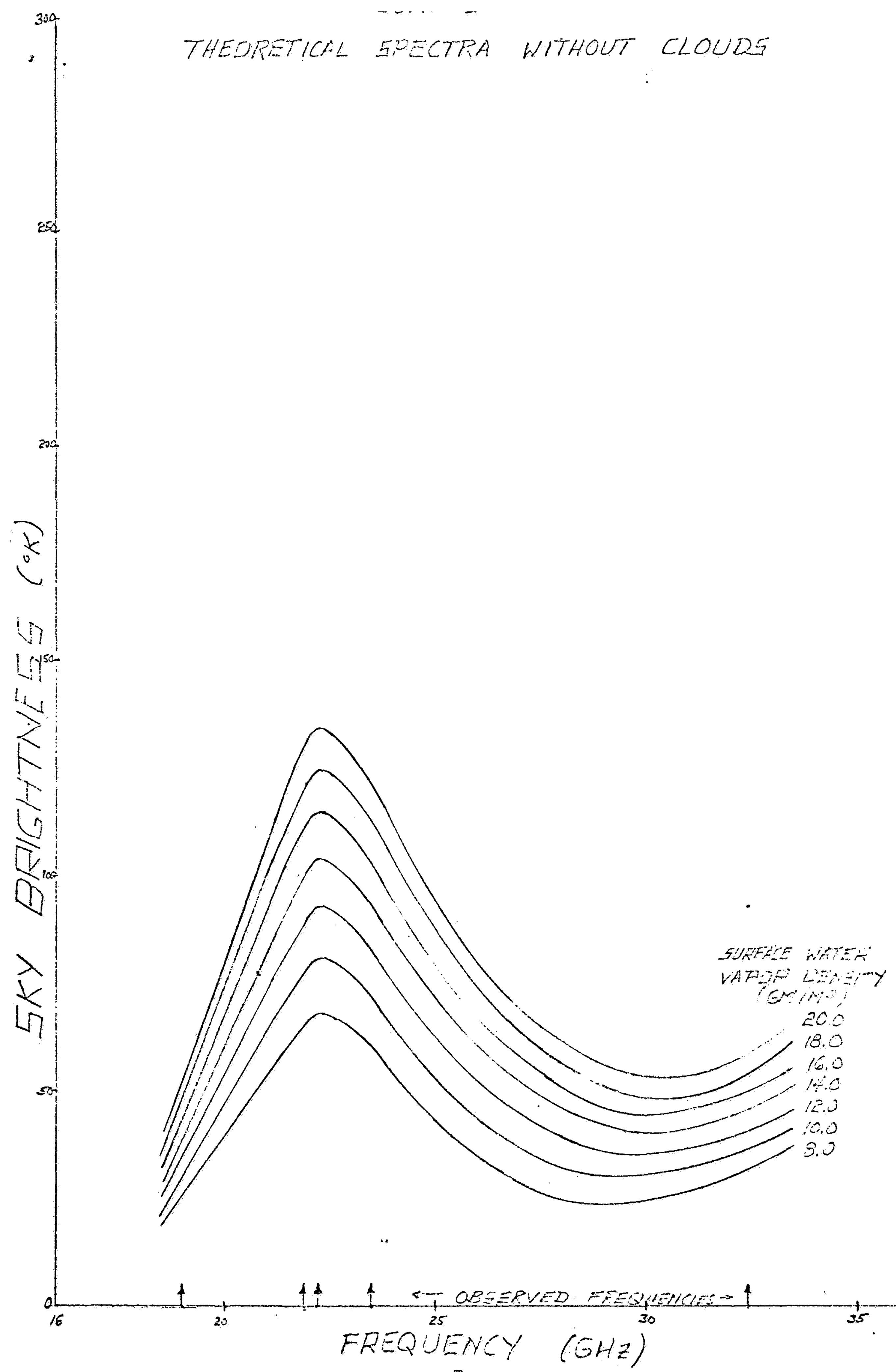
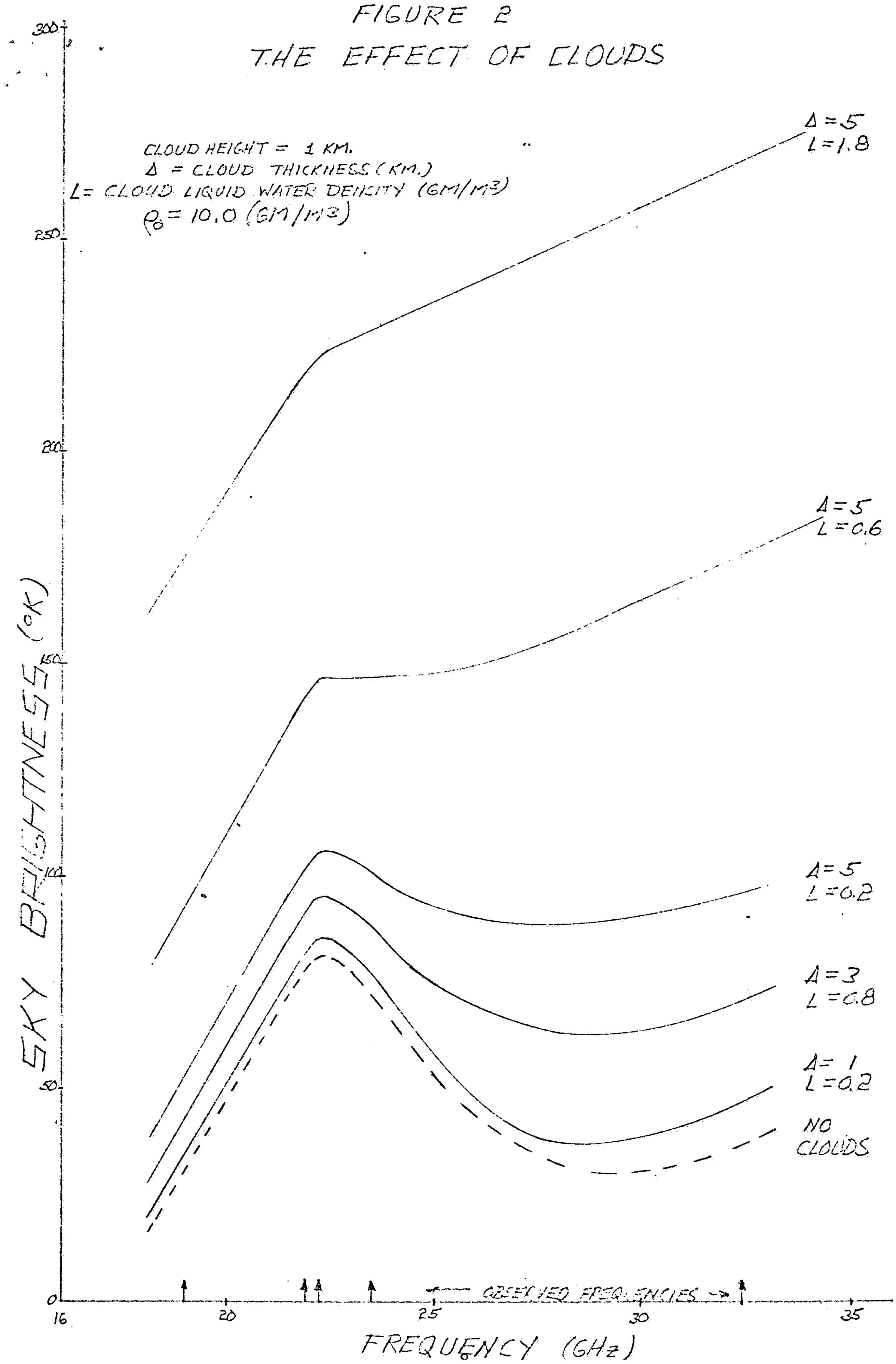
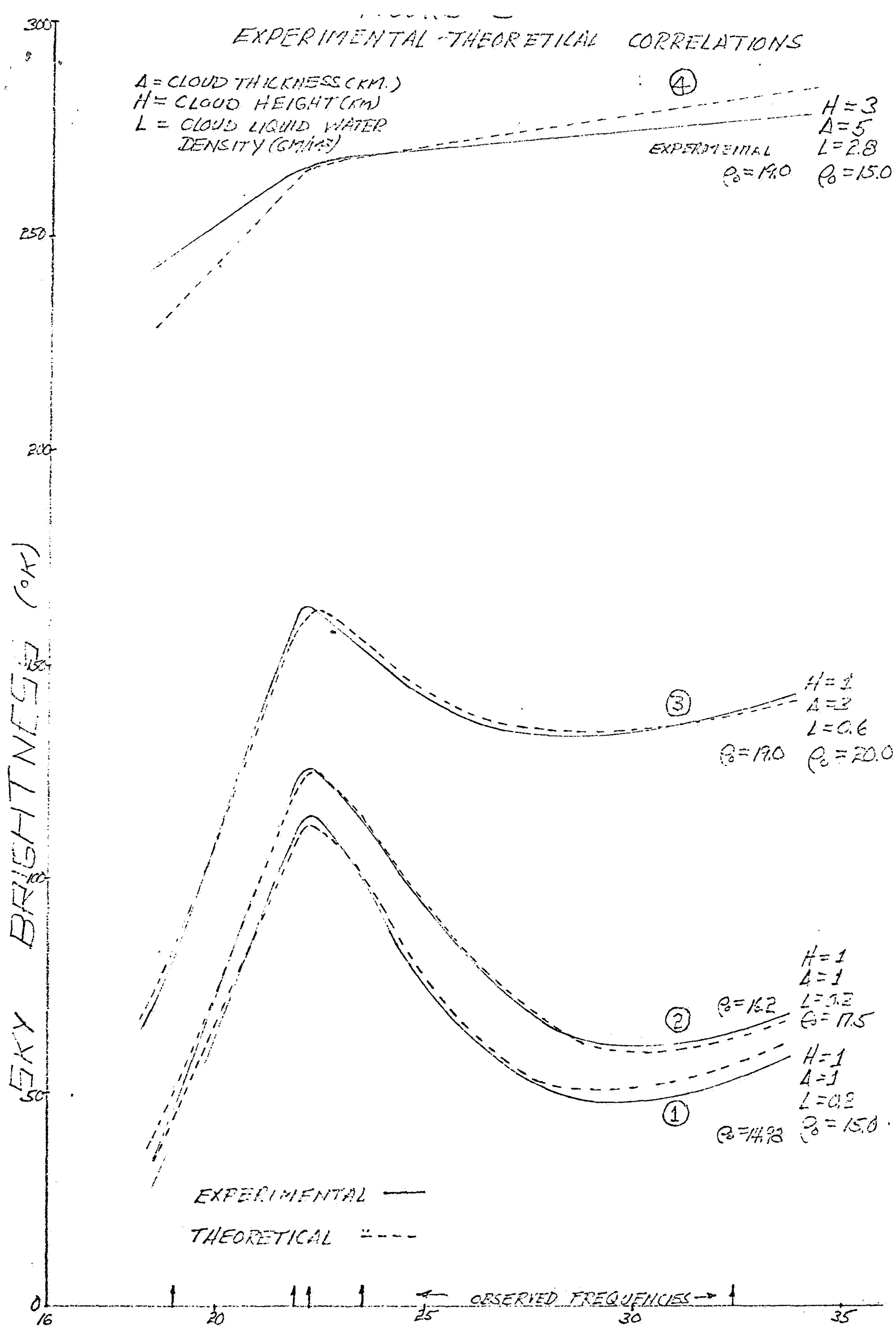

THEORETICAL SPECTRA WITHOUT CLOUDS
SKY BRIGHTNESS (°K)
300
250
200
150
100
50
0
SURFACE WATER
VAPOR DENSITY
(GM/M³)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
← OBSERVED FREQUENCIES →
16
20
25
30
35
FREQUENCY (GHz)

FIGURE 2

THE EFFECT OF CLOUDS





EXPERIMENTAL - THEORETICAL CORRELATIONS
Δ = CLOUD THICKNESS (KM.)
H = CLOUD HEIGHT (KM)
L = CLOUD LIQUID WATER DENSITY (GM/M³)
④
H = 3
Δ = 5
L = 2.8
EXPERIMENTAL
ρ₀ = 19.0
ρ₀ = 15.0
③
H = 1
Δ = 3
L = 0.6
ρ₀ = 19.0
ρ₀ = 20.0
②
ρ₀ = 16.2
H = 1
Δ = 1
L = 1.2
ρ₀ = 17.5
①
H = 1
Δ = 1
L = 0.2
ρ₀ = 14.78
ρ₀ = 15.0
EXPERIMENTAL
THEORETICAL
SKY BRIGHTNESS (°K)
OBSERVED FREQUENCIES
FREQUENCY (GHz)
0
50
100
150
200
250
300
16
20
25
30
35

FIGURE 4

FRONT MODEL