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Millimeter-Wave Properties of the Atmosphere: Laboratory Studies and Propagation Modeling

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MILLIMETER-WAVE PROPERTIES OF THE ATMOSPHERE LABORATORY STUDIES AND PROPAGATION MODELING

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Laboratory measurements have been performed at 138 GHz of water vapor attenuation α_x for pure vapor (H_2O) and its mixtures with air, nitrogen (N_2), oxygen (O_2), and Argon (Ar). Temperatures ranged from 8 to 43 °C, relative humidities from 0 to 95% and total pressures reached 1.5 atm. A computer-controlled resonance spectrometer was employed. The results are interpreted in terms of underlying absorption mechanisms. Broadening efficiencies m of mixtures H_2O + N_2, O_2, Ar agree among themselves with those measured within cores of the 22 and 183 GHz H_2O absorption lines. The m-factors are applied to predict what share α_ℓ of the total α_x results from the complete pressure-broadened H_2O spectrum. A substantial amount of the self-broadening term proportional to the square of vapor pressure is left unaccounted. The negative temperature coefficient of the excess absorption is consistent with a dimer $(H_2O)_2$ model. An empirical formulation of the experimental findings is incorporated into the parametric propagation model MPM that utilizes a local (30x H_2O, 48x O_2) line base to address frequencies up to 1000 GHz. Details of MPM are given in two Appendixes. Predictions of moist air attenuation and delay by means of the revised MPM program generally compare favorably with reported (10 - 430 GHz) data from both field and laboratory experiments.

Key Words: atmospheric attenuation and delay; laboratory studies of moist air attenuation; millimeter/submillimeter-wave spectral range; propagation program MPM; radio path data

1. INTRODUCTION

Extending the radio spectrum into the near-millimeter region (NMMW: 0.1-1 THz) is an active area for research. Possible applications lie in short-range communications, radar, radiometry, and radio astronomy. Atmospheric effects of transmission and emission are described by the complex refractivity $\underline{N}$ that provides a measure of the interactions between radiation and the atmospheric propagation medium. A reliable N-model allows calculation of frequency-dependent rates for delay (real part) and attenuation (imaginary part) based on measurable meteorological variables. Dry air and atmospheric water vapor are major millimeter-wave absorbers; so are suspended droplets (haze, fog, cloud) and precipitating water drops that emanate from the vapor

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phase. Laboratory research and analytical studies have been conducted with the primary purpose of understanding power attenuation α (dB/km) and group delay β (ps/km). Emphasis was placed on the fundamental concepts that support an $\underline{N}$ formulation.

Refractivity N for moist air can be obtained, in principle, by a line-by-line summation over all molecular absorption lines. In practice, various approximations are employed to reduce labor and computer time, since the number of contributing spectral lines by the dominant absorbers (water vapor and oxygen) and by various trace gases (e.g., O_3) exceeds 10,000. A practical propagation model, indexed MPM (and described in Appendix A and B), consists of local H_2O (30x) and O_2 (48x) lines below 1 THz and an approximation to the contributions by H_2O lines above 1 THz [1] - [3].

The experiments have been performed at 138 GHz to measure absolute attenuation rates by dry air, moist air, water vapor, and water-vapor mixtures with nitrogen (N_2), oxygen (O_2), and argon (Ar) at temperatures between 8 and 43°C, total pressures up to 1.5 atm, and relative humidities between 0 and 95 percent. The experimentally observed absorption is not described by standard line shape models. Such failure reveals difficulties in modeling frequency, temperature, and pressure dependences for moist air attenuation. An unexplained excess is identified for which the name "water-vapor continuum" was coined since it appears to increase smoothly with frequency within the NMMW range.

Experimental studies are compared with model calculations. The MPM program is a user-friendly, PC-operated code that generates numerical values of $\alpha(f)$ and $\beta(f)$ for frequencies f up to 1000 GHz. Input parameters are five measurable atmospheric quantities: barometric pressure P, ambient temperature T, relative humidity RH (absolute humidity v), suspended droplet water content w, and rainfall rate R. Controlled laboratory measurements were limited to moist air studies (P, T, RH), and the data obtained at 138 GHz are reasonably complete and accurate to assess water vapor pressure and temperature dependences for the water-vapor continuum. Both variabilities point to the distinct possibility of an absorption mechanism related to water vapor that is not accounted for by molecular theory of H_2O.

This report is organized in three parts. The first part (Section 2) gives details of the experimental setup, its achieved performance, and a summary of reduced data. After many improvements, a detection sensitivity of

$\alpha_{min} \approx 0.05$ dB/km or $1.2 \times 10^{-7} cm^{-1}$ was realized. In the second part (Section 3), results from the laboratory experiments are applied (a) to calibrate the MPM program with an empirical continuum term, (b) to demonstrate the parametric flexibility of the code (i.e., f, v(RH), and P can be selected as variables), and (c) to conjecture on the physical basis for a water vapor continuum that is defined by the limited H_2O line base of MPM. Finally Section 4 contains examples of recently reported data from laboratory and field experiments on water vapor absorption (10-430 GHz) and their comparison with MPM predictions.

2. LABORATORY STUDIES OF MOIST AIR ABSORPTION AT 138 GHZ

Controlled experiments that simulate atmospheric conditions provide test cases for studying specific contributions to $\underline{N}$. Assessments of basic physical principles underlying the attenuation rate α are difficult to make from measurements in the actual atmosphere. The objective of this study was to measure water vapor (continuum) absorption. A test frequency of 138 GHz was selected because of its remoteness from local H_2O lines. The expected window attenuation falls in the range 0.1 to 5 dB/km and the required detection sensitivity calls for a long (>0.1 km) effective path length, which can be attained with a resonant absorption cell.

The response curve A(f) of an isolated, high Q-value resonance is detected with a power (square-law) detector. Both, the peak value a_0 at center frequency f_R and the bandwidth b_0 spread over a range $f_R \pm b_0/2$ at the level $a_0/2$ might be used to detect the relative attenuation,

$$\alpha_r = 8.686(\sqrt{a_0/a} - 1) = 8.686(b/b_0 - 1) \quad \text{dB}, \qquad (1)$$

of an absorbing gas that changes the corresponding quantities to a and b when introduced into the resonator. Around 138 GHz it is possible to design a compact (20 cm mirror spacing) Fabry-Perot resonator with a loaded Q-value on the order of 4×10^5, which defines ($Q = f_R/b_0$) a resonance bandwidth, $b_0 = 350$ kHz.

A crucial question to be resolved is whether amplitude (a_0/a) or frequency (b/b_0) detection schemes provide the optimum sensitivity for the spectrometer. After extensive testing it was found that digital averaging of A(f), displayed over a frequency span $\Delta f_M = f_R \pm 6b_0$, was capable of resolving

$a_0/a = 1.002$ (512 pts)--but only $b/b_0 = 1.015$ even with 1024 pts. Amplitude peak-value detection provided optimum sensitivity for absorption studies. The frequency span Δf_M is needed to establish the baseline $A(f) = 0$ of the resonance response. In addition, a detection at f_R avoids corrections for dispersive distortions of $A(f)$ [4].

Absolute calibration of absorption is accomplished by defining an equivalent path length (b_0 in kHz),

$$L_E = 47.71/b_0 \quad \text{km}, \tag{2}$$

for the resonance spectrometer operating at f_R. From (1) and (2) follows that the absolute power attenuation rate of an absorbing gas is given by

$$\alpha = 0.1820\ b_0(\sqrt{a_0/a} - 1) \quad \text{dB/km}. \tag{3}$$

If the estimations ($a_0/a = 1.002$, $b_0 = 350$ kHz) can be achieved, then the projected detection sensitivity, $\alpha_{min} = 0.064$ dB/km, is adequate for the planned water vapor studies.

2.1 Experimental Arrangement

The measuring system consists of the millimeter-wave resonance spectrometer and a humidity simulator. An insulated box contains a high-vacuum stainless steel vessel that houses a temperature-controlled mini-lake (10 cm across) and the resonator. Temperatures are controlled to better than 1/100 of a degree Celsius, pressure ranges over seven orders of magnitude (10^3 to 10^{-4} torr), and relative humidity is varied between 0 and 99.5 percent.

Schematical diagrams of physical and electronic (Figure 1) arrangements and a photograph of the equipment (Figure 2) convey an overview of the experiment. A temperature-controlled water reservoir serves as the vapor source. Electropolished stainless steel was used exclusively as construction material. Various hydrophobic coatings were studied as possible means for neutralizing the absorption/desorption cycle of surfaces exposed to water vapor [5], but were abandoned in favor of slightly heating the mirrors of the resonator. Four fast-responding ($\tau < 1$s) temperature sensors inside the cell signaled any disturbance of isothermal conditions. Data acquisition was computer controlled.

The resonator inside a vacuum chamber (Figure 1b) is the heart of the absorption spectrometer. A key-word summary of its specifications reads as follows: Fabry-Pérot reflection-type, semiconfocal arrangement, 10 cm mirror diameter, 40 cm curvature radius, mirror heating: 1°C/0.3 W, Fresnel number: 6; pinhole coupling: circular, 0.65 mm diameter, 0.075 mm double Mylar vacuum/pressure seal, coupling factor k = 0.0550; resonance frequency, selected for optimum performance of the available klystron, f_R = 137.80 GHz, temperature compensated ($\Delta f/f_R = 0.9 \times 10^{-6}/°C$) and insensitive to pressure loads from 0 to 2 atm; resonance bandwidth: b_0 = 334 kHz yielding an effective path length, L_E = 0.141 km (Eq. 2), mirror spacing: $x_R = 182\ \lambda/2 = 198.0$ mm; micrometer tuning: 0.3175 mm/rev ≡ 2500 SU/rev (SU = scale unit on micrometer) with a resolution, Δx_R = 0.127 μm/SU, which converts into a frequency change,

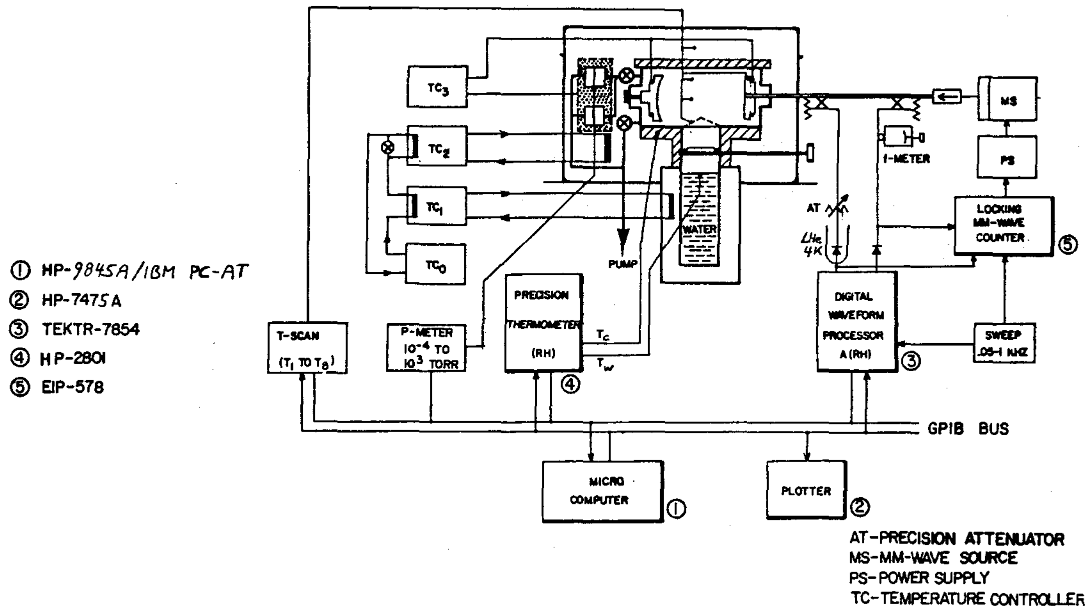
$$\Delta f_R = -f_R(\Delta x/x)_R = -88.4 \text{ kHz/SU}. \tag{4}$$

Over a 2.5 cm tuning range of the micrometer, the resonance at x_R was the "best" out of 52 choices with respect to other-mode interferences and Q-values.

The detector of the resonance pulse A(t) was an InSb bolometer, cooled to 4.2 K-LHe, and connected by a WR-12 waveguide mount. The maximum voltage output of the preamplifier was 10 V. A power-linear response of 4.2 V/mW was measured up to 1.0 V. With a 50-kHz detection bandwidth, the noise power was about 5 nW. The bolometer bias (92 mV) served as cryogenic thermometer (T_D).

The power source was a 138 GHz klystron (20 mW) that was frequency-modulated by a sawtooth voltage generator to provide frequency-to-time domain conversion. The modulation frequency was exactly 500 Hz derived from a 10 MHz frequency standard. The linear sawtooth ramp was gated at exactly 1925 μs, the fly-back time took only 2 μs, which eliminated A(t) from the retrace. The modulation sensitivity of the klystron was determined to be 12.56(13) MHz/V by using the resonance peak a_0 as frequency marker, tuned with the resonator micrometer to the end points of the ramp and checked for linearity over a modulation voltage range from 0.500 to 3.000 V. A tuning uncertainty of 1 SU introduced about 1 percent error in determining the frequency-to-voltage conversion factor.

(a)



(b)

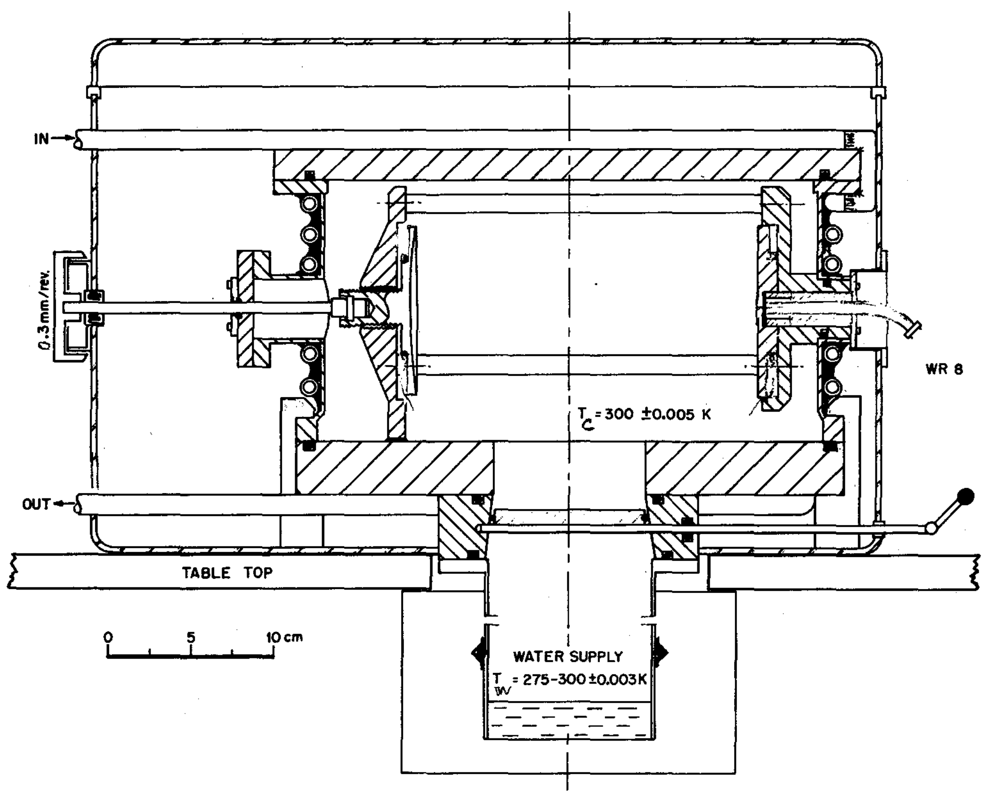


Figure 1. Millimeter-wave spectrometer for controlled moist air studies: (a) schematic and (b) cell design.

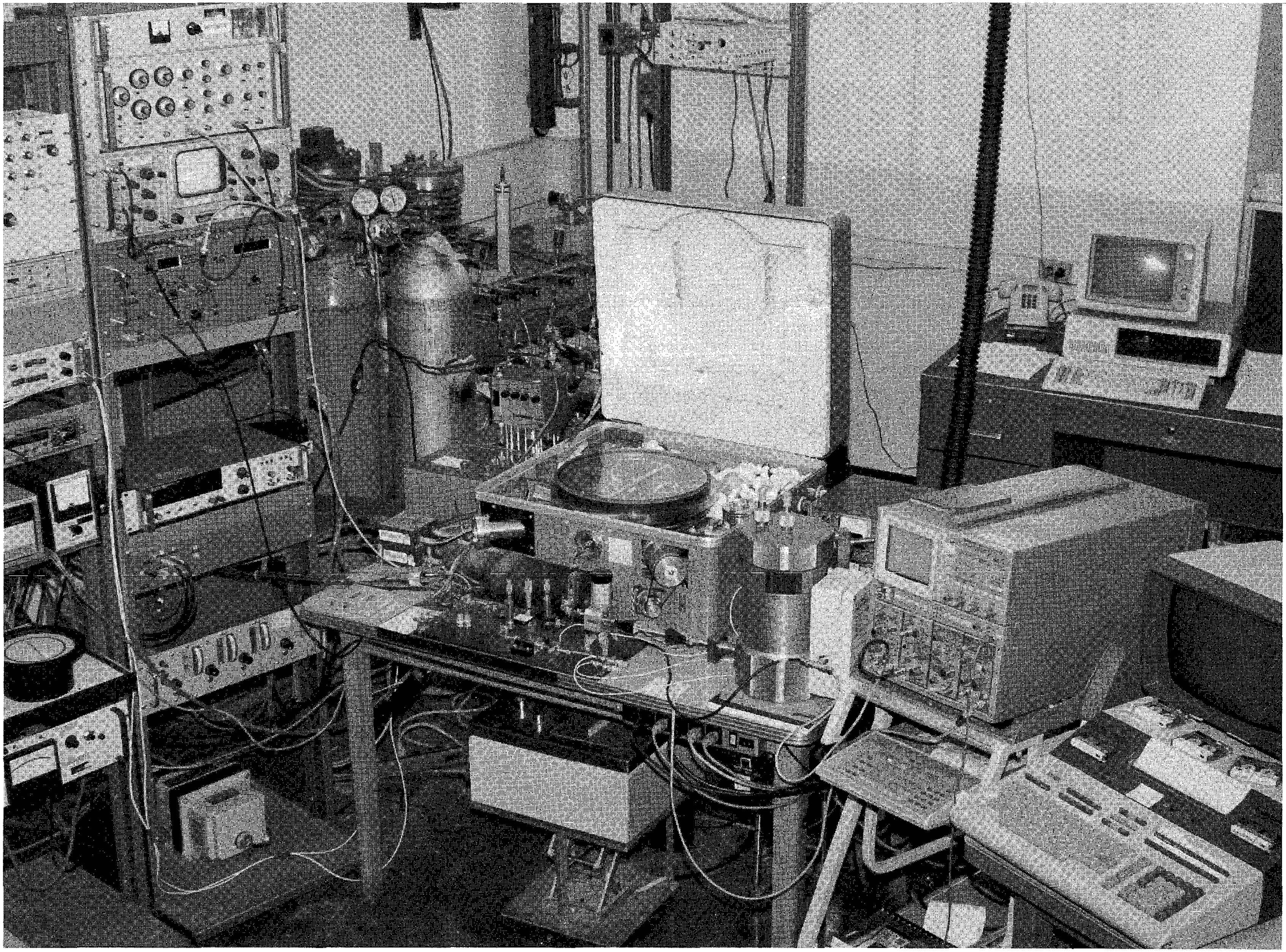


Figure 2. Photograph of millimeter-wave spectrometer.

The reference power $a_0 = k \cdot a_K$ for (1) was measured by periodically (30s) switching on computer command to a 36 V modulation voltage, which displayed the power mode $A_K(t)$ with a peak value, a_K = 909 mV and a bandwidth, b_K = 186 MHz. This feature provided an automatic calibration of α_r (1) when the power level changed during a data run (e.g., refractive-tuning reduces f_R and the peak value a_K can change when the klystron is readjusted).

An electronic lock-on circuit centered the resonance f_R within one time frame; that is, the klystron center frequency $f_K(a_K)$ was prevented from drifting with reference to f_R. A flat baseline $A(t) = 0$ was established by adjusting f_K in such a way that two adjacent A(t) frames were displayed on a control scope and kept level. The reflected resonance signal A(t) could be eliminated by injecting a steel rod into the resonance volume. This measure provided baseline reference data in the "low" (0.36 V) and more accurate peak readings a_K in the "high" (36 V) mode of the modulator.

The waveform processor for A(t) was a digital storage oscilloscope, synchronized with the sawtooth modulator and capable of resolving 512/1024 pts per 2000 µs. Operational resolution was typically 3.91 µs/pt. The modulator voltage for A(t)-detection was 0.360 V resulting in a frequency resolution of 9.2 kHz/pt, which is an improvement over (4). Extensive averaging of the repetitive waveforms A(t) 100 times, and $A_K(t)$ 50-times, was performed in real time to improve the signal-to-noise ratio of the a and b results.

For a measurement of the resonance bandwidth b_0, the digitizing increments were doubled (1024 pts) and the modulation voltage was varied in the 0.150 to 0.400 V range, allowing the resolution uncertainty to be reduced to ±5 kHz. The resultant error in an absolute calibration of α (3) was less than 3 percent.

The computer of the spectrometer had a control-program that was designed to be flexible in order to allow changes in data collection procedures. It is written in BASIC with about 500 lines of code to control the readings of eight temperatures, two pressures, and a/b values from the waveform processor and to store the data on a magnetic medium for future processing. The program is time controlled. The fastest acquisition time for a complete measurement cycle was 30 seconds.

Measurements begin by starting the internal program of the waveform-processor, which does 100 averages on the output A(t) from the InSb detector. Since averaging takes about 14 seconds, the computer program continues data recovery from the temperature sensors which measure chamber (T_c), water bath (T_w), room (T_r), gas ($T_{1,2,3}$), mirror (T_m) temperatures, and data from the total pressure meter (P). By this time the oscilloscope is nearly ready with its data so the computer program returns to wait for the final steps in the scope program. After the scope completes 100 averages on A(t) it normalizes (by setting cursors at 0.1 and 0.9 of the time base) the trace to remove any baseline slope, then stores the waveform. Next, an auxiliary output from the scope switches the sweep generator voltage from low (0.36 V) to high (36 V). The scope input changes to the power envelope of the klystron with the lock-on disabled. The scope program performs 50 averages on the power curve and stores the waveform A_K. The next computer step is to call for the a/b and a_k/b_k values of the stored waveforms.

All of the measured data were temporarily stored in computer memory and transferred along with time-of-day to magnetic tape or disk storage for safe keeping and later recovery and processing.

Real-time data were plotted on the CRT of the computer to follow the progress of an experiment. The selection of what was displayed is part of the program configuration. Two typical examples of 1-hour operating periods are shown in Figure 3. Figure 3a demonstrates the automatic calibration to α_r = 0 dB for input power variations of 1 dB. The reference power trace a_K was reduced by a factor 0.05 for display, but the correct coupling factor k = 0.0550 was applied for the relative attenuation trace (1) $\alpha_r = 8.686\ (\sqrt{k \cdot a_K/a} - 1) = 0$ dB. Each 1-hour frame represents averages of about 10^7 actually acquired data points. Detection sensitivity and long-term stability are displayed in Figure 3b.

Program configuration is stored in a separate file on disk. An auto-start function is available for studies that are conducted unattended. In the event of a power failure the program will automatically restart.

Post processing of data repeats calibrated signal corrections as done in the real-time mode. Scatter plots of α_r are made versus pressure in a point-mode (e.g., Figure 6).

2.2 Moist Air Attenuation Measurements

The objective of the experiments was to perform pressure scans of the attenuation rate α due to water vapor absorption in moist air. An extensive series of controlled measurements was performed at 137.8 GHz to determine

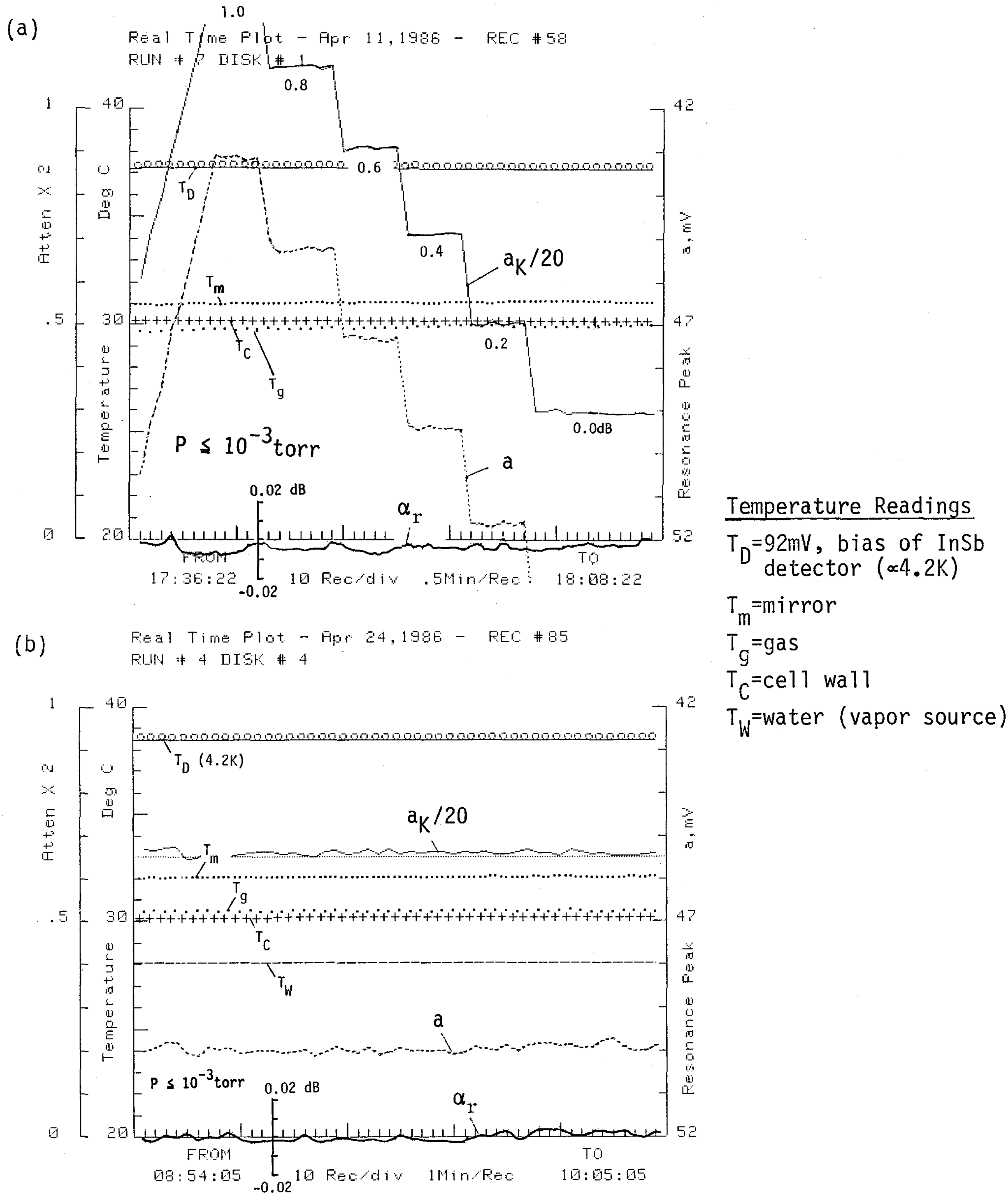


Figure 3. Mm-wave spectrometer operational data (five temperatures T;) peak values of reference and reflected signals a_K, and a; and relative attenuation (α_r) for a 1-hour measurement period with an evacuated cell (f_R = 137.8 GHz):
(a) automatic calibration to α_r = 0 dB for changes, Δa_K = 0-1 dB;
(b) detection stability and sensitivity
($\alpha_{min} \approx 0.006/0.13 \leq 0.05$ dB/km).

$\alpha(P = e+p)$. Data $\alpha(T, e, p)$ were taken covering the following range of parameters:

temperature	$T = 316$ to 282 K;
vapor pressure	$e = 0$ to e_1 (RH < 95%); and
total pressure	$P = e_1 + p$, where $p = 0$ to 1200 torr (capacitance manometer), $p = 0$ to 3 atm (aneriod manometer)*.

Maximum vapor pressure e_1 was determined by the temperature T_W of the water reservoir.

With the spectrometer performance optimized at $P = 0$ (see Figure 3b), an additional set of problems appeared when the gas pressure was varied. Introducing and removing gas from an enclosure changes the temperature T_g of a sample (Figure 4). Only pressure scan rates below ± 100 torr/min ensured quasi-static gas conditions, $T_g = T_C$. Typically, the pressure was varied in steps. While the gas settled, the klystron frequency f_K was retuned to balance the baseline of $A(t)$.

Working with water vapor often brought disappointing results with respect to reproductibility. Condensation effects on both mirrors and pinhole coupling were avoided (see p. 5). One source was the "piston" effect where local compression condenses part of the vapor; another error source was the slow diffusion-mixing of water vapor with stagnant air. We calculated the diffusion time constant for vapor molecules to travel 30 cm inside the cell against 1 atm of dry air to be

T	(K)	315	300	285
τ_D	(min)	5.4	6.0	6.7 .

It takes a period longer than $5 \cdot \tau_D$ for a homogeneous moist air mixture $P = e_1 + p$ to develop. A measurement of $a(P)$ shown in Figure 5a indicates even longer time periods. Water pressure $e_1(T_W)$ settled with no delay when the H_2O-valve was opened. Dry air injection first reduced e_1 (piston effect) and then it took up to 1 hour to obtain a stable value $a(e_1+p)$. Mixing was accelerated to less than 5 minutes by installing a fan, driven by a magnetically coupled rotary vacuum feed-through.

*Experimental pressure scale is measured in torr; the prediction model MPM uses the pressure unit 1 kPa = 10 mb = 7.5006 torr.

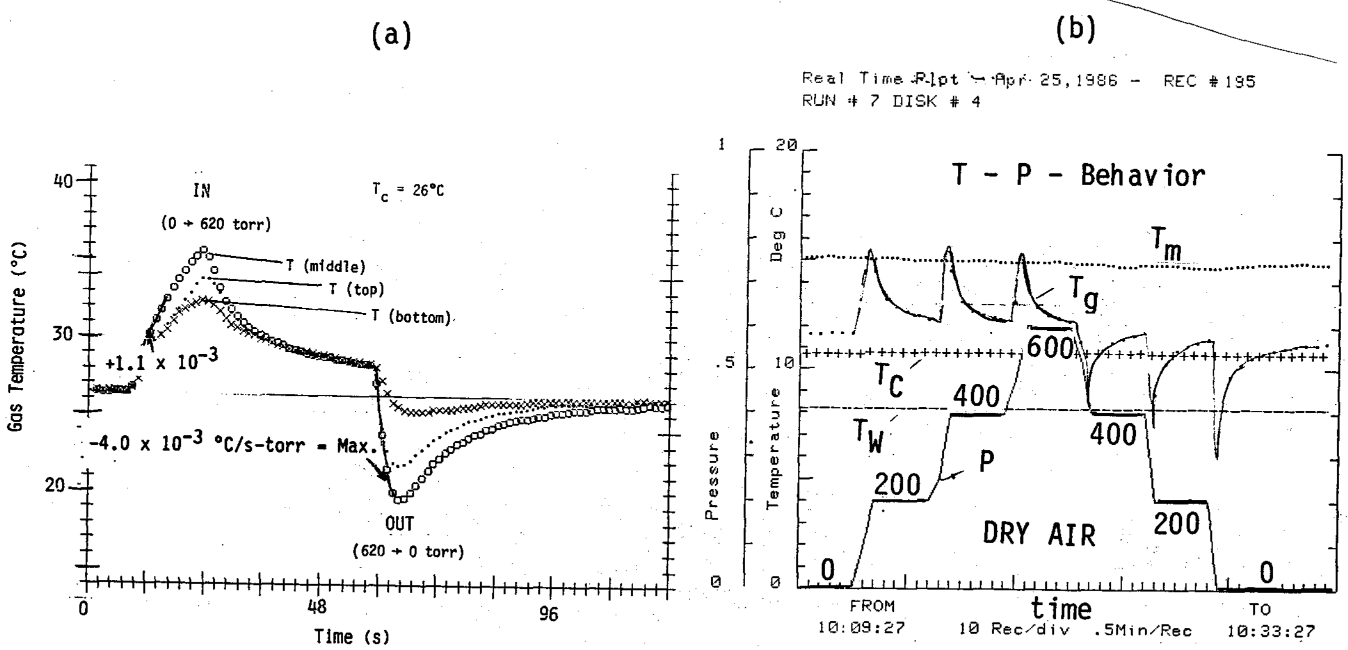


Figure 4. Temperature responses inside the spectrometer cell:
(a) time-response test of gas temperature (T_g) sensors,
(b) temperature-vs.-pressure behavior for a typical dry air case.

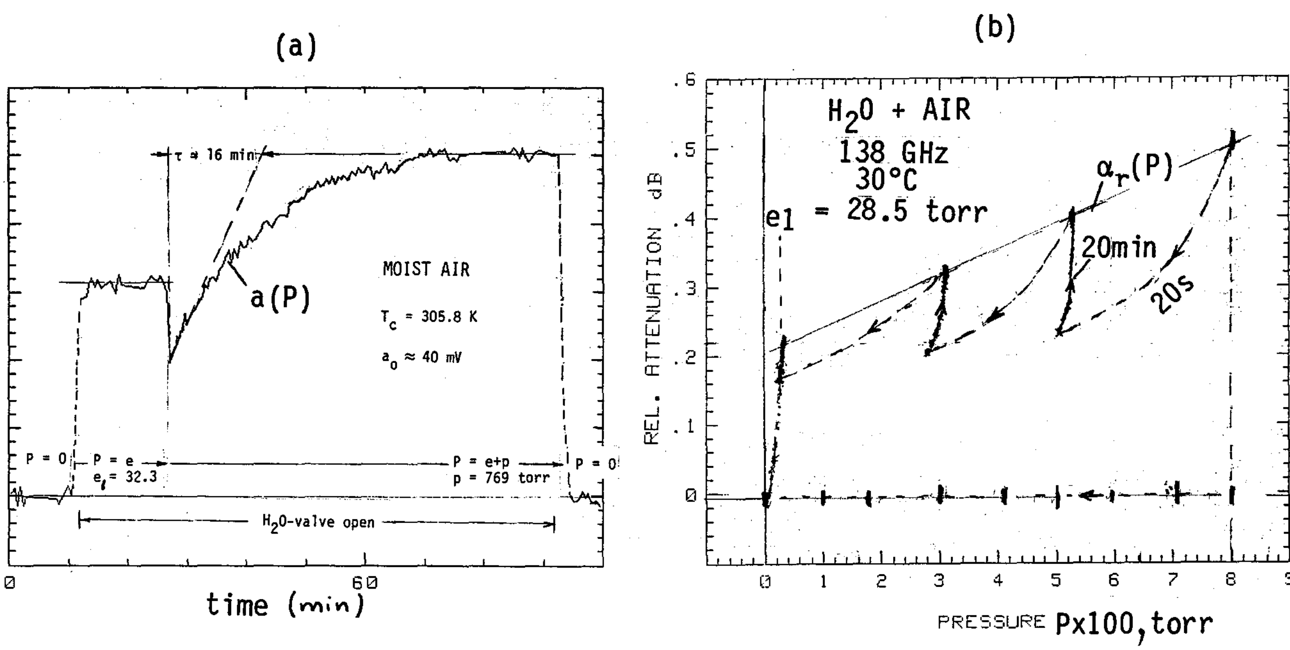


Figure 5. Mixing effects of H_2O + AIR from time series of 138 GHz attenuation:
(a) piston effect and diffusion mixing;
(b) decompression condensation during pump-down over open vapor source.

One other effect was observed when dealing with moist air inside a vessel: reducing the total pressure P caused the water vapor to condense by decompression cooling. Even with the water vapor supply fully exposed to the air mixture, it took a long time (20 min) to reestablish the initial vapor pressure e_1 as indicated by $\alpha_r(P)$ in Figure 5b (mixing fan was off).

2.3 Water Vapor and Moist Air Attenuation Results

Moist air attenuation α at a frequency f that falls within the millimeter-wave window range centered at 140 GHz, can be expressed by [6], [7]

$$\alpha = k_s(T)\ e^2 + k_f(T)\ ep + k_d(T)\ p^2 \quad \text{dB/km}, \tag{5}$$

where e and p in kPa are partial pressures of water vapor and dry air, respectively. Pressure-broadening theory of the H_2O rotational spectrum predicts ($e > 0.01$ kPa) a fixed ratio m between air-(ep) and self-(e^2) broadening; i.e.,

$$m = k_f/k_s. \tag{6}$$

An extensive series of controlled laboratory measurements was performed at 137.8 GHz to determine the k-coefficients of (5) and (6). Table 1 is a summary of over 2500 individual data points $\alpha(T, e, p)$.

At T = 303 K, the foreign-gas broadener AIR (p) was replaced by its principal constituents N_2, O_2, and Ar. These results are listed in Table 2. The broadening efficiency m is useful to explain H_2O absorption processes that support (5) since $\alpha = k_s e\ (e+mp)$. Pure oxygen (O_2) measurements for pressures up to 2.4 atm against Ar as the "loss-free" reference provided an estimate of k_d when multiplying the result by 0.21.

Data of Table 1 were further reduced to a reference temperature T_o = 300 K. Temperature dependence of the $k_{s,f,d}$ coefficients was fitted to a power law,

$$k(T) = k\theta^x \quad \text{dB/km-kPa}^2, \tag{7}$$

where $\theta = 300/T$ is an inverse T-parameter.

The results for moist air attenuation at 137.8 GHz, when expressed by (5) to (7), led to

Table 1. Comparison between Measured (X) and Model-Predicted (M-MPM, see Section 3) Coefficients $k_{s,f}$ of (5). Experimental conditions: f = 137.8 GHz, T = 282-316°K, P = e_1 + p, p = 0-110 kPa

	T	e_1(RH)	Moist Air k_s	k_f	m	Dry Air k_d
	K	kPa	dB/km-kPa^2 x10^{-2}		x10^{-2}	dB/km-kPa^2 x10^{-6}
X	315.5	7.49 (90%RH)	8.01	0.485	6.06	-
M			7.85	0.481	6.13	1.93
X	305.9	4.45 (90%RH)	10.9	0.540	4.95	-
M			10.81	0.530	4.90	2.10
X	303.2	3.80 (90%RH)	12.0	0.558	4.65	2.2
M			11.84	0.545	4.60	2.11
X	296.1	2.51 (90%RH)	15.0	0.59	3.9	-
M			15.08	0.589	3.91	2.29
X	286.7	1.39 (90%RH)	21.0	0.65	3.1	-
M			21.22	0.649	3.06	2.46
X	281.8	1.05 (94%RH)	25.7	0.68	2.65	-
M			25.49	0.687	2.70	2.64

Table 2. Attenuation Measurements of Water-Vapor/Air-Constituent Mixtures (f=137.8 GHz, T=303 K, E_1=3.80 kPa) Expressed with k_x-Coefficients of (5), and Corresponding Broadening Efficiencies m_x (6). Included are Line-core Measurements m_L and their Predictions m_1 and k_1 Transposed to 138 GHz

	FAR WING (303K)				LINE CORE (300K)		
	k_x	k_1	m_x	m_1	m_L		
f(GHz)	137.8		137.8		22.2	183.3	
					[16]	[16]	[11]
Species	dB/km-kPa^2 x10^{-2}		x10^{-2}			x10^{-2}	
H_2O	12.0	2.55	100	100	100	100	100
AIR	0.558		4.65	21.9*	20.8	22.7	22.1($\theta^{-0.6}$)
N_2	0.627		5.23	24.6	22.8	24.9	
O_2	0.322		2.68	12.6	14.0	14.3	
Ar	0.222		1.85	8.7	11.4	10.3	
	Linewidth (MHz/kPa)				135.0	143.0	151.9($\theta^{1.1}$)

*Reference value (line-core average)

$$k_s(T) = 0.133(4)\theta^{10.3(3)},$$
$$k_f(T) = 5.68(5)10^{-3}\theta^{3.0(4)}, \qquad (8)$$
$$k_d(T) \approx 2.2(5)10^{-6}\theta^{2.8},$$

and

$$m = 0.0427/\theta^{7.3}.$$

Digits in parentheses give the standard deviation from the mean in terms of the final listed digits. Typical examples of data plots $\alpha_r(e)$ and $\alpha_r(e_1 + p)$ are exhibited in Figure 6. All experimental results supported the formulation in (5). Model predictions of the experimental data are given in Figure 14 (Section 3.4).

3. ATMOSPHERIC PROPAGATION MODEL MPM
(see Appendix A and B for Details)

Dry air and atmospheric water vapor are major millimeter-wave absorbers; so are suspended droplets (haze, fog, cloud) and precipitating water drops that emanate from the vapor phase. A practical model (designated program code: MPM) was formulated that simulates the refractive index $\underline{n} = n' - jn''$ of the atmospheric propagation medium for frequencies up to 1000 GHz [1] - [3]. Since the interaction with a neutral atmosphere is relatively weak, the refractive index is converted into a refractivity in units of parts per million,

$$\underline{N} = (\underline{n} - 1)\ 10^6 \quad \text{ppm}.$$

3.1 Features of the Program

A user-friendly parametric program was developed that calculates the values of the complex refractivity $\underline{N}$ for atmospheric conditions as a function of the variables f, P, T, RH, w_A (A/B/C/D), w, and R, as listed in Appendix A (Section A.1.1).

The output of MPM are three radio path-specific quantities:

- attenuation $\alpha(f)$ dB/km
- refractive delay β_0 ns/km
- dispersive delay $\beta(f)$ ps/km

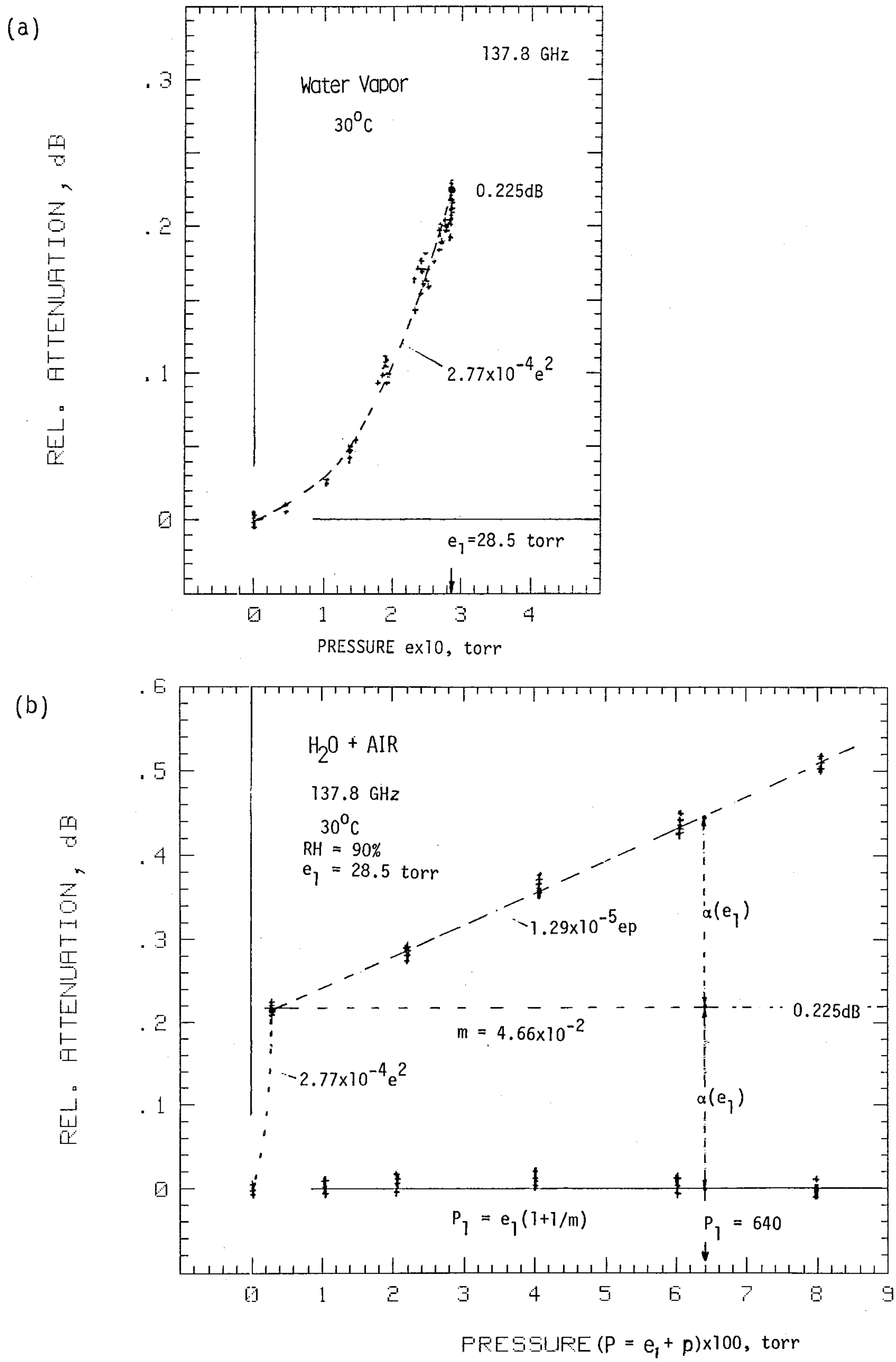


Figure 6. Typical raw data plots of relative attenuation $\alpha(P)$ for pressure scans at 137.8 GHz introducing (a) water vapor, $P = e$, and (b) H_2O + Air, $P = e_1 + p$.

The height range 30 to 100 km is treated approximately excluding the detailed O_2-Zeeman effect and trace gas spectra (e.g., O_3, CO, N_2O, etc.). Program MPM is written with extensive comments to run on IBM-XT/AT + 8087 coprocessor, or equivalent, microcomputers.

Extensive revisions of the MPM code have been made recently. The latest version is described in Appendix A. Details include (a) a revised set of overlap coefficients a_5 [(A-12)] in the dry air line table (see page 66) for the 60 GHz oxygen band based on a molecular fitting scheme reported by Rosenkranz [10]; (b) a relative humidity-driven growth model for hygroscopic aersol addressing haze conditions for RH = 90 to 99.9% [(A-3)]; (c) a new double-Debye model describing the complex permittivity $\underline{\varepsilon}(f,T)$ of water for f = 0 - 1000 GHz, T = -10 to 30°C [(A-17)]; and (d) an improved fog/cloud model that includes a dispersive delay term [(A-16)].

A nonlinear least-squares fitting scheme was applied to dielectric data sets $\underline{\varepsilon}(f,T)$ reported below 1 THz. Various spectral functions (relaxation and resonance) were considered, and the double-Debye model provided the best fit [15]. The Rayleigh approximation of the fog/cloud model was tested with experimental results on fog attenuation at 50, 82, 141, and 246 GHz and on differential fog delay between 246/82 GHz. All measured data were found consistent with model predictions. Moist air effects and fog effects of α and β were assumed to be additive [14].

3.2 MPM Calibration

Experimental results at 138 GHz, as described by (5) and (8), contain foremost contributions from water vapor continuum absorption. Equation (5) was used to "calibrate" the program MPM by enforcing the agreement between experimental and predicted data. The continuum, assuming an f^2 dependence, is defined by (see (14a) of [1])

$$\alpha_c \equiv 0.1820\ f\ N_e''(f), \qquad (9)$$

where the imaginary part of refractivity $\underline{N}$ is given by (Table 3)

$$N_e'' = f(3.57\ e^2\theta^{10.5} + 0.113\ e\ p\ \theta^3)10^{-5} \qquad (10)$$

and f is in GHz. A comparison in Table 1 shows that at 138 GHz, within experimental uncertainties, a good fit was obtained.

In addition to (10), new width data [11] for the 183 GHz H_2O line (b_3 listed in Table 1 of [1] was increased by 11.6%) were used to update the MPM program; also, b_3 parameters of the 325 and 380 GHz H_2O lines were increased by 10 percent. Other MPM modifications were a change in the nonresonant line width γ_o of dry air from 5.6×10^{-3} to 4.8×10^{-3} [10], the elimination of the roll-off term $1/[1 + (f/60)^2]$ (part of equation 13a in [1]), and the imposing of a high frequency cut-off $F''(f) = 0$ [see Eq. (A-9)] for $f \geq (\nu_o + 40\gamma)$ [12].

3.3 Interpretation of H_2O Continuum Absorption

Since MPM employs a limited (≤ 1 THz) H_2O line base, it is of interest to find out which share of k_s and k_f (8) can be attributed to far-wing behavior of the rotational H_2O spectrum extending beyond 1 THz [6]. Results in Table 2 indicate broadening efficiency ratios ξ at 138 GHz; e.g.,

$$\xi = m(H_2O + N_2)/m(H_2O + Ar), \qquad (11)$$

which are similar to those observed at cores of the 22 and 183 GHz lines. Consequently, k_f can be interpreted as a foreign-gas broadening effect whereby MPM lines account for about 30 percent of the rotational H_2O spectrum. Table 3 lists the assessment at 300 K ($\theta = 1$). When the line core argument ($m_L = 0.208/\theta^{0.5}$) is extended to k_s, then a substantial share,

Table 3. Summary Data of H_2O line Spectrum and H_2O Excess Attenuation at 137.8 GHz, T = 300 K

a) Experiment-versus-MPM Predictions

	MOIST AIR						DRY AIR	
	k_s	x_s	k_f	x_f	m	x_m	k_d	x_d
	$x10^{-2}$		$x10^{-2}$		$x10^{-2}$		$x10^{-6}$	
X	13.2	10.5	0.570	3.0	4.32	-7.5	2.2	-
M	13.15	10.51	0.5666	3.09	4.309	-7.42	2.10	2.35

b) Local H_2O Lines in MPM (31% of c):

M	0.802	3.5	0.175	3.8	21.8	0.3

c) Complete H_2O Line Spectrum (m = 0.22 assumed - see Table 2)

	2.59	3.5	0.57	3.0	22	-0.5

d) Excess H_2O Absorption:

Eq. (12)	10.3	12.5

Table 4. Reported Data on $(H_2O)_2$ Dimer Concentration e_D/e over the Temperature Range for 300 to 386 K

T , kPa	300	358.4	367.1	375.9	386.4
e , kPa	2.80	58.27	81.47	111.9	159.3
e_D , kPa	0.0024	0.44	0.76	1.28	2.27
e_D/e , $x10^{-3}$	0.9	7.6	9.4	11.4	14.2
e_D/e^2 , $x10^{-4}$	3.1	1.30	1.15	1.02	0.895
*Reference	[8]	[9]			

$$\alpha_i \simeq 0.103\ e^2\theta^{12.5} \quad \text{dB/km} \tag{12}$$

where $\alpha_i = (\alpha_x - \alpha_L)$ is not supported by the H_2O monomer line spectrum ($\theta^{12.5} \approx -4.3\%/K$).

At this point one might speculate about $(H_2O)_2$ dimer absorption. An estimate of the partial dimer vapor pressure

$$e_D \simeq 3.12 \times 10^{-4}\ e^2\theta^5 \quad \text{kPa}, \tag{13}$$

was obtained by fitting data on physical dimer properties given in Table 4. A strong 138 GHz attenuation rate,

$$\alpha_i \simeq 330\ e_D\theta^{7.5} \quad \text{dB/km}, \tag{14}$$

results when (12) and (13) are combined ($\theta^{7.5} \approx -2.5\%/K$).

3.4 MPM Predictions

Features of the user-friendly atmospheric propagation model MPM were discussed in Section 3.1. The microcomputer version is written in IBM Professional FORTRAN with extensive comments that guide the user to appropriate references for specific formulations. Three parametric presentations have been found useful in practical applications, which are addressed in separate subprograms:

Profiles	Variable	Parameters
A. Frequency	f	P, T, RH(v), w_A, w, R.
B. Humidity	RH,v	f, P, T, w_A, w.
C. Pressure	P	f, T, RH(e).

A copy of the line code for program MPM-N/A (frequency profiles) is shown in Appendix B. The detailed structure of MPM comes best to light in graphical examples. Typical sea level behavior of MPM-predicted rates, α and β, is illustrated in Figures 7 to 13. Across the millimeter-wave spectrum (Figures 7 and 8) one recognizes more or less transparent window ranges (W1 to W5) separated by molecular resonance peaks. Calculations of total radio path

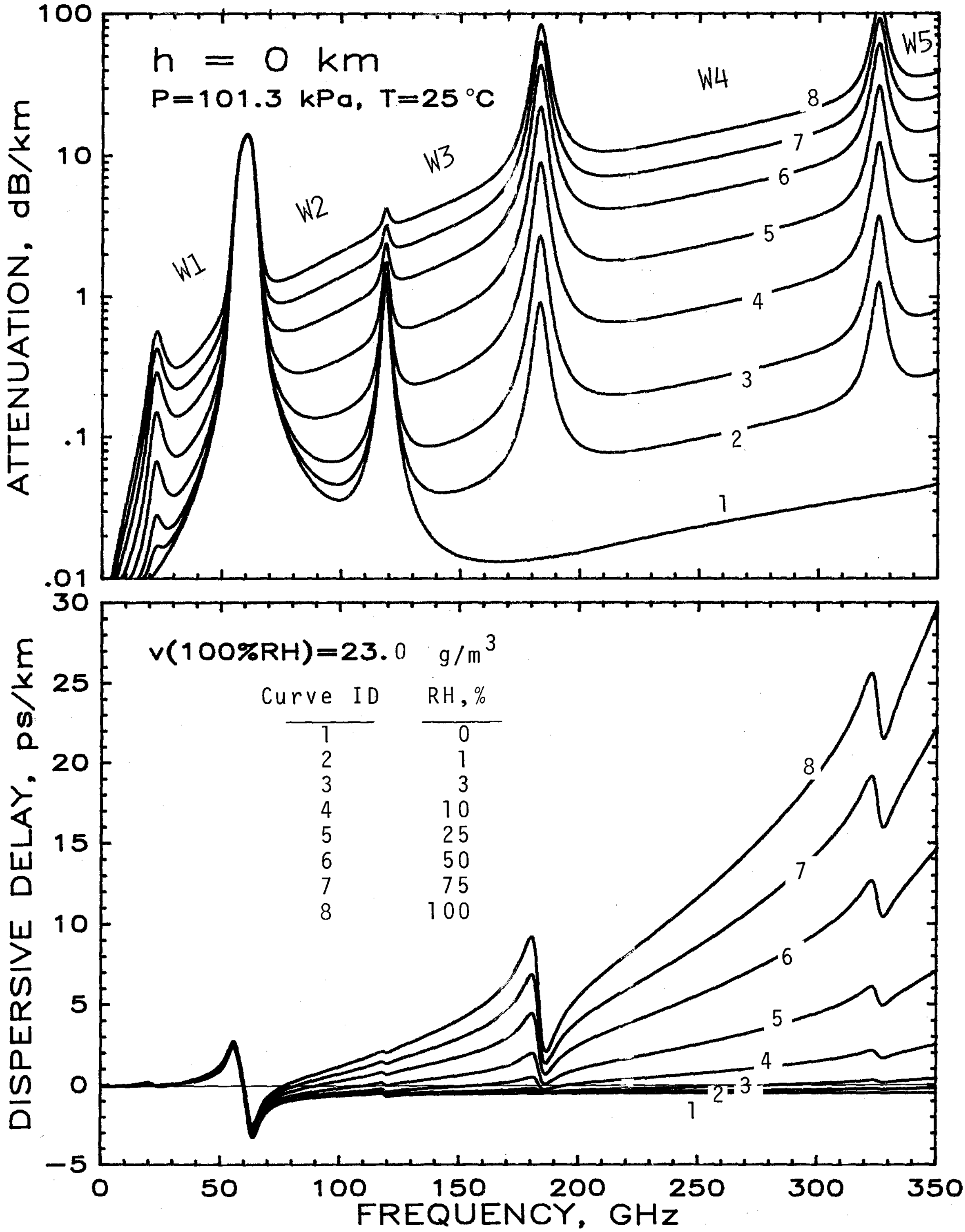


Figure 7. MPM-predicted specific values of attenuation α and dispersive delay β at sea level height h=0 km (P=101.3 kPa, T=25°C, RH=0 to 100%) over the frequency range, f=1 to 350 GHz. Window ranges are marked W1 to W5.

attenuation A [dB], delay B [ps], and atmospheric noise temperature T_A [K] require distributions of P(x), T(x), RH(x) along the propagation direction x to be known [2].

Spectroscopic properties of the air-broadened water vapor line centered at 183 GHz are demonstrated in Figure 9. Accuracy of supporting line parameters (stength, width, shift) determines the reliability of predictions needed for remote sensing applications with respect to atmospheric humidity. With respect to line shape studies one observes that wing data from the delay spectrum $\beta(f)$ are unaffected by dry air pressure p. Outside a line-center frequency range $\nu_0 \pm 5\gamma$, dispersion N'(f) is independent of a particular shape function F'(f) such as (A-9b).

A major concern for most MMW systems is their performance in rain. A simplified classification of rain events is given in Appendix A (A.1.1). When neglecting any statistical nature of rain within a radio path, the calculation scheme (A-18) provides an estimate on $\alpha(f)$ and $\beta(f)$. Predictions (Figure 10) are based on adding to the known state of moist air (P-T-RH) only one additional parameter, namely the point rainfall rate R.

Of some importance is the fog/cloud prediction program in MPM. Systems operating in the MMW range offer an attractive alternative to electro-optical systems when operation has to be assured during periods of adverse weather (rain, cloud, fog, haze, high humidity). Current interest is focused on the frequency range 90 to 350 GHz where an optimum trade-off between atmospheric obscurations and angular resolution can be achieved. All atmospheric loss and delay effects have to be known accurately in order to analyze the potential for all-weather performance. The suspended water droplet (SWD) formulation (A-16) and (A-17) of MPM is an addition to the state of saturated air (P-T-RH=100%) as illustrated in Figure 11. Key parameters are SWD content w in g/m^3 and temperature T in °C.

Another atmospheric ingredient is the mass concentration w_A of hygroscopic aerosol (HAE). Solution droplets appear for RH > 80%, and haze conditions develop as RH approaches 100 percent. These conditions can be modeled by assuming that at the reference humidity, RH = 80%, the HAE concentration w_A(RH = 80%) is known. The RH dependent swelling/shrinking w(RH) is described approximately up to RH = 99.9% by a growth model (A-3).

Relative humidity RH is <u>the</u> variable that governs physical processes taking place in the atmosphere with respect to water vapor. Practical models

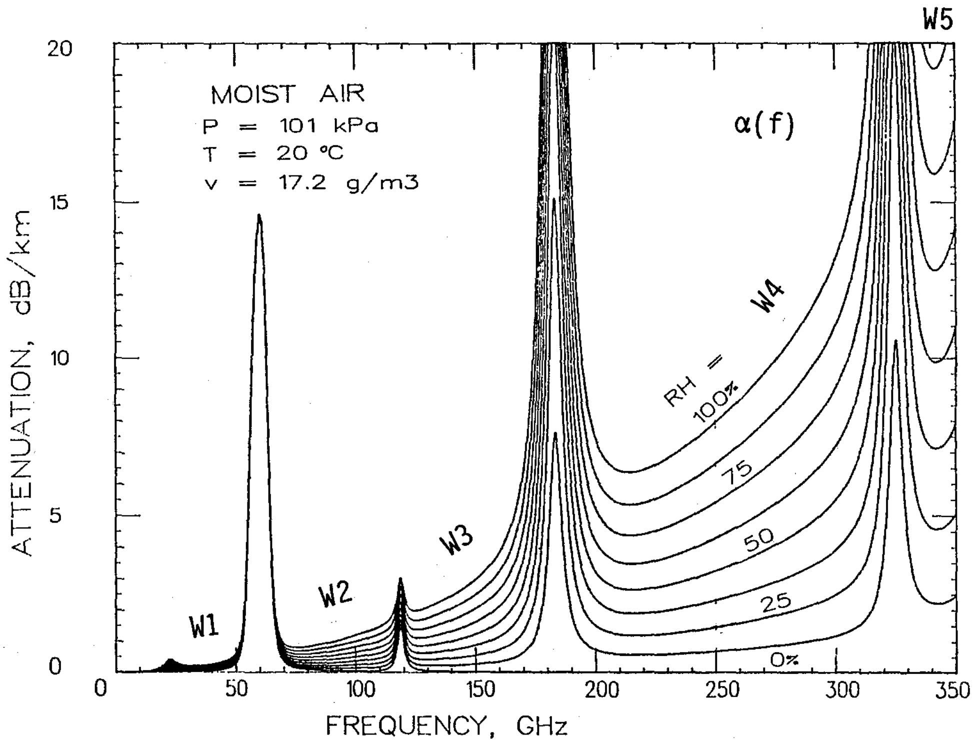


Figure 8. Water vapor absorption in window ranges for constant relative humidity increments (ΔRH = 12.5%) at a sea level condition.

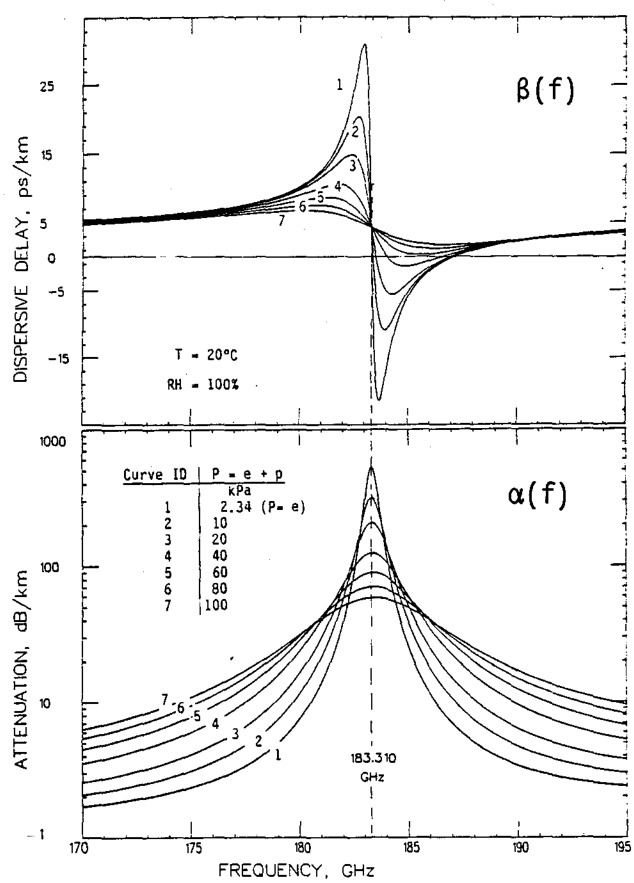


Figure 9. Pressure-broadening (AIR) example of the 183 GHz H_2O line.

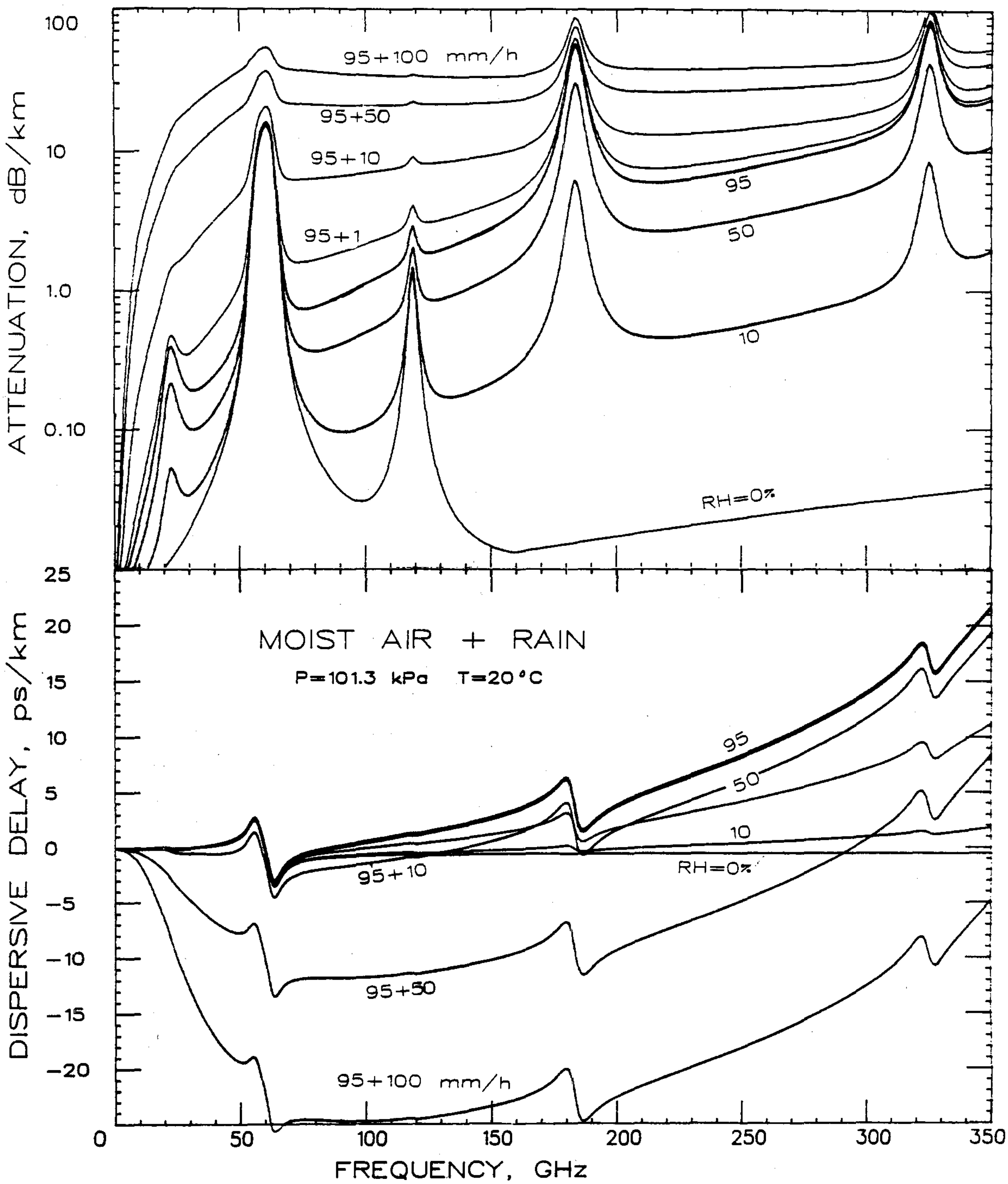


Figure 10. Attenuation α and delay β rates for three rain events (R=10, 50, and 100 mm/h) added to a moist air (RH=95%) sea level condition. Also shown are dry air (0% RH) and moist air (50% RH) characteristics.

(a)

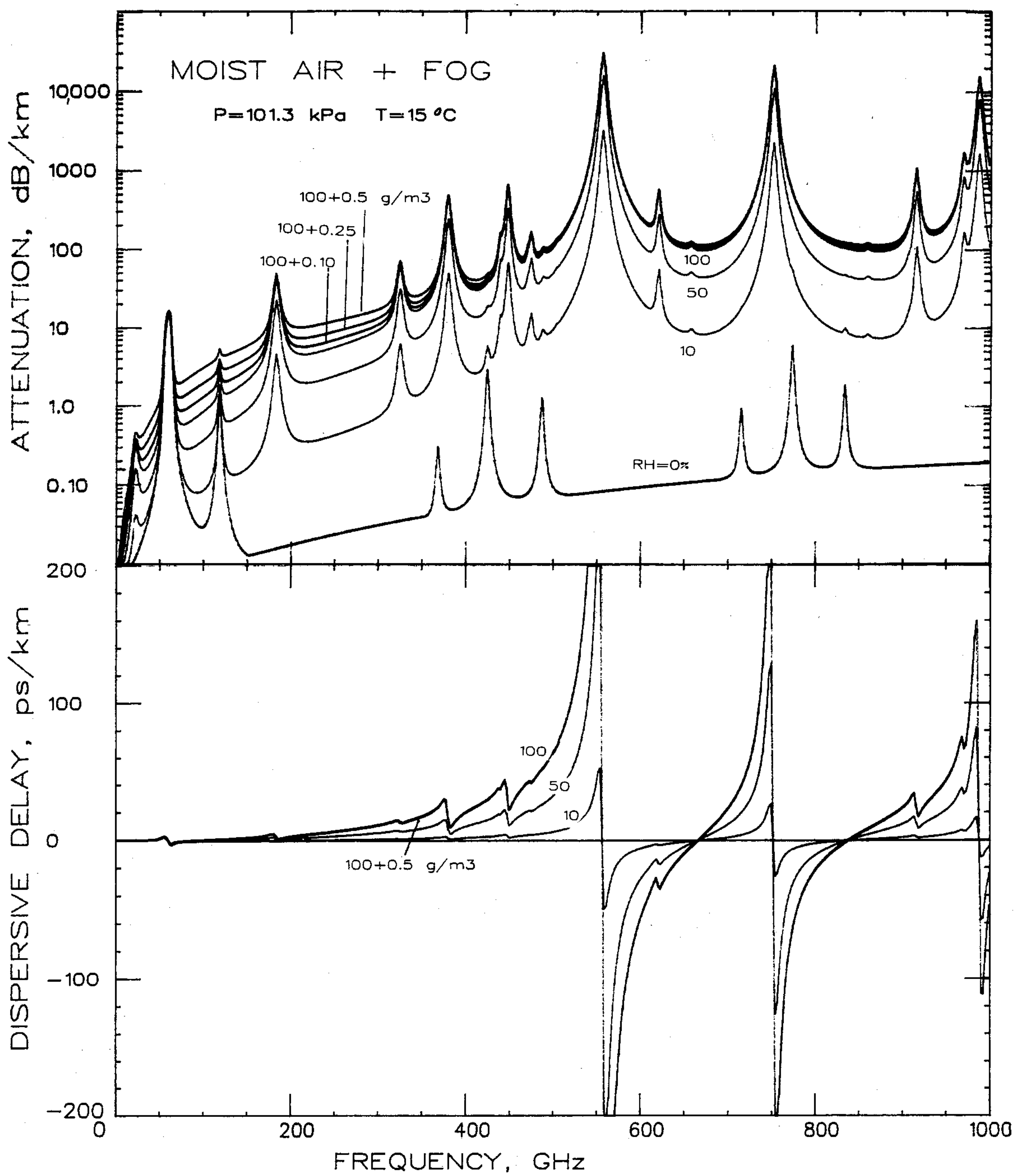


Figure 11. Attenuation α and delay β rates for three fog events (w = 0.10, 0.25, and 0.5 g/m^3) added to a saturated air (RH=100%) sea level condition. Also shown are dry air (0% RH) and moist air (50% RH) characteristics: (a) f = 1-1000 GHz,

(b)

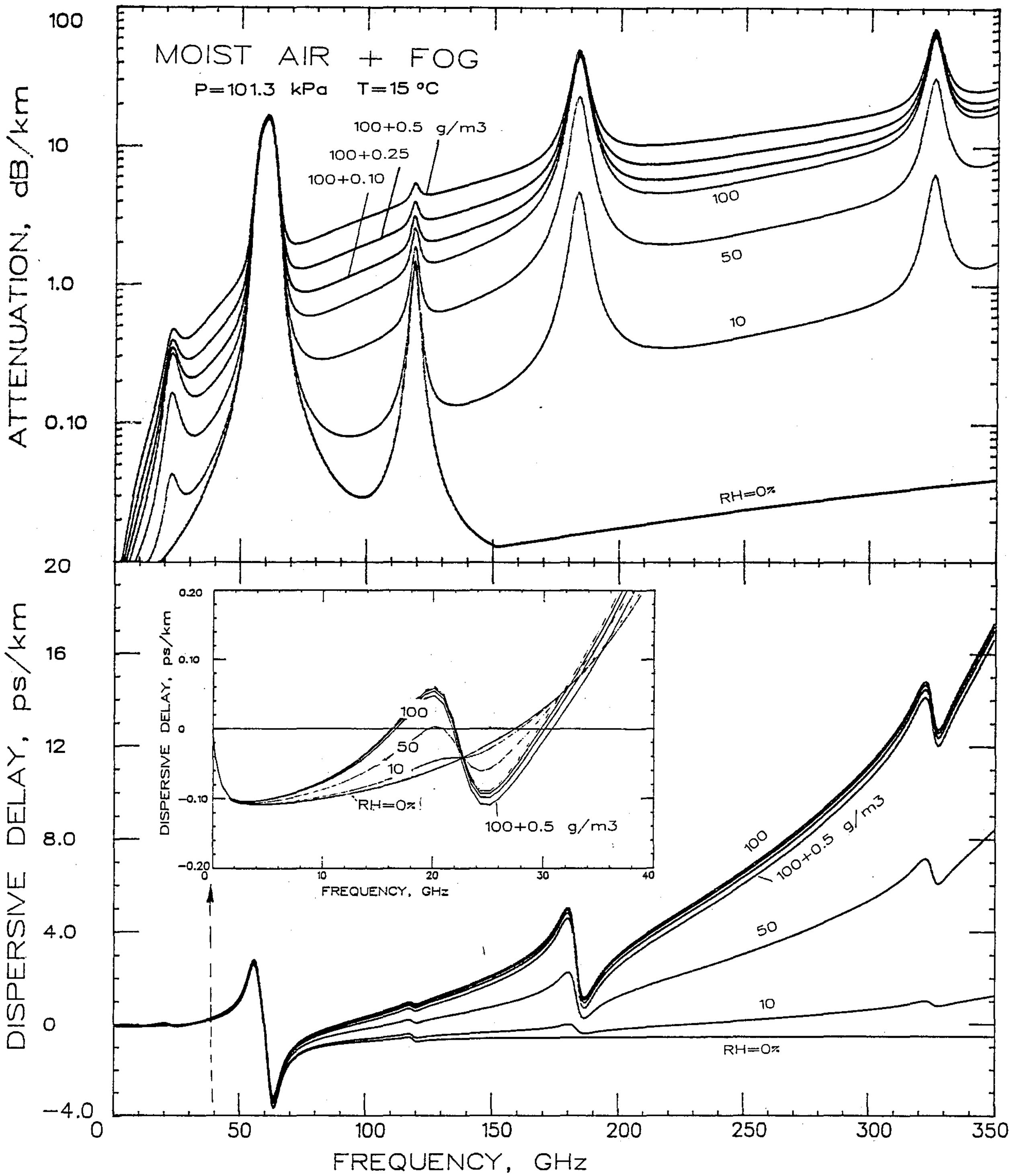


Figure 11. continued: (b) f = 1-350 GHz and f = 0-40 GHz (insert).

for RH parameterization exceeding saturation are not available. Both absolute humidity (v) and suspended haze droplet concentration (w_A) can be expressed in terms of RH variability. Absolute (v) and relative (RH) humidity are interrelated through the ambient temperature T.

Sulfates are the major RH-active ingredient of both urban and rural aerosols; so is sodium chloride for maritime species. The atmosphere is never free from HAE, with greatest concentrations near the surface and scale heights on the order of 1 km. Above RH = 90%, suspended water droplets have developed carrying the HAE essence in solutions. Average values of w_A lie between 0.01 and 1 mg/m^3. The humidity parameterization in MPM is demonstrated by the examples given in Figures 12 and 13.

Pressure variability comes into play when modeling height dependencies. Cumulative calculations of α/β for a slanted radio path through the neutral atmosphere (e.g., ground-to-satellite) encounter pressures, P = 100 to 0 kPa, which narrows the molecular absorption lines until they vanish altogether. Pressure-, Zeeman-, and Doppler-broadening [(A-11)] have to be considered over the height range 0 to 90 km. Another need for a formulation of pressure profiles arises from spectroscopic studies applying pressure-scanning techniques. A simulation of laboratory measurements discussed in Section 2.3 is exhibited in Figure 14.

4. EXPERIMENTAL-VERSUS-MODEL (MPM) DATA

Corroborative experimental data of sufficient quality to scrutinize MPM predictions are scarce. Reliability, precision, and limited scope of supporting meteorological data often compromise the accuracy of results deduced from field observations. Generally, laboratory experiments are more accurate by simulating controlled electromagnetic and atmospheric conditions crucial to validate a specific model aspect. In this manner, contributions from water vapor lines (22 and 183 GHz) and from oxygen lines (48 to 70, 119 GHz) have been evaluated [1], [4], [10], [11], [16]. Theoretical refinements are motivated to improve the interpretation of empirical laboratory data by establishing a connection to the physics of the problem. For example, a set of our unpublished dispersion (N') results on dry air, taken during 1976 between 53.6 and 63.6 GHz, provided reference data for an elaborate reformulation of interference coefficients that describe the 60 GHz O_2 bandshape [10]. The new

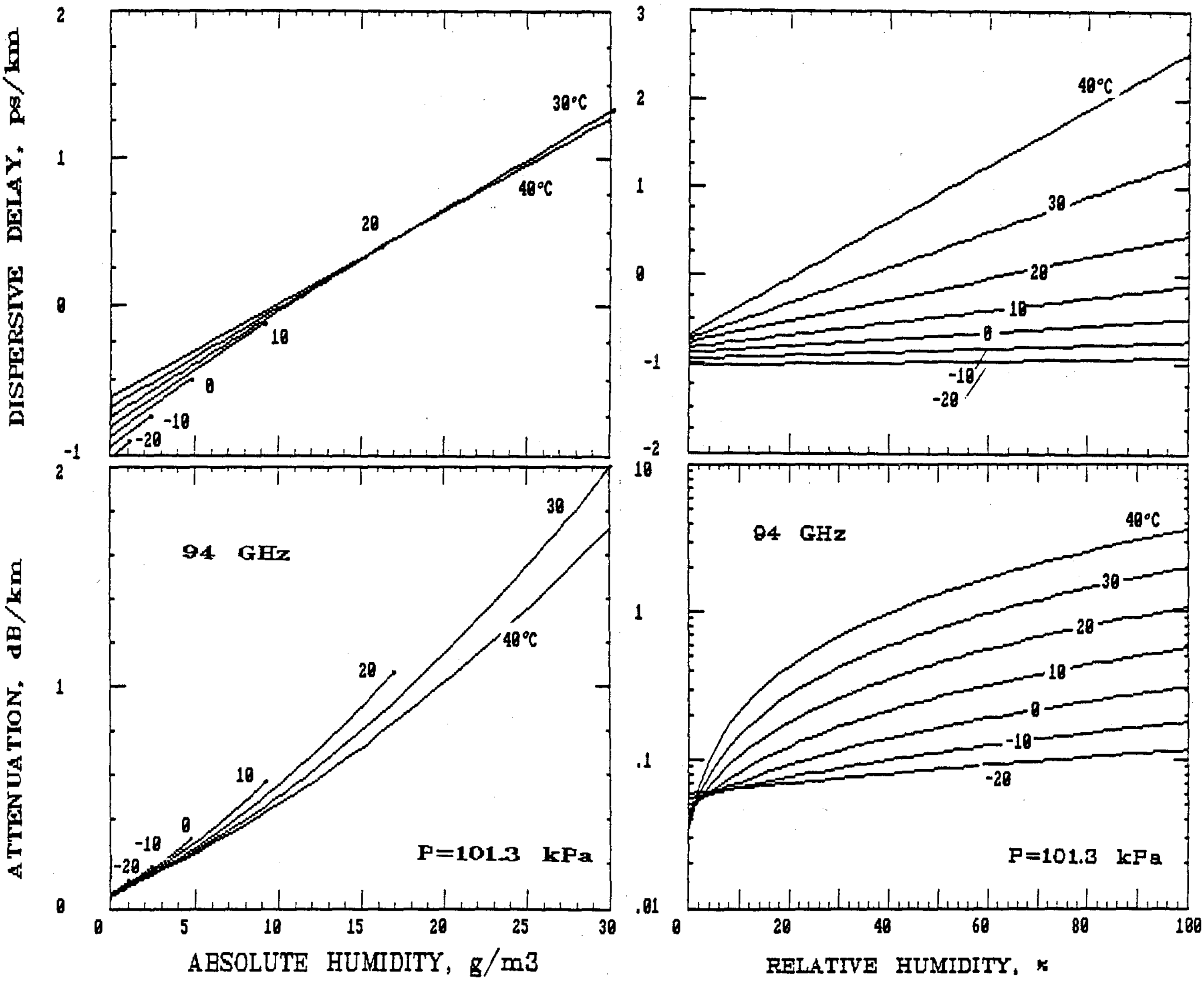


Figure 12. Absolute (v) and relative (RH) humidity dependence of attenuation α and delay β at f = 94 GHz for various sea level conditions (P = 101.3 kPa and T = -20 to 40°C).

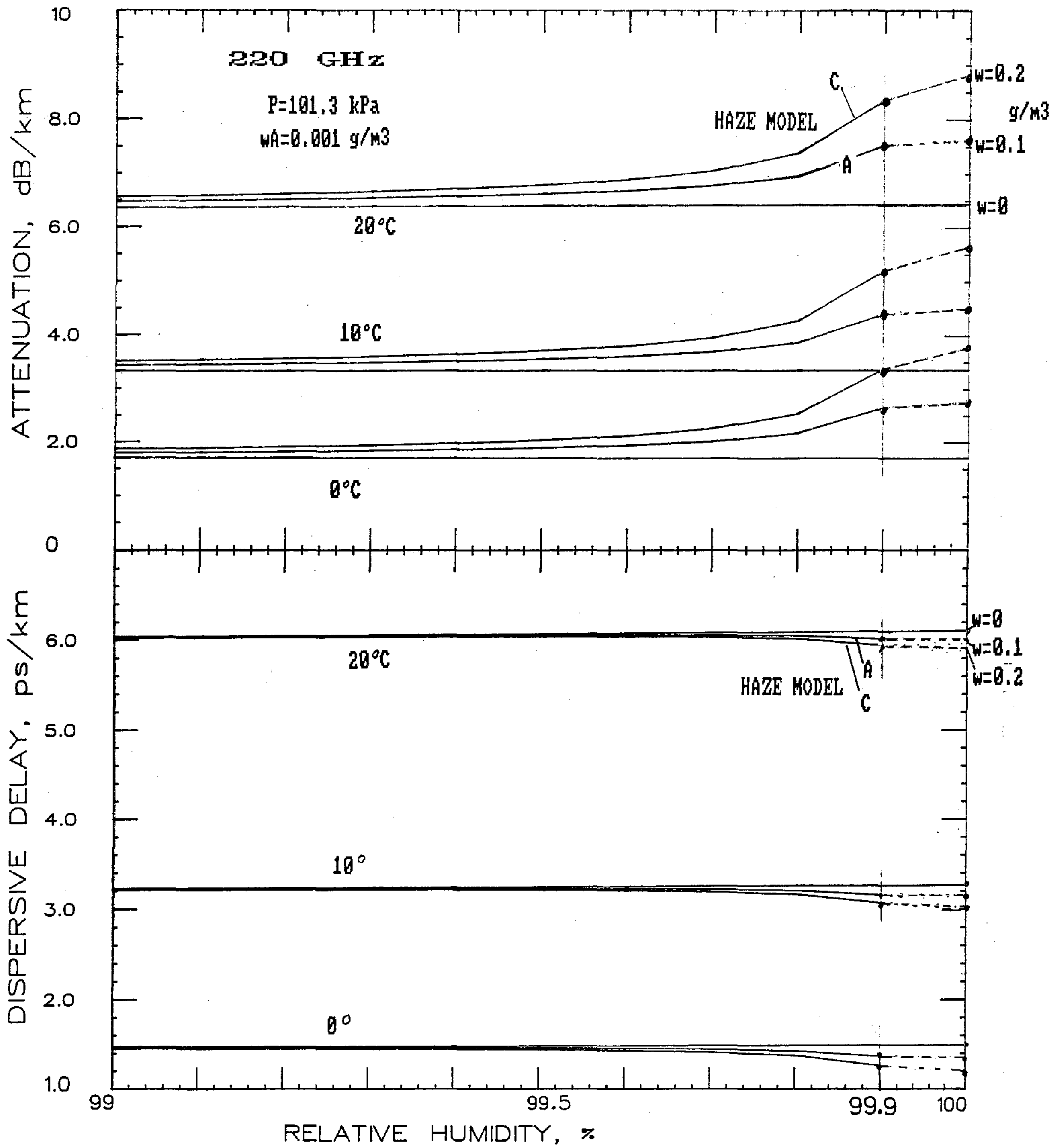


Figure 13. Two haze cases (A:1 mg/m^3 and C:1 mg/m^3) for prefog (RH = 99-99.9%) and fog (w=0.1 and 0.2 g/m^3) conditions at three temperatures (0, 10, 20°C) displaying the associated attenuation α and delay β rates at f = 220 GHz.

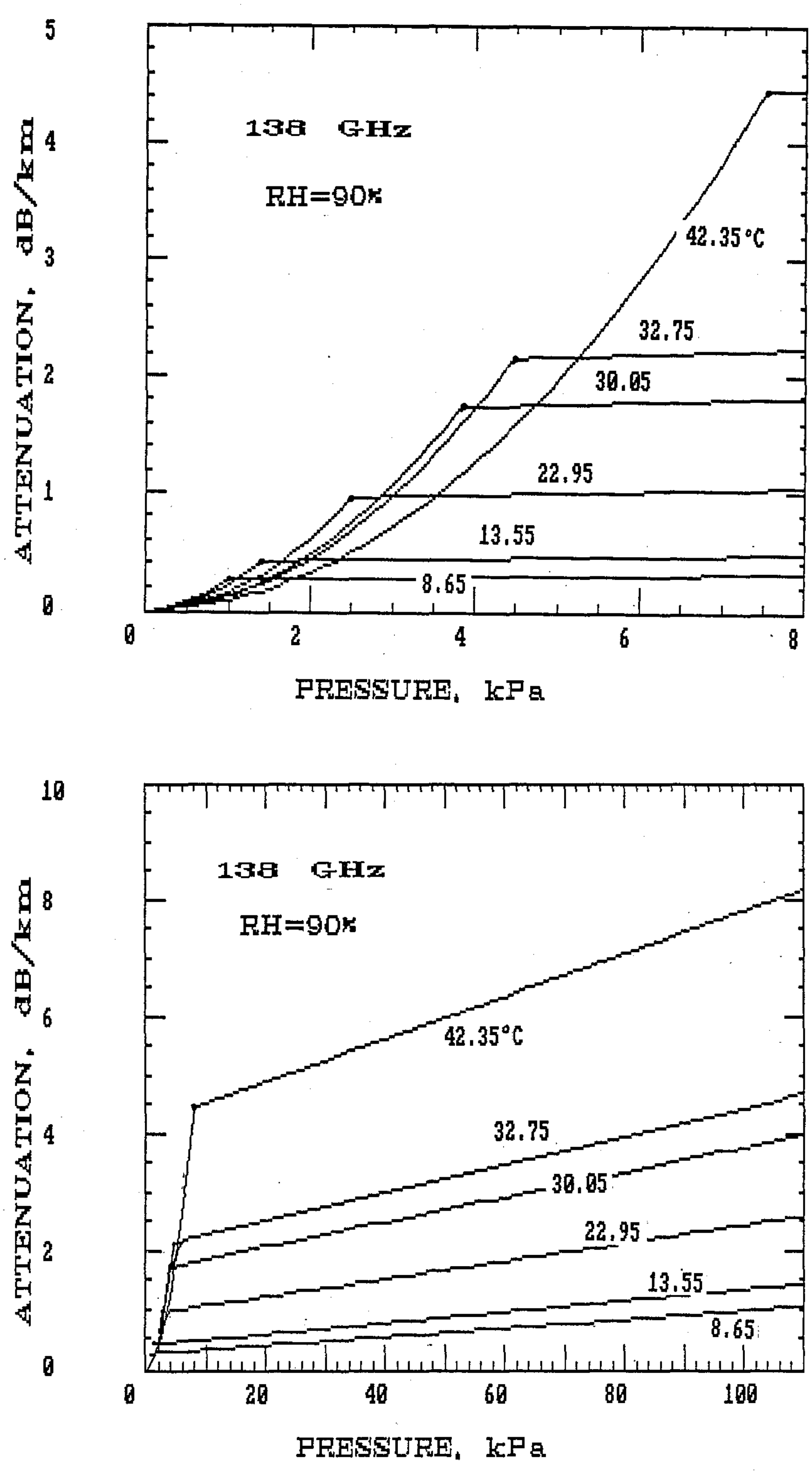


Figure 14. Pressure profiles at f = 138 GHz simulating the laboratory attenuation measurements presented in Section 2.3.

coefficients a_5 (see page 66) were adapted for MPM, and Table 5 demonstrates the degree of agreement.

4.1 Laboratory Measurements

The results on moist air attenuation at 138 GHz [i.e., (5), (8)] provided clues to a formulation of an empirical MPM water vapor continuum. Data from other researchers were evaluated to check if the assumptions of (10) held up at different frequencies. Water vapor attenuation at frequencies between 330 and 430 GHz is compared with MPM predictions in Figure 15. The data were available in graphic form and had to be digitized by us. Considering the many difficulties that plague absolute calibrations, a comparison of model vs. experiment is encouraging. No anomalous absorption features have been uncovered.

Two laboratory studies of the 183-GHz water vapor line have been reported by a French group [11], [17]. We adapted the width results [11] for the line table of MPM. A detailed analysis of temperature-dependent wing data [17] is given in Table 6. Equation (5) was applied to reduce both experimental and MPM data for an intercomparison. At +1 GHz from the line center, the attenuation rate for pure water-vapor shows a discrepancy of 21 percent. The origin of such disagreement has to be attributed to the 183-GHz line broadening formulation but not to the rather small contribution from the continuum.

4.2 Field Measurements

Ultimately, it is up to field experiments to garner realistic evidence in support of model predictions. When conducted with care at different locations under a variety of natural conditions, such experiments prove to be quite costly.

Data from ITS field studies on the propagation of millimeter waves were evaluated for water-vapor attenuation rates at 96.1 GHz [18], [19]. Clear air data and MPM predictions are in close agreement, allowing for the temperature dependence, as demonstrated in Figure 16. The mission of these experiments was to establish a data base for 11.4 to 96.1 GHz propagation in a humid climate (Huntsville, AL, April-August 1986). A similar comparison was not so favorable for a set of data displayed in Figure 17. The results were obtained over a 1.5 km line-of-sight path in the Soviet Union at subfreezing

Table 5. Measured (EXP) and Predicted (MPM) Dispersion in Dry Air at 300 K (Interference Coefficients from Rosenkranz [10])

Nearby Line	Frequency	Dispersion N'(f) EXP	Dispersion N'(f) MPM	Frequency	Dispersion N'(f) EXP	Dispersion N'(f) MPM
		p = 53.3 kPa			p = 80.0 kPa	
	GHz	ppm		GHz	ppm	
25-	53.588	0.30	0.300	53.585	0.43	0.439
23-	54.123	0.35	0.338	54.119	0.50	0.490
19-	55.214	0.40	0.407	55.210	0.58	0.576
17-	55.776	0.42	0.421	55.772	0.60	0.589
15-	56.356	0.41	0.398	56.352	0.59	0.565
13-	56.960	0.38	0.350	56.956	0.45	0.502
3+	58.439	0.19	0.174	58.435	0.26	0.253
7-	59.156	0.08	0.076	59.152	0.12	0.110
5+	59.583	0.03	0.027	59.579	0.03	0.032
5-	60.296	-0.075	-0.084	60.292	-0.11	-0.134
7+	60.425	-0.135	-0.122	60.421	-0.17	-0.170
9+	61.141	-0.275	-0.252	61.136	-0.383	-0.361
11+	61.790	-0.335	-0.342	61.785	-0.510	-0.522
13+	62.400	-0.480	-0.475	62.396	-0.685	-0.679
3-	62.475	-0.510	-0.495	62.471	-0.720	-0.705
15+	62.987	-0.590	-0.578	62.983	-0.80	-0.800
17+	63.558	-0.610	-0.589	63.554	-0.841	-0.831

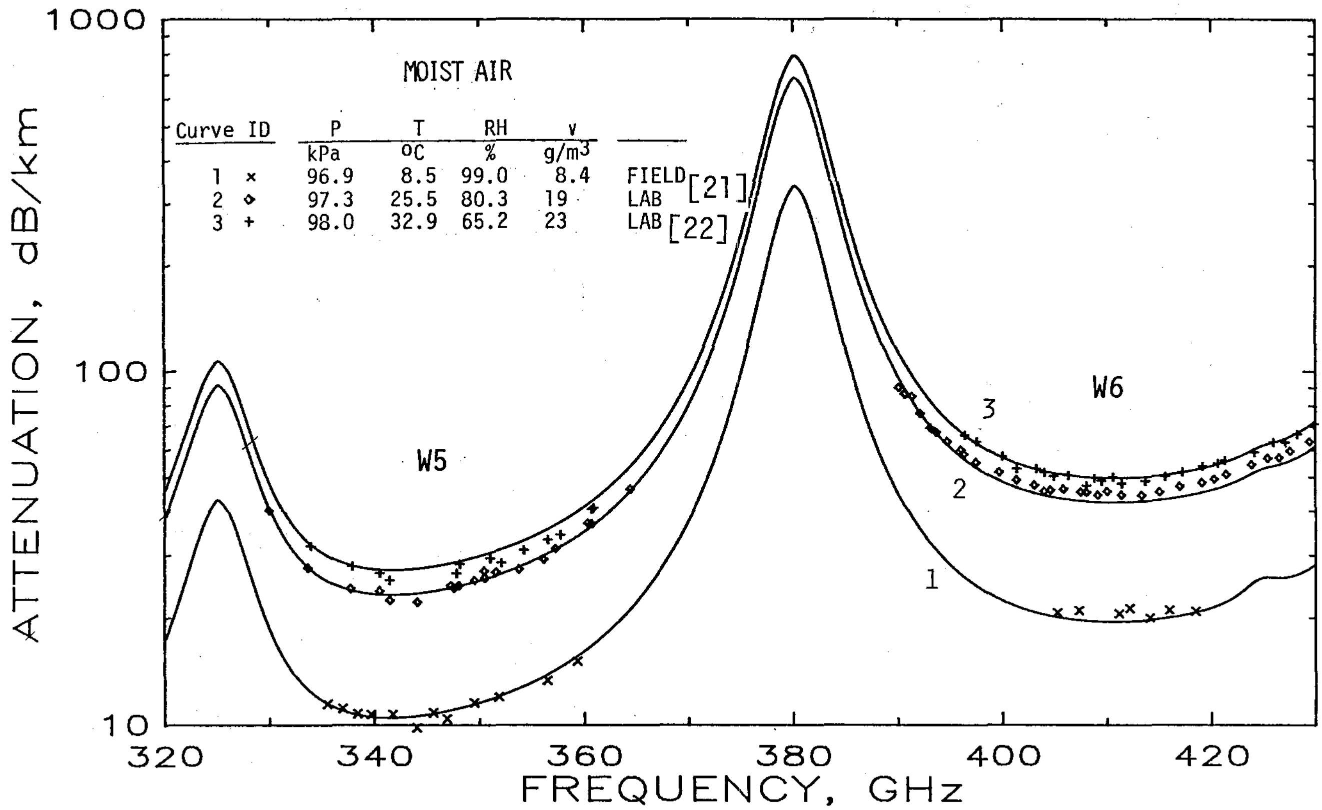
Table 6. Comparison between MPM-Predicted and Experimental Attenuation for Water Vapor (e) and Moist Air ($P = e_1 + p$) in the Wing Region of the H_2O Line Centered at ν_o = 183.310 GHz

f,	GHz	ν_o + 3.0			ν_o + 1.0			ν_o + 0.4		
					MPM - PREDICTIONS					
	e_1	1.766kPa (13.25 torr)			1.059kPa (7.94 torr)			0.529kPa (3.97 torr)		
	T/K	Lines	Cont.	Total	Lines	Cont.	Total	Lines	Cont.	Total
α, dB/km	310	3.66	0.53	4.19	11.35	0.19	11.54	17.37	0.05	17.41
	300	4.17	0.70	4.87	12.90	0.25	13.15	19.73	0.06	19.79
	290	4.76	0.95	5.71	14.17	0.33	15.05	22.49	0.08	22.58
	P	100kPa (750 torr)			100kPa (750 torr)			100kPa (750 torr)		
α, dB/km	310	21.52	1.83	23.52	21.39	0.95	22.52	11.66	0.43	12.27
	300	23.59	2.07	25.86	23.10	1.06	24.35	12.57	0.47	13.24
	290	25.92	2.40	28.53	25.00	1.19	26.41	13.58	0.51	14.31

DATA REDUCTION: MPM-vs-EXPERIMENT

		MPM	EXP*	X/M %	MPM	EXP*	X/M %	MPM	EXP*	X/M %
k_s	300	1.56	1.67	7.1	11.72	14.2	21.2	70.56	75.3	6.7
x_s	-	4.56	4.1	-10.1	3.99	3.9	-2.3	3.88	3.5	-9.8
k_f	300	0.121	0.136†	12.4	0.107	-			N.A.	
x_f	-	2.48	2.7	8.9	1.96	-			N.A.	
m	300	0.0776	0.0814	4.9	0.0913	-			N.A.	

*Reference [17], †N_2-result reduced by 0.907.



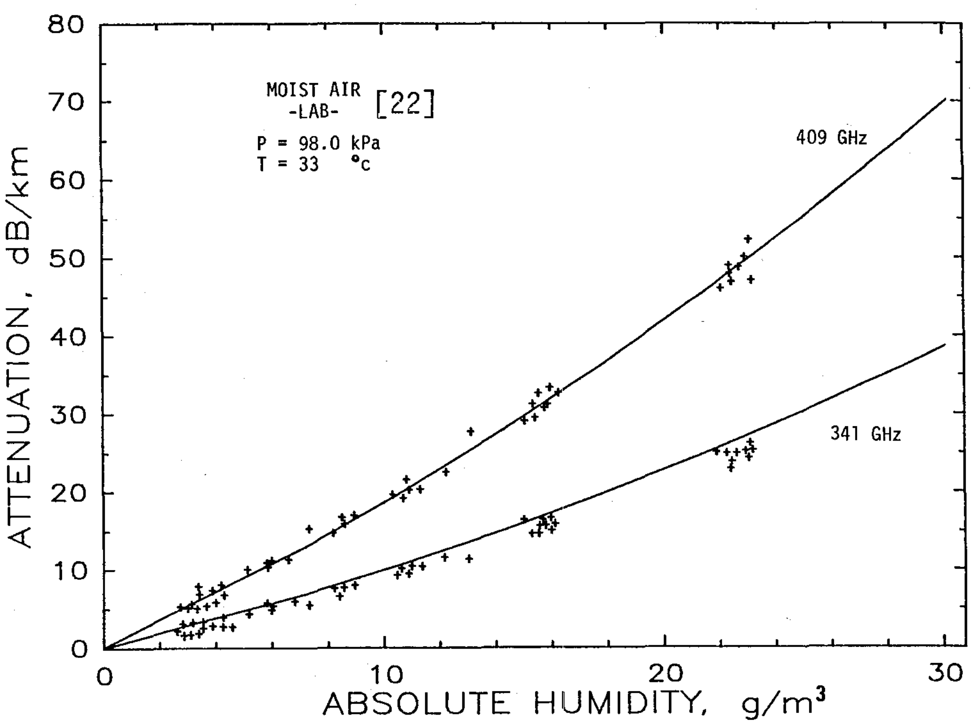


Figure 15. Moist air attenuation $\alpha(f)$ across the atmospheric window ranges W5 and W6 (320 to 430 GHz) at temperatures 8.5, 25.5, and 32.9°C: data points [21], [22]; solid lines, MPM.

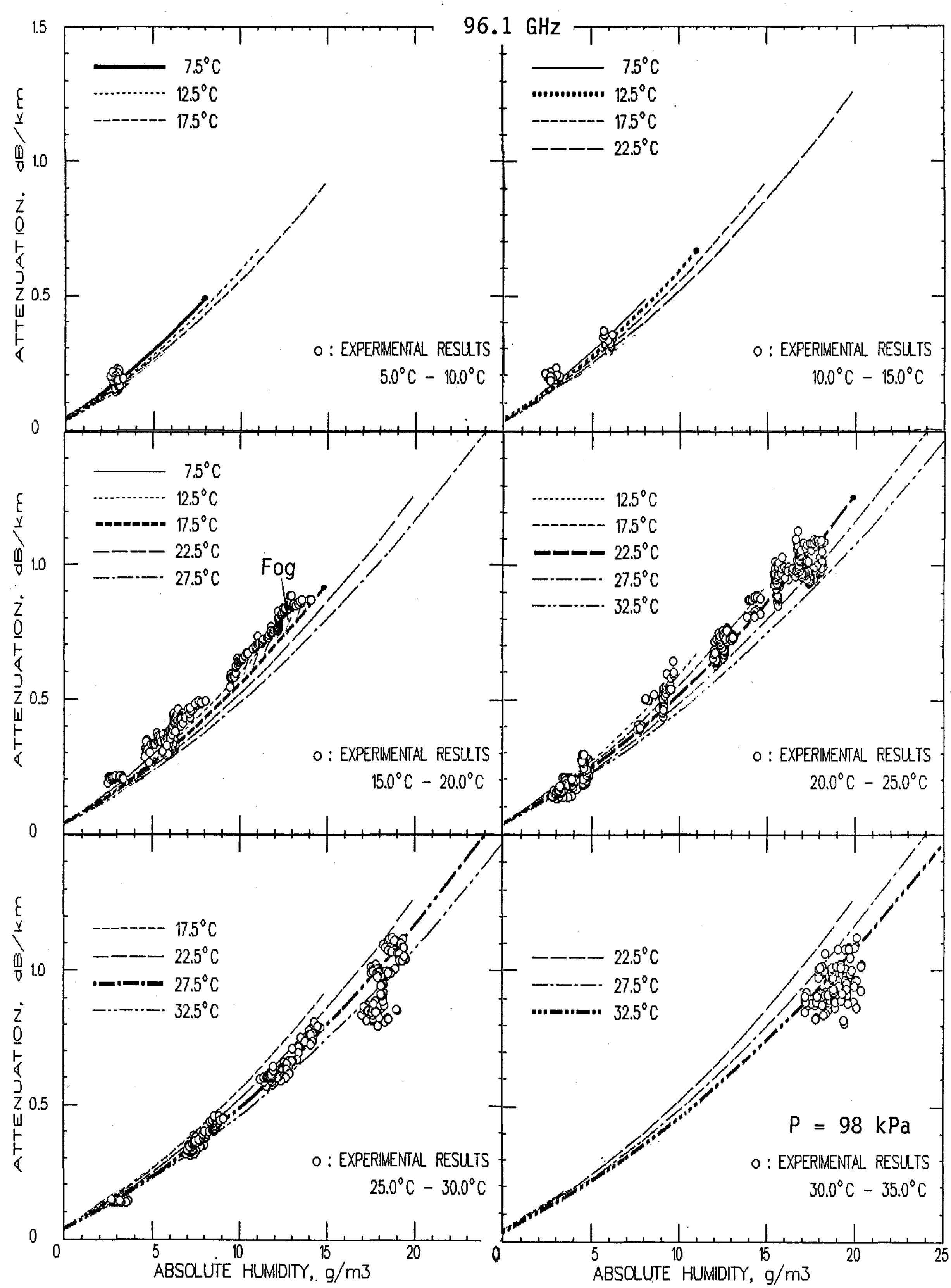


Figure 16. Moist air attenuation $\alpha(\nu)$ measured at 96.1 GHz over a 21.4 km line-of-sight path located in Huntsville, AL ($h \simeq 0.3$ km) for six temperature groups between 2.5 and 37.5°C [19] data points are 5-min averages for 4.5 days (5/4-6, 8/15-16/1986); solid lines, MPM.

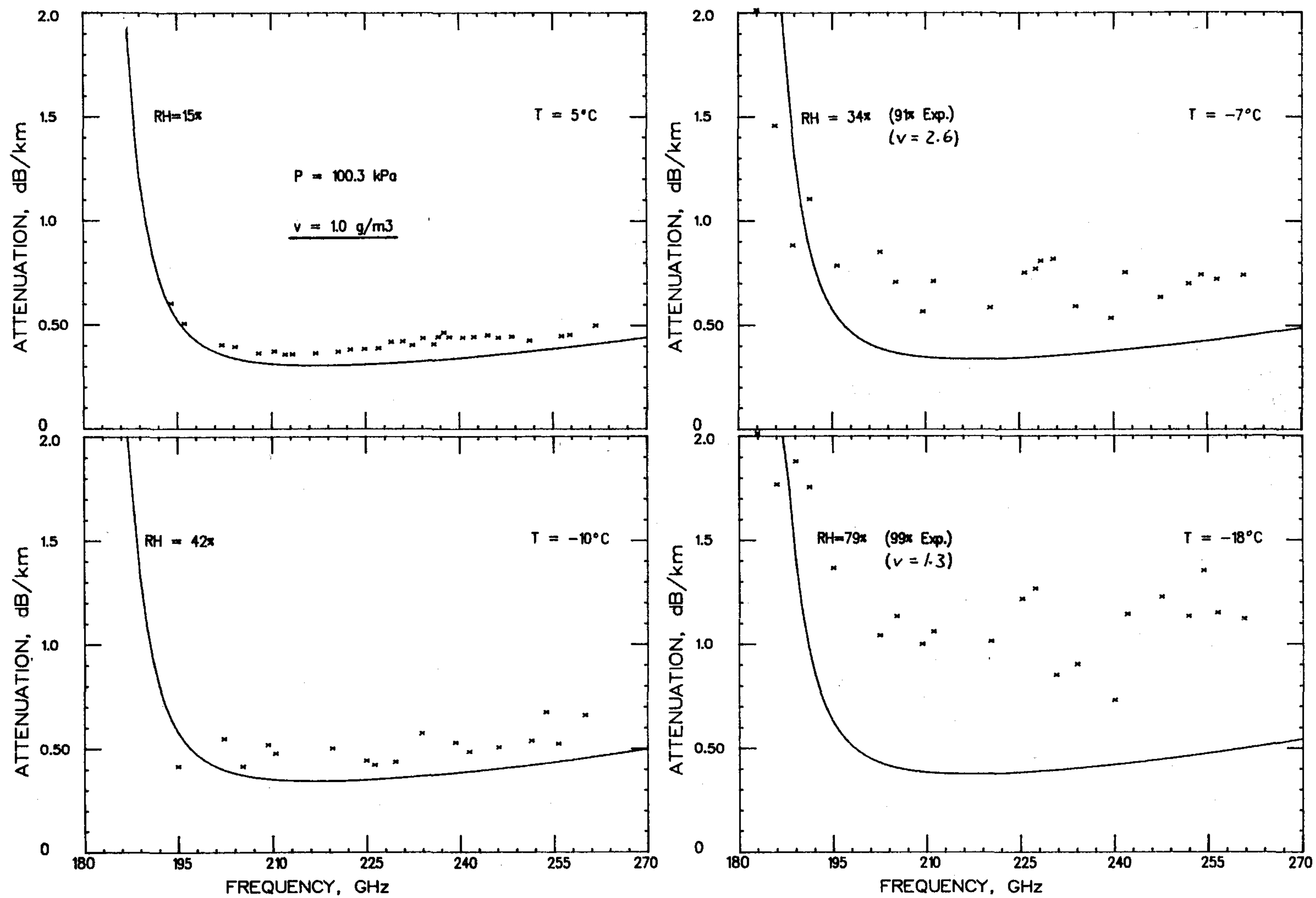


Figure 17. Water vapor attenuation rates α(v) across the atmospheric window range W4 at four temperatures, 5, -7, -10, and -18°C: data points [20]; solid lines, MPM.

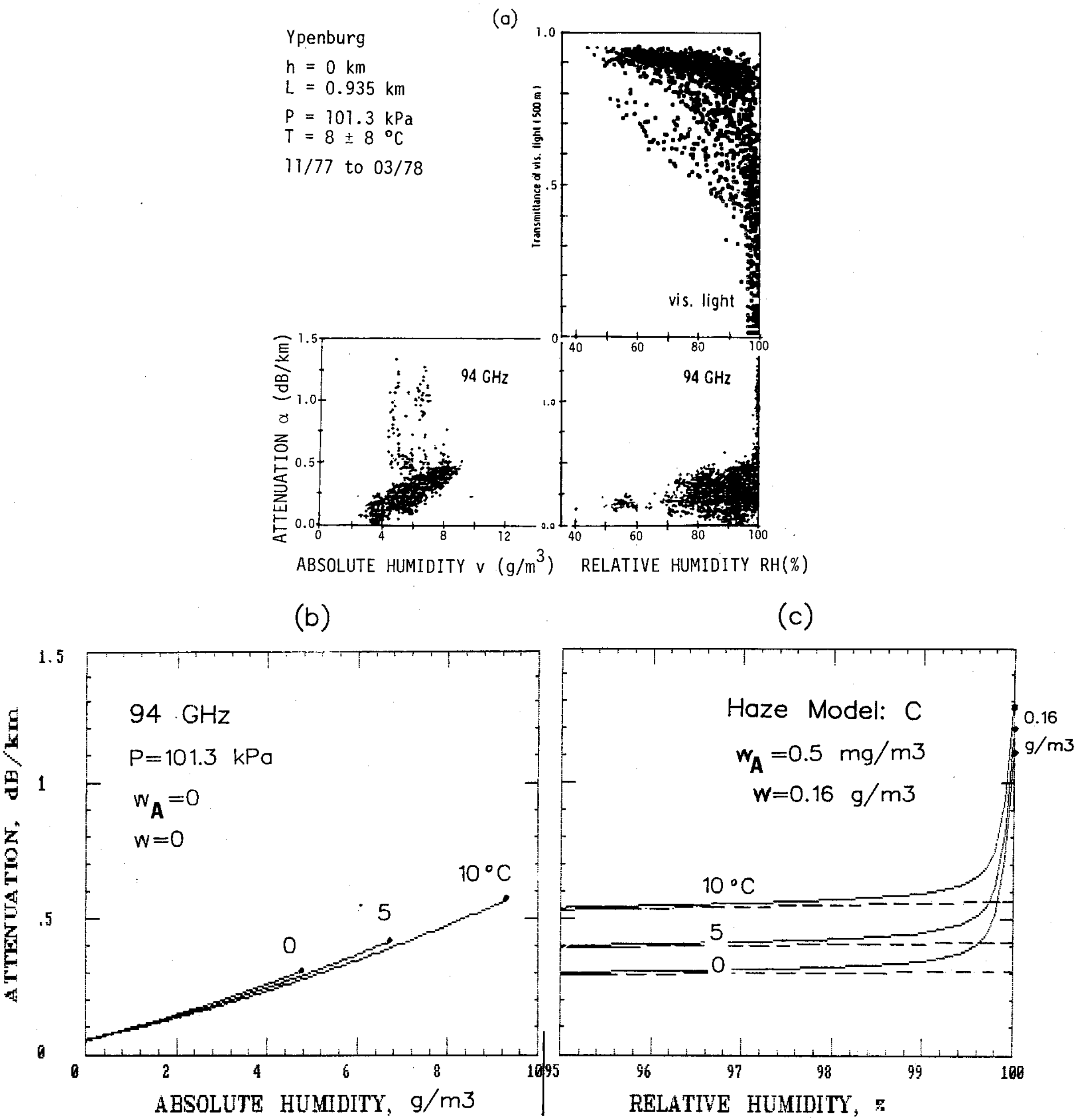


Figure 18. Terrestrial path attenuation at 94 GHz and 0.65 µm (visible light) under nonprecipitating conditions as a function of absolute (v) and relative (RH) humidity [3]: (a) data points, 5-min averages taken every 30 min during a period of 4 months [23]; (b) MPM simulation of (a) for absolute humidity; (c) MPM simulation of (a) over the range, RH = 95 to 100%, including haze model C.

temperatures for frequencies between 192 and 260 GHz [20]. Experimental uncertainties are not discussed, the extreme environmental conditions may have played a role. On the other hand, 335 - 420 GHz field data (included in Figure 15), that were reported by another group from the Soviet Union [21], [22] agree remarkably well with MPM predictions.

Attenuation data at 94 GHz have been recorded in a coastal region of the Netherlands [23]. Data, when presented in Figure 18 versus absolute humidity v, display significant random excess attenuation over MPM predictions. The same data plotted versus RH places all excess attenuation at RH > 98%. Haze and fog conditions probably were present as evident from optical transmission data. The highest excess of 0.8 dB/km requires $w \approx 0.16$ g/m^3, a value typical for heavy fog.

Figure 19 presents atmospheric noise temperatures measured against zenith at two different sites simultaneously at 10, 33, and 90 GHz [24]. Predictions with the MPM radio path program reproduce the frequency correlations quite correctly, which tends to confirm the f^2 assumption made for H_2O continuum absorption (10). In addition, model data set a limit for total precipitable water vapor V[mm] carried by the air mass. Noise exceeding this limit probably originates from suspended droplets. Data trends stemming from differences in the f-dependence of moist air and SWD absorption support such assumption.

5. CONCLUSIONS

Radio properties of the atmosphere are both a barrier and a boon to applications in the 10-1000 GHz spectral range. The first part of this report gave a somewhat detailed description of a laboratory experiment that had to apply latest advances in digital electronics and cryogenic detection to derive at 138 GHz two attenuation coefficients, k_s and k_f (8). At first sight, these two quantities describe the attenuation rate of moist air over a rather inconspicuous range from 0.1 to 10 dB/km; however, a more detailed analysis revealed the k-formulation provides conclusive evidence on temperature and pressure dependence of the water vapor continuum. Attaching an f^2 dependence to the 138-GHz results turned a frequency limited (< 1 THz) propagation model into a useful tool capable of operating in frequency, humidity, and pressure domains of the atmosphere.

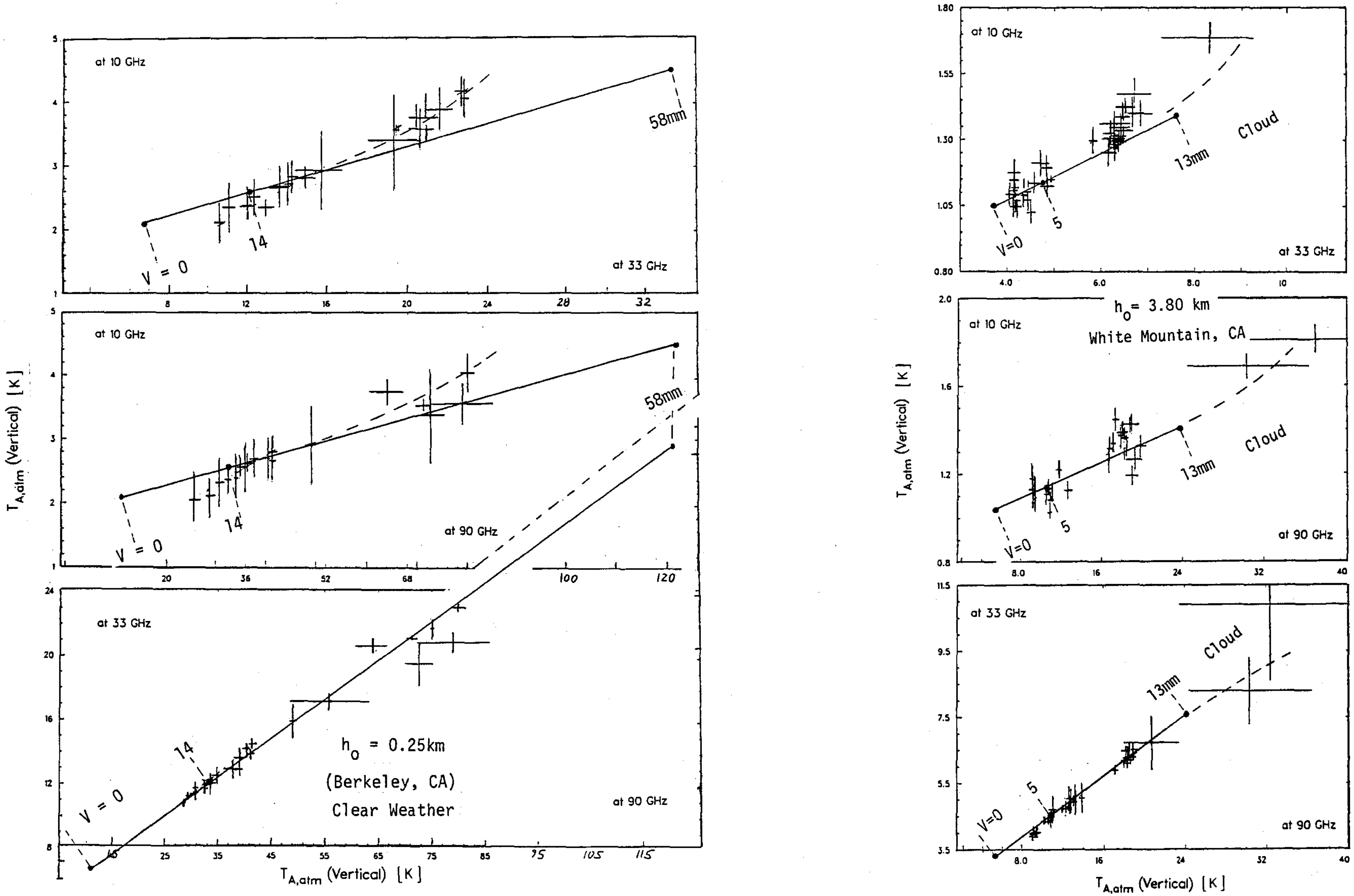


Figure 19. Correlated vertical atmospheric noise temperatures T_A at the frequency pairs 10/33, 10/90, and 33/90 GHz. Path-integrated water vapor is $V = \int v dh$ mm. The measurements were conducted from two sites located at height levels h_o = 0.25 and 3.30 km: data points [24]; solid lines, MPM with a mean July height profile (0-30 km) of P, T, RH for San Francisco, CA [3].

The report discussed details of contributions to modeling atmospheric MMW properties, foremost the attenuation calibration of MPM employing new laboratory results on moist air. Water vapor continuum absorption and, above RH = 90%, droplet attenuation are both affected by relative humidity RH. For haze formation, the range up to RH = 99.9% was modeled. So far, in fog and cloud situations, when RH exceeds 100 percent, values for w cannot be model-generated from the atmospheric water vapor content.

The code MPM was readily accepted by radio scientists and engineers. About 90 requests for copies of MPM have been honored since January 1986. Quotes from received comments were encouraging: "MPM proved of considerable value," -- "documentation is about the best I have ever seen," -- "technical flow, model development and general visibility for application efforts is superior," etc. The Microwave Group of the International Radiation Commission largely adopted MPM as atmospheric transmission code [25].

Although MPM was found capable of predicting atmospheric NMMW propagation limitations, several shortcomings still exist. They are, for example, the missing confirmation for a physical basis of water vapor continuum absorption (e.g., [7], [13]) dominating transmission in atmospheric window ranges centered at 90, 140, 220, 340 GHz and higher; needed measurements of spectroscopic parameters (i.e., shape, strength, width and shift) for spectral lines of the main absorbers (O_2 and H_2O) over the full atmospheric temperature range (300-200 K); and a lack for reliable subfreezing transmission data to clarify the problems that are indicated by Figure 17. Further parametric (frequency, pressure, humidity, temperature, gas composition such as H_2O + AIR) studies are proposed to realize the benefits obtainable from the high-humidity performance of the spectrometer that has been perfected to overcome a great deal of difficulties. Pressure-broadening of the 183-GHz line uniquely identifies monomer behavior (see Table 6). A comparative study of wing (f_0 ±6 GHz) and far-wing (220 GHz) responses to T and v(RH) variations would allow an apportioning of local line (known) and continuum (unknown) contributions.

6. ACKNOWLEDGMENTS

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APPENDIX A

THE REFRACTIVE INDEX OF THE NEUTRAL ATMOSPHERE FOR FREQUENCIES UP TO 1000 GHz

Hans J. Liebe

A.1. INTRODUCTION

Dry air and atmospheric water vapor are major millimeter-wave absorbers; so are suspended droplets (haze, fog, cloud) and precipitating water drops that emanate from the vapor phase. A practical model (designated program code: MPM) was formulated that simulates the refractive index $\underline{n} = n' - jn''$ of the atmospheric propagation medium for frequencies up to 1000 GHz [1], [3]*. The main purpose of the program is to express the electromagnetic properties of the neutral atmosphere in terms of available and/or measurable quantities.

The free propagation of a plane electromagnetic wave at frequency f and an initial field strength E_0 in an isotropic gas medium over distance L is described by the complex transmission factor

$$\underline{\tau} \equiv E(L)/E_0 = \exp[-(2\pi f/c)(n'' + jn')L]$$

where n'(f) and n"(f) are frequency-dependent measures of delay and loss, and c is the speed of light in vacuum. Since the interaction with a neutral atmosphere is relatively weak, the refractive index is converted into a refractivity

$$\underline{N} = (\underline{n} - 1)10^6 \qquad \text{ppm},$$

in units of parts per million.

Refractivity N for moist air can be obtained, in principle, by a summation over all absorption features in a given volume element. In practice, various degrees of approximations are employed to reduce labor and computer time required, since the number of contributing spectral lines by the dominant absorbers (water vapor and oxygen) and by various trace gases (e.g., O_3) exceeds 10,000. The model MPM consists of local H_2O (30x) and O_2 (48x) lines

* [ ] See 7. REFERENCES in main text.

below 1 THz and an empirical approximation to the contributions by H_2O lines above 1 THz. To complete the model, continuum spectra for dry air, suspended water droplets (haze, fog, cloud), and rain are added. The supporting spectroscopic data base contains more than 450 coefficients.

A.1.1 Features of Program MPM

A parametric program was developed (see Section A.2) that calculates the values of the complex refractivity

$$\underline{N} = N_0 + N'(f) - jN''(f) \qquad \text{ppm}$$

or corresponding path-specific quantities of particular interest to radio engineering; i.e.,

refractive delay	β_0	ns/km,
dispersive delay	$\beta(f)$	ps/km, and
attenuation	$\alpha(f)$	dB/km;

for atmospheric conditions as a function of the variables f, P, T, RH, w_A (A/B/C/D), w, and R, as listed in the scheme below:

Variable	Symbol	Validity Range	Medium
frequency	f	≤ 1000 GHz	
barometric pressure temperature relative humidity	P T RH	120-0 kPa - 50- + 50°C 0-100%	Moist Air
haze model: code A, B, C, D (or combinations thereof) plus hygroscopic aerosol reference concentration	w_A(80%RH)	RH=80-99.9% 0-1 mg/m^3	Haze
suspended water droplet concentration	w(100%RH)	0-10 g/m^3	Fog, Cloud
rainfall rate	R	0-200 mm/h	Rain

The height range 30 to 100 km is treated approximately excluding the detailed O_2-Zeeman effect and trace gas spectra (e.g., O_3, CO, N_2O, etc.).

A.1.2 Physical Variables

The purpose of this section is to relate measurable variables to N model-specific variables, whereby the state of dry air is described by a partial air pressure p in kPa, a relative inverse temperature variable is $\theta = 300/(273.15 + T)$ with T in °C, and relative humidity is given by

$$RH = (e/e_s)100 = (v/v_s)100 = 4.151 \times 10^{-9}(e/\theta^5)\exp(22.64\theta) \leq 100\%. \qquad \text{(A-1)}$$

Equation (A-1) governs physical processes taking place in the atmosphere with respect to water vapor. Absolute (v) and relative (RH) humidity are interrelated through

$$v = 1.739 \times 10^9 RH\cdot\theta^5\exp(-22.64\theta) = 7.223\ e\ \theta \quad g/m^3 \qquad \text{(A-2)}$$

where e is the partial water vapor pressure in kPa as part of the total (barometric) pressure $P = p + e$.

Water vapor variability at sea level (e.g., P = 101 kPa, θ = 1.016 or 22°C) is typically

	Dry	Normal	Humid	Saturated
v	1	10	17	20g/m^3
RH	5	50	85	100 %

Suspended hydrometeors are described by the liquid water concentration w, which relates approximately to optical (0.55 μm) visibility U(km). A schematic categorization can be made by

	Haze	Fog	Stratus Cloud	Convective Cloud
w ≤	10^{-2}	10^{-1}	1	5 g/m^3
U ≥	1.1	0.27	0.07	0.03 km

Another atmospheric ingredient is hygroscopic aerosol with a mass concentration w_A in mg/m^3. Solution droplets appear for RH > 80%, and haze conditions develop as RH approaches 100 percent. The growing haze droplets can reach values ($w < 0.1$ g/m^3) sufficient to contribute to medium losses. Haze conditions are modeled by assuming that at the reference humidity, RH = 80%, the concentration w_A(RH=80%) is known. Any RH-dependent swelling/shrinking of w(RH) up to RH=99.9% is modeled by

$$w = w_A(C1-RH)/C2(100-RH) = w_A\, g(RH), \qquad (A-3)$$

where g(RH) is a growth function. The following values have been reported for C1, C2:

Case	Aerosol Species	C1	C2	g(RH=99.9%)
A	Rural	117	1.87	91
B	Urban	128	2.41	117
C	Maritime	183	5.31	162
D	C + Strong Wind (>10 km/h)	197	5.83	167

Average values of w_A for given stabilized climatic situations can be found in the literature. Typical values for w_A lie between 0.01 and 0.5 mg/m^3 and the increase to w can be substantial as indicated by the maximum prefog values g(99.9%).

Precipitation originates as a statistical event within clouds suspended in saturated air. Its vertical distribution is separated into two regions by the height of the 0°C isotherm, which can vary between 6 km and ground level depending on season and latitude. The lower part is mostly liquid drops, and the upper region consists of frozen particles with occasional supercooled droplet loadings by strong updrafts.

Point rain rates R have proven useful in modeling rain-induced $\underline{N}$ effects. Rain rate can be related to percent time, t_R, a given value occurs over the period of an "average" year; to the effective rain cell extent L_R/L; and to the instaneous suspended liquid water concentration,

$$w_R = m\,R \qquad g/m^3.$$

In terms of these variables, an hypothetical local rain may be classified as follows (horizontal path, L = 10 km):

	Drizzle	Steady	Heavy	Downpour	Cloudburst	
R	1	5	20	100	250	mm/h
t_R	2	0.5	0.07	0.001	0.0001	% per yr
L_R/L	1	1	0.7	0.35	0.2	
m	0.1	0.07	0.05	0.04	0.04	

These numbers may differ substantially for given locations.

The simple coefficient scheme reveals some fundamentals of rain. Changes in the factor m indicate rain rate-dependent characteristics of drop-size distributions. Widespread steady rain occurs more uniformly and favors small drop sizes (≤1 mm diameter) that stay in the air longer. Heavy showers are more localized, favor larger drops, and occur less frequently.

A.2. MODEL FOR COMPLEX REFRACTIVITY

The complex refractivity in N units (i.e., ppm ≡ 10^{-6})

$$\underline{N}(f;P/T/RH,w_A/w,R) = N_o + N'(f) - jN''(f) \quad \text{ppm} \qquad \text{(A-4)}$$

is a macroscopic measure of interactions between radiation and absorbers. The refractivity consists of a frequency-independent term N_o plus various spectra of refractive dispersion N'(f) and absorption N"(f).

In radio engineering it is customary to express the imaginary part of (A-4) as power attenuation α and the real part as group delay β (with reference to vacuum) as follows:

$$\alpha = 0.1820\ f\ N''(f) \quad \text{dB/km} \qquad \text{(A-5a)}$$

and

$$\beta = 3.336[N_o + N'(f)] \quad \text{ps/km}, \qquad \text{(A-5b)}$$

where frequency f is in gigahertz (GHz) throughout.

Radio refractivity is defined to be $\underline{N} = N_o$ at f = 0 and consists of four terms; i.e.,

$$N_o = N_p^o + N_e^o + N_w^o + N_R^o.$$

The individual contributions are described for dry air by

$$N_p^o = 2.588\ p\ \theta, \tag{A-6}$$

for water vapor by

$$N_e^o = 2.39\ e\ \theta + 41.6\ e\ \theta^2, \tag{A-7}$$

for the SWD term N_w^o by (A-16c), and for the rain term N_R^o by (A-18c). The results (A-6) and (A-7) have been determined experimentally at microwave frequencies where dispersive contributions N(f) are negligible.

A calculation of the spectrum $\underline{N}(f)$ for frequencies up to 1000 GHz consists of several additive parts:

- resonance information of n_a=48 oxygen lines and n_b=30 water vapor lines
- nonresonant O_2 and pressure-induced N_2 absorption ($\underline{N}_p$)
- continuum absorption from far-wing contributions of strong H_2O lines falling in the frequency range 1-30 THz ($\underline{N}_e$)
- suspended water droplet SWD term ($\underline{N}_w$)
- rain-effect approximation($\underline{N}_R$)

Absorption and dispersion spectra are obtained from line-by-line calculations plus various continuum spectra $\underline{N}_{p,e,w,R}$ according to

$$N''(f) = \underbrace{\sum_{i=1}^{n_a} (SF'')_i + N''_p}_{\text{Dry Air}} + \underbrace{\sum_{i=1}^{n_b} (SF'')_i + N''_e}_{\cdot\text{Water Vapor}} + \underbrace{N''_w}_{\cdot\text{SWD}} + \underbrace{N''_R}_{\cdot\text{Rain}} \tag{A-8a}$$

$$N'(f) = \sum_{i=1}^{n_a} (SF')_i + N'_p + \sum_{i=1}^{n_b} (SF')_i + N'_e + N'_w + N'_R \tag{A-8b}$$

where S is the line strength in kilohertz, and F' and F" are real and imaginary parts of a line shape function in GHz^{-1}.

A.2.1 Local Line Absorption and Dispersion

The Van Vleck-Weisskopf function is modified to describe to first-order line overlap effects, which leads to local absorption and dispersion line profiles in the form and

$$F''(f) = \left[\frac{1}{X} + \frac{1}{Y} - \frac{\delta}{\gamma}\left(\frac{\nu_o - f}{X} + \frac{\nu_o + f}{Y}\right)\right] A \qquad \text{(A-9a)}$$

$$F'(f) = \frac{Z - f}{X} + \frac{Z + f}{Y} - \frac{2}{\nu_o} + \delta\left(\frac{1}{X} - \frac{1}{Y}\right) A \qquad \text{(A-9b)}$$

with the abbreviations $A = \gamma f/\nu_o$,

$$X = (\nu_o - f)^2 + \gamma^2, \qquad Y = (\nu_o + f)^2 + \gamma^2, \qquad Z = (\nu_o^2 + \gamma^2)/\nu_o \ .$$

Standard line shapes $F''(f)$, including the modified Van Vleck-Weisskopf function (A-9), predict in frequency regions of local line dominance about the same results for $N''(f)$ as long as $F''(f)$ exceeds by 0.1% the peak value at $f = \nu_o$. Far-wing contributions of smaller magnitude depend very much upon the chosen shape function. For $f \to \infty$, the wing response of (A-9a) becomes non-physical and is cut off; i.e., $F'' = 0$ when $f \geq (\nu_o + 40\gamma)$. So far, no line shape has been confirmed that predicts absorption intensities over ranges 10^{-3} to $< 10^{-6}$ of $F''(\nu_o)$. Far-wing contributions from strong infrared water vapor lines, where $\alpha(\nu_o)$ can exceed 10^6 dB/km, are accounted for summarily by empirical correction [see (A-15a)].

The line parameters are calculated by the expressions below:

Symbol	O_2 Lines in Air	H_2O Lines in Air	Eq.
S, kHz	$a_1 p\ \theta^3 \exp[a_2(1-\theta)]$	$b_1 e\ \theta^{3.5} \exp[b_2(1-\theta)]$	(A-10)
γ, GHz	$a_3(p\theta^{(0.8-a_4)} + 1.1e\theta)$	$b_3(p\theta^{0.6} + 4.80e\theta^{1.1})$	(A-11)
δ	$a_5 p\ \theta^{a_6}$	0	(A-12)

Line center frequencies ν_o and the spectroscopic coefficients $a_1(\geq 10^{-7}$ Hz/Pa) to a_6 and $b_1(\geq 10^{-3}$ Hz/Pa) to b_3 for strength S, width γ, and overlap correction δ are listed in the Line Data File of MPM (see Appendix B).

For the O_2 lines in air, (A-9) to (A-12) are valid for altitudes $h \leq 35$km ($p > 0.7$ kPa), where lines are pressure-broadened. Higher up, Zeeman-splitting and Doppler-broadening of the Zeeman components must be taken into account (Liebe and Gimmestad, 1978). An estimate for $h > 35$ km is made by geometrically adding to the pressure proportional width γ_a in (A-11) a second term

$$\gamma_h = \left[\gamma_a^2 + (25H)^2\right]^{0.5} \quad \text{GHz} \qquad \text{(A-11a)}$$

where H is the scalar Earth magnetic field strength in Tesla, ranging from 0.2 to 0.9 x 10^{-4}. The O_2 spectrum vanishes around H ≈ 90 km.

For the H_2O lines in air, Doppler-broadening has to be considered at altitudes above 60 km (p < 0.07 kPa). An approximation is made by replacing the width γ_b in (A-11) with

$$\gamma_h = (\gamma_b^2 + \gamma_D^2)^{0.5} \quad \text{GHz} \qquad \text{(A-11b)}$$

where $\gamma_D^2 = 2.14\nu_o^2 \times 10^{-12}/\theta$ is the squared Doppler width. In applications requiring the detailed mesospheric line shape it is necessary to apply the more correct Voigt line shape.

A.2.2 Continuum Spectra for Air

Continuum spectra in (A-8) identify dry air and water vapor terms $\underline{N}_p + \underline{N}_e$ and must be added to the selected group of local (MPM) O_2 and H_2O resonance lines described by (A-9). Continuum absorption increases monotonically with frequency.

The dry air continuum

$$N_p''(f) = f\left(2a_o\{\gamma_o[1 + (f/\gamma_o)^2]\}^{-1} + a_p p\, \theta^{1.5}\right) p\theta^2 \qquad \text{(A-12a)}$$

and

$$N'_p(f) = a_o\{[1 + (f/\gamma_o)^2]^{-1} - 1\}\ p\ \theta^2 \qquad \text{(A-12b)}$$

make a small contribution at ground level pressures due to the nonresonant O_2 spectrum below 10 GHz and a pressure-induced N_2 spectrum that is effective above 100 GHz. A width parameter for the Debye spectrum of O_2 is formulated in accordance with (A-11) to be $\gamma_o = 4.8 \times 10^{-3}(p + 1.1e)\theta^{0.8}$(GHz) [10]. The continuum coefficients are $a_o = 3.07 \times 10^{-4}$ and $a_p = 1.40(1-1.2f^{1.5}10^{-5})10^{-10}$.

Water vapor continuum absorption has been a major source of uncertainty in predicting millimeter-wave attenuation, especially in the window ranges. Moist-air attenuation α at a frequency that falls within a window can be expressed by

$$\alpha = k_s(T)e^2 + k_f(T)e\ p + k_d(T)p^2 . \qquad \text{(A-13)}$$

A series of controlled laboratory measurements was performed at 137.8 GHz to determine the k-coefficients. Data $\alpha(T,e,p)$ were taken covering the following range of parameters:

temperature	$T = 8$ to 43 °C
vapor pressure	$e = 0$ to e_1(RH ≤ 95%) and
total pressure	$P = e_1 + p$, where $p = 0$ to 150 kPa.

Experimental data were reduced to a reference temperature $T_o = 26.85$ °C ($\theta = 1$). The temperature dependence of each k-coefficient ($k_{s,f,d}$) was fitted to a power law $k(T) = k\theta^x$. Moist-air attenuation at $f_x = 137.8$ GHz behaved as follows:

$$k_s = 0.133(4)\theta^{10.3(3)}, \quad k_f = 5.68(5)10^{-3}\theta^{3.0(4)}, \quad k_d = 2(1)10^{-6}\theta^3. \qquad \text{(A-14)}$$

Values in parentheses give the standard deviation from the mean in terms of final listed digits. The experimental results (A-14) contain foremost contributions from water vapor continuum absorption and were used to "calibrate" MPM by enforcing agreement between experimental and predicted data; further, an f^2 dependence was assumed.

The water vapor continuum is derived from fitting experimental data (A-14) in the case of

$$N_e''(f) = f(b_f p + b_e e)e\ \theta^3 \qquad \text{(A-15a)}$$

and based on theoretical data in the case of

$$N_e'(f) = f^2 b_o e\ \theta^3 , \qquad \text{(A-15b)}$$

where

$$b_f = 1.13 \times 10^{-6},$$
$$b_e = 3.57 \times 10^{-5}\theta^{7.5}, \text{ and}$$
$$b_o = 6.47 \times 10^{-6} .$$

In summary, (A-15) is needed to supplement local line (MPM) contributions, the coefficient b_f is valid only for the selected local line base treated with line shape (A-9), and the strong self-broadening component $b_e e^2$ is nearly unaffected by (A-9). The coefficient b_0 and both exponents in (A-15b) were obtained by fitting dispersion results of line-by-line calculations for the rotational H_2O spectrum above 1 THz.

A.2.3 Suspended Water Droplet Continuum (Haze, Fog, Cloud)

Suspended water droplets (SWD) in haze, fog, or clouds are millimeter wave absorbers. Their size range of radii is below 50 µm, which allows the Rayleigh approximation of Mie scattering theory to be used for calculating refractivity contributions $\underline{N}_w$ to (A-8) in the form [14] (see p. 73)

$$N_w''(f) = (9/2)w/\varepsilon''(1 + \eta^2), \qquad \text{(A-16a)}$$

$$N_w'(f) = (9/2)w\ [1/(\varepsilon_0 + 2) - \eta/\varepsilon''(1 + \eta^2)], \qquad \text{(A-16b)}$$

and

$$N_w^0 = (3/2)w\ [1 - 3/(\varepsilon_0 + 2)], \qquad \text{(A-16c)}$$

where $\eta = (2 + \varepsilon')/\varepsilon''$; ε', ε'' are real and imaginary, and ε_0 static parts of the permittivity for water. The contribution of (A-16c) is added to equation (A-6).

Values for the dielectric spectra $\underline{\varepsilon}(f)$ of water are calculated with a new double-Debye model [15]:

$$\varepsilon'(f) = \varepsilon_2 + (\varepsilon_0 - \varepsilon_1)/[1 + (f/f_D)^2] + (\varepsilon_1 - \varepsilon_2)/[1 + (f/f_S)^2], \qquad \text{(A-17a)}$$

$$\varepsilon''(f) = f\ (\varepsilon_0 - \varepsilon_1)/f_D[1 + (f/f_D)^2] + (\varepsilon_1 - \varepsilon_2)/f_S[1 + (f/f_S)^2]\ , \qquad \text{(A-17b)}$$

$$\varepsilon_0 = 77.66 + 103.3(\theta - 1), \qquad \text{(A-17c)}$$

where $\varepsilon_1 = 5.48$, $\varepsilon_2 = 3.51$,

$$f_D = 20.09 - 142(\theta - 1) + 294(\theta - 1)^2 \quad \text{GHz, and}$$
$$f_S = 590 - 1500(\theta - 1) \quad \text{GHz.}$$

Equation (A-17) is valid for frequencies up to 1000 GHz over a temperature range from -10 to +30 °C.

A.2.4 Rain Effects

The refractivity of rain is identified in (A-8) by $\underline{N}_R = N'_R + jN''_R$. Drop diameters (0.1 - 6 mm) and millimeter wavelengths are comparable, thus causing appreciable interactions due to Mie absorption and scattering. Bypassing elaborate, lengthy Mie calculations which require drop shape and size distributions as well as the complex dielectric properties of water (A-17), rain refractivity spectra are approximated via (see p. 73)

$$N''_R(f) = aR^b \tag{A-18a}$$

$$N'_R(f) = -N^o_R\,[x^{2.5}/(1 + x^{2.5})] \tag{A-18b}$$

$$N^o_R = R(3.68 - 0.012R)/f_R \tag{A-18c}$$

where $f_R = 53 - R(370 - 1.5R)10^{-3}$ GHz and $x = f/f_R$.

Frequency-dependent coefficient a and exponent b were calculated using drop size spectra of Laws and Parsons and a temperature of T = 0 °C. A regression fit to individual (a,b)-pairs over the frequency range from 1 to 1000 GHz resulted in the following calculation scheme:

$a = x_1 f^{x_2}$			$b = x_3 f^{x_4}$		
f	x_1	x_2	f	x_3	x_4
GHz			GHz		
1 to 2.9	3.51×10^{-4}	1.03	1 to 8.5	0.851	0.158
2.9 to 54	2.31×10^{-4}	1.42	8.5 to 25	1.41	-0.0779
54 to 180	0.225	-0.301	25 to 164	2.63	-0.272
180 to 1000	18.6	-1.151	164 to 1000	0.616	0.0126

A.3. CONCLUSIONS

The parametric model MPM for atmospheric refractivity

$$\underline{N}(f,P/T/RH,\ w_A/w,R)$$

was developed for applications in areas such as telecommunications, remote sensing, and radio astronomy. Details of its structure and operation are explained in the extensive COMMENTS part of the code. The memory capacity required for MPM is 355 kbytes.

The format of the numerical print-out is demonstrated by the identical example given in Table A-1 for the $\underline{N}$ version and in Table A-2 for the α/β version. A plotting system at the user's choice (e.g., HALO) can be added to include features such as auto or manual scaling, multiple cases (e.g., nine curves with up to 500 points each), special labels, etc. An example of a graphical presentation for a sea level condition of moist air (w_A = w = R = 0) exhibits spectra at various relative humidities (RH = 0-100%) for the $\underline{N}$ version in Figure A-1 and for the identical case as α/β version in Figure A-2.

A.4. ADDITIONAL REFERENCE

Liebe, H. J. and G. G. Gimmestad (1978), Calculation of clear air refractivity, Radio Science 20, no. 2, pp. 245 - 251.

Table A-1.

FREQUENCY PROFILES OF ATMOSPHERIC COMPLEX REFRACTIVITY

INPUT Valid Parameter ranges indicated by [ ]):

CASE	PRES.,P (kPa)	TEMP.,T (C)	REL. HUM.,RH (%)	HAZE MODEL (mg/m3)	SUSP. DROP.,w (g/m3)	RAIN RATE,R (mm/hr)
[1-9]	[0 -110]	[+/-50]	[0-100]	[0-1]	[0-10]	[0-200]
1	101.3	15.0	100.0	: 0.00	1.000	10.0

Minimum Frequency F1 0.000 (GHz)
Maximum Frequency F2 [1000.]1000.000 (GHz)
Frequency Step [max 500] dF 100.000 (GHz)

OUTPUT:
Case Number: 1 (No = 351.18 ppm)

MOIST AIR (v= 12.81 g/m3)

FREQUENCY (GHz)	DRY AIR +	WATER VAPOR +	HAZE, FOG CLOUD +	RAIN	= TOTAL
	N''-IMAGINARY PART (ppm) / N'-REAL PART (ppm)				
0.000	+++++++++	+++++++++	+++++++++	+++++++++	+++++++++
	0.220E-09	-.317E-07	0.278E-08	0.431E-08	-.244E-07
100.000	0.168E-02	0.454E-01	0.242E+00	0.317E+00	0.607E+00
	-.219E+00	0.321E+00	-.139E+00	-.226E+00	-.264E+00
200.000	0.476E-03	0.149E+00	0.288E+00	0.190E+00	0.629E+00
	-.170E+00	0.107E+01	-.299E+00	-.266E+00	0.334E+00
300.000	0.561E-03	0.174E+00	0.284E+00	0.120E+00	0.579E+00
	-.162E+00	0.352E+01	-.391E+00	-.275E+00	0.269E+01
400.000	0.807E-03	0.481E+00	0.276E+00	0.869E-01	0.845E+00
	-.157E+00	0.619E+01	-.450E+00	-.278E+00	0.530E+01
500.000	0.104E-02	0.118E+01	0.268E+00	0.675E-01	0.152E+01
	-.162E+00	0.192E+02	-.495E+00	-.279E+00	0.183E+02
600.000	0.846E-03	0.225E+01	0.260E+00	0.549E-01	0.257E+01
	-.159E+00	-.172E+02	-.532E+00	-.280E+00	-.182E+02
700.000	0.977E-03	0.101E+01	0.252E+00	0.461E-01	0.131E+01
	-.157E+00	0.687E+01	-.563E+00	-.281E+00	0.587E+01
800.000	0.117E-02	0.112E+01	0.242E+00	0.396E-01	0.140E+01
	-.161E+00	-.635E+01	-.589E+00	-.281E+00	-.738E+01
900.000	0.101E-02	0.795E+00	0.232E+00	0.347E-01	0.106E+01
	-.159E+00	0.716E+01	-.611E+00	-.281E+00	0.611E+01
1000.000	0.103E-02	0.603E+01	0.223E+00	0.308E-01	0.628E+01
	-.159E+00	-.134E+02	-.629E+00	-.282E+00	-.145E+02

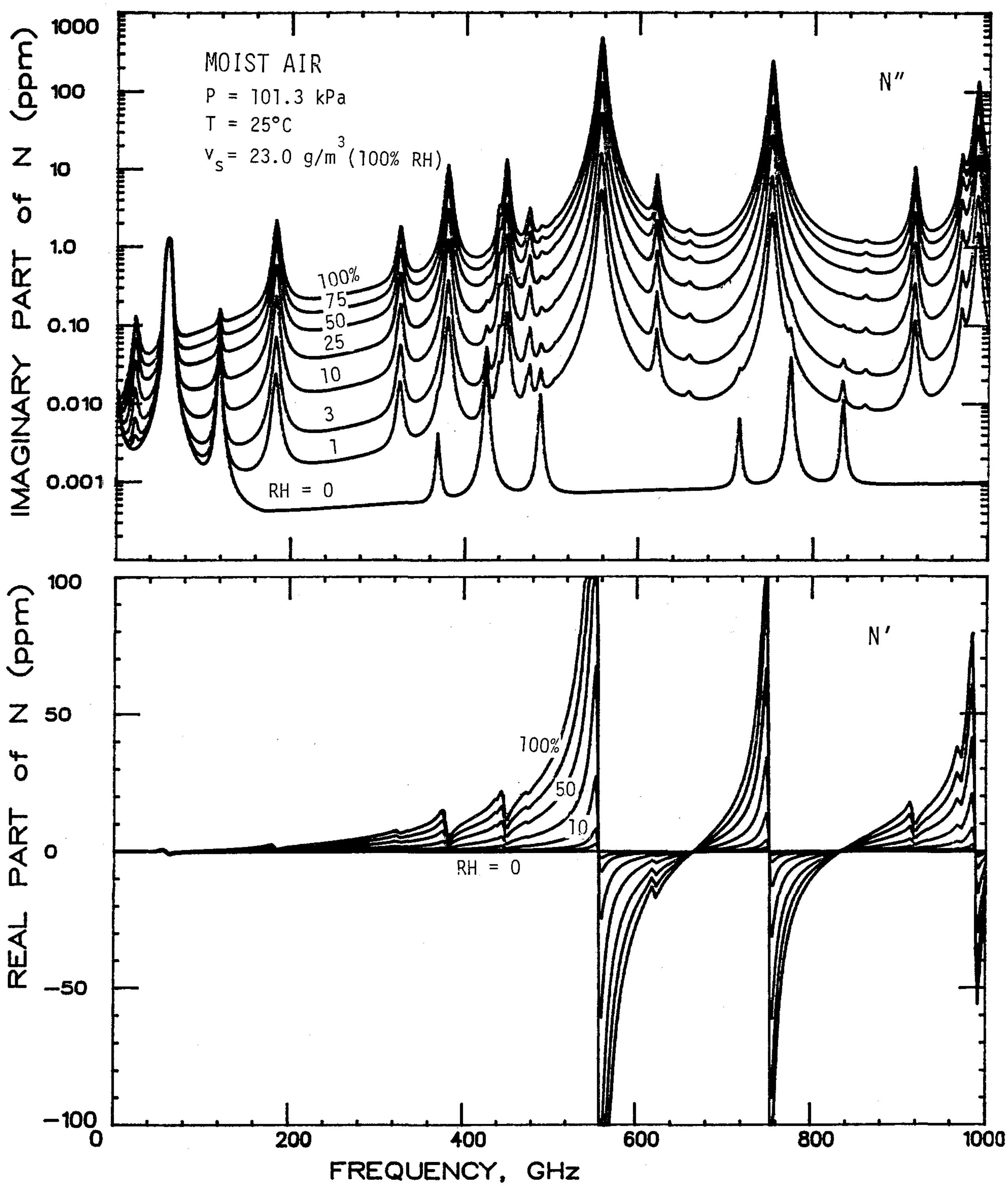

Figure A-1. Moist air refractivity $\underline{N} = N' - jN''$ for sea level condition (P,T) and various relative humidities (RH) over the frequency range from 0 to 1000 GHz.

Table A-2.

FREQUENCY PROFILES OF ATTENUATION AND DELAY RATES

INPUT Valid Parameter ranges indicated by [ ]):

CASE	PRES.,P (kPa)	TEMP.,T (C)	REL. HUM.,RH (%)	HAZE MODEL (mg/m3)	SUSP. DROP.,w (g/m3)	RAIN RATE,R (mm/hr)
[1-9]	[0 -110]	[+/-50]	[0-100]	[0-1]	[0-10]	[0-200]
1	101.3	15.0	100.0	: 0.00	1.000	10.0

Minimum Frequency F1 0.000 (GHz)
Maximum Frequency F2 [1000.]1000.000 (GHz)
Frequency Step [max 500] dF 100.000 (GHz)

OUTPUT:
Case Number: 1 (Refractive delay = 1171.5 ps/km)

MOIST AIR (v= 12.81 g/m3)

α - ATTENUATION (dB/km)
β - DISPERSIVE DELAY (ps/km)

FREQUENCY (GHz)		DRY AIR	+ WATER VAPOR	+ HAZE, FOG CLOUD	+ RAIN	= TOTAL
0.000	α	0.00	0.00	0.00	0.00	0.00
	β	0.00	0.00	0.00	0.00	0.00
100.000	α	0.03	0.83	4.41	5.78	11.05
	β	-0.73	1.07	-0.46	-0.75	-0.88
200.000	α	0.02	5.44	10.50	6.93	22.88
	β	-0.57	3.56	-1.00	-0.89	1.11
300.000	α	0.03	9.50	15.52	6.57	31.62
	β	-0.54	11.75	-1.30	-0.92	8.99
400.000	α	0.06	35.02	20.11	6.32	61.51
	β	-0.52	20.64	-1.50	-0.93	17.68
500.000	α	0.09	107.25	24.43	6.14	137.92
	β	-0.54	64.18	-1.65	-0.93	61.06
600.000	α	0.09	246.00	28.44	6.00	280.53
	β	-0.53	-57.35	-1.77	-0.94	-60.59
700.000	α	0.12	128.84	32.07	5.87	166.91
	β	-0.52	22.92	-1.88	-0.94	19.58
800.000	α	0.17	162.65	35.28	5.77	203.87
	β	-0.54	-21.20	-1.96	-0.94	-24.63
900.000	α	0.17	130.27	38.08	5.68	174.20
	β	-0.53	23.88	-2.04	-0.94	20.37
1000.000	α	0.19	1097.36	40.50	5.61	1143.65
	β	-0.53	-44.84	-2.10	-0.94	-48.40

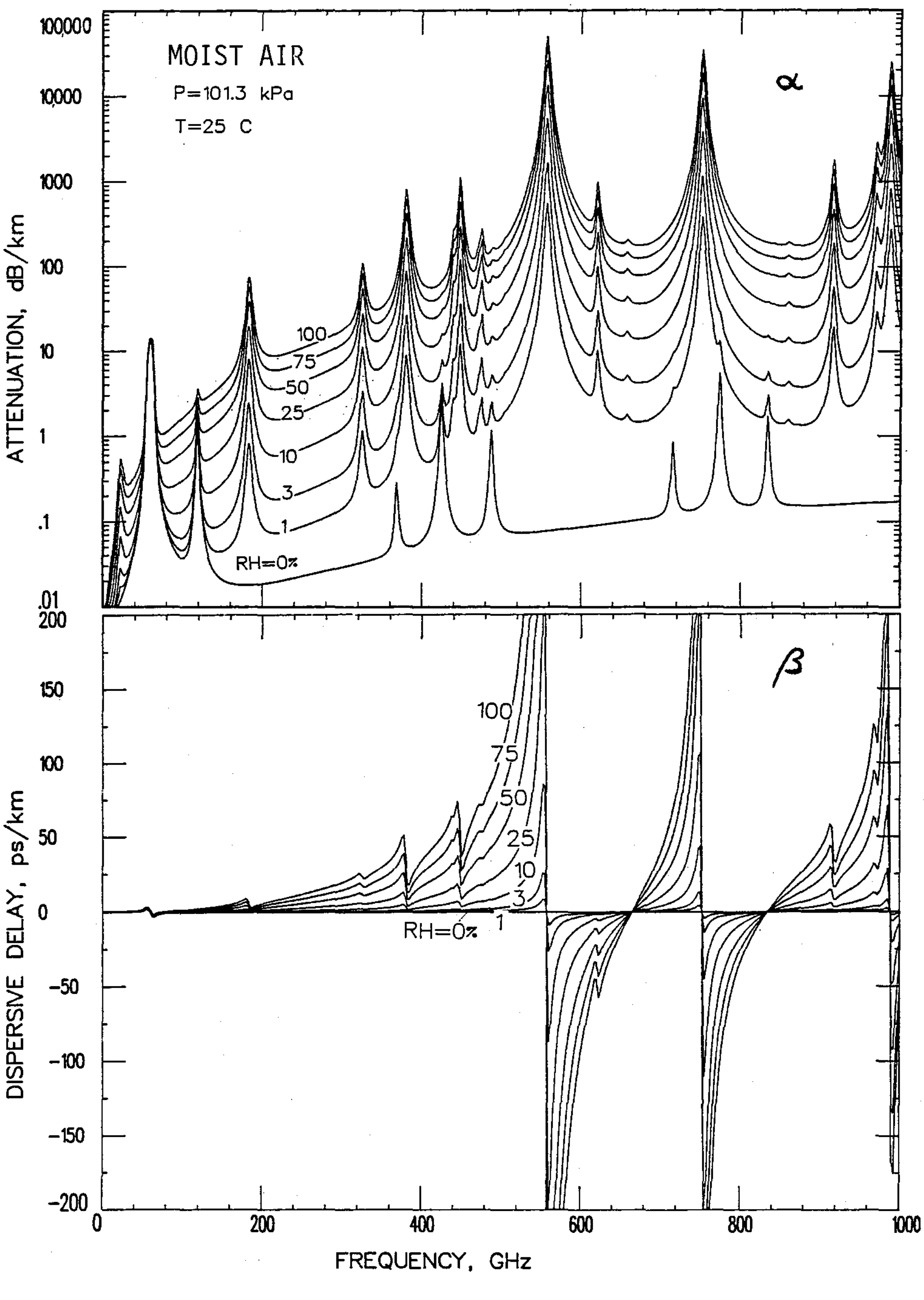

Figure A-2. Moist air attenuation (α) and delay (β) rates for sea level condition (P,T) and various relative humidities (RH) over the frequency range from 1 to 1000 GHz.

APPENDIX B

PRINTOUT OF MPM-N PROGRAM FOR VERSION A
(Frequency Profiles)

The computer program MPM-N is written in FORTRAN 77 with extensive comments to run on IBM-XT/AT + 8087/80287 coprocessor, or equivalent, microcomputers.

Program MPM-N is available on 5 1/4" diskettes, either in double (360 kbyte) or quadruple (1.2 Mbyte) density. Requests may be addressed to NTIA/ITS.S3, 325 Broadway, Boulder, CO 80303-3328 (ATTN: Dr. H. Liebe). Please provide the necessary disks.

ID for FORTRAN 77 (IBM Professional 8-bit compiler) version (disk No. 1):

MPM1	FOR	45675	7-16-87	-N/A Frequency Profiles
MPM2	FOR	29762	7-08-87	-N/B Humidity Profiles
MPM3	FOR	24564	6-11-87	-N/C Pressure Profiles
OXYGEN	DAT	3267	7-13-87	Line Data
WATER	DAT	1166	10-23-86	Tables
5 File(s)		254976 bytes free		

ID for EXECUTABLE version (disk No. 2):

MPM1	EXE	354565	7-08-87	-N/A Frequency Profiles
OXYGEN	DAT	3267	7-13-87	Line Data
WATER	DAT	1166	10-23-86	Tables
3 File(s)		1024 bytes free		

The executable code length for MPM2 and 3 is 402 and 356 kbyte, respectively.

```
C       PROGRAM MPM-N
C       AUGUST 1987
C------------------------------------------------------------------------
C       COMPLEX RADIO REFRACTIVITY OF ATMOSPHERIC AIR (1 TO 1000 GHz).
C       Hans J. Liebe
C       Institute for Telecommunication Sciences
C       NTIA/ITS.S3
C       325 BROADWAY
C       Boulder, CO  80303
C
C       Adapted for IBM-PC Professional FORTRAN  by:
C               John Stricklen   (1-303-497-3195, FTS 320-3195)
C
C       Contents:
C       A. FREQUENCY PROFILES
C       B. HUMIDITY  PROFILES
C       C. PRESSURES PROFILES OF MOIST AIR
C------------------------------------------------------------------------
C                    A. FREQUENCY PROFILES
C------------------------------------------------------------------------
C  Program MPM-N/A calculates frequency profiles of the complex radio
C  refractivity N of ATMOSPHERIC AIR over a frequency range f=1 to
C  1000 GHz. The output is expressed in Real part of N and
C  Imaginary part of N and specific rates of power attenuation A
C  (Im. of N) and propagation delay B (Re. of N).
C
C                         OUTPUT:
C         *  Real part of refractivity       N' (f)  in   ppm
C         *  Imaginary part of refractivity  N''(f)  in   ppm
C         *  Nondispersive Refractivity      No      in   ppm
C  or
C         *  Attenuation                     A(f)    in   dB/km
C         *  Dispersive Delay                B(f)    in   ps/km
C         *  Refractive Delay                Bo      in   ps/km
C
C
C  Frequency range, moist air, rain conditions (specified by five
C  meterological variables P=p+e, T, RH, wA or w, RR), and haze model
C  code (A, B, C, or D) are the required input information to be
C  entered from the keyboard.
C
C                         INPUT:                       Valid Range:
C         *  Frequency range      f1, f2   in GHz        1 to 1000
C              and step size        df     in GHz        >= 1.E-05
C                                                        (max. 500 freqs.)
C         *  Barometric pressure    P      in kPa        0.0  to 120
C         *  Temperature            T      in  C         -50 to 50
C         *  Relative humidity      RH     in  %         0 to 100
C             [absolute humidity is calculated as v(RH,T) in g/m3
C                                                or e(RH,T) in kPa.]
C         *  Haze model (RH = 80 to 99.9%):
C             code A(rural), B(urban), C(maritime), and D(C +strong wind)
C             plus hygroscopic aerosol reference
C             concentration       wA(80%RH) in mg/m3     0 to 1
C         *  Suspended water droplet
C             concentration         w       in g/m3      0 to 10
C         *  Rain Rate              RR      in mm/hr     0 to 200
C
C  COMMENTS:
```

```
C  The computation of attenuation A and delay B is described in
C  References [1] to [3].
C
C  MOLECULAR effects due to oxygen, nitrogen, and water vapor
C  are considered as detailed in [1].
C
C  This MPM version has been corrected for typesetting errors in [1]
C  and revised to include:
C  (a) an improved water vapor continuum spectrum and a haze model
C      reported in [2];
C  (b) an improved model for liquid water dielectric properties and
C      RAYLEIGH absorption and phase delay by suspended water droplets
C      (radii < 50 microns) such as haze, fog, and clouds [3];
C  (c) a rain attenuation model by Olsen, et.al. [4], as well as
C      dispersive delay due to rain approximated from results reported by
C      Zuffery [5];
C  (d) new line data for the 183 GHz water vapor line [6];
C  (e) a VW shape cutoff, setting F"=0 for f > (vo +40 x widths)  [7];
C  (f) a new set of overlap correction coefficients A5 [8];
C  (g) an improved water vapor saturation pressure equation based on
C      degrees Celsius [9] (see comments in program);
C  (h) an approximation for Zeeman (O2) and Doppler (H2O) line broadening [10].
C
C    REFERENCES:  [1] H.J. Liebe,"An updated model for millimeter wave
C                     propagation in moist air", Radio Science, vol. 20
C                     no. 5, pp. 1069-1089, 1985.
C
C                 [2] H.J. Liebe,"A contribution to modeling atmospheric
C                     mm-wave properties", FREQUENZ (J. Telecom.), vol.
C                     41 , no. 1/2, pp. 31-36, 1987.
C
C                 [3] H.J. Liebe, T. Manabe, and J.P. Stricklen,
C                     "Millimeter-wave attenuation and delay for a fog event",
C                     IEEE Digest: 12th Int. Conf. Infrared and Millimeter
C                     Waves, Orlando, FL, December, 1987.
C
C                 [4] R. L. Olsen, D. V. Rogers, and D. B. Hodge,
C                     "The aRb relation in the calculation of rain
C                     attenuation", IEEE Trans. Ant. Prop., vol. AP-26,
C                     no. 2, pp. 318-329, 1978.
C
C                 [5] C.H. Zuffery, "A study of rain effects on EM waves
C                     in the 1-600 GHz range", MS-THesis, Dept.
C                     Electrical Eng., University of Colorado, Boulder,
C                     CO 80309, Feb., 1972.
C
C                 [6] A. Bauer, M. Godon, and B. Duterage, "Self- and
C                     air-broadened linewidth of the 183 GHz absorption
C                     in water vapor", J. Quant. Spectrosc. Radiat.
C                     Transf., vol. 32, no. 2, pp. 167-175, 1985.
C
C                 [7] R. J. Hill, "Absorption by the tails of the oxygen
C                     microwave resonances at atmospheric pressures", IEEE
C                     Trans. AP-35, no.2, pp. 198-204, 1987.
C
C                 [8] P. W. Rosenkranz, "Interference coefficients for
C                     overlapping oxygen lines in air", J. Quant. Spectr.
C                     Rad. Transf., in review, 1987.
C
C                 [9] W. Boegel, "Neue Naeherungsgleichungen fuer den
C                     Saettigungsdruck des Wasserdampfes, DFVLR Bericht
C                     DLR-FB 77-52, 1977.
C
```

```
C
C                [10] H. J. Liebe and G. B. Gimmestad, "Calculation of
C                     clear air EHF refractivity", Radio Sci., vol. 13,
C                     no. 2, pp. 245-251, 1978.
C------------------------------------------------------------------
C
C******* LIST OF VARIABLES *********
C
C       FMIN    Minimum Frequency
C       FMAX    Maximum frequency
C       STEP    Step Size between frequencies.
C       NF      No. of frequencies.
C       NCASE   No. of cases.
C       PBT(10) Pressures
C       TCT(10) Temperatures.
C       RHT(10) Rel. Humidities
C       WT(10)  Droplet concentrations.
C       RR(10)  Rain Rate
C       HZ(10) Haze growth models.
C*********************************************************************
C       MAIN PROGRAM
C*********************************************************************
C
        COMMON /AIR/ NCASE,PBT(10),TCT(10),RHT(10),WT(10),R(10)
        COMMON /FREQS/ FMIN,FMAX,STEP,NF
        COMMON /RAIN/ RR(10),WA(10)
        COMMON /ANS1/ D(12,501,10),ATT(501,10),DISP(501,10)
        COMMON /ANS/ FREQA(501),No(10),Bo(10),EV(10)
        COMMON /O2line/ F0O2(48),A(6,48)
        COMMON /H2O/ F0water(30),B(3,30)
        COMMON /HAZE/ HZ(10)
        CHARACTER*1 HZ
C
C*********************************************************************
C
        WRITE(*,1101)
1101    FORMAT(//////////)
        WRITE(*,2)
2       FORMAT(80(1H*),/,5X,' Executing PARAMETRIC ATTENUATION and ',
     + 'DISPERSIVE DELAY Program',/,80(1H*))
        WRITE(*,4)
4       FORMAT(///)
C
C ****** INITIALIZE ALL DATA VALUES ***************
C
C         OXYGEN LINE DATA
        CALL OXYDA1
C         WATER VAPOR LINE DATA
        CALL VAPDA1
        NCASE=1
        FMIN=10.
        FMAX=100.
        STEP=10.
C  STANDARD SEA LEVEL CONDITIONS FOR PRESSURE, TEMP., AND HUMIDITY
        DO 3 I=1,10
        PBT(I)=101.3
        TCT(I)=15.0
        RHT(I)=50.
        HZ(I)=' '
3       CONTINUE
C
C*****************************************************
C
10      CALL MENU(IMENU)
        IF (IMENU.EQ.1) THEN
          CALL INSTR
        ELSE IF (IMENU.EQ.2) THEN
          CALL EDITSUMM(1)
        ELSE IF (IMENU.EQ.3) THEN
          CALL SAVETABL(2)
        ELSE IF (IMENU.EQ.4) THEN
          CALL COMPUTE(NCASE)
        ELSE IF (IMENU.EQ.5) THEN
          CALL SAVETABL(0)
        ELSE IF (IMENU.EQ.6) THEN
          CALL SAVETABL(1)
        ELSE IF (IMENU.EQ.7) THEN
          WRITE(*,*)'Quitting Program... Normal termination.'
        GOTO 20
        ELSE
          WRITE(*,*)'NOT a valid menu option.'
        ENDIF
        GOTO 10
20      STOP
        END
C------------------------------------------------------------------
        SUBROUTINE INSTR
        WRITE(*,1)
1       FORMAT(///)
        WRITE(*,*)'The menu options are:'
        WRITE(*,*)'1)  Instructions'
        WRITE(*,*)'2)  Edit Data'
        WRITE(*,*)'3)  Summary of current data'
        WRITE(*,*)'4)  Process Data'
        WRITE(*,*)'5)  Print Results'
        WRITE(*,*)'6)  Save results to Disk'
        WRITE(*,*)'7)  Quit'
        WRITE(*,*)
        WRITE(*,*)'1)  You have found the instruction set.'
        WRITE(*,*)
        WRITE(*,*)'2)  The input data includes the frequency range and'
        WRITE(*,*)'    step, the parameter that you wish to vary, the'
        WRITE(*,*)'    number of cases and the values of pressure,'
        WRITE(*,*)'    temperature, relative humidity, and rain rate.'
        WRITE(*,*)'    For RH = 80 to 99.9%, a haze model predicts for'
        WRITE(*,*)'    four cases (A=rural, B=urban, C=maritime, and'
        WRITE(*,*)'    D=C+strong wind) the shrinking and swelling by'
        WRITE(*,*)'    hygroscopic aersol concentrations specified at'
        WRITE(*,*)'    80% RH.  At 100% RH a suspended water droplet'
        WRITE(*,*)'    concentration can be added to simulate fog or'
        WRITE(*,*)'    cloud conditions.'
        WRITE(*,*)
        WRITE(*,*)'    The value that appears in parentheses () is the'
        WRITE(*,*)'    default value and will be used if you simply '
        WRITE(*,*)'    press the RETURN key.  To enter a new value'
        WRITE(*,*)'    type the value and press the RETURN key.'
        WRITE(*,*)
        WRITE(*,*)'    The computer will ask you which parameter you'
```

```
      WRITE(*,*)'    wish to vary and you should type P, R, or T'
      WRITE(*,*)'    for Pressure, Relative humidity, or Temperature'
      WRITE(*,*)'    respectively.  The other two parameters will'
      WRITE(*,*)'    be fixed at the same value for every case'
      WRITE(*,*)'    and you will be prompted for these values.'
      WRITE(*,*)'    You will then be prompted for a value of your'
      WRITE(*,*)'    selected parameter for each separate case.'
      WRITE(*,*)'    For every case in which the relative humidity'
      WRITE(*,*)'    is 100% you will be prompted to enter a value'
      WRITE(*,*)'    for the suspended droplet concentration, and '
      WRITE(*,*)'    for cases in which the humidity is above 80%'
      WRITE(*,*)'    you will be asked for a hygroscopic aerosol'
      WRITE(*,*)'    content at 80%.  This is used to calculate the'
      WRITE(*,*)'    water droplet content using the haze growth'
      WRITE(*,*)'    model of [2].'
      WRITE(*,*)
      WRITE(*,*)'    The units on the parameters are:'
      WRITE(*,*)'    Pressure in kPa.  '
      WRITE(*,*)'    Relative Humidity in %'
      WRITE(*,*)'    Temperature in degrees C'
      WRITE(*,*)'    Water Droplet concentration in grams/meter'
      WRITE(*,*)'    cubed'
      WRITE(*,*)'    Rain rate in millimeters per hour'
      WRITE(*,*)'    These are given in the prompt'
      WRITE(*,*)
      WRITE(*,*)'3)  This gives a summary of all the current input'
      WRITE(*,*)'    data.  It is a good idea to request a summary'
      WRITE(*,*)'    after you edit the data to make sure that all'
      WRITE(*,*)'    of the decimals are in the right place etc.'
      WRITE(*,*)
      WRITE(*,*)'4)  This option causes the data to be used to '
      WRITE(*,*)'    generate a table of attenuation and dispersion.'
      WRITE(*,*)'    This must be done every time you change the '
      WRITE(*,*)'    data to update the table.'
      WRITE(*,*)
      WRITE(*,*)'5)  The table of attenuation and dispersion will be'
      WRITE(*,*)'    printed to the console.  To make a hard copy you'
      WRITE(*,*)'    may use the CTRL-PRTSC key or to make a disk'
      WRITE(*,*)'    file you can use the menu option given next'
      WRITE(*,*)'    and print the file.  The output is in tabular'
      WRITE(*,*)'    form with the components of the total'
      WRITE(*,*)'    attenuation and dispersion shown in two lines'
      WRITE(*,*)'    with the attenuation above the dispersion.'
      WRITE(*,*)
      WRITE(*,*)'6)  This saves the results to a file you specify.'
      WRITE(*,*)
      WRITE(*,*)'7)  This stops program execution.'
      WRITE(*,1)
      RETURN
      END
C-----------------------------------------------------------------------


C-----------------------------------------------------------------------
      SUBROUTINE MENU(IMENU)
C
      CHARACTER*1 IVAL
      WRITE(*,1)
1     FORMAT(' Enter the number of the option you wish to choose.,'/,
     +        /,'   1 - Instructions',
     +        /,'   2 - Edit Data',
     +        /,'   3 - Summary of current data',
     +        /,'   4 - Process Data',
     +        /,'   5 - Print Results ',
     +        /,'   6 - Save output to Disk file',
     +        /,'   7 - Quit',//)
C
100   WRITE(*,2)
2     FORMAT(' OPTION ? ')
      READ(*,3) IVAL
3     FORMAT(A1)
      IF((IVAL.EQ.'1').OR.(IVAL.EQ.'2').OR.(IVAL.EQ.'3').OR.
     + (IVAL.EQ.'4').OR.(IVAL.EQ.'5').OR.(IVAL.EQ.'6').OR.(IVAL.EQ.'7'))
     + THEN
      READ(IVAL,4,ERR=100) IMENU
4     FORMAT(I1)
      ELSE
      WRITE(*,*)'Invalid option.'
      GOTO 100
      ENDIF
      RETURN
      END
C-----------------------------------------------------------------------
      SUBROUTINE EDITSUMM(IFLAG)
C  THIS ROUTINE PRINTS SUMMARY AND/OR EDITS THE DATA.
C
C  IFLAG=1 IS FOR EDIT MODE--ANYTHING ELSE IS A SUMMARY.
C  NFLAG IS INDEX FOR PARAMETER VARIATION
C
      COMMON /AIR/ NCASE,PBT(10),TCT(10),RHT(10),WT(10),R(10)
      COMMON /FREQS/ FMIN,FMAX,STEP,NF
      COMMON /RAIN/ RR(10),WA(10)
      COMMON /HAZE/ HZ(10)
      CHARACTER*1 HZ
      CHARACTER*8 IVAL
C***************************************************
C
10    FORMAT(A8)
C
C  ZERO OUT THE DROPLET CONCENTRATIONS
      IF(IFLAG.EQ.1) THEN
      DO 100 I=1,10
      WT(I)=0.0
      HZ(I)=' '
100   CONTINUE
      ENDIF
200   CONTINUE
C ******  FREQUENCY DATA  **********************
300   WRITE(*,4) FMIN
4     FORMAT(' Minimum Frequency, GHz (',F7.2,') ')
      IF(IFLAG.EQ.1)THEN
        READ(*,10) IVAL
         IF(IVAL.EQ.' ')THEN
         GOTO 400
         ELSE
         READ(IVAL,8,ERR=300) FMIN
8         FORMAT(F8.0)
         ENDIF
C  CHECK FOR VALID RANGE ON FMIN
      IF((FMIN.GT.0.).AND.(FMIN.LE.1000.)) GOTO 400
      WRITE(*,*)'Minimum Freq. must satisfy 0 < FMIN <= 1000.'
      GOTO 300
```

```
C     LINE DATA FILES    (Table I in [1])
C     (read as separate data files by MPM)
C
C
CCoefficients A5 after Rosenkranz [8], for 118.75 GHz line after Hill [7]
C    FO                A1          A2          A3     A4       A5       A6
C  49.452379          0.12       11.830       8.40    0       6.600    1.7
C  49.962257          0.34       10.720       8.50    0       6.600    1.7
C  50.474238          0.94        9.690       8.60    0       6.600    1.7
C  50.987748          2.46        8.690       8.70    0       6.600    1.7
C  51.503350          6.08        7.740       8.90    0       6.627    1.8
C  52.021409         14.14        6.840       9.20    0       6.347    1.8
C  52.542393         31.02        6.000       9.40    0       6.046    1.8
C  53.066906         64.10        5.220       9.70    0       5.719    1.9
C  53.595748        124.70        4.480      10.00    0       5.400    1.8
C  54.129999        228.00        3.810      10.20    0       5.157    2.0
C  54.671157        391.80        3.190      10.50    0       4.783    1.9
C  55.221365        631.60        2.620      10.79    0       4.339    2.1
C  55.783800        953.50        2.115      11.10    0       4.011    2.1
C  56.264777        548.90        0.010      16.46    0       2.772    0.9
C  56.363387       1344.00        1.655      11.44    0       3.922    2.3
C  56.968180       1763.00        1.255      11.81    0       3.398    2.5
C  57.612481       2141.00        0.910      12.21    0       1.145    3.2
C  58.323874       2386.00        0.621      12.66    0       0.317   -2.5
C  58.446589       1457.00        0.079      14.49    0       6.270    0.8
C  59.164204       2404.00        0.386      13.19    0      -4.119    0.1
C  59.590982       2112.00        0.207      13.60    0       6.766    0.5
C  60.306057       2124.00        0.207      13.82    0      -6.183    0.7
C  60.434775       2461.00        0.386      12.97    0       3.290   -0.4
C  61.150558       2504.00        0.621      12.48    0      -1.591    3.5
C  61.800152       2298.00        0.910      12.07    0      -2.068    2.9
C  62.411212       1933.00        1.255      11.71    0      -4.158    2.3
C  62.486253       1517.00        0.078      14.68    0      -4.068    0.9
C  62.997974       1503.00        1.660      11.39    0      -4.482    2.2
C  63.568515       1087.00        2.110      11.08    0      -4.442    2.0
C  64.127764        733.50        2.620      10.78    0      -4.687    2.0
C  64.678900        463.50        3.190      10.50    0      -5.074    1.8
C  65.224067        274.80        3.810      10.20    0      -5.403    1.9
C  65.764769        153.00        4.480      10.00    0      -5.610    1.8
C  66.302088         80.09        5.220       9.70    0      -5.896    1.8
C  66.836827         39.46        6.000       9.40    0      -6.194    1.7
C  67.369595         18.32        6.840       9.20    0      -6.468    1.8
C  67.900862          8.01        7.740       8.90    0      -6.718    1.7
C  68.431001          3.30        8.690       8.70    0      -6.70     1.7
C  68.960306          1.28        9.690       8.60    0      -6.60     1.7
C  69.489021          0.47       10.720       8.50    0      -6.60     1.7
C  70.017342          0.16       11.830       8.40    0      -6.60     1.7
C 118.750341        945.00        0.000      16.30    0      -0.134    0.8
C 368.498350         67.90        0.020      19.20    0.6    0         1
C 424.763120        638.00        0.011      19.16    0.6    0         1
C 487.249370        235.00        0.011      19.20    0.6    0         1
C 715.393150         99.60        0.089      18.10    0.6    0         1
C 773.838730        671.00        0.079      18.10    0.6    0         1
C 834.145330        180.00        0.079      18.10    0.6    0         1
C
```

```
C
C Width B3 of 183, 325, and 380 GHz lines increased by 10% [6]
C  FO          B1        B2      B3
C  22.235080   0.1090   2.143   27.84
C  67.813960   0.0011   8.730   27.60
C 119.995940   0.0007   8.347   27.00
C 183.310117   2.3000   0.653   31.64
C 321.225644   0.0464   6.156   21.40
C 325.152919   1.5400   1.515   29.70
C 336.187000   0.0010   9.802   26.50
C 380.197372  11.9000   1.018   30.36
C 390.134508   0.0044   7.318   19.00
C 437.346667   0.0637   5.015   13.70
C 439.150812   0.9210   3.561   16.40
C 443.018295   0.1940   5.015   14.40
C 448.001075  10.6000   1.370   23.80
C 470.888947   0.3300   3.561   18.20
C 474.689127   1.2800   2.342   19.80
C 488.491133   0.2530   2.814   24.90
C 503.568532   0.0374   6.693   11.50
C 504.482692   0.0125   6.693   11.90
C 556.936002 510.0000   0.114   30.00
C 620.700807   5.0900   2.150   22.30
C 658.006500   0.2740   7.767   30.00
C 752.033227 250.0000   0.336   28.60
C 841.073593   0.0130   8.113   14.10
C 859.865000   0.1330   7.989   28.60
C 899.407000   0.0550   7.845   28.60
C 902.555000   0.0380   8.360   26.40
C 906.205524   0.1830   5.039   23.40
C 916.171582   8.5600   1.369   25.30
C 970.315022   9.1600   1.842   24.00
C 987.926764 138.0000   0.178   28.60
C
C
C
```

```
C
C*********************************************************************
C                             EXAMPLE FOR A.
C*********************************************************************
C
C        FREQUENCY PROFILES OF ATTENUATION AND DELAY RATES
C
C INPUT  Valid Parameter ranges indicated by [ ]):
C
C                                  REL.          HAZE     SUSP.    RAIN
C CASE    PRES.,P    TEMP.,T     HUM.,RH        MODEL    DROP.,w  RATE,R
C          (kPa)       (C)        (%)          (mg/m3)   (g/m3)  (mm/hr)
C [1-9] [0.0-110] [+/-50]      [0-100]         [0-1]    [0-10]   [0-200] MOIST AIR
C                                                                          +
C  1      101.3       15.0       99.5         C: 1.00   0.033      0.0    HAZE
C  2      101.3       15.0      100.0          : 0.00   1.000     10.0    FOG, RAIN
C
C Minimum Frequency F1              0.000 (GHz)
C Maximum Frequency F2 [1000.]1000.000 (GHz)
C Frequency Step [max 500] dF  100.000 (GHz)
C
C
C----------------------------------------------------------------
C OUTPUT:
C   Case Number:  1  (Refractive delay = 1164.49 ps/km)
C.              ------------------------------------------------
C                 MOIST AIR  (v= 12.74 g/m3)
C               DRY      WATER       HAZE, FOG
C               AIR   +  VAPOR    +  CLOUD +      RAIN     = TOTAL
C               ------------------------------------------------
C FREQUENCY                  ATTENUATION (dB/km)
C                                DISPERSIVE DELAY (ps/km)
C
C    (GHz)
C    0.000       0.00      0.00      0.00      0.00      0.00
C                 0.00      0.00      0.00      0.00      0.00
C  100.000       0.03      0.82      0.14      0.00      0.99
C                -0.73      1.06     -0.02      0.00      0.32
C  200.000       0.02      5.40      0.34      0.00      5.76
C                -0.57      3.55     -0.03      0.00      2.95
C  300.000       0.03      9.44      0.51      0.00      9.98
C                -0.54     11.69     -0.04      0.00     11.11
C  400.000       0.06     34.82      0.65      0.00     35.53
C                -0.52     20.53     -0.05      0.00     19.96
C  500.000       0.09    106.65      0.80      0.00    107.54
C                -0.54     63.86     -0.05      0.00     63.27
C  600.000       0.09    244.65      0.93      0.00    245.67
C                -0.53    -57.07     -0.06      0.00    -57.65
C  700.000       0.12    128.10      1.04      0.00    129.27
C                -0.52     22.80     -0.06      0.00     22.22
C  800.000       0.17    161.71      1.15      0.00    163.03
C                -0.54    -21.09     -0.06      0.00    -21.69
C  900.000       0.17    129.49      1.24      0.00    130.89
C                -0.53     23.76     -0.07      0.00     23.16
C 1000.000       0.19   1091.46      1.32      0.00   1092.96
C                -0.53    -44.61     -0.07      0.00    -45.21
C
```

```
C   Case Number:  2  (Refractive delay = 1169.10 ps/km)
C               ------------------------------------------------
C                 MOIST AIR  (v= 12.81 g/m3)
C               DRY      WATER       HAZE, FOG
C               AIR   +  VAPOR    +  CLOUD +      RAIN     = TOTAL
C
C               ------------------------------------------------
C FREQUENCY                  ATTENUATION (dB/km)
C                                DISPERSIVE DELAY (ps/km)
C
C    (GHz)
C    0.000       0.00      0.00      0.00      0.00      0.00
C                 0.00      0.00      0.00      0.00      0.00
C  100.000       0.03      0.83      4.41      5.77     11.04
C                -0.73      1.07     -0.46      0.00     -0.12
C  200.000       0.02      5.44     10.50      6.92     22.87
C                -0.57      3.56     -1.00      0.00      2.00
C  300.000       0.03      9.50     15.52      6.56     31.61
C                -0.54     11.75     -1.30      0.00      9.90
C  400.000       0.06     35.02     20.11      6.31     61.50
C                -0.52     20.64     -1.50      0.00     18.61
C  500.000       0.09    107.25     24.43      6.13    137.91
C                -0.54     64.18     -1.65      0.00     61.99
C  600.000       0.09    246.00     28.44      5.99    280.52
C                -0.53    -57.35     -1.77      0.00    -59.66
C  700.000       0.12    128.84     32.07      5.87    166.90
C                -0.52     22.92     -1.88      0.00     20.52
C  800.000       0.17    162.65     35.28      5.76    203.86
C                -0.54    -21.20     -1.96      0.00    -23.70
C  900.000       0.17    130.27     38.08      5.67    174.19
C                -0.53     23.88     -2.04      0.00     21.31
C 1000.000       0.19   1097.36     40.50      5.60   1143.64
C                -0.53    -44.84     -2.10      0.00    -47.46
C
C
C*********************************************************************
C
```

```
      ENDIF
400   WRITE(*,5) FMAX
5     FORMAT(' Maximum Frequency, GHz (',F7.2,') ')
      IF(IFLAG.EQ.1)THEN
        READ(*,10) IVAL
         IF(IVAL.EQ.' ')THEN
         GOTO 500
         ELSE
         READ(IVAL,8,ERR=400) FMAX
         ENDIF
C  CHECK FOR VALID RANGE ON FMAX
      IF((FMAX.GE.FMIN).AND.(FMAX.LE.1000.)) GOTO 500
      WRITE(*,*)'Maximum Freq. must satisfy FMIN <= FMAX <= 1000.'
      GOTO 400
      ENDIF
500   WRITE(*,6) STEP
6     FORMAT(' Frequency Step, GHz (',F7.2,') ')
      IF(IFLAG.EQ.1)THEN
        READ(*,10) IVAL
         IF(IVAL.EQ.' ')THEN
         GOTO 600
         ELSE
         READ(IVAL,8,ERR=500) STEP
         IF(STEP.EQ.0.) THEN
              IF(FMAX-FMIN.EQ.0) THEN
               STEP=1.
               GOTO 511
              ENDIF
          WRITE(*,*)' STEP must be greater than 0'
          GOTO 500
          ENDIF
         ENDIF
C  CHECK FOR VALID # OF FREQS. (MAX=501)
511   FF=(FMAX-FMIN)/STEP+1
      IF(FF.GT.501) THEN
      WRITE(*,7) (FMAX-FMIN)/502
7     FORMAT(' Minimum STEP for given freq. range is ',F7.2)
      GOTO 500
      ENDIF
      NF=INT(FF)
      ENDIF
C  ******** PARAMETER VARIATION  ***********
600   CONTINUE
      IF(IFLAG.NE.1) GOTO 700
      WRITE(*,*)'Which param. would you like to vary (P, R, T) ? '
      READ(*,10)IVAL
      IF(IVAL.EQ.'P'.OR.IVAL.EQ.'p') THEN
       NFLAG=1
       GOTO 700
     ELSEIF(IVAL.EQ.'R'.OR.IVAL.EQ.'r')THEN
       NFLAG=2
       GOTO 700
      ELSEIF(IVAL.EQ.'T'.OR.IVAL.EQ.'t')THEN
       NFLAG=3
       GOTO 700
      ELSE
       GOTO 600
      ENDIF
C  ******* NUMBER OF CASES  ****************
700   CONTINUE
      P=PBT(1)
      RH=RHT(1)
      T=TCT(1)
       WRITE(*,11) NCASE
11    FORMAT(' No. of Cases (',I2,')  ')
      IF(IFLAG.NE.1)GOTO 800
       READ(*,10)IVAL
       IF(IVAL.EQ.' ')THEN
        GOTO 800
        ELSE
        READ(IVAL,12,ERR=700) NCASE
12    FORMAT(I1)
      IF(NCASE.GE.10) THEN
      WRITE(*,*)'NO. of Cases must be less than 10.'
      GOTO 700
      ENDIF
      ENDIF
C  *****  PRESSURE, TEMPS, RH, DROP CONC. *********
800   CONTINUE
      IF(IFLAG.EQ.1) THEN
      IF(NFLAG.NE.1) THEN
        WRITE(*,9) P
9       FORMAT(' Pressure for all cases (kPa) (',F7.2,') ')
        READ(*,10) IVAL
         IF(IVAL.EQ.' ') GOTO 830
        READ(IVAL,8,ERR=800) P
         DO 831 I=1,10
831      PBT(I)=P
         GOTO 830
      ENDIF
830   IF(NFLAG.NE.2)THEN
        WRITE(*,19) RH
19      FORMAT(' Rel. Humidity for all cases (%) (',F7.2,') ')
        READ(*,10) IVAL
         IF(IVAL.EQ.' ') GOTO 840
        READ(IVAL,8,ERR=800) RH
         DO 832 I=1,10
832      RHT(I)=RH
         GOTO 840
      ENDIF
840   IF(NFLAG.NE.3)THEN
        WRITE(*,20) T
20      FORMAT(' Temperature for all cases (C) (',F7.2,') ')
        READ(*,10) IVAL
         IF(IVAL.EQ.' ') GOTO 850
        READ(IVAL,8,ERR=800) T
         DO 833 I=1,10
833      TCT(I)=T
         GOTO 850
      ENDIF
850   CONTINUE
C******  PRESSURE  ***************
      IF(NFLAG.EQ.1)THEN
        DO 801 I=1,NCASE
821       WRITE(*,13)I,PBT(I)
13        FORMAT(' Pressure for case # ',I1,' (kPa) (',F7.2,') ')
          READ(*,10) IVAL
          IF(IVAL.EQ.' ') GOTO 801
          READ(IVAL,8,ERR=821) PBT(I)
801   CONTINUE
```

```
        ENDIF
C******* TEMPERATURE ***************
        IF(NFLAG.EQ.3) THEN
          DO 802 I=1,NCASE
822         WRITE(*,14)I,TCT(I)
14          FORMAT(' Temperature for case # ',I1,' (C) (',F7.2,') ')
            READ(*,10) IVAL
            IF(IVAL.EQ.' ') GOTO 802
            READ(IVAL,8,ERR=822) TCT(I)
802     CONTINUE
        ENDIF
C**********  HUMIDITY  *****************
        IF(NFLAG.EQ.2)THEN
          DO 803 I=1,NCASE
823         WRITE(*,15)I,RHT(I)
15          FORMAT(' Rel. Hum. for case # ',I1,' (%) (',F6.2,') ')
            READ(*,10) IVAL
            IF(IVAL.EQ.' ') GOTO 803
            READ(IVAL,8,ERR=823) RHT(I)
803     CONTINUE
        ENDIF
        ENDIF
C********** DROP. CONC. ******************
        IF(IFLAG.EQ.1)THEN
          DO 804 I=1,NCASE
          IF(RHT(I).GE.99.9)THEN
834        WRITE(*,22)I,WT(I)
22         FORMAT(' Drop. Conc. for case # ',I1,' (g/m3) (',F6.2,') ')
           READ(*,10)IVAL
           IF(IVAL.EQ.' ')GOTO 804
           READ(IVAL,8,ERR=834) WT(I)
           GOTO 804
           ENDIF
C
C*********** HAZE MODEL [2] **************
             IF(RHT(I).LT.80.) GOTO 804
844          WRITE(*,23)I,WA(I)
23       FORMAT(' Aerosol conc. at 80% RH for case # ',
     +             I1,' (mg/m3) (',f6.2,') ')
             READ(*,10)IVAL
             IF(IVAL.EQ.' ')GOTO 824
             READ(IVAL,8,ERR=844) WA(I)
C
824           IF(WA(I).EQ.0.) GOTO 804
             WRITE(*,16)I,HZ(I)
16           FORMAT(' Haze Model for case # ',I1,/,
     +       ' (A-RURAL,B-Urban,C-Maritime,D-C+strong Wind) (',A1,') ')
             READ(*,10)IVAL
         IF(IVAL.EQ.' ') THEN
            HZ(I)=HZ(I)
            ELSEIF((IVAL.EQ.'A').OR.(IVAL.EQ.'B').OR.(IVAL.EQ.'C').OR.
     +       (IVAL.EQ.'D')) THEN
            HZ(I)=IVAL
            ELSE
             GOTO 824
            ENDIF
             IF(HZ(I).EQ.'A') THEN
              C1=117.
              C2=1.87
             ELSEIF(HZ(I).EQ.'B')THEN
              C1=128.
              C2=2.41
             ELSEIF(HZ(I).EQ.'C')THEN
              C1=183.
              C2=5.13
             ELSEIF(HZ(I).EQ.'D')THEN
              C1=197.
              C2=5.83
             ELSE
              GOTO 824
             ENDIF
             WT(I)=WA(I)*((C1-RHT(I))/(C2*(100.-RHT(I))))*(1.E-3)
804     CONTINUE
        ELSE
        WRITE(*,17)
17      FORMAT('  CASE ',3X,' PRES. ',3X,' TEMP. ',3X,'  HUM. ',5X,
     +   ' DROP. ','     RAIN  ')
        DO 805 I=1,NCASE
        WRITE(*,18) I, PBT(I),TCT(I),RHT(I),WT(I),RR(I)
18      FORMAT(3X,I2,2X,5(3X,F7.2))
805     CONTINUE
        ENDIF
900     CONTINUE
C********  RAIN RATE  ***********************
        IF(IFLAG.EQ.1)THEN
        DO 902 I=1,NCASE
922     WRITE(*,21)I,RR(I)
21      FORMAT(' Rain Rate for case # ',I1,' (mm/hr) (',F7.2,') ')
        READ(*,10)IVAL
        IF(IVAL.EQ.' ') GOTO 902
        READ(IVAL,8,ERR=922) RR(I)
902     CONTINUE
        ENDIF
1000    CONTINUE
        RETURN
        END
C-----------------------------------------------------------------------
        SUBROUTINE SAVETABL(IFLAG)
      COMMON /ANS1/ D(12,501,10),ATT(501,10),DISP(501,10)
      REAL No,Bo
      COMMON /ANS/ FREQA(501),No(10),Bo(10),EV(10)
      COMMON /AIR/ NCASE,PBT(10),TCt(10),RHt(10),Wt(10),R(10)
        COMMON /RAIN/ RR(10),WA(10)
        COMMON /HAZE/ HZ(10)
      COMMON /FREQS/ FMIN,FMAX,STEP,NF
        CHARACTER*1 HZ,IVAL
        CHARACTER*20 SAVE
        INTEGER*2 DFLAG,HFLAG
C
C    IFLAG = 0 MEANS PRINT TO CONSOLE
C    IFLAG = 1                FILE
C    IFLAG = 2        PRINT SUMMARY TO CONSOLE
C
        DFLAG=0
        HFLAG=0
        IF(IFLAG.EQ.2)THEN
        OPEN(1,FILE='CON')
        GOTO 110
        ENDIF
C
```

```
      WRITE(*,*)'Press C for Complex Refractivity output '
      WRITE(*,*)'or ENTER for normal output '
      READ(*,101)IVAL
      IF((IVAL.EQ.'C').OR.(IVAL.EQ.'c'))THEN
      FFLAG=1
      ELSE
      FFLAG=0
      ENDIF
C
      WRITE(*,*)'Press D to supress dispersion data '
      WRITE(*,*)'Press H to print only the input information'
      WRITE(*,*)'Press ENTER for a normal printout'
      WRITE(*,*)
      READ(*,101)IVAL
101   FORMAT(A1)
      IF((IVAL.EQ.'D').OR.(IVAL.EQ.'d'))THEN
      DFLAG=1
      ELSEIF((IVAL.EQ.'H').OR.(IVAL.EQ.'h'))THEN
      HFLAG=1
      ELSE
      DFLAG=0
      HFLAG=0
      ENDIF
C
      IF (FFLAG.EQ.1)THEN
       CALL SAVREF(IFLAG,DFLAG,HFLAG)
       RETURN
      ENDIF
C
110   CONTINUE
C
      IF (IFLAG.EQ.1)THEN
      WRITE(*,*)'Enter a DOS filename (PRN for a printout): '
      READ(*,12) SAVE
12    FORMAT(A20)
      IF(SAVE.EQ.'PRN')THEN
      OPEN(1,FILE=SAVE,ERR=900)
      ELSE
      OPEN(1,FILE=SAVE,STATUS='NEW',ERR=900)
      ENDIF
      ELSEIF(IFLAG.EQ.0)THEN
      OPEN(1,FILE='CON')
      ELSE
      ENDIF
C
1     FORMAT(//)
C
      WRITE(1,175)
175   FORMAT(8X,'FREQUENCY PROFILES OF ATTENUATION AND DELAY RATES')
      WRITE(1,*)
      WRITE(1,*)'INPUT ',
     +  ' Valid Parameter ranges indicated by [ ]):'
      WRITE(1,*)
C
      WRITE(1,6)
6     FORMAT
     +('                              REL.        HAZE     SUSP.   RAIN')
      WRITE(1,7)
7     FORMAT
     +(' CASE   PRES.,P   TEMP.,T   HUM.,RH     MODEL   DROP.,w  RATE',
     + ',R')
      WRITE(1,75)
75    FORMAT
     +('         (kPa)      (C)      (%)',
     +'         (mg/m3)  (g/m3)  (mm/hr)')

      WRITE(1,76)
76    FORMAT
     +(' [1-9] [0.0-110] [+/-50]   [0-100]      [0-1]',
     +'    [0-10]  [0-200]')
C
      WRITE(1,*)
      DO 10 LP=1,NCASE
      WRITE(1,8)LP,PBT(LP),TCT(LP),RHT(LP),HZ(LP),WA(LP),
     +   WT(LP),RR(LP)
8     FORMAT(I3,3(3X,F7.1),7X,A1,': ',F4.2,1X,F7.3,1X,F7.1)
10    CONTINUE
      WRITE(1,*)
      WRITE(1,2) FMIN
2     FORMAT(' Minimum Frequency F1         ',F8.3,' (GHz)')
      WRITE(1,3) FMAX
3     FORMAT(' Maximum Frequency F2 [1000.]',F8.3,' (GHz)')
      WRITE(1,4) STEP
4     FORMAT(' Frequency Step [max 500] dF ',F8.3,' (GHz)')
      WRITE(1,*)
      WRITE(1,*)
C
      IF(IFLAG.EQ.2)RETURN .
      IF(HFLAG.EQ.1)RETURN
C
      WRITE(1,45)
45    FORMAT(62(1H-))
      WRITE(1,*)'OUTPUT:'
C
      DO 200 LP=1,NCASE
      WRITE(1,9) LP,No(LP)*3.336
9     FORMAT('   Case Number: ',I2,'  (Refractive delay = '
     +    ,F7.2,' ps/km)')
C
    WRITE(1,16)
16  FORMAT(11X,51(1H-))
    WRITE(1,17)R(LP)
17  FORMAT(15X,'MOIST AIR  (v= ',F5.2,' g/m3)')
    WRITE(1,18)
18  FORMAT(13X,'DRY     WATER      HAZE, FOG')
    WRITE(1,19)
19  FORMAT(13X,'AIR   +  VAPOR    +  CLOUD +    RAIN   ',
   +  ' = TOTAL  ')
    WRITE(1,16)
    WRITE(1,14)
14  FORMAT(' FREQUENCY ',17X,'ATTENUATION (dB/km)')
      IF(DFLAG.EQ.0)THEN
    WRITE(1,15)
15  FORMAT('        ',24X,'DISPERSIVE DELAY (ps/km)')
      ENDIF
      WRITE(1,*)'   (GHz)'
      DO 100 IF=1,NF
      SM1=D(1,IF,LP)+D(2,IF,LP)
      SM2=D(3,IF,LP)+D(4,IF,LP)
      WRITE(1,11)FREQA(IF),SM1,SM2,D(5,IF,LP),D(11,IF,LP),
```

```
     +        ATT(IF,LP)
11        FORMAT(F9.3,2X,F8.2,3(1X,F8.2),2X,F8.2)
          IF(DFLAG.EQ.0)THEN
          WRITE(1,30)D(6,IF,LP)+D(7,IF,LP),D(8,IF,LP)+D(9,IF,LP),
     +                 D(10,IF,LP),D(12,IF,LP),DISP(IF,LP)
30        FORMAT(12X,F8.2,4(2X,F8.2))
          ENDIF
100       CONTINUE
          WRITE(1,*)
200       CONTINUE
          CLOSE(1)
          RETURN
900       WRITE(*,13) SAVE
13        FORMAT(' ERROR Opening file: ',A20)
          RETURN
          END
C---------------------------------------------------------------------
          SUBROUTINE SAVREF(IFLAG,DFLAG,HFLAG)
        COMMON /ANS1/ D(12,501,10),ATT(501,10),DISP(501,10)
        REAL No,Bo
        COMMON /ANS/ FREQA(501),No(10),Bo(10),EV(10)
        COMMON /AIR/ NCASE,PBT(10),TCt(10),RHt(10),Wt(10),R(10)
          COMMON /RAIN/ RR(10),WA(10)
          COMMON /HAZE/ HZ(10)
        COMMON /FREQS/ FMIN,FMAX,STEP,NF
          CHARACTER*1 HZ,IVAL
          CHARACTER*20 SAVE
          INTEGER*2 DFLAG,HFLAG
C
          IF (IFLAG.EQ.1)THEN
          WRITE(*,*)'Enter a DOS filename (PRN for a printout): '
          READ(*,12) SAVE
12        FORMAT(A20)
          IF(SAVE.EQ.'PRN')THEN
          OPEN(1,FILE=SAVE,ERR=900)
          ELSE
          OPEN(1,FILE=SAVE,STATUS='NEW',ERR=900)
          ENDIF
          ELSEIF(IFLAG.EQ.0)THEN
          OPEN(1,FILE='CON')
          ELSE
          ENDIF
C
1         FORMAT(//)
C
          WRITE(1,175)
175       FORMAT(8X,'FREQUENCY PROFILES OF ATMOSPHERIC COMPLEX',
     + ' REFRACTIVITY')
          WRITE(1,*)
          WRITE(1,*)'INPUT ',
     +  ' Valid Parameter ranges indicated by [ ]):'
          WRITE(1,*)
C
          WRITE(1,6)
6         FORMAT
     +('                       REL.        HAZE     SUSP.    RAIN')
          WRITE(1,7)
7         FORMAT
     +(' CASE    PRES.,P   TEMP.,T   HUM.,RH    MODEL    DROP.,w  RATE',
     + ',R')
          WRITE(1,75)
75        FORMAT
     +('        (kPa)      (C)      (%)',
     +'        (mg/m3)  (g/m3)  (mm/hr)')
          WRITE(1,76)
76        FORMAT
     +(' [1-9] [0.0-110] [+/-50]   [0-100]       [0-1]',
     +'    [0-10]  [0-200]')
C
          WRITE(1,*)
          DO 10 LP=1,NCASE
          WRITE(1,8)LP,PBT(LP),TCT(LP),RHT(LP),HZ(LP),WA(LP),
     +      WT(LP),RR(LP)
8         FORMAT(I3,3(3X,F7.1),7X,A1,': ',F4.2,1X,F7.3,1X,F7.1)
10        CONTINUE
          WRITE(1,*)
          WRITE(1,2) FMIN
2         FORMAT(' Minimum Frequency F1        ',F8.3,' (GHz)')
          WRITE(1,3) FMAX
3         FORMAT(' Maximum Frequency F2 [1000.]',F8.3,' (GHz)')
          WRITE(1,4) STEP
4         FORMAT(' Frequency Step [max 500] dF ',F8.3,' (GHz)')
          WRITE(1,*)
          WRITE(1,*)
C
          IF(IFLAG.EQ.2)RETURN
          IF(HFLAG.EQ.1)RETURN
C
          WRITE(1,45)
45        FORMAT(62(1H-))
          WRITE(1,*)'OUTPUT:'
C
          DO 200 LP=1,NCASE
          WRITE(1,9) LP,No(LP)
9         FORMAT('    Case Number: ',I2,'  (No = ',F7.2,' ppm)')
C
        WRITE(1,16)
16      FORMAT(11X,66(1H-))
        WRITE(1,17)R(LP)
17      FORMAT(15X,'   MOIST AIR  (v= ',F5.2,' g/m3)')
        WRITE(1,18)
18      FORMAT(13X,' DRY        WATER       HAZE, FOG')
        WRITE(1,19)
19      FORMAT(13X,' AIR    +    VAPOR    +    CLOUD +      RAIN    ',
     +  ' = TOTAL   ')
        WRITE(1,16)
        WRITE(1,14)
14      FORMAT(' FREQUENCY ',22X,'IMAGINARY PART (ppm)')
          IF(DFLAG.EQ.0)THEN
        WRITE(1,15)
15      FORMAT('         ',31X,'REAL PART (ppm)')
          ENDIF
          WRITE(1,*)'   (GHz)'
          DO 100 IF=1,NF
          SM1=(D(1,IF,LP)+D(2,IF,LP))/(.182*FREQA(IF))
          SM2=(D(3,IF,LP)+D(4,IF,LP))/(.182*FREQA(IF))
          SM3=D(5,IF,LP)/(.182*FREQA(IF))
          SM4=D(11,IF,LP)/(.182*FREQA(IF))
          WRITE(1,11)FREQA(IF),SM1,SM2,SM3,SM4,
```

```
     +        ATT(IF,LP)/(.182*FREQA(IF))
11      FORMAT(F9.3,5(3X,E9.3))
        IF(DFLAG.EQ.0)THEN
        SM1=(D(6,IF,LP)+D(7,IF,LP))/3.336
        SM2=(D(8,IF,LP)+D(9,IF,LP))/3.336
        WRITE(1,30)SM1,SM2,D(10,IF,LP)/3.336,D(12,IF,LP)/3.336,
     +    DISP(IF,LP)/3.336
30      FORMAT(12X,5(3X,E9.3))
        ENDIF
100     CONTINUE
        WRITE(1,*)
200     CONTINUE
        CLOSE(1)
        RETURN
900     WRITE(*,13) SAVE
13      FORMAT(' ERROR Opening file: ',A20)
        RETURN
        END
C------------------------------------------------------------------------
      SUBROUTINE COMPUTE(LOOP)
C******************************************************************
C  THIS SUBROUTINE COMPUTES THE ATTENUATION & DISPERSIVE DELAY RATES
C******************************************************************
      COMMON /ANS1/ D(12,501,10),ATT(501,10),DISP(501,10)
      COMMON /ANS/ FREQA(501),No(10),Bo(10),EV(10)
      COMMON /AIR/ NCASE,PBt(10),TCt(10),RHt(10),Wt(10),R(10)
      COMMON /RAIN/ RR(10),WA(10)
      COMMON /FREQS/ FMIN,FMAX,STEP,NF
      REAL No,Bo
      DIMENSION AD(12)
C
      NF=(FMAX-FMIN)/STEP +1.5
C   NUMBER OF FREQUENCIES
      DO 800 LP=1,LOOP
C*********************************
      Pbi=PBt(LP)
      Tci=TCt(LP)
      Rhi=RHt(LP)
      Wi=Wt(LP)
      RRi=RR(LP)
C*********************************
C
      DO 55 IF=1,NF
      DO 55 I=1,8
55    D(I,IF,LP)=0.
      WRITE(*,56) LP,LOOP
56    FORMAT(' Computing for  ***** Case',I3,' of',I3,' *****')
C
60    DO 100 IF=1,NF
C    FREQUENCY LOOP
      F=FMIN + (IF-1)*STEP
      FREQA(IF)=F
        IF(F.EQ.0.)F=1.E-6
C    SAVE FREQUENCY
      CALL Gas1(F,IF,Ad,Pbi,Rhi,Tci,Wi,RRi,V,Es,E,P,Tau,Nwv,Eps,fr)
        EV(LP)=E
85    DO 95 I=1,12
      D(I,IF,LP)=Ad(I)
95      CONTINUE
D         WRITE(*,*)'D(12)= ',D(12,IF,LP)
```

```
100   CONTINUE
C
        R(LP)=7.223*E*V
C  NONDISPERSIVE REFRACTIVITY No in ppm and DELAY Bo in ps/km [1].
        No(LP)=(2.588*P+(41.6*V+2.39)*E)*V+Nwv
        Bo(LP)=3.336*No(LP)
C   COMPUTE No,Bo
        DO 510 IF=1,NF
C  ADD TOTAL ATTENUATION AND DISPERSION
        ATT(IF,LP)=D(1,IF,LP)+D(2,IF,LP)+D(3,IF,LP)+D(4,IF,LP)+
     +             D(5,IF,LP)+D(11,IF,LP)
        DISP(IF,LP)=D(6,IF,LP)+D(7,IF,LP)+D(8,IF,LP)+
     +             D(9,IF,LP)+D(10,IF,LP)+D(12,IF,LP)
510     CONTINUE
800   CONTINUE
      RETURN
      END
C------------------------------------------------------------------------
      SUBROUTINE Gas1(F,Mt,Ad,Pb,Rh,Tc,W,RR,V,Es,E,P,Tau,Nwv,Eps,fr)
C******************************************************************
C        COMPUTES SPECIFIC ATTENUATION & DISPERSIVE DELAY RATES
C        USING LINE DATA
C******************************************************************
      COMMON /O2line/ FOO2(48),A(6,48)
C   OXYGEN LINES
      COMMON /H2O/ FOwater(30),B(3,30)
C   WATER VAPOR LINES
      DIMENSION AD(12),GAMD2(30)
        DIMENSION S(48),GAMMA(48),DELTA(48),SH(30),GAMH(30),DELH(30)
      REAL NIPP,NDPP,NOXPP,NVPP,NWPP,Noxp,Ndp,Nip,Nrp,NS,NU
C
      IF(Mt.GT.1) GO TO 40
C   ONLY CALC THESE FOR 1st FREQUENCY
C
      V=300./(Tc+273.15)
C   RELATIVE INVERSE TEMPERATURE
C         COMPUTE WATER VAPOR PARTIAL PRESSURE E in kPa
C   Eqn. (1)  [1] -- CORRECTED!
C     Es=2.409*V**5*10**(10.-9.834*V)
        Es=0.61078*(EXP(((18.61-Tc/240.7)*Tc)/(256.1+Tc)))
C   New Es [9] -- either version may be used.
      E=Es*Rh/100.
        P=Pb-E
        IF(P.LT.0)THEN
         P=0.
         Pb=E
        ENDIF
C
C          COMPUTE LINE FACTORS S,Gamma,Delta
      DO 10 I=1,48
C   For OXYGEN
      S(I)=A(1,I)*P*V**3*EXP(A(2,I)*(1.-V))*1.E-6
      GAMMA(I)=A(3,I)*(P*V**(.8-A(4,I)) + 1.1*E*V)*1.E-3
        IF(Pb.LT.0.7)THEN
        GAMMA(I)=(GAMMA(I)**2+(25*0.6E-4)**2)**0.5
C  Zeeman approximation for .6 Gauss, [10]
        ENDIF
10    DELTA(I)=A(5,I)*P*V**A(6,I)*1.E-3
      DO 20 I=1,30
C   For WATER VAPOR
```

```
      SH(I)=B(1,I)*E*V**3.5*EXP(B(2,I)*(1.-V))
c  Slightly different temperature dependence for width, following [6].
      GAMH(I)=B(3,I)*(P*V**.6 + 4.8*E*V**1.1)*1.E-3
        IF(Pb.LT.0.7)THEN
        GAMD2(I)=(2.14*FOwater(I)**2)*1E-12/V
        GAMH(I)=(GAMH(I)**2+GAMD2(I))**0.5
C  Doppler approximation [10]
        ENDIF
20    DELH(I)=0.
C
C      WATER VAPOR CONTINUUM
C      Eqn. (14)  [1]; was revised in [2], Eqn. (10)
40    Bf=1.13E-6
      Bs=3.57E-5
      Nipp=(Bf*E*P*V**3.0 + Bs*E**2*V**10.8)*F
      Bo=6.47E-6
      Nip=E*Bo*F**2.05*V**2.4
C
C       DRY AIR CONTINUUM
C       Eqn. (13)  [1] -- CORRECTED!
      Ao=6.14E-4
      An=1.40E-10 *(1.-1.2E-5*F**1.5)
      GAMMAo=4.8E-3*(P+1.1*E)*V**.8
C     FAC=1./(1.+F**2/3600.)
C    Nonresonant rolloff FAC taken out.
        FAC=1.
      Ndpp=(Ao*P*V**2*GAMMAo*FAC/(F*F + GAMMAo**2) + An*P*P*V**3.5)*F
      Ndp =P*Ao/2.*V**2*(1./(1.+(F/GAMMAo)**2)-1.)
C
C          MOLECULAR OXYGEN LINES
      S1=0
      S2=0
      DO 60 I=1,48
      CALL FPPFP(F,FOO2(I),GAMMA(I),DELTA(I),FPP,FP,0)
      S1=S1+S(I)*Fpp
60    S2=S2+S(I)*Fp
      Noxpp=S1
C  N'' FROM OXYGEN
      Dox=S2 + Ndp
        Ad(6)=3.336*S2
        Ad(7)=3.336*Ndp
C  D FROM OXYGEN
C
C          WATER VAPOR LINES
      S1=0
      S2=0
      DO 70 I=1,30
      CALL FPPFP(F,FOWATER(I),GAMH(I),DELH(I),FPP,FP,1)
      S1=S1+SH(I)*Fpp
70    S2=S2+SH(I)*Fp
      Nvpp=S1
C   N'' FROM WATER VAPOR
      Dv=S2 + Nip
        Ad(8)=3.336*S2
        Ad(9)=3.336*Nip
C   D FROM WATER VAPOR
C
C          LIQUID WATER DIELECTRIC CONSTANT AND
C          FOG/CLOUD RAYLEIGH TERMS [3]
        fD=20.09-142*(V-1)+294*(V-1)**2
        NU=(F/fD)
        fS=590.-1500*(V-1)
        NS=F/fS
        Epinf=5.48
        Eopt=3.51
C   EPSILON SUB INFINITY
        Eps=103.3*(V-1)+77.66
C   EPSILON SUB S
        Epp=Eopt+(Eps-Epinf)/(1+NU**2)+(Epinf-Eopt)/(1+NS**2)
C EPSILON'
        Eppp=((Eps-Epinf)*NU)/(1+NU**2)+((Epinf-Eopt)*NS)/(1+NS**2)
C EPSILON''
        Ep=(2.+Epp)/Eppp
C   SUSPENDED WATER DROPLET EXTINCTION
        Nwpp=(4.50*W/(Eppp*(1.+Ep**2)))
C N'' FROM WATER DROPLETS
        Dw=-4.5*W*(Ep/(Eppp*(1+Ep*Ep)))+4.5*W/(Eps+2.)
        Nwv=1.5*W*(1.-(3./(Eps+2.)))
C
C ATTENUATION DUE TO RAIN [4]
C
        ARAIN=0.
        BRAIN=0.
        ATRAN=0.
        Nrp=0.
        IF (RR.EQ.0.) GOTO 501
C    ALPHA CALCULATION
        IF(F.GE.2.9) GOTO 300
          GA=6.39E-5
          EA=2.03
          GOTO 330
300     CONTINUE
        IF(F.GE.54.) GOTO 310
          GA=4.21E-5
          EA=2.42
          GOTO 330
310     IF(F.GE.180.) GOTO 320
          GA=4.09E-2
          EA=0.699
          GOTO 330
320     GA=3.38
        EA=-0.151
330     ARAIN=GA*(F**(EA))
C
C      BETA CALCULATION
        IF(F.GE.8.5) GOTO 340
          GB=0.851
          EB=0.158
          GOTO 370
340     IF(F.GE.25.) GOTO 350
          GB=1.41
          EB= -0.0779
          GOTO 370
350     IF(F.GE.164.)GOTO 360
          GB=2.63
          EB= -0.272
          GOTO 370
360     GB=0.616
        EB=0.0126
370     BRAIN=GB*(F**(EB))
```

```
        ATRAN=ARAIN*RR**(BRAIN)
C
C    RAIN DELAY approximated after ZUFFEREY [5] who
C    used MARSHALL-PALMER drop size spectra and 20 deg. C
        fr=53.-0.37*RR+1.5E-3*RR**2
        Nro=(RR*(3.68-0.012*RR))/fr
        X=F/fr
        Nrp=-Nro*(X**2.5/(1+X**2.5))
501     CONTINUE
C
C CALC ABSORPTION
      Ad(1)=.182*F*Noxpp
C OXYGEN LINE ABSORPTION
      IF(Ad(1).LT.0.) Ad(1)=0.
C   Cannot be less than 0.
      Ad(2)=.182*F*Ndpp
C NONRESONAT DRY AIR ABSORPTION
      Ad(3)=.182*F*Nvpp
C WATER VAPOR LINE ABSORPTION
      Ad(4)=.182*F*Nipp
C WATER VAPOR CONTINUUM ABSORPTION
      Ad(5)=.182*F*Nwpp
C SUSPENDED WATER DROPLET EXTINCTION
C     Ad(6)=3.336*S2
C OXYGEN LINE DISPERSIVE DELAY (SEE ABOVE)
C     Ad(7)=3.336*Ndp
C OXYGEN NON-RESONANT DISP. DELAY (SEE ABOVE)
C     Ad(8)=3.336*S2
C WATER VAPOR CONTIUUM DISPERSIVE DELAY (SEE ABOVE)
C     Ad(9)=3.336*Nip
C WATER VAPOR LINE DISPERSIVE DELAY (SEE ABOVE)
      Ad(10)=3.336*Dw
C WATER DROPLET DISPERSIVE DELAY
      Ad(11)=ATRAN
C ATTENUATION DUE TO RAIN
        Ad(12)=3.336*Nrp
D        WRITE(*,*)'Ad(12)= ',Ad(12)
C RAIN DELAY
      RETURN
      END
C-----------------------------------------------------------------
      SUBROUTINE FPPFP(F,Vo,GAMMA,DELTA,Fpp,Fp,FLAG)
C*****************************************************************
C   CALC Fpp & Fp -- VW line shape functions
C*****************************************************************
      G2=GAMMA*GAMMA
      VMF=Vo-F
      VPF=Vo+F
        CUTOFF=40.
      Fpp=F/Vo*((GAMMA-VMF*DELTA)/(VMF**2+G2) +
     +          (GAMMA-VPF*DELTA)/(VPF**2+G2))
        IF(FLAG.EQ.1)THEN
        IF(F.GT.(Vo+CUTOFF*GAMMA)) Fpp=0.
C  SET ABSORPTION TO ZERO IF F IS > NU+40*GAMMA
C  High-frequency wing problem of VW shape function for H2O lines [7]!
C  Intensities <(approx. 7.5 E-4 Fpp) are neglected.
        ENDIF
      Fp=(VMF + GAMMA*(GAMMA+F*DELTA)/Vo)/(VMF**2+G2) +
     +   (VPF + GAMMA*(GAMMA-F*DELTA)/Vo)/(VPF**2+G2) - 2./Vo
      RETURN
```



```
      END
C-----------------------------------------------------------------
      SUBROUTINE Oxydal
      COMMON /O2line/ F0O2(48),A(6,48)
C   PUT MOLECULAR OXYGEN LINE DATA OF [1] IN A(1:6,1:48)
      OPEN (2,FILE='OXYGEN.DAT',ERR=900)
C  DUMMY READ TO ALLOW FOR COMMEMTS.
        READ(2,*)
        READ(2,*)
      READ (2,*,ERR=910) (F0O2(I),(A(J,I),J=1,6),I=1,48)
      CLOSE (2)
      RETURN
900   WRITE(*,901) IOS
901   FORMAT('Could not OPEN OXYGEN.DAT file, error=',I6)
        WRITE(*,*)'Check that OXYGEN.DAT is in the current directory.'
      STOP 'Could not OPEN OXYGEN file.'
910   STOP 'ERROR READing OXYGEN file.'
      END
C-----------------------------------------------------------------
      SUBROUTINE Vapdal
      COMMON /H2O/ F0water(30),B(3,30)
C       PUTS WATER VAPOR LINE DATA OF [1] IN B(1:3,1:30)
      OPEN (2,FILE='WATER.DAT',ERR=900)
C   DUMMY READ TO ALLOW FOR COMMENTS.
        READ(2,*)
        READ(2,*)
      READ (2,*,ERR=910) (F0water(I),(B(J,I),J=1,3),I=1,30)
      CLOSE (2)
      RETURN
900   WRITE(1,901) IOS
901   FORMAT('Could not OPEN WATER file, error=',I6)
        WRITE(*,*)'Check that WATER.DAT is in the current directory.'
      STOP 'Could not OPEN WATER file.'
910   STOP 'ERROR READing WATER file.'
      END
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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Laboratory measurements have been performed at 138 GHz of water vapor attenuation α_x for pure vapor (H_2O) and its mixtures with air, nitrogen (N_2), oxygen (O_2), and Argon(Ar). A computer-controlled resonance spectrometer was employed. The results are interpreted in terms of underlying absorption mechanisms. A substantial amount of the self-broadening term proportional to the square of vapor pressure is left unaccounted. The negative temperature coefficient of the excess absorption is consistent with a dimer (H_2O_2) model. An empirical formulation of the experimental findings is incorporated into the parametric propagation model MPM that utilizes a local (30x H_2O, 48x O_2) line base to address frequencies up to 1000 GHz. Details of MPM are given in two Appendices. Predictions of moist air attenuation and delay by means of the revised MPM program generally compare favorably with reported (10 - 430GHz) data from both field and laboratory measurements.

16. Key Words *(Alphabetical order, separated by semicolons)*

atmospheric attenuation and delay; laboratory studies of moist air attenuation; millimeter/submillimeter-wave spectral range; propagation program MPM; terrestrial radio path data

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