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ATTENUATION AND PHASE DELAY OF RADIO WAVES IN AIR BELOW 1000 GHZ FOR HEIGHTS 0 TO 100 KM

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Moist air is characterized for the frequency range 10 to 1000 GHz as a nonturbulent propagation medium. The medium is treated as an ensemble of molecules in which spectral features of water vapor and oxygen constitute the main absorbers. An adequate permanent spectroscopic data base consists of three parts: (i) resonance information for 30 H_2O lines between 22 and 1097 GHz and 44 O_2 lines between 50 and 834 GHz in the form of intensity coefficients and center frequency for each line; (ii) an empirical water vapor continuum spectrum; and (iii) a liquid water attenuation term for haze and cloud conditions. The overlap problem of the 60 GHz oxygen band is taken into account. The data base is applied in a dual computer program to calculate and to plot attenuation rates (dB/km), refractivity (ppm), and refractive dispersion (ppm) throughout the neutral atmosphere.

The first part covers the hydrosphere (i.e., 0 to 20 km) and requires pressure, temperature, and relative humidity as input data. Part two addresses isolated line behavior over the height range 20 to 100 km, wherein the geomagnetic field strength H is an additional input parameter due to the Zeeman effect of the O_2 molecules. Each oxygen line splits proportional with H into numerous sub-lines, which superimpose to form a Zeeman pattern spread over a megahertz scale and exhibiting a shape that depends very much upon polarization and orientation of the interacting radiation. Patterns of three main polarization cases are considered.

The unified treatment is central to radio wave propagation problems in the neutral atmosphere up to 1000 GHz. The formulation is in engineering terms, fully traceable, and does not include quantum mechanical complications. Various typical examples for a model atmosphere demonstrate the utility of the approach, provide new information, and underline the serious role that water vapor plays above 150 GHz.

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INTRODUCTION

MOIST AIR IS CHARACTERIZED FOR THE FREQUENCY RANGE 1 TO 1000 GHZ AS A NON-TURBULENT PROPAGATION MEDIUM. THE MEDIUM IS TREATED AS AN ENSEMBLE OF MOLECULES IN WHICH SPECTRAL FEATURES OF WATER VAPOR AND OXYGEN CONSTITUTE THE MAIN ABSORBERS. AN ADEQUATE PERMANENT SPECTROSCOPIC DATA BASE CONSISTS OF THREE PARTS:

- RESONANCE INFORMATION FOR 30 H_2O LINES BETWEEN 22 AND 1097 GHZ AND 44 O_2 LINES BETWEEN 50 AND 834 GHZ
- EMPIRICAL WATER VAPOR CONTINUUM SPECTRUM
- LIQUID WATER ATTENUATION TERM FOR HAZE AND CLOUD CONDITIONS

THE OVERLAP PROBLEM OF THE 60 GHZ OXYGEN BAND IS TAKEN INTO ACCOUNT, AND THE DATA BASE IS APPLIED IN TWO COMPUTER PROGRAMS TO CALCULATE AND TO PLOT SPECIFIC ATTENUATION (DB/KM) AND REFRACTIVE DISPERSION (PPM) THROUGHOUT THE NEUTRAL ATMOSPHERE.

<u>PROGRAM 1</u> COVERS THE HYDROSPHERE (0 TO 30 KM) AND REQUIRES THE INPUT DATA
PRESSURE P - TEMPERATURE T - REL. HUMIDITY RH

<u>PROGRAM 2</u> ADDRESSES ISOLATED LINE BEHAVIOR OVER THE HEIGHT RANGE 30 TO 100 KM, WHEREIN THE
GEOMAGNETIC FIELD STRENGTH H

IS AN ADDITIONAL INPUT PARAMETER DUE TO THE ZEEMAN EFFECT OF THE O_2 MOLECULES. EACH OXYGEN LINE SPLITS PROPORTIONAL WITH H INTO NUMEROUS SUB-LINES, WHICH SUPERIMPOSE TO FORM A ZEEMAN PATTERN SPPEAD OVER A MEGAHERTZ SCALE AND EXHIBITING A SHAPE THAT DEPENDS VERY MUCH UPON POLARIZATION AND ORIENTATION OF THE INTERACTING RADIATION. PATTERNS OF THREE MAIN POLARIZATION CASES ARE CONSIDERED.

THE UNIFIED TREATMENT IS CENTRAL TO RADIO WAVE PROPAGATION PROBLEMS IN THE NEUTRAL ATMOSPHERE UP TO 1000 GHZ. THE FORMULATION IS IN ENGINEERING TERMS, FULLY TRACEABLE, AND DOES NOT INCLUDE QUANTUM MECHANICAL COMPLICATIONS. EXAMPLES FOR A MODEL ATMOSPHERE DEMONSTRATE THE UTILITY OF THE APPROACH AND UNDERLINE THE SERIOUS ROLE THAT WATER VAPOR PLAYS ABOVE 150 GHZ.

MODELING PROPAGATION PROPERTIES

PROPAGATION PARAMETERS

		DEFINITION	ENGINEERING VERSION	
PLANE WAVE EQUATION	E/E_0	$\exp(\Gamma L)$	Frequency f	GHz
PROPAGATION CONSTANT	Γ	$j(2\pi f/c)n$	$-0.115\alpha + j(\beta + 2.10\times10^4 f)$	1/km
REFRACTIVE INDEX	n	$v/c = n' + j\,n''$	$1 + N \times 10^{-6}$	ppm
COMPLEX REFRACTIVITY	N	$(n - 1)\,10^6$	$(N_0 + D) \dot{+} j\,N''$	ppm
POWER ATTENUATION	α	$20\log e\cdot(2\pi f/c)n''$	$0.182\,f\,N''(f)$	dB/km
EXCESS WAVE DELAY	t	$(n'/c) - 1$	$(\beta/2\pi f)10^3 = 3.34[N_0 + D(f)]$	ps/km

MODEL FOR $\alpha(f)$ AND $D(f)$

VARIABLES AND VALIDITY RANGE:

FREQUENCY	$f = 1 - 1000$	GHz
ALTITUDE	$h = 0 - 100$	km
RELATIVE HUMIDITY	$RH = 0 - 100$	%
MAGNETIC FIELD STRENGTH	$H = 0 - 1$	Gauss
WAVE POLARIZATION	HL - VL - RC - LC	
ORIENTATION ANGLE	$\theta = 0 - 90°$	

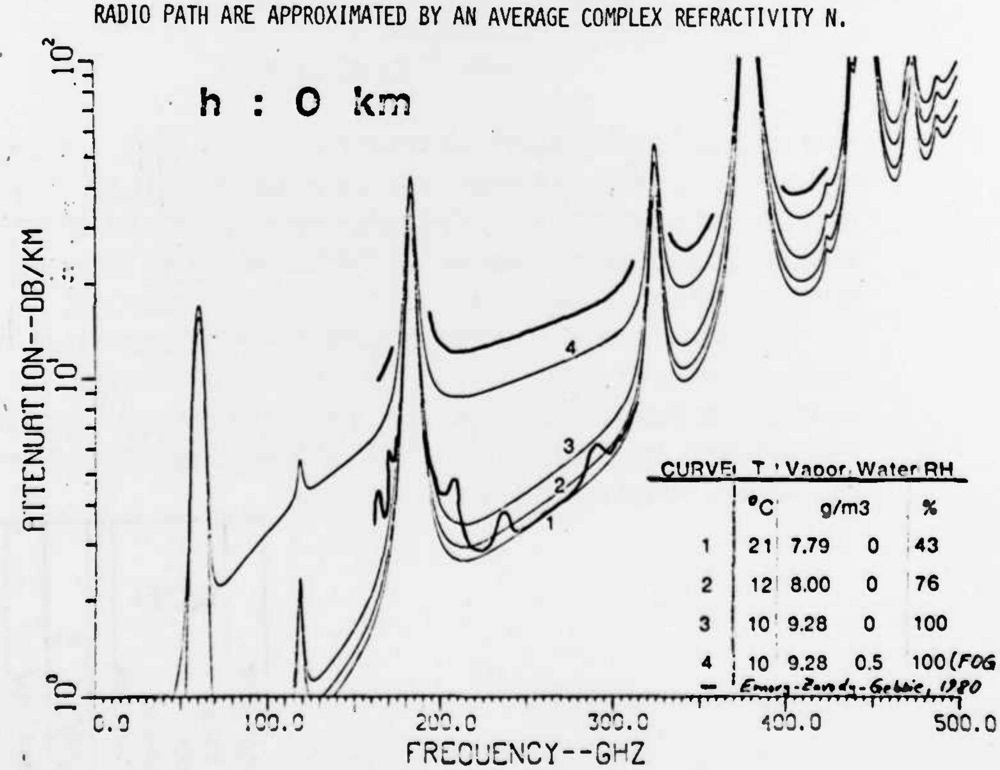
Tropospheric Effects

MEAN VALUES AND LIMITS OF

ABSORPTIVE LOSS OF COHERENT RADIATION

TIME OF PROPAGATION BETWEEN TWO POINTS

ARE CONSIDERED FOR MODELING. THE CHARACTERISTICS OF A SHORT, HORIZONTAL RADIO PATH ARE APPROXIMATED BY AN AVERAGE COMPLEX REFRACTIVITY N.



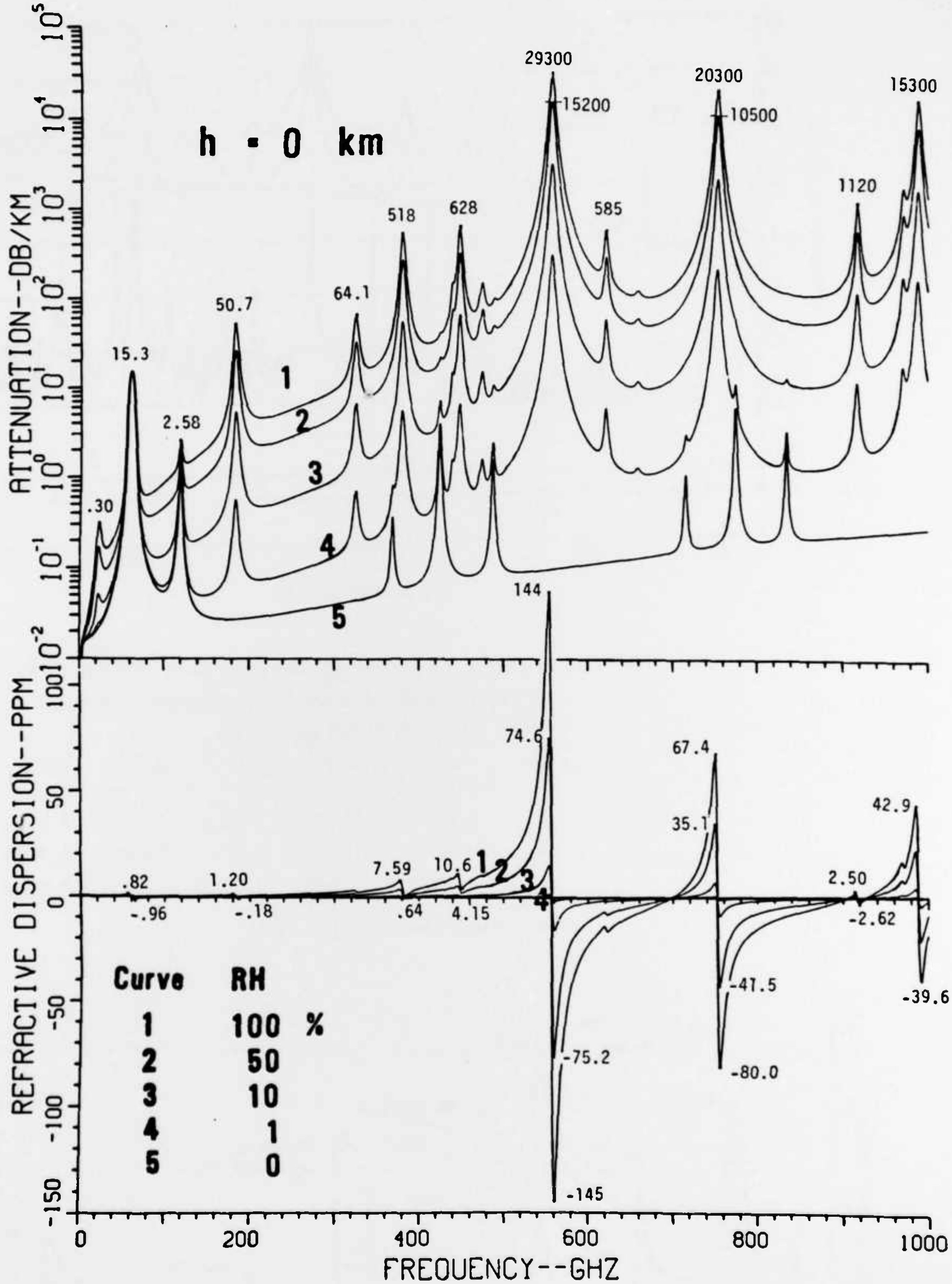


FIG. 1. ATTENUATION α IN DB/KM AND REFRACTIVE DISPERSION D IN PPM FOR DRY (RH = 0%) TO SATURATED (RH = 100%) AIR AT SEA LEVEL h = 0 KM OVER THE FREQUENCY RANGE 1 TO 1000 GHz.

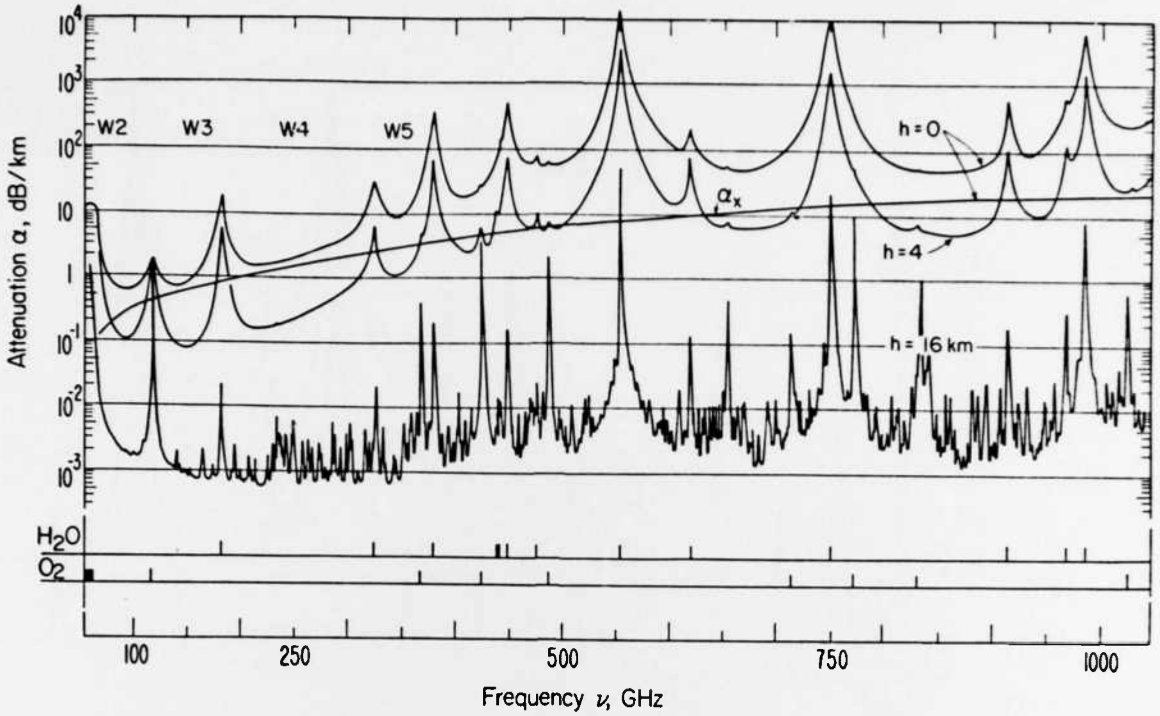
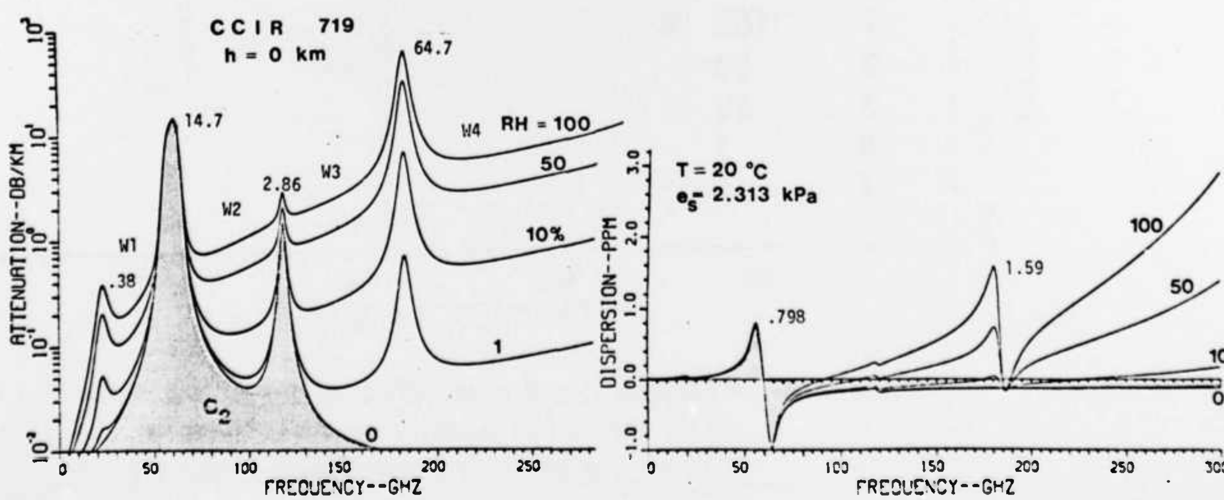


FIG. 2. ATTENUATION α AT THE ALTITUDES, h = 0, 4, AND 16 KM. THE FOLLOWING ATMOSPHERIC CONDITIONS AND TRACE MOLECULAR NUMBER DENSITIES $M(m^{-3})$ WERE USED IN THE CALCULATION:

h, KM	p, KPA	e, PA	$M(O_3)$	M(CO)	$M(N_2O)$
0	101.0	786.0	6.78E17	1.91E18	7.12E18
4	61.6	133.0	5.77E17	1.28E18	4.76E18
16	10.4	0.061	3.01E18	2.59E17	9.67E17

(after Burch and Clough, 1979)



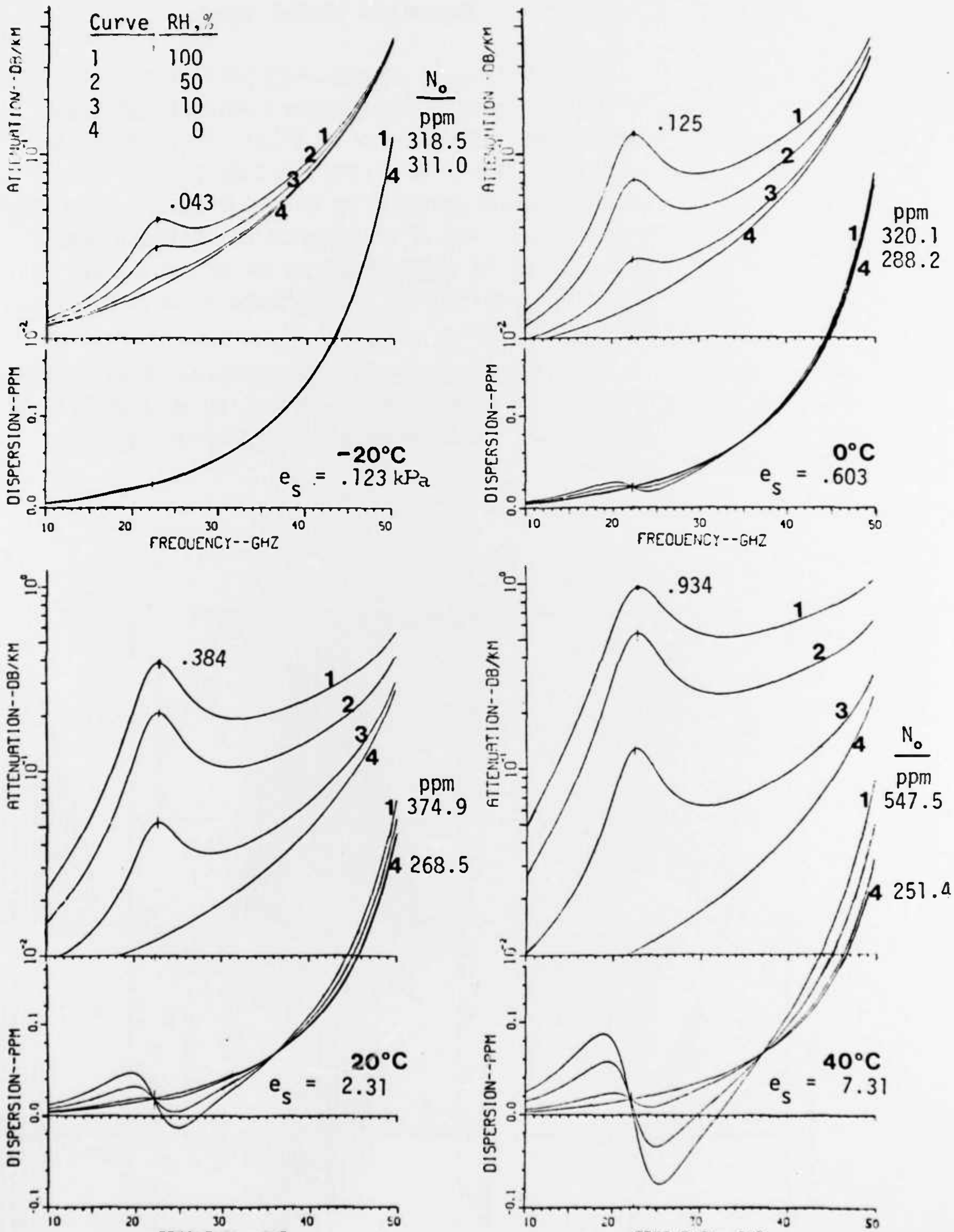
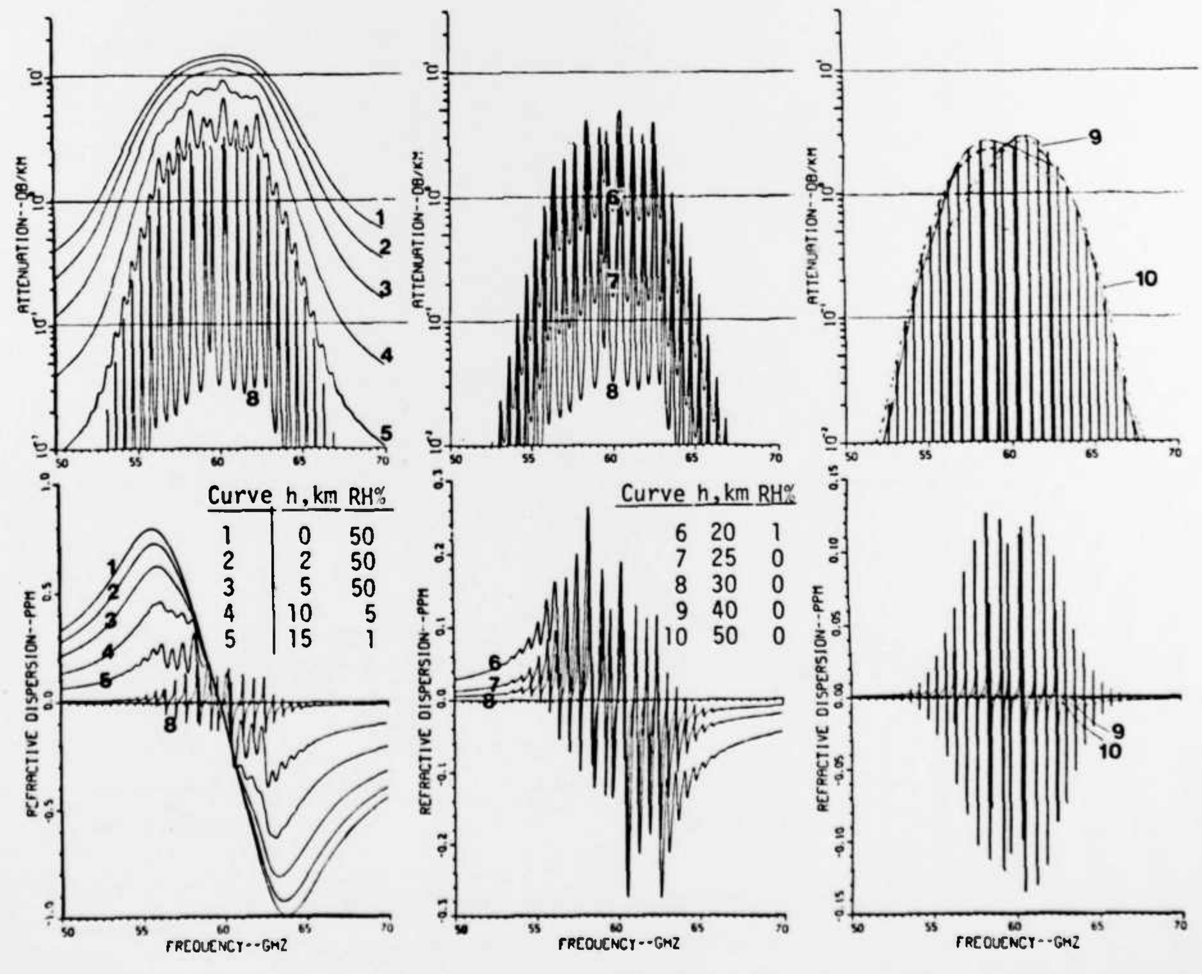


FIG. 3. ATTENUATION α IN DB/KM, REFRACTIVITY N_0, AND REFRACTIVE DISPERSION D IN PPM FOR DRY (RH = 0%) TO SATURATED (RH = 100%) AIR AT SEA LEVEL, h = 0 KM AND TEMPERATURES, T = -20°C TO + 40°C OVER THE FREQUENCY RANGE 10 TO 50 GHz.

Mesospheric ZEEMAN Effect

ZEEMAN SPLITTING OF ISOLATED OXYGEN LINES DUE TO THE INFLUENCE OF THE EARTH'S MAGNETIC FIELD STRENGTH H INTRODUCES CONSIDERABLE COMPLICATIONS. THE PRESENCE OF THE STEADY FIELD H (IN UNITS OF GAUSS) SPLITS EACH OF THE $K^{\pm}$ LINES INTO THREE GROUPS OF $(2K^{\pm} \pm 1)$ SUB-LINES, THEREBY REDISTRIBUTING THE LINE ATTENUATION OVER A FIXED FREQUENCY RANGE. PART OF THE PROGRAM P2 IS A SUBROUTINE WHICH CALCULATES THE LINE CENTER FREQUENCIES AND THE LINE STRENGTH COEFFICIENTS. IN PRINCIPLE, THREE DIFFERENT ZEEMAN PATTERNS $\pi_{1,2,3}$ ARE POSSIBLE FOR ANY $K^{\pm}$ LINE.

ADDITIONAL INFORMATION HAS TO BE PROVIDED BEFORE THE MESOSPHERIC O_2 LINE PATTERN CAN BE CALCULATED, THAT IS, THE POLARIZATION OF THE RADIO WAVE AND ITS ORIENTATION WITH RESPECT TO THE GEOMAGNETIC FIELD $\vec{H}$.



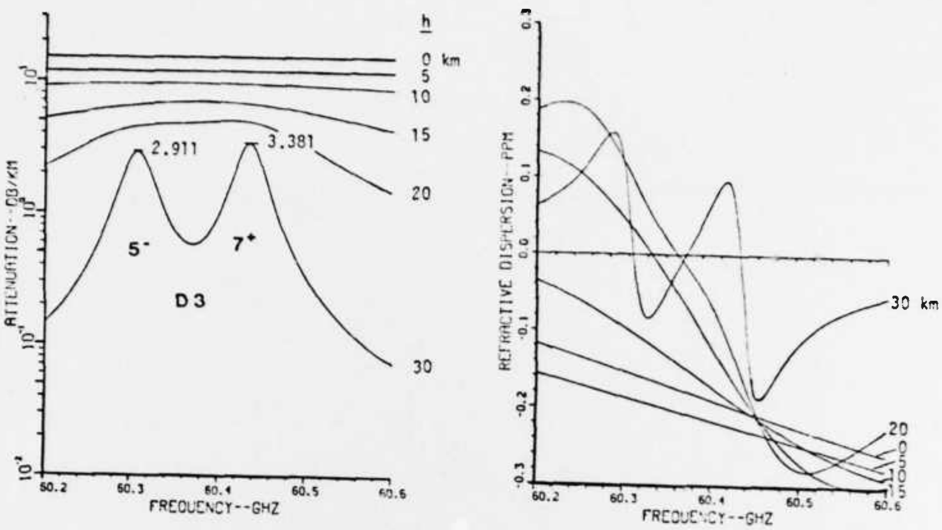
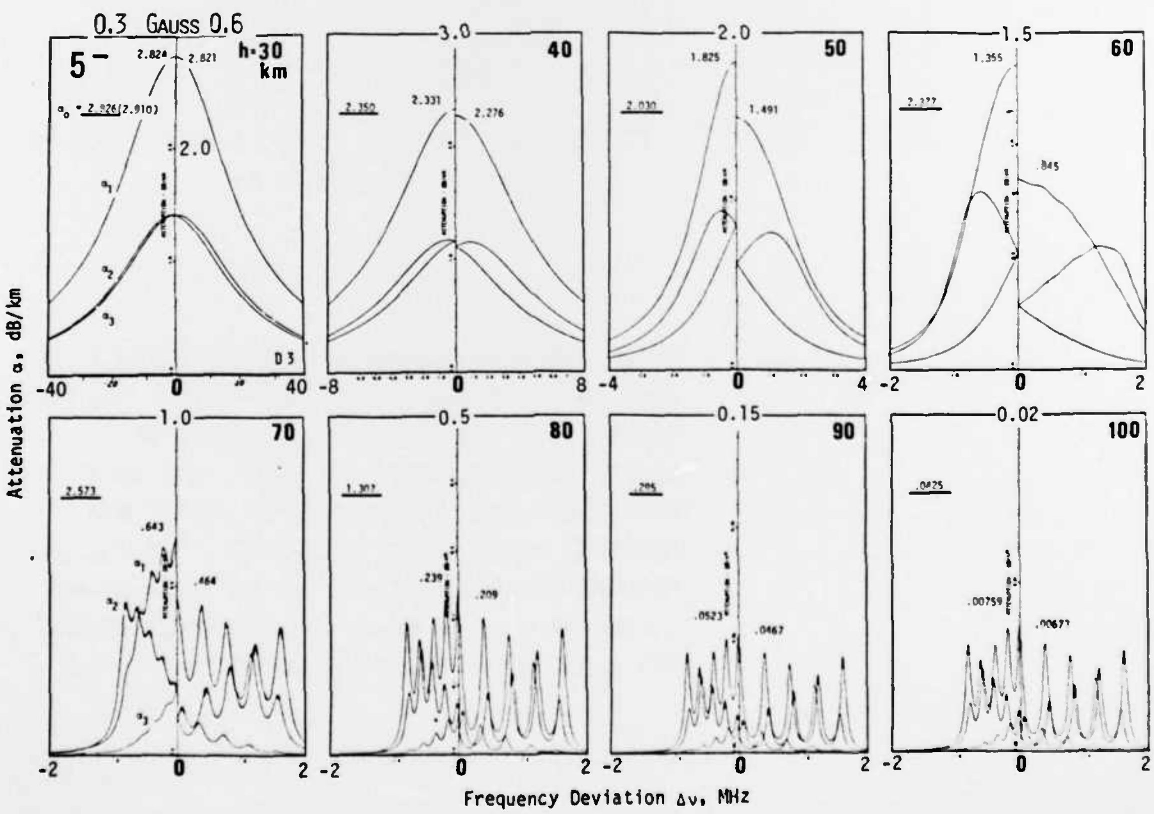


FIG. 4. ATTENUATION α IN DB/KM AND REFRACTIVE DISPERSION D IN PPM AT THE OXYGEN MICROWAVE BAND CENTER FOR THE ALTITUDES, h = 0 TO 30 KM COVERING THE FREQUENCY RANGE 60.2 TO 60.6 GHz.



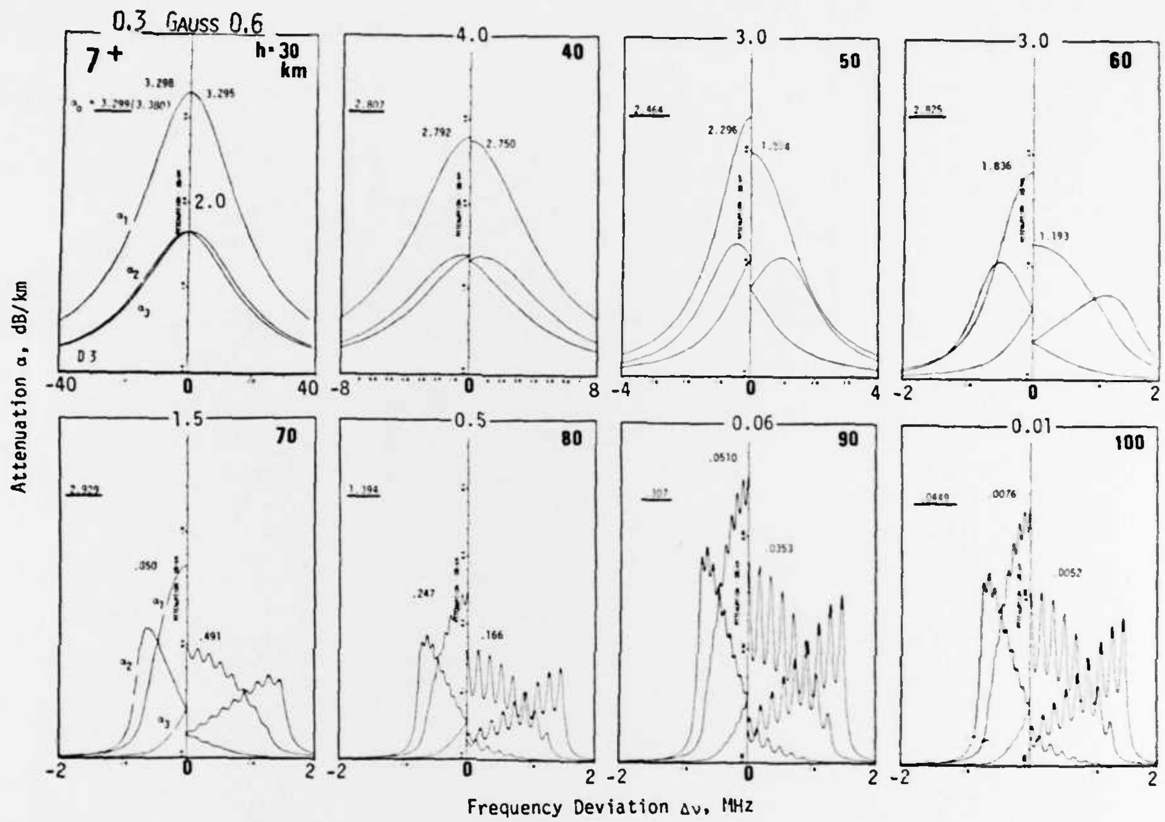


FIG. 5. ZEEMAN ATTENUATION PATTERNS OF THE OXYGEN MICROWAVE LINES K = 5^- AND 7^+ FOR ALTITUDES h = 30 TO 100 KM. EACH FRAME DISPLAYS $\pi(\alpha_1)$, $\sigma^+(\alpha_2)$, AND $\sigma^-(\alpha_3)$ PATTERNS FOR THE MAGNETIC FIELD STRENGTHS, H = 0.3 (LEFT HAND) AND H = 0.6 GAUSS (RIGHT HAND). THE PATTERNS ARE SYMETRIC WITH RESPECT TO THE CENTER AXIS (INTERCHANGE σ^+ AND σ^-). THE FREQUENCY DEVIATION IS BETWEEN ± 40 MHz FOR h = 30 AND ± 2 MHz FOR h = 60 TO 100 KM. THE MAXIMUM ATTENUATION RATE α_0 IS THAT OF THE ISOLATED UNSPLIT LINE (H = 0).

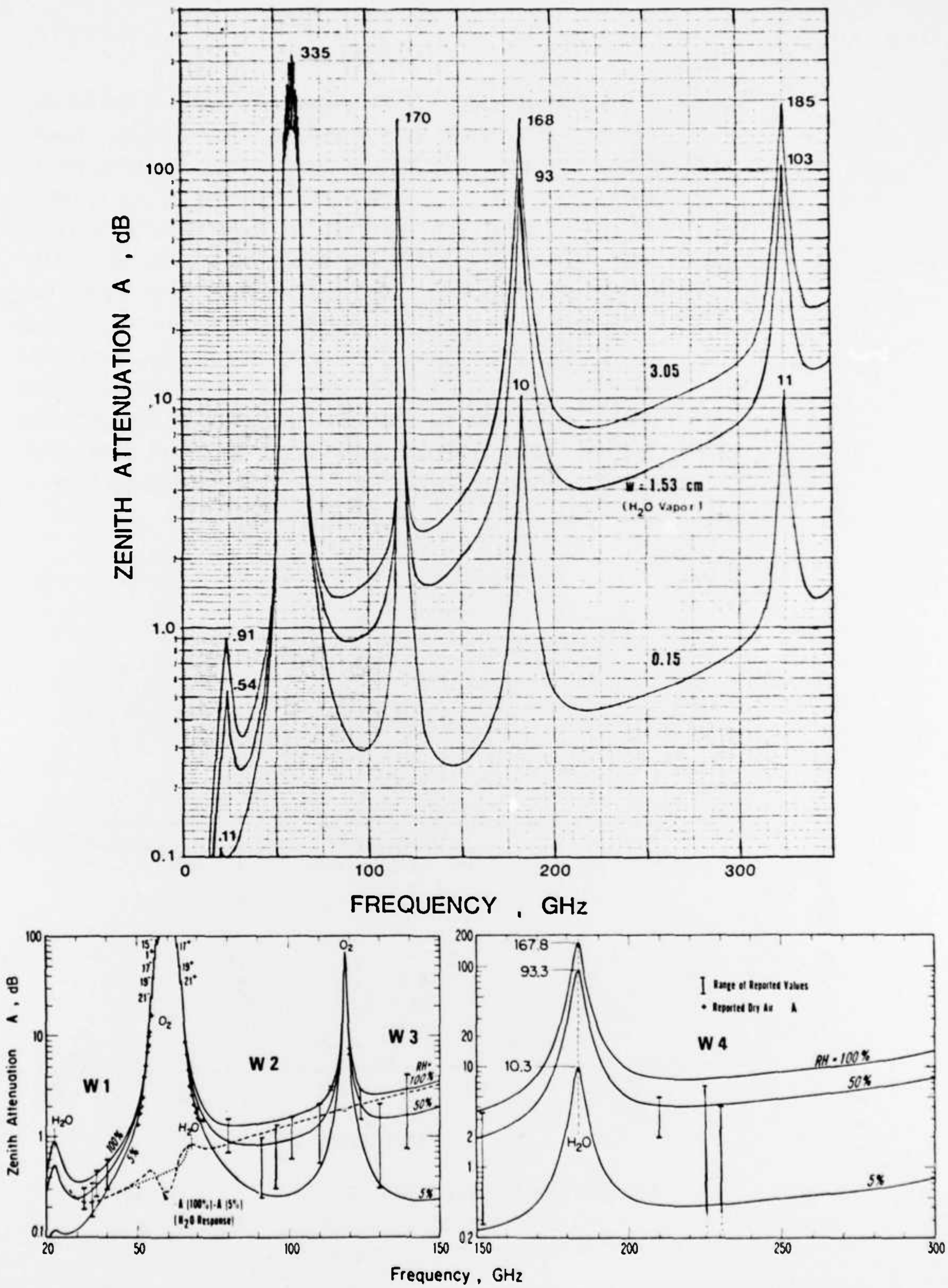


FIG. 6. ZENITH ATTENUATION A OF THE U.S. STANDARD ATMOSPHERE 1976 FOR DRY (0.15 CM). MODERATE (1.53 CM), AND HUMID (3.05 CM) AIR OVER THE FREQUENCY RANGE 10 TO 300 GHz. THE RELATIVE HUMIDITY RH WAS ASSUMED TO BE CONSTANT FOR h = 0 KM TO 8 KM.

Cumulative Effects
(ZENITH PATH)

A STANDARD EXAMPLE FOR AN INHOMOGENEOUS MEDIUM IS THE ONE-WAY ZENITH RESPONSE THROUGH THE U.S. STANDARD ATMOSPHERE 1976. FIGURES 6 AND 7 DISPLAY THE CUMULATIVE ATTENUATION A AND CUMULATIVE PHASE DISPERSION $\Delta\phi$, FOR WHICH 43 (58) HEIGHT LEVELS UP TO $h = 30$ (100) KM ARE SUMMED. THESE CURVES REPRESENT THE ONE-WAY ZENITH PATH BEHAVIOR. THREE HUMIDITY PROFILES WERE USED TO MODEL RH = 5, 50, AND 100% IN EACH OF 26 HEIGHT LAYERS BETWEEN $h = 0$ AND 8 KM. THE RH DROPS RAPIDLY BELOW 1% ABOVE $h = 8$ KM. THE FREQUENCY RANGE 55 TO 65 GHz IS OPAQUE ($A > 30$ dB) FOR ANY SYSTEM ATTEMPTING TO LOOK THROUGH. FREQUENCIES AROUND 57 AND 63 GHz YIELD THE MAXIMUM AND MINIMUM PHASE DISPERSION FOR THE 60-GHz BAND, WHICH IS ALMOST INDEPENDENT OF THE WATER VAPOR CONTENT. COMPARISON OF THE ZENITH ATTENUATION A WITH MEASUREMENTS YIELDS REASONABLE GOOD AGREEMENT WHEN THE EMPIRICAL WATER VAPOR ABSORPTION CONTINUUM IS USED IN THE CALCULATION.

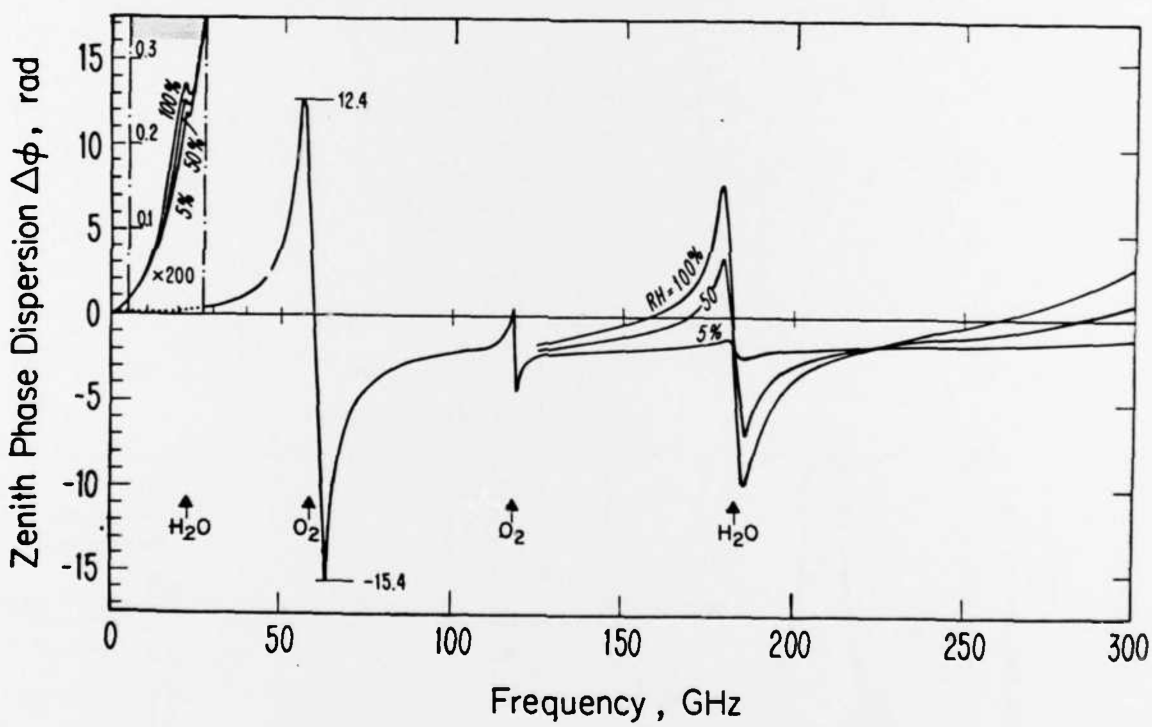


FIG. 7. ZENITH PHASE DISPERSION $\Delta\phi = \phi - \phi_0$ FOR THE SAME CONDITIONS SPECIFIED IN FIG. 6. THE FREQUENCY-INDEPENDENT DELAY TIME DUE TO $\phi_0[N_0(H)]$ IS:

W,CM	0.153	1.53	3.05
t,NS	7.666	7.977	8.266

CONCLUSIONS

MOIST AIR WAS CHARACTERIZED AS AN ATMOSPHERIC PROPAGATION MEDIUM. THE BASIC PHYSICS OF MOLECULAR ABSORPTION IN A RADIO PATH HAS BEEN CAST INTO A MODEL WITH OPTIMUM COMPUTER RUN TIME, BUT WITHOUT UNDUE APPROXIMATIONS. THE PAPER HAS PROVIDED GRAPHICAL AND NUMERICAL EXAMPLES, AND THE FORMULATION OF DISPERSION HAS BEEN CLARIFIED. SHORTCOMINGS OF THE PRESENT MODEL LIE IN THE MISSING SPECTROSCOPIC DATA BASE FOR TRACE GASES, AND IN THE LACK OF A MODEL THAT DESCRIBES THE RH-DEPENDENT WATER UPTAKE BY VARIOUS ATMOSPHERIC AEROSOL DISTRIBUTIONS.

SETTING UP THE PROGRAMS P1 AND P2 WAS STRAIGHTFORWARD. THE ROUTINE IS OPERATED, EVEN BY NON-EXPERT USERS, SIMPLY BY CALLING THE PROGRAM NAME, CHOOSING FROM A BATTERY OF 10 MODEL ATMOSPHERES, AND TYPING-IN THE INTERACTIVELY REQUESTED INPUT PARAMETERS: METEROLOGICAL DATA ARE CONVERTED INTO PROPAGATION DATA. DETRIMENTAL EFFECTS SUCH AS FLUCTUATIONS IN AMPLITUDE, PHASE AND GROUP VELOCITIES, AND THE DIRECTION OF THE RADIO WAVE MAY BE PREDICTED FROM SPATIAL AND TEMPORAL VARIATIONS OF P-RH-T.

THE MODEL MAY SERVE AS A REFERENCE FOR COMPARISON WITH CURRENT RESEARCH. THIS IS ESPECIALLY VALUABLE WITH RESPECT TO STUDIES OF WATER VAPOR EXCESS ABSORPTION, A WEAKNESS IN THE PRESENT MODEL SINCE IT IS ONLY ACCOUNTED FOR BY AN EMPIRICAL CORRECTION. THE TASK AHEAD IS RESEARCH INTO THE NATURE OF H_2O EXCESS ABSORPTION, ALREADY UNDERWAY IN SEVERAL LABORATORIES INCLUDING OURS AT THE INSTITUTE FOR TELECOMMUNICATION SCIENCES, NTIA.

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LIEBE, H. J. (1981), MODELING ATTENUATION AND PHASE OF RADIO WAVES IN AIR AT FREQUENCIES BELOW 1000 GHZ, RADIO SCIENCE 16 (6), NOV-DEC.