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SUMMARY OF 1974-1977 ACTIVITIES

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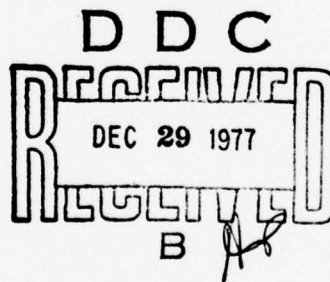
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EHF TRANSFER AND SHIELDING PROPERTIES OF AIR

SUMMARY OF 1974-1977 ACTIVITIES

H.J. LIEBE

G.G. GIMMESTAD



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PREFACE

This is the final report on work performed at the Institute for Telecommunication Sciences on "Atmospheric Transfer and Shielding Properties in the 50 to 75 GHz Band" (ARO Proposal NR. 12233 GS). The report was prepared for DoD - Army Research Office, Geosciences Division (Dr. A. Dodd, Director), which supported part of the work under MPIR Nos. 14-74, 16-75, and 20-76. Other funding came from NOAA - National Environmental Satellite Service, Suitland, Maryland 20233, and OT/ITS, Division of Applied Electromagnetic Science.

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EHF TRANSFER AND SHIELDING PROPERTIES OF AIR

(SUMMARY OF 1974-1977 ACTIVITIES)

H. J. Liebe and G. G. Gimmestad*

The microwave spectrum of oxygen (O_2 -MS) was investigated with a pressure-scanning dual-resonator spectrometer between 53 and 64 GHz and with a non-resonant cavity spectrometer at 119 GHz under simulated atmospheric conditions. This summary is intended as a wrap-up and guide to the various outputs covering three main topics: new spectroscopic measurement technique; extensive O_2 -MS laboratory studies; and engineering formulation and modeling of clear air (molecular) EHF radio path transfer properties.

Key Words: Atmospheric propagation; dispersion spectroscopy; EHF transfer function; oxygen microwave spectrum.

1. INTRODUCTION

The FHF (30-300 GHz) range is receiving renewed attention, particularly from DoD for strategic applications in communication, guidance, and remote sensing. Systems that operate at these frequencies through the atmosphere experience selective attenuation, transit time variations, and noise caused permanently by molecular absorption in air and intermittently by scattering and dielectric loss in precipitation and clouds. The ability to predict system performances under actual operational conditions is a remaining major problem limiting the use of the EHF spectrum.

In clear air it is absorption by oxygen that dominates atmospheric transfer properties over the first half of the

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EHF range (<150 GHz), while in the second half, and actually up into the infrared region, water vapor is the main absorber. If the correct correspondences to the molecular spectra are known, the transfer properties are predictable from easy-to-obtain height profiles of meteorological variables. The Institute for Telecommunication Sciences had proposed verification experiments to clarify inaccuracies and arbitrary assumptions in existing theories. Specifically, five tasks were formulated:

1. to understand and interpret the relevant spectroscopy and translate complicated quantum mechanical treatments into manageable schemes;
2. to design an extremely sensitive laboratory experiment and confirm its ability to provide accurate truth data;
3. to perform extensive measurements under simulated atmospheric conditions ($h \sim 0$ to 80 km) within the EHF range;
4. to deduce from scores of laboratory results a more universal data base; and finally,
5. to incorporate that base into a computer model for evaluating altitude-dependent transfer characteristics of modeled radio paths.

In this summary, reference is made to a series of publications (P1 to P19, see Section 4.1), which are the result of four years of effort and which report more or less satisfactory solutions to various aspects of the above stated tasks. The original abstracts of nine of the more important papers are given in Appendix A. News stories related to project activities are collected in Appendix B.

2. IMPROVED DATA BASE

The complex refractivity N in parts per million was chosen to be the engineering (macroscopic) measure of the

interaction between EHF radiation and air molecules (P14-16). For practical evaluations, we want N expressed in terms of frequency (ν), pressure (p), and temperature (T) in most direct form. The spectra of the molecules O_2 (60 and 119 GHz) and H_2O [22 and 183 GHz, plus about 2000 additional lines up to 31 THz (Rothman and McClatchey, 1976)], however, lead to a complicated N-formula involving more than 200 line parameters and several additional constants.

2.1. Spectroscopic Parameters

In principle, it is possible to calculate atmospheric molecular absorption from theories based on first principles (e.g., Lam, 1977). A substantial simplification for the O_2 -spectrum was introduced by Rosenkranz (1975) who approximated the 60 GHz band shape and its narrowing due to line overlap with a set of four parameters each (center frequency, strength, width, interference coefficient) for the 36 significant lines. In frequency-insensitive ($\nu = \text{const.}$) applications, a further step in simplification is possible without significant loss of accuracy, i.e., selection of a power law presentation $N = kp^X T^Y$ (P15; Poon, 1977). In all cases, it is line parameters which determine the quantitative value of N and, ultimately, the reliability of EHF transmission predictions (e.g., Greenebaum, 1975, a,b).

The majority of the O_2 line parameters were measured by us with 1 to 3 percent uncertainties, which constitutes a substantial improvement over the scarce previously reported data (P6-10). The experimental part of the research made Rosenkranz's approach an experimentally verified theory over the significant ranges (52-68 GHz, 117-121 GHz) of the oxygen spectrum (P6).

2.2. Preliminary Results on Foreign-Gas-Broadening of O_2 Lines

Very recent measurements of O_2 -MS linewidths for binary gas mixtures O_2 -X and for air produced some unexpected inter-

esting results. These results are summarized in Table 1 and discussed in full detail in a forthcoming Ph.D. thesis by G. Gimmestad (P9). Most of the foreign perturbers X were chosen to be atmospheric constituents. Concurrently with the foreign gas width measurements, ratio measurements of air-to-O₂ peak line intensities were performed. The broadening efficiency for dry air derived from both methods agreed within experimental error. The small difference between O₂ and air widths was cast into a simple model (P16) modifying the EHF clear air prediction scheme reported in (P14, P15).

The results of Table 1 are important in molecular physics. The width parameters depend directly on the assumed molecular "shape" (intermolecular potential). Any additional quantum number dependence of the broadening efficiency η (P6, P7) indicates deviations from the potential form used so successfully to predict the selfbroadened O₂-O₂ width (Lam, 1977).

3. EHF RADIO PATH MODELING

Table 1 summarizes 16 computer programs written to cope with molecular, experimental, and modeling tasks resulting from studies of the atmospheric O₂ and H₂O EHF spectra. The programs have been updated as new theoretical (Rosenkranz, 1975; Lam, 1977) and experimental (P6, P7, P16) results became available. Cumulative attenuation along a ray trajectory S₁ → S₂ is defined by

$$A = \int_{S_1}^{S_2} \alpha(s) ds \quad (\text{dB})$$

yielding the power transmittance (opacity)

Table 1. Results of Foreign-gas Broadening Study on O₂-HS Lines
 [T = 300 K; p(O₂) = 2 to 3, p(X) = 0 to 8 torr; (ν-ν₀) = ± 5 MHz; H ≈ 0 Gauss].

Molecule X	Air Compos. ppm/vol.	Broadening Efficiency m(O ₂ -X)												Mass ppm/torr	Refrac- tivity
		k: 3 ⁺	5 ⁺	7 ⁻	9 ⁺	11 ⁺	13 ⁻	15 ⁺	17 ⁻						
O ₂ a)	209476	1	1	1	1	1	1	1	1	1	1	1	1	32	0.318
AIR b)	10 ⁶	0.99	0.98	0.98	0.97	0.98	0.98	0.96	0.95	-----	-----	-----	-----	28.9	0.345
He	5.24	0.72	0.73	0.74	0.73	0.75	0.75	0.75	0.77	-----	-----	-----	-----	4	0.0422
Ne	18.18	0.62	0.63	0.62	0.63	0.62	0.62	0.60	0.58	-----	-----	-----	-----	20	0.0811
Ar	9340	0.85	0.83	0.82	0.77	0.78	0.77	0.72	0.69	-----	-----	-----	-----	40	0.332
Kr	1.14	0.84	0.83	0.81	0.81	0.78	0.74	0.70	-----	-----	-----	-----	-----	84	0.508
Xe	0.087	0.92	0.90	0.89	0.89	0.83	0.77	0.72	-----	-----	-----	-----	-----	131	0.809
H ₂	0.5	1.13	1.10	1.12	1.15	1.19	-----	1.18	-----	-----	-----	-----	-----	2	0.163
D ₂	-----	1.01	-----	-----	-----	-----	-----	1.02	-----	-----	-----	-----	-----	4	-----
N ₂	780840	0.98	0.97	0.94	0.96	0.95	0.92	0.91	0.93	-----	-----	-----	-----	28	0.352
CO c)	0.19	1.00	-----	-----	-----	-----	-----	0.93	-----	-----	-----	-----	-----	28	0.422
NO c)	0.001	1.00	-----	-----	-----	-----	-----	0.98	-----	-----	-----	-----	-----	30	0.400
N ₂ O c)	0.3	1.16	-----	-----	-----	-----	-----	1.11	-----	-----	-----	-----	-----	44	0.669
H ₂ O	variable	-----	-----	-----	1.25	-----	-----	-----	-----	-----	-----	-----	-----	18	5.87
CO ₂	322	1.15	1.12	-----	-----	-----	-----	1.09	-----	-----	-----	-----	-----	44	0.593
C ₂ H ₂ c)	-----	1.29	-----	-----	-----	-----	-----	1.12	-----	-----	-----	-----	-----	26	0.889
CH ₄	1.5	1.17	1.21	1.19	1.19	1.18	-----	1.14	-----	-----	-----	-----	-----	16	0.531
C ₂ H ₆	-----	1.35	-----	-----	-----	-----	-----	1.29	-----	-----	-----	-----	-----	30	0.884
C ₃ H ₈ c)	-----	1.41	-----	-----	-----	-----	-----	1.33	-----	-----	-----	-----	-----	44	1.232
C ₄ H ₁₀ c)	-----	1.53	-----	-----	-----	-----	-----	1.46	-----	-----	-----	-----	-----	58	1.594

a) m = 1 by definition.

b) Data from peak dispersion ratios AIR-to-O₂ [P5].

c) These gases were kindly provided by the NOAA Aeronomy Laboratory.

$$\tau = \exp (-A / 4.343) .$$

In general, for a slant path the integration has to be carried out along a curved ray; in practice, several restrictive assumptions are made. Table 2 lists some new results obtained with program No. 14. They were obtained by a numerical integration through a layered atmosphere for a zenith path. The altitude increments $\Delta s \sim ds$ were chosen, so that $\alpha(\Delta s)$ was quasi-homogeneous. The initial step size over the first 11 kilometers was 0.1 km, after which 0.05 or 0.025 km suffices. The computer program monitors the percentage change of α , and a change of $> 1\%$ results in (a) step size being cut in half and (b) repetition of the computation. On the other hand, the size is doubled when a change of $< 0.49\%$ is produced by the layer. Another program feature is that the summation ceases either when $A > 200$ dB or $\alpha < 0.01$ dB/km. About 10^3 layers are required for $h = 0$ to outer space.

The programs No. 16 and No. 14 will be documented in an upcoming OT/ITS catalog of "computer programs and associated data bases for performance predictions of 10 to 100 GHz radio systems" (Collins, private communication, 1977). Program listings, card decks, lengthy numerical printouts, etc., could be made available to interested parties. The output format provides answers for systems operating in the earth's neutral gas mantle (0 to 80 km height, 0 to 90° slant path angle).

4. RESEARCH OUTPUT

4.1. Publications

Publications 1 to 19 (15 completed) are an up-to-date account of existing and planned output stemming from research or activities under the joint sponsorship (see Preface). For a better overview, the titles are arranged under four sub-headings:

Table 3. One-Way Dry Air Zenith Path Attenuation
(sea level to outer space)

FREQUENCY ν		ZENITH PATH RESPONSE ⁺			
Line (MAX), Window (MIN) Positions	Even Steps	A	τ	Exp	
	(GHz)	(dB)			
53.60 MAX		9.6	1.10	- 1	Semi-Transparent
53.9 MIN		11.7	6.76	- 2	
	54.0	12.3	5.89	- 2	
54.13 MAX		14.9	3.24	- 2	
54.4 MIN		17.5	1.78	- 2	
	54.5	18.4	1.45	- 2	
54.67 MAX		23.9	4.07	- 3	
54.95 MIN		26.0	2.51	- 3	
	55.0	27.2	1.91	- 3	
55.22 MAX		37.4	1.82	- 4	
55.5 MIN		39.8	1.05	- 4	
55.78 MAX		52.5	5.62	- 6	Opaque
56.0		58.9	1.29	- 6	
56.3		73.8	4.2	- 8	
	56.5	80.4	9.1	- 9	
	57.0	111	7.2	-12	
	57.5	114	3.9	-12	
	58.0	120	1.0	-14	
	58.5	166	2.4	-17	
	59.0	150	9.8	-16	
	59.5	168	1.4	-17	
	60.0	163	1.1	-17	

⁺U. S. Standard Atmosphere 1976 for p(h), T(h)

- a) New Spectroscopic Measurement Technique (Dispersion Pressure Scanning)
- P1. A refraction spectrometer for atmospheric gas studies at millimeter wavelengths (Liebe, OT Report 74-35, April 1974).
- P2. Pressure-scanning mm-wave dispersion spectrometer (Liebe, Rev. Sci. Instr. 46, 817-825, July 1975).*+
- (P3). High resolution millimeter wave phase meter (Liebe-Diede, Rev. Sci. Instr.; in preparation).
- b) Experimental Studies of H₂O and O₂ Spectra
- P4. Laboratory measurements and analysis of atmospheric propagation factors between 20 and 110 GHz (Liebe-Welch, Proc. Mm Wave Techniques Conf., pp. B2/1-6, 1974).
- P5. Studies of oxygen and water vapor microwave spectra under simulated atmospheric conditions (Liebe, OT Report 75-65, June 1975).*+
- P6. Atmospheric oxygen microwave spectrum - experiment versus theory (Liebe-Gimmestad-Hopponen, IEEE Trans. AP-25, 327-335, May 1977).*+
- P7. The EHF spectrum of atmospheric oxygen (Liebe-Gimmestad-Hopponen,, Proc. URSI Internat. Open Symp. Comm. F; La Baule, France; pp 619-624, May 1977).*
- P8. Millimeter oxygen attenuation measurements (Gimmestad et al., J. Quant. Spectr. Rad. Tr. 16, 899-900, Oct. 1976; 17, 795, June 1977).*+
- (P9). The pressure-broadened microwave line spectrum of oxygen (Gimmestad, Ph.D. Thesis, Dept. of Physics, University of Colorado; in preparation).+
- (P10). Dispersion studies of the oxygen microwave spectrum Part I: Line spectrum; Part II: Band spectrum (Liebe-Gimmestad-Hopponen, JQSRT, in preparation).

* Abstract see Appendix A.

+ Acknowledgement of ARO Support.

c) Atmospheric EHF Transfer Characteristics

- P11. Molecular transfer characteristics of air between 40 to 140 GHz (Liebe, IEEE Trans. MTT-23 380-386, April 1975).*+
- P12. Transfer characteristics of air between 10 and 150 GHz (Liebe, Active Microwave Workshop Report, NASA SP-376, pp. 348-359, 1975).
- P13. Transfer properties of the clear atmosphere (Liebe, Proc. Kleinheubacher Tagung Bd. 20, pp. 329-331, 1976).
- P14. FHF properties of air (Liebe, NTZ Communication J. 30, 76-84, Jan. 1977).*+
- P15. Variability of EHF air refractivity with respect to temperature, pressure, and frequency (Liebe-Hopponen, IEEE Trans. AP-25, 336-345, May 1977).*+
- P16. Calculation of clear air EHF refractivity (Liebe-Gimmestad, Radio Science, March/April 1978, accepted).*
- P17. 30 and 60 GHz line-of-sight amplitude measurements (Degenhardt-Hartmann-Liebe-Loidl, MPI-Aeronomy Report ME-1, August 1977)
- (P18). Atmospheric medium characterization and modeling for EHF propagation (Liebe-Hopponen, NATO/AGARD EPP Symp. invited review paper, April 1978; in preparation).

d) Miscellaneous

- P19. Citation analysis of OT/ITS MM Wave Lab. Studies (Liebe, OT/ITS Tech. Memo. July 1976).

4.2. Presentations

Conferences:

1. H. J. Liebe, "Oxygen microwave attenuation from laboratory measurements," Third Annual Conf. Telecommunications for Government, Boulder, CO., October 1-3, 1974.

2. H. J. Liebe, "Pressure-scanning refraction spectrometer for atmospheric gas studies at mm-waves," 1974 Annual URSI Meeting, Boulder, CO., October 14-17, 1974.
3. H. J. Liebe, "Absolute intensity measurements of the O₂ microwave spectrum under simulated atmospheric conditions," Colloquium of URSI-IUGG, Commission on Radio Meteorology, Bournemouth, England, May 13-20, 1975.
4. H. J. Liebe, "Variability of atmospheric oxygen spectra between 40 and 140 GHz," 1975 USNC/URSI Meeting, Boulder, Colorado, October 20-23, 1975.
5. H. J. Liebe, "EHF transfer properties of clear air," 4th Annual Conf. Telecommunications for Government Boulder, Colorado, November 11-13, 1975.
6. J. D. Hopponen, "Computer sensitivity studies of the atmospheric oxygen microwave spectrum," (same meeting as #7, below)
7. H. J. Liebe, "Advances in the formulation of the atmospheric O₂ spectrum," Third Annual IEEE/AP-S Denver Symposium, May 7, 1976.
8. H. J. Liebe, "EHF transfer properties of the clear atmosphere," URSI-NTG, Kleinheubach, W. Germany, October 7, 1976.
9. G. G. Gimmestad, "Pressure broadening of O₂ lines by noble gases," AAAS National Meeting, Denver, February 22, 1977.
10. G. G. Gimmestad and H. J. Liebe, "Pressure broadening of oxygen microwave lines by other atmospheric gases," National Radio Science Meeting (URSI, IEEE), January 9-13, 1978.

Seminars:

- K. Lam, "Microwave pressure broadening in the terrestrial atmosphere," OT Technical Seminar, July 16, 1975.
- H. J. Liebe, "The atmospheric filter between 40 and 140 GHz," OT/ITS Technical Seminar, Boulder, Colorado January 16, 1975.

- "Role of spectroscopy in microwave propagation," EM Wave Seminar, Boulder, Colorado, February 4, 1975.
- "Atmospheric mm-wave spectra," DFVLR Inst. Microwaves, Oberpfaffenhofen, W. Germany, November 25, 1976.
- "Spectroscopy of H₂O, O₂, and HCN over the range 20 to 300 GHz," Inst. Applied Physics, Univ. Bern, Switzerland; January 12, 1977.
- "Propagation problems of 60 GHz broadband signals," CERN, SPS Seminar, Geneva, January 13, 1977.
- "The technical importance of gas resonances at FHF," HF Symposium, Techn. University Hannover, W. Germany, February 9, 1977.
- "Quantitative spectroscopy over the 10 to 300 GHz range," Max-Planck-Inst. Molecular Spectrosc., Giessen, W. Germany, March 11, 1977.
- "New measurement techniques for mm-wave spectroscopy," Max-Planck-Inst. Solid State Phys., Stuttgart, W. Germany, May 18, 1977.
- "Atmospheric research with mm-waves," Max-Planck-Inst. Aeronomy, Lindau, W. Germany; June 3, 1977.
- "Anomalous water vapor absorption at FHF," Electromagnetics Seminar, IEEE Local APS, Boulder, Colorado, October 17, 1977.

4.3. Citation Analysis

On the assumption that the number of citations reflects to a certain degree the long term impact of a particular research project, an ad hoc citation analysis of the ITS Millimeter Wave Transmission Spectroscopy project was performed covering the period 1970-1976 (P19). It revealed that nineteen papers have been referenced by other authors more than 200 times (including six earlier papers on the 22 GHz water vapor line). Owing to the basic interdisciplinary nature of the subject matter, references can be found in the geophysical, spectro-

scopic, astronomical, and chemical literature besides the journals used by microwave and communication system engineers.

5. CONCLUSIONS

Molecular absorption is detrimental, as well as in special cases, advantageous to FHF systems operating through the atmosphere. Transfer and emission properties can be predicted from meteorological height profiles. They depend upon frequency and vary with pressure, temperature (and magnetic field strength), and with the nature and length of the radio path. Computations for a specified situation and observational mode need a complete account of molecular line parameters and nonresonant spectra. Experimental, analytical, and numerical results of this research project have contributed to clarify for practitioners the framework needed to predict FHF properties of air (Pl6).

In atmospheric science, cloud-penetrating remote sensing at EHF is a promising measurement technique and has made use of our basic results. For example, ground-based radiometry measures temperature profiles (e.g., Westwater et al., 1976) and mesospheric water vapor distribution (Radford et al., 1977) while on a global scale, satellite instruments monitor passively atmospheric water (vapor) (Grody, 1976) and temperature (Poon, 1977) and, actively (radar-mode), surface pressure (Mathews, 1975).

A highly speculative thought is concerned with weather modification by transferring, via molecular absorption, substantial amounts of energy into the atmosphere. The energy is collected in space by large solar cell arrays and converted into the EHF range (a 50 km² array is projected to produce about 10 GW).

Several points on atmospheric O₂ and H₂O EHF spectra still await experimental clarification; i.e., (a) the temperature dependence of O₂-MS intensities, (b) parameters for weaker ($K^+ > 17$) O₂ lines, (c) line fine structure studies below 5 torr in the presence of a weak magnetic field (Zeeman effect), and (d) window intensity data at ~ 50, 100, 150 GHz. A little understood anomalous water vapor absorption (P5) reduces atmospheric transparency in the window regions. Theory underestimates the attenuation by as much as a factor 5 when only the monomeric form of H₂O is considered. The quantitative details of the anomalous, nonresonant absorption are not known.

6. REFERENCES

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- Waters, J. W. (1976), Absorption and emission by atmospheric gases (Chapter 2.3 in Methods of Experimental Physics Vol. 12B; editor M. Meeks), Academic Press, New York.
- Westwater, R. E., M. T. Decker, and F. O Guiraud (1976), Atmospheric temperature and moisture sensing from ocean data buoys by microwave radiometry, Proc. Symp. Rad. in the Atmosphere, Garmisch-Partenkirchen, W. Germany, August, F-P6.

APPENDIX A

Abstracts of Papers

1. IEEE Trans MTT 23, 380-386 (April 1975)
2. Rev. Sci. Instr. 46, 817-725 (July 1975)
3. IEEE Trans AP-25, 327-335 (May 1977)
4. IEEE Trans AP-25, 336-346 (May 1977)
5. NTZ Communications Journal 30, 76-84 (January 1977)
6. J. Quant, Spectr. Rad. Transf. 16, 899-900 (October 1976)
7. OT Report 76-65 (June 1975)
8. Proc. URSI Com. F. Open Symposium, La Baule, France, 619-624 (April 1977)
9. Radio Science (March/April 1978)

1. Molecular Transfer Characteristics of Air Between 40 and 140 GHz

HANS J. LIEBE, SENIOR MEMBER, IEEE

Abstract—Radio wave propagation in the 40–140-GHz band through the first hundred kilometers of the clear atmosphere is strongly influenced by many (>30) lines of the oxygen microwave spectrum (O₂-MS) and to a lesser extent by water vapor. A unified treatment of molecular attenuation and phase dispersion is formulated whereby results of molecular physics are translated into frequency-, temperature-, and pressure-dependencies. The propagation factors are developed for O₂ continuum—($h < 10$ km) and line—($h > 20$ km) spectra taking into account pressure-broadening ($h < 40$ km), Zeeman-splitting ($h > 40$ km), and Doppler broadening ($h > 60$ km). The influence of water vapor is discussed briefly. The filter characteristics of dry air are evaluated for various path models. Examples of computer plots of attenuation and dispersion rates are given as a function of altitude h for homogeneous, zenith, and tangential path geometries through the 1962 U. S. standard atmosphere.

Manuscript received February 20, 1974; revised October 23, 1974. This work was supported in part by the NOAA-National Environmental Satellite Service under Order NA-755-73 and the U. S. Army Research Office (ARO 14-74).

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2. Pressure-scanning mm-wave dispersion spectrometer*

H. J. Liebe

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(Received 18 February 1975; in final form, 3 April 1975)

A differential refraction spectrometer for measuring the absolute intensity distribution of microwave spectra in gases by means of dispersion pressure profiles is described. The instrument was applied to study the 60 GHz band spectrum of oxygen under simulated atmospheric conditions (10^{-3} – 10^3 Torr, 252–325 K). The detection sensitivity for dispersion was better than 1 part in 10^9 using two high- Q ($\sim 4 \times 10^5$) resonators at 2:1 related frequencies and a sampling phase meter. Illustrative examples of data taken around 61 GHz, their reduction to spectroscopic parameters, and problems related to dynamic limitations are dealt with.

*This work was supported in part by NOAA-NESS (5-13155) and by the U. S. Army Research Office (ARO 14-74).

3. Atmospheric Oxygen Microwave Spectrum— Experiment versus Theory

HANS J. LIEBE, SENIOR MEMBER, IEEE, GARY G. GIMMESTAD, AND JERRY D. HOPPONEN

Abstract—The microwave spectrum of oxygen (O_2 -MS) was investigated with a pressure-scanning dispersion spectrometer between 53.5 and 63.6 GHz under simulated atmospheric conditions. First, the strength and width parameters of 21 lines ($K^{\pm} = 1$ to 25) were determined from low pressure (<20 torr) data with accuracies on the order of 1 to 4 percent and the results extended to other lines ($K^{\pm} = 25$ to 35). Then, O_2 -MS intensities (dispersion and attenuation by oxygen and air) were measured between 100 and 800 torr and compared with Rosenkranz's band shape model. A set of interference coefficients was established to produce good agreement between experiment and theory. Also, at 61 GHz the refractivities of 13 atmospheric gases were checked. The improved calculation scheme of atmospheric molecular EHF (~40 to 140 GHz) characteristics is presented as a transfer function incorporating a set of 144 line parameters (36 each of position, strength, width, and interference) with frequency, pressure and temperature dependencies.

Manuscript received January 19, 1976; revised May 14, 1976. This work was supported in part by the NOAA-National Environmental Satellite Service under Order 5-13155 and the U.S. Army Research Office (ARO 16-75).

4. Variability of EHF Air Refractivity with Respect to Temperature, Pressure, and Frequency

HANS J. LIEBE, SENIOR MEMBER, IEEE, AND JERRY D. HOPPONEN

Abstract—EHF transfer properties of air are expressed by a complex refractivity N , yielding phase dispersion and attenuation due to the microwave spectrum of oxygen. Based upon an experimentally verified theory (Rosenkranz band shape), the variability of N with respect to temperature, pressure, and frequency variations is analyzed across the 40 to 140 GHz band for atmospheric conditions up to 40 kilometers in altitude (300-200°K, 760-5 torr). The discussion centers on the usefulness of such information when treating problems of possible propagation limitations imposed by turbulent air and of remote sensing atmospheric states.

Manuscript received April 29, 1976; revised July 26, 1976. This work was supported in part by the U.S. Army Research Office (ARO 16-75)

The authors are with the Institute for Telecommunication Sciences, Office of Telecommunications, U.S. Department of Commerce, Boulder, CO 80302.

EHF Properties of Air

ntz

By Hans Joachim Liebe*

Nachrichtentechnische Zeitschrift
ntz - Communications Journal

Organ der Nachrichtentechnischen Gesellschaft
im VDE (NTG)

30. Jahrgang, Januar 1977, Heft 1, Seiten 1 bis 100

EHF Properties of Air

Abstract - EHF spectra of the clear atmosphere are expressed by transfer and emission functions using a complex refractivity as the measure for the interaction between radiation and gas. The refractivity is expressed as a function of frequency, dry air and water vapor pressure, and temperature. No reference is made to complicated quantum-mechanical descriptions. The engineering presentation of the main transfer characteristics requires five parameters each for 46 O₂ and 15 H₂O lines plus a nonresonant H₂O absorption spectrum. Several examples of calculated atmospheric spectra are given, and recent advances in the application of such basic information to radio wave propagation and remote sensing are discussed.

(Manuscript received on September 30, 1976)

* Herrn Professor Dr.-Ing. F. W. Gundlach zum 65. Geburtstag gewidmet. Presently with the Max-Planck-Institut für Aeronomie, Lindau-Katlenburg, W-Germany, sponsored by a "Humboldt Award". The work was supported in part by NOAA-NESS and DoD-ARO.

Communication from the Office of Telecommunications, Institute for Telecommunication Sciences, Boulder, Colorado, USA

6.

J. Quant. Spectrosc. Radiat. Transfer, Vol. 16, pp. 899-900 Pergamon Press 1976. Printed in Great Britain

MILLIMETRE WAVE OXYGEN ATTENUATION MEASUREMENTS†

G. G. GIMMESTAD‡, D. T. LLEWELLYN-JONES and H. A. GEBBIE
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(Received 12 March 1976)

Abstract—A new measurement of the oxygen absorption line at 118,750 MHz under carefully controlled laboratory conditions shows the line broadening parameter at 300°K to be 2.11 ± 0.05 MHz/torr.

†Supported in part by the U.S. Army Research Office (ARO 16-75) and by NATO. The work described in this note was carried out at the Appleton Laboratory and is published with permission of the Director.

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7.

STUDIES OF OXYGEN AND WATER VAPOR MICROWAVE SPECTRA

OT REPORT 75-65

June 1975

HANS J. LIEBE

12. Type of Report and Period Covered

OT Report
(Final Report, Part III) *

14. SUPPLEMENTARY NOTES

*Part I is OT Report 73-10, Part II is OT Report 74-35

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.)

Atmospheric radio wave propagation in the 40 to 140 GHz band is influenced by microwave spectra of oxygen (O_2 -MS) and water vapor. The report treats the complementary roles of controlled laboratory experiments and computer analysis for providing detailed molecular transfer characteristics. A pressure-scanning differential refractometer was operated at fixed frequencies between 58 and 61.5 GHz. The variability of O_2 and H_2O spectra with frequency, pressure, temperature, and magnetic field strength was studied under conditions which occur in the atmosphere. Results obtained (a) for oxygen and air on the 9^+ line, the $7^+/5^-$ and $3^+/9^-$ doublets, and the continuum spectrum, and (b) for water vapor on nonresonant effects, are reported. The experimental O_2 -MS data are used in theoretical analysis of attenuation and dispersion rates which are extended to other lines, to frequencies identified for remote sensing applications, and to temperature and pressure sensitivities between 40 and 140 GHz.

Number of pages

U.S. Army Research Office, Durham, NC 27706, under MIPR No. ARO 14-74, dated May 28, 1974, monitored by Mr. E. Fliegler, USECOM-AMSEL-NLM-1, Ft. Monmouth, NJ 07703, supported part of this work during the period July 1, 1974, to May 31, 1975.

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28 Avril - 6 Mai 1977

Proceedings,
pp. 619-625

THE EHF SPECTRUM OF ATMOSPHERIC OXYGEN

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SUMMARY

The dry air mass of the first hundred kilometers in altitude is a unique filter and generator over the 40 to 140 GHz range with transfer, shielding, and emission properties not found at any lower frequency. The resulting propagation limitations and remote sensing opportunities are mainly caused by the microwave spectrum of oxygen (O_2 -MS), which is a complicated spectroscopic problem due to more than thirty individual lines around 60 GHz and one line at 119 GHz. This paper presents and updates spectroscopic details of laboratory O_2 -MS experiments and gives examples of analytical and numerical evaluations of a new transfer function for homogeneous and slanted (e.g., ground-to-satellite) radio paths.

9.

CALCULATION OF CLEAR AIR EHF REFRACTIVITY

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to be published in
Radio Science
(March/April 1978)

(Received June 25, 1977; revised October 15, 1977)

A practical calculation procedure is presented for the complex refractivity N of air in the EHF (30 to 300 GHz) region. The absorption line spectra of the major constituents O_2 and H_2O and of the trace gases O_3 and CO are expressed in a coefficient scheme relating N directly to frequency, dry air and water vapor pressure, temperature, and trace gas number density. The spectroscopic parameters for the O_2 lines incorporate new experimental results obtained from our laboratory studies. The formulation allows radio engineers to make straightforward computations of transfer, shielding, and emission properties for modeled radio paths based upon the physical parameters of the atmosphere.

APPENDIX B

Relevant "TELENOTES"*

Excepts from:

August 1974
January 1975
April 1975
June 1975
December 1975
February 1976
May 1976
July 1976
July 1977
August 1977
(November 1977)

*Employee Newsletter of the Office of Telecommunications.

TELENOTES

Employee Newsletter of the Office of Telecommunications
Washington, D.C. Boulder, Colorado

U.S. DEPARTMENT OF COMMERCE / Office of Telecommunications

August 1974

Vol. 4 No. 8

DoD Supports 50-75 GHz Studies

The Applied Electromagnetic Science Division (AEMS) of ITS has opened new vistas of scientific research through the fundamental contributions of Dr. M. C. Thompson in the development of a novel measurement technique (U. S. Patent 3-300-330), and the transformation of this technique into a unique pressure-scanning millimeter wave spectrometer by Dr. Hans. J. Liebe.

Four U. S. Army agencies (the Communications Laboratory, Ft. Monmouth, N. J.; the Atmospheric Sciences Laboratory, White Sands, N. M.; the Communications Command, Ft. Huachuca, Ariz.; and the Missile Command, Huntsville, Ala.) are backers of a new basic research project entitled, "Atmospheric Transfer and Shielding Properties in the 50 to 75 GHz Band," which is being undertaken by Liebe and jointly sponsored by ITS and the U. S. Army Research Office-Durham.

The problem addressed by this study is to establish reliable transfer properties of the clear atmosphere in the frequency range and will be tackled by laboratory measurements and analytical computations. Laboratory measurements with the ITS millimeter wave refraction spectrometer will cover the full range of the meteorological variables for the first 100 km of altitude. The object of the investigations is the intensity distribution (attenuation and dispersion) of the oxygen microwave spectrum under the simulated atmospheric conditions. Simulated conditions are necessitated by the discrepancies between existing theory and field measurements.

The analytical portion of the study brings together the experimental and theoretical results to predict the shielding and transfer properties of the earth's mantle. Existing ITS computer

routines are being refined by J. D. Hopponen, also of AEMS, to evaluate with improved reliability the shielding and transfer properties between 40 and 80 GHz as a function of altitude, path geometry, and power density.

The advantage of the laboratory studies lies in the ability to systematically control atmospheric conditions within the desired altitudes (0-100 km). To accomplish this, ITS has developed the computer controlled refraction spectrometer with an investment of \$75,000.

The purpose of this investigation is to enable the design and construction of wideband communications systems accounting for atmospheric effects. Examples of these systems are: tactical broadband communications systems where the atmospheric microwave spectrum of oxygen affords both interference and transmission security, and remote sensing of environmental conditions using satellite (NIMBUS-E, TIROS) or ground based (MIT or NOAA-ERL) radiometers. NASA is another Federal agency which will benefit from this study.

January 1975

Vol. 5 No. 1

ITS Staff to ARPA Meeting

Dr's. Hans J. Liebe, Moody C. Thompson, Jr., and Lockett E. Wood, all of ITS, Div. 3, participated in the ARPA Millimeter Wave Workshop held at the Applied Physics Laboratory of Johns Hopkins University on December 16-18, 1974.

ARPA had invited about 100 experts to formulate in five panels--Communications, Radar, Phenomenology, Systems, Components--the directions for future research. The ITS staff members contributed to the recommendations of the first three panels.

Liebe To Present Paper in England

Dr. Hans J. Liebe, Applied Electromagnetic Science Division of ITS, has been invited to participate with about 20 other experts from around the world in a workshop on atmospheric spectroscopy, sponsored by the International Scientific Radio Union and the International Union of Geodesy and Geophysics. The international blue-ribbon panel will meet in Bournemouth, England, May 13-20.

The United States delegation to the meeting will number ten, two of whom are from the Boulder Laboratories, U.S. Department of Commerce. In addition to Dr. Liebe, Dr. Peter Kuhn of the NOAA research laboratories will attend.

Dr. Liebe will present a paper entitled "Absolute Intensity Measurements of the O_2 Microwave Spectrum Under Simulated Atmospheric Conditions." He will also be a panel member for a discussion group on "Recent Advances in Atmospheric Spectroscopy."

The workshop will address the widespread interest in propagation of electromagnetic waves in millimeter and far infrared range and the use of such waves for remote probing. Recommendations will be generated, advising on the present state of the art and on the direction of future research. Studies in this field are becoming increasingly important since the use of the radio spectrum above 20 GHz hinges on accurate spectroscopy.

While in England to attend this prestigious meeting, Dr. Liebe will also visit the Radio Space Research Station in Slough, England, and the National Physics Laboratory at Teddington, England. The government laboratory at Slough is the British equivalent of the Institute for Telecommunication Sciences in Boulder.

June 1975

Vol. 5 No. 6

60 GHz Link in Operation

The Office of Telecommunications scientists at Boulder Laboratories have installed and are operating a millimeter-wave communications link at a nominal 60 GHz in studies designed to expand the usable spectrum for communications purposes.

A 100 meter link operating at 57.6 GHz and transmitting a carrier signal only is operating between a laboratory and an antenna on the roof of the Boulder Labs. The received signal is being recorded and studied for signal fluctuations.

The magnitude of the attenuation (15 db per kilometer) from oxygen absorption, however, provides one distinct benefit in a certain application. This attenuation precludes any distant propagation of the signal, which makes it attractive for a secure communications link that is relatively immune to interception or monitoring by an unauthorized source.

In the second phase of this study, a new link will be established from the Boulder Laboratories to the top of a University of Colorado building at a distance of approximately 1 km. This link will actually be 3 links operating at 9.6, 28.8, and 57.6 GHz. The first frequency will be used as the reference signal because good data are available, much of it resulting from studies by Dr. Moody C. Thompson, the Group Chief within the Applied Electromagnetic Science Division where the work is being done. The 28.8 GHz link will exhibit more rain attenuation and greater effects from atmospheric turbulence than the reference signal. The 57.6 GHz link will exhibit greater attenuation from atmospheric conditions than the other two and will additionally suffer from oxygen band absorption.

When this 3-frequency link is established, an important additional parameter will be added to the study. Instead of transmitting the carrier signal only, a 1 gigabit quadra-phase digital communication system will be added. Bit error rate measurements for different atmospheric conditions will be recorded on the upper 2 frequencies for purposes of comparison. Autocorrelation techniques, with a 2 nanosecond resolution, will be used to study transfer characteristics of the channel.

Primary responsibility for the engineering portion of this study is assigned to Edmond J. Violette, assisted by Albert R. Mitz.

Data obtained from the 3-frequency link to be used in phase two will serve to verify theoretical and laboratory predictions developed at ITS or lead to their modification. Dr. Randolph H. Ott has developed predictions on the effects of air turbulence on such communication links. Since atmospheric parameters will be closely monitored during the field measurements, these measurements should indicate the validity of Dr. Ott's predictions. Dr. Hans J. Liebe has been engaged in laboratory measurements of the effects of oxygen absorption on millimeter waves. The relationship between his laboratory measurements and field observations will also be of interest. Drs. Harold T. Dougherty and George A. Hufford will find the same measurements of interest in relation to portions of their theoretical work.

OT Contributes to NASA Workshop

Dr. Hans J. Liebe, an engineer in the Applied Electromagnetic Science Division of ITS, was one of 68 experts participating in a working group meeting on the utilization of active microwave systems in NASA applications programs last summer. The meeting produced a comprehensive document of 502 pages, the Active Microwave Workshop Report, NASA SP-376, which has just been published.

Dr. Liebe contributed to the Atmosphere Panel Section a chapter entitled "Molecular Transfer Characteristics of Air Between 10 and 150 GHz."

ITS, which has been conducting research in atmospheric spectroscopy for NASA, was recently evaluated as follows:

A NASA monitor of the work conducted by Dr. Liebe referred to his work, saying that "a most worthwhile body of research resulted." The monitor also stated that Dr. Liebe's laboratory is unique in the world, and the accuracy of his results are by far the best obtained to date. A specific reference is made to Dr. Liebe's results by research scientists at MIT in a new model of the oxygen absorption coefficient. In his summary, the monitor stated that he believed that "a unique capability for high quality research in microwave spectroscopy under the full range of atmospheric conditions exists at OT/ITS."

new data base eliminates large uncertainties of past semi-empirical approaches and emphasizes the importance of molecular spectroscopy in EHF propagation problems. The relatively stable dry air mass of the first hundred kilometers in altitude is a unique filter and generator over this band with transfer, shielding, and emission properties not found at any lower frequency.

Many difficulties had to be overcome to grasp the problem, which existed since the theoretical work of VanVleck in 1947, and which had evaded previous attempts of an experimental solution. On various occasions, committees (URSI-IUGG, NSF, NAS, NASA, NOAA) as well as leading scientists (VanVleck, Birnbaum, Staelin, Waters, and others) had stressed the need for a reliable confirmation of the atmospheric O₂-MS (i.e., a controlled laboratory experiment). That need moved to the foreground with the advent of spectrum extension in telecommunications (OT Five-Year Plan 1975-79) and the use of remote sensing of global temperature structure via satellite (NIMBUS E, F and TIROS N) to which the O₂-MS is central.

With support by NASA and NOAA, and later by DoD-ARO, ITS set out in 1972 to use its expertise in microwave dispersion measurements. The dispersion technique had been pioneered by M. C. Thompson and M. Vetter, both with ITS, with their development of the first true dispersion detector (dual mode cavity). Successful O₂-MS measurements necessitated a new quantitative spectroscopic technique that evolved from this work and that should prove valuable to microwave spectroscopy in general.

OT Data Base for EHF Propagation

A 3½-year research effort by a small, dedicated ITS research group culminated in the paper, "Atmospheric Oxygen Microwave Spectrum - Experiment Versus Theory -," to appear in IEEE Transactions on Antennas and Propagation. The group, under the leadership of Dr. Hans J. Liebe, includes Gary Gimmestad and Jerry Hopponen, and has been joined in the past by Arthur H. Diederich, Uri Mingelgrin, Maurice Vetter, and William M. Welch, all with the Applied Electromagnetic Science Division.

The paper for IEEE describes a formulation of the oxygen microwave spectrum - O₂-MS - expressing transfer characteristics of clear air in radio engineering terms (attenuation and phase dispersion). Several thousand individual measurements were made to obtain pieces of a complicated spectroscopic jigsaw puzzle and then reduced to a reliable set of 144 spectroscopic parameters, which, in turn, are needed to predict transmission at one frequency in the 40 to 140 GHz band. The

Local IEEE Contributions

OT staff members contributed the majority of papers to the third annual one-day symposium of the Denver/Boulder Chapter of the IEEE Antennas & Propagation Society which was held Friday, May 7, at the National Center for Atmospheric Research.

- H. J. Liebe: "Advances in the Formulation of the Atmospheric Oxygen Microwave Spectrum";
- J. D. Hopponen: "Computer Sensitivity Studies of the Atmospheric Oxygen Microwave Spectrum";
- E. J. Violette: "Discussion of 60 GHz Channels";
- R. H. Ott and M. C. Thompson, Jr.: "Predicted Radio Frequency Spectra for Propagation Through a Random, Complex, Turbulent Medium";

Liebe Honored by West Germany

Dr. Hans J. Liebe, electronics engineer with the Applied Electromagnetic Science Division of ITS, has been honored by the Federal Republic of Germany with a Senior U.S. Scientist Award of the Alexander von Humboldt-Foundation. The award is granted to outstanding U.S. scientists in recognition of past accomplishments in research in the field of physical sciences and is intended to promote scientific cooperation between the institutions in the Federal Republic of Germany and the United States.

Dr. Liebe was nominated for the award by Professor G. Pfozter, director at the Max-Planck-Institut, Lindau, who cited three outstanding contributions by Dr. Liebe as the basis for the award:

1) Advanced concepts for millimeter wave communications (Dr. Liebe was a co-worker in a team that in 1966 first amplified a coherent signal at 258 GHz and developed an array of new devices).

2) New spectroscopic technique called "millimeter wave dispersion pressure-scanning," which evolved from a differential refraction detector reported by Thompson-Vetter, OT/ITS, in 1968.

3) Valuable research results presented in over 30 publications and addressing basic problems in atmospheric millimeter wave propagation and remote sensing.

This type of research provides part of the data base needed for the rapidly growing fields of high-data-rate communication and atmospheric remote sensing.

Liebe Returns from West German Guest Tour

Dr. Hans J. Liebe, Advisor to the Applied Electromagnetic Science Division, and his family have just returned from nine memorable months abroad as guests of the West German government, which honored his ITS research work on atmospheric millimeter wave propagation with a Humboldt Award (see TELENOTES, July 1976).

His home base was the Max-Planck-Institute for Aeronomy, Lindau/Harz, where he directed the setting up of a geophysical mm-wave research program and met a host of other American scientists, some presently or formerly from Boulder Laboratories. From there, he toured essentially all important German EHF research facilities, presenting 12 invited seminar talks.

In his travels, Liebe visited other Max-Planck-Institutes (Meteorology - Hamburg, Radioastronomy in Bonn and their 100-meter dish at Effelsberg, Solid State Physics - Stuttgart, Spectroscopy - Giessen, universities (Berlin, Hannover, Munich, Giessen), and government laboratories (DFVLR - Oberpfaffenhofen, where he stayed two months with the Institute for Microwaves, Heinrich Hertz - Berlin, Wehrphysik - Werthoven)

In Lindau, a 30/60 GHz line-of-sight link (500 m) was set up and differential amplitude measurements were performed supported by an all-out meteorological sensing program. The results are to be analyzed for turbulence signatures of the ground-to-air interface. Another project initiated is concerned with ground-based strato-mesospheric temperature soundings using a 53 GHz spectral line radiometer. A generous temporary loan of mm-wave devices from the Boulder Labs helped significantly in providing a starting point for these projects.

Army Cites OT Research

Dr. Arthur V. Dodd, Director of the Geosciences Division, U.S. Army Research Office (ARO), at Research Triangle Park, North Carolina, recently selected 3 projects out of over 70 for a presentation as examples for outstanding accomplishments by investigators supported by ARO. The ITS millimeter wave laboratory work on "Accurate Clear Air EHF Transfer Characteristics" was one of the three chosen. Dr. Hans J. Liebe, Applied Electromagnetic Science Division, is leader of the project.

The basic work has current and potential applications (atmospheric transmission, satellite communications, atmospheric sciences) important to the military.

The Army Research Office's support during fiscal years 1975 to 1977 led to a series of definitive papers on the atmospheric millimeter wave spectrum of oxygen.

Liebe Invited to AGARD Meeting

Dr. Hans J. Liebe of the Applied Electromagnetic Science Division of ITS has been invited to present a review paper on "Atmospheric Medium Characterization and Modeling for EHF Propagation" at the NATO/AGARD EPP Symposium on "Operational Modeling of Aerospace Propagation Environment" which is to be held in Lisbon, Portugal, in April 1978. The invitation was expressed by Dr. H. Soicher, Chairman of the Program Committee, who is with the U.S. Army Electronics Command in Ft. Monmouth, N.J. The meeting is called by the AGARD Electromagnetic Wave Propagation Panel.

Van Vleck and Anderson Inspired ITS Research

This year's American Nobel prize winners in physics, J. H. Van Vleck, former Hollis professor at Harvard University (retired since 1969), and P. W. Anderson, his student who is now at Bell Laboratories and Princeton University, laid the ground work for the long-term ITS research on laboratory studies of atmospheric millimeter wave propagation. Van Vleck's calculations on water vapor and oxygen absorption have become classics. They explained as early as 1947 the opacity of the atmosphere around the 22, 60, 119 and 183 GHz regions of the spectrum, which otherwise would be ideal for wideband ground and ground-to-satellite communication. Anderson introduced in 1949 the first theoretical procedure to compute the width of a spectral line heretofore a purely empirical parameter. Both researchers viewed the quantitative understanding of molecular spectra in all their fascinating complications as important insight into the molecular microscale. With their theories and a few accurately measured parameters one can describe not only transfer, shielding and emission properties of the atmosphere, but also the structure of a molecule using solely macroscopic quantities such as pressure, temperature and frequency.

It is these "few" parameters for oxygen and water vapor that have kept a small ITS research group busy for ten years [see Telenotes, February, 1976]. In fact, all of ITS's millimeter wave propagation work goes back to the original work of Van Vleck.

Before his retirement, Van Vleck had given much encouragement for ITS's controlled laboratory experiments. In a letter to H. Liebe he commented: "It impressed me as very refined and interesting work and how I would have liked to have had it in 1943". In 1968, during a discussion with H. Liebe, Van Vleck personally went to a copy machine located quite a ways from his office to duplicate a hard-to-get paper of his-leaving his visitor with a jokebook! At that time he loved to chat about molecular spectroscopy as much as about Colorado and his trips to the Rockies especially to the Garden of the Gods.

BIBLIOGRAPHIC DATA SHEET

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13.		13.	

14. SUPPLEMENTARY NOTES

15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography of literature survey, mention it here.)

The microwave spectrum of oxygen (O_2 -MS) was investigated with a pressure-scanning, dual-resonator spectrometer between 53 and 64 GHz and with a nonresonant cavity spectrometer at 119 GHz under simulated atmospheric conditions. This summary is intended as a wrap-up and guide to the various outputs covering three main topics: New spectroscopic measurement techniques; extensive O_2 -MS laboratory studies; engineering formulation and modeling of clear air (molecular) EHF radio path transfer properties.

16. Key words (Alphabetical order, separated by semicolons)

Atmospheric propagation; dispersion spectroscopy, EHF transfer function; oxygen microwave spectrum.

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