Estimates of Atmospheric Attenuation Sensitivity with Respect to Absolute Humidity at 337 GHz

JAMES M. GALM, STUDENT MEMBER, IEEE, FRANCIS L. MERAT, MEMBER, IEEE, AND PAUL C. CLASPY, SENIOR MEMBER, IEEE

Abstract—**A 640-m field transmissometer was operated for a three-day period during late July 1986. Using an optically pumped, near-millimeter wave laser as the source, clear-air relative attenuation measurements were collected at an operating frequency of 337 GHz. Concurrent with the relative attenuation measurements, the ambient and dew point temperatures were recorded. An expression was synthesized to provide absolute humidity measurements from the recorded temperatures. By assuming static attenuation due to atmospheric constituents other than water vapor, the sensitivity of attenuation to absolute humidity at 337 GHz was estimated at a number of temperatures. Comparison of these new estimates to a previous investigation at the same frequency indicates general agreement.**

I. INTRODUCTION

IN THE NEAR-MILLIMETER wave region, water vapor is the primary absorbing species in clear atmosphere [1]. The experimental results described in this paper are intended to extend the body of empirical measurements regarding clear-air atmospheric attenuation sensitivity to water vapor concentration. An ongoing research program has provided an instrumented outdoor propagation facility, equipped with a 337 GHz near-millimeter wave laser source. Data were acquired from 1200 EDT 29 July through 0000 EDT 2 August 1986. A description of the transmissometer is presented, followed by a discussion of the techniques used to analyze the measured quantities. Justification of the technique in terms of basic assumptions is given. The results of the investigation follow, including a discussion of confidence in the sensitivity estimates.

II. TRANSMISSOMETER DESCRIPTION

The investigation was carried out at the same physical site as that used by Gasiewski [2]—the NASA Lewis Research Centers Plumb Brook Station in Sandusky, OH. A 1.62-km long grass-covered airstrip provided an acceptable location for the propagation measurements.

Locations of the transmissometer components are shown in Fig. 1. The actual propagation path used a slightly sloping trajectory: 2.5 m above ground level at the transmitter end, 1.5 m above ground at the receiver, with a total span of 640 m. The sloping path matched the uneven heights of the transmitting and receiving apertures.

The laser source used for the investigation was an Apollo Lasers, Inc. model 122 FIR system. Extensive modifications to the FIR resonator were made to allow it to operate efficiently at a wavelength of 0.89 millimeters using 1-1-difluorethylene as the laser gas [3], [4]. The receiving systems used in this investigation incorporated synchronous detection of the electronically chopped NMMW signal. Two such receivers were used: one receiver measured a fraction of the NMMW signal at the field point (the field receiver), while a second receiving system monitored a fraction of the total power emitted by the laser (the reference receiver), thus providing relative signal intensity measurements at both ends of the transmissometer. Each receiver incorporated an EL-TEC model 408 lithium tantalate pyroelectric detector, which was amplified by a second-order low-pass filter having a -3 dB frequency of 40 Hz. This filter restricted the detectors' baseband spectral response to those frequencies of primary interest.

As noted, one receiver provided a reference signal proportional to the total laser output power. A small polyethylene beam splitter was mounted close (approximately 25 mm) to the output coupler of the laser. A polyethylene lens (25 mm diameter, 25 mm focal length) focused the sampled NMMW power onto the pyroelectric detector element. The field receiver, located 640 m east of the transmitter, consisted of a 1.6-m diameter, 0.66-m focal length silvered metal parabolic reflector [5], with a pyroelectric detector element at its focus.

Meteorological data were recorded simultaneously with the data from the two above-mentioned receivers. An EG & G model 220 automatic temperature and dew point system was installed 320 m east of the transmitter along the north edge of the airstrip, providing data from with absolute humidity could be calculated. Mean solar intensity readings were provided by an EPPLEY Laboratory model 15 solar pyrheliometer. An EG & G model 207 forward scattering type optical visibility meter provided data to confirm that the atmospheric sample was in fact clear of rain and/or fog while making clear air measurements. Data from the receivers and

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The authors are with the Department of Electrical Engineering and Applied Physics, Case Western Reserve University, Cleveland, OH 44106.

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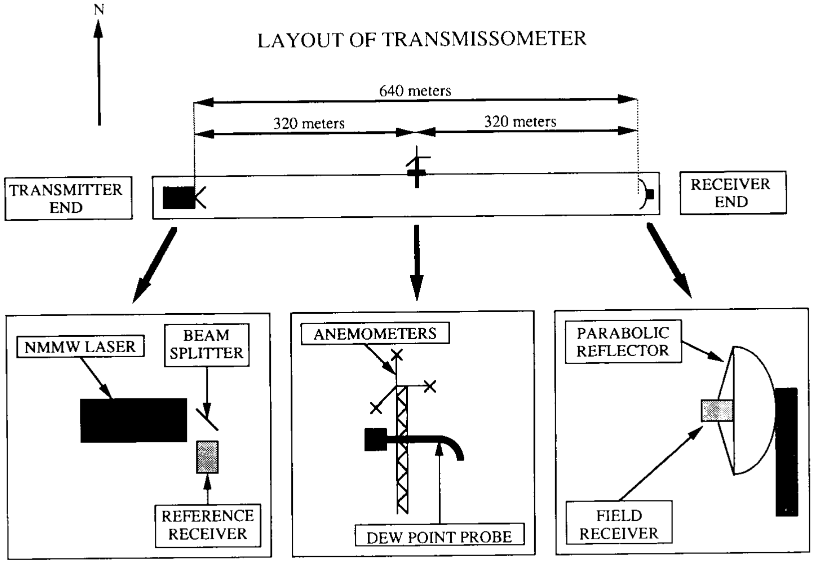

Fig. 1. Layout of transmissometer.

meteorological instruments were collected via a fiber optic microcomputer network [5], [6].

II. Data Analysis

The standard definition of the attenuation constant α of a plane wave [1],

$$\frac{I}{I_0} = e^{-\alpha z} \qquad (1)$$

where

I intensity of the field wave,
I_0 intensity of the transmitted wave,
z propagation distance in meters, and
α attenuation constant, (Np/m) yields

$$\alpha = \frac{1}{z} \ln \frac{I_o}{I} \text{ Np/m}, \qquad (2)$$

from which α may be calculated knowing the plane wave intensities at both the transmitting end and the receiving end of the transmissometer and the propagation distance.

Alternatively, one may express

$$\alpha = \frac{10}{z} \log \frac{I_0}{I} \text{ dB/km}, \qquad (3)$$

in the more familiar units of dB/km. In this investigation, the data available from the receiver systems were:

1) V_0, a voltage proportional to the total power emitted by the transmitter,
2) V, a voltage proportional to the total power incident at the plane of the receiver.

Since both receiving systems were fixed in space during the entire course of the investigation, there exists a calibration constant k', such that

$$\frac{I_0}{I} = \frac{V_0}{V} k' \qquad (4)$$

allowing an expression for the attenuation constant,

$$\alpha = \frac{10}{z} \log \frac{V_0}{V} + \frac{10}{z} \log k', \qquad (5a)$$

$$\alpha = \frac{10}{z} \log \frac{V_0}{V} + k, \qquad (5b)$$

in dB/km, based on the measured quantities and k or k'.

The origin of the calibration constant k is a combination of the following assumed constant factors:

1) the nonunity fraction of NMMW power extracted by the beam splitter driving the reference receiver;
2) the nonunity fraction of NMMW power incident at the field receiver plane actually intercepted by the field receiver;
3) the responsivities of the individual pyroelectric detector elements;
4) absorption by molecular species other than water vapor.

Since physical measurement of the calibration constant k would be unfeasible, the attenuation measurements made in this investigation determined the attenuation constant α relative to atmospheric water vapor concentration. Thus, the measurements contained herein must be considered relative measurements—they cannot be considered measures of absolute attenuation, since absolute attenuation can have contributions from atmospheric molecular species other than water vapor [7].

Determination of the constant k under the above premise for any subset of the data points involved plotting the points with absolute humidity on the X axis and relative attenuation on the Y axis. A least squares analysis then provided the best-fitting straight line through the data subset. The Y axis intercept was then taken to be k for that subset of points, and

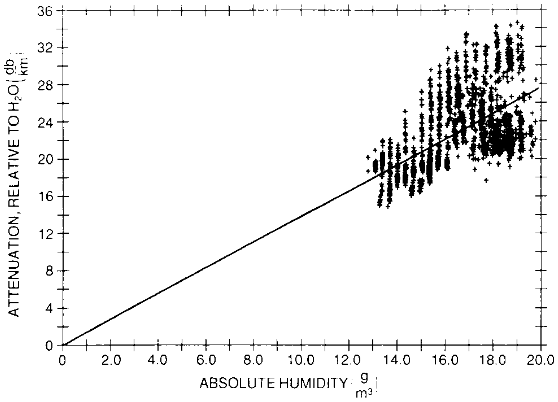

Fig. 2. Attenuation versus absolute humidity, all data points.

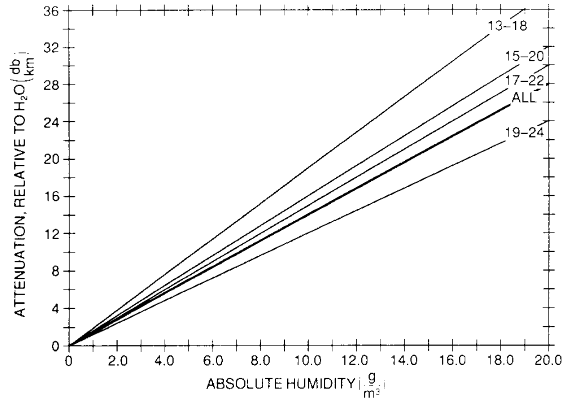

Fig. 3. Attenuation versus humidity, by temperature partition.

was subtracted from the relative attenuation α of each point in the subset. This procedure provided attenuation curves that fit the criteria stated above, without the necessity of physically measuring the calibration constant k. The slopes of the resulting lines were taken to be the linear sensitivity of attenuation α to absolute humidity.

Raw data collected from the EG & G hygrometer consisted of ambient and dew point temperature measurements. Determination of absolute humidity data from the measured physical quantities for a large number of points requires a closed form expression. The formula used was derived from the standard expression, as presented by Goff [8], for saturation vapor pressure of water. The absolute humidity, in grams of H_2O per cubic meter as a function of measured ambient and dew point temperatures was thus available.

IV. Collected Data and Results

After removal of all data frames recorded during laser tuning, each signal channel of the collected data was examined versus time. A small number of data points were regarded as anomalous, and were removed according to the following justifications:

1) loss of temperature data due to the EG & G dew point system's self standardization cycle;
2) NMMW signal loss due to external events such as deer grazing in the propagation path.

Fig. 2 presents the complete ensemble of data points taken during the course of the investigation, plotted to determine the overall sensitivity of attenuation to absolute humidity. The data set was then divided into subsets, or partitions, of ambient temperature ranges. The choice of partition width involved a trade off between resolution of the desired sensitivity and the high variance associated with a small temperature range. A partition width of 5° C yielded consistent results, while allowing a uniform partition width and temperature increment. Fig. 3 shows the results of the five temperature range partitions, along with the total sensitivity over all data points (denoted "all").

Table I presents estimates of the sensitivity values taken from the slopes of the lines fitted to the data points in each data partition.

TABLE I
Eestimated Sensivity of Relative Attenuation to Absolute Humidity (dB/km/gH$_2$O/m^3)

Temperature Range (C)	Solar Intensity Range (cal/cm^2/min)			
	All	0-0.1	0.05-0.5	0.1-1.5
13-18	1.9	2.0	1.6	0.9
15-20	1.6	1.6	1.1	1.1
17-22	1.5	1.7	1.0	0.4
19-24	1.2	1.4	1.2	0.5
All	1.4			

TABLE II
Variance of Sensitivity Estimates

Temperature Range (C)	Solar Intensity Range (cal/cm^2/min)			
	All	0-0.1	0.05-0.5	0.1-1.5
13-18	0.018	.019	.030	.18
15-20	0.0063	.0070	.013	.0077
17-22	0.0060	.0095	.017	.026
19-24	0.012	.025	.030	.028
All	0.0023			

TABLE III
Number of Data Points, by Partition

Temperature Range (C)	Solar Intensity Range (cal/cm^2/min)			
	All	0-0.1	0.05-0.5	0.1-1.5
13-18	423	406	37	17
15-20	864	822	63	42
17-22	903	694	211	209
19-24	638	242	277	396
All	1747			

The sensitivity estimates are further characterized by the variance of the slope associated with each partition, as in Table II. The number of data points in each partition is presented in Table III. Table IV presents the coefficient of correlation between relative attenuation and ambient temperature for all data partitions. In this context, the coefficients of correlation expresses the degree of dependence of attenuation on humidity, hence the degree to which attenuation may be considered a linear function of humidity, based on the statistics of the measured points. Based on this criterion, sensitivity estimates having a coefficient of correlation less than approximately 0.5 might be sufficiently uncorrelated to be

TABLE IV
COEFFICIENT OF CORRELATION, BY PARTITION

Temperature Range (C)	Solar Intensity Range (cal/cm^2/min) All	0-0.1	0.05-0.5	0.1-1.5
13-18	0.563	0.579	0.848	0.462
15-20	0.553	0.552	0.792	0.892
17-22	0.550	0.562	0.498	0.170
19-24	0.397	0.506	0.382	0.136
All	0.565			

considered dubious. Six of the 17 estimates presented fail to reach this level, and were generally ones occurring during periods of high temperature of high solar intensity. It is possible that the integration times used in the receiving systems were not sufficiently long to filter the effects of atmospheric humidity turbulence along the transmissometer. While data concerning the atmospheric turbulence structure functions [9] were not available during this investigation, the apparent decrease of the sensitivity estimates and increasing estimate variance with increasing solar intensity indicates that solar driven turbulence does in fact impact near ground transmissometer measurements carried out in the field.

One possible method of assigning an interval of confidence to the sensitivity estimates is to consider an interval centered on the mean of the distribution (the estimate itself) having a width equal to two times the standard deviation of the sample data. With variances ranging from 0.0060 to 0.018 for partitions representing all solar intensities, a general interval of confidence of ± 0.1 dB/km/g/m^3 could be assigned. This interval would suggest an "error bar" of approximately 10 %.

The results obtained by Gasiewski [2] for the sensitivity of attenuation to humidity at various temperatures were compared with the estimates presented in table 1. Although the measurement methods, transmissometer geometries and signal processing techniques used by Gasiewski were significantly different from those used in this investigation, his sensitivity measurements agree with the overall sensitivity estimates presented here to within approximately $\pm 10\%$. Gasiewski estimates the error associated with his measurements to be $\pm 10\%$, thus indicating general agreement between the two sets of experimental results.

Theoretical models of clear air atmospheric attenuation [10], [11] provide additional support for the above experimental estimates. In particular, the millimeter-wave propagation model (MPM) presented by Liebe [12] yields approximate attenuation sensitivities of 1.55 (dB/km/g/m^3) at 20°C and 1.62 (dB/km/g/m^3) at 15°C under humidity and pressure conditions similar to those encountered in this experiment. The estimates provided in this investigation agree with the MPM derived values to within approximately $\pm 10\%$, further validating the experimental technique.

V. SUMMARY AND CONCLUSION

This paper has presented the results of a field experiment used to collect the necessary electromagnetic and meteorological data to estimate the sensitivity of atmospheric attenuation to absolute humidity under typical midsummer conditions in the midwestern United States. Temperatures ranging from 13°-24° C yielded attenuation sensitivities ranging from 1.9 to 1.2 dB/km/g/m^3. Solar intensities ranging from 0 to 1.5 cal/cm^2/min were observed.

As stated, the results of this investigation are statistical in nature, thus must be regarded as estimates of the desired attenuation sensitivity values. As with any estimate, there is an uncertainty associated with the results, described by the statistical properties of the data ensemble. The primary parameters that characterize this uncertainty, including the variance associated with each estimate and the coefficient of correlation between the quantities involved, have been presented.

Comparison of the final estimates with those found by Gasiewski in 1983 indicates general agreement to within 10%. Since the receiving, signal processing and data analysis techniques used in this investigation differed significantly from those used by Gasiewski, one may conclude that the results of both investigations are probably good approximations of the actual physical parameters being estimated. In addition, the estimates are further corroborated by comparison with the results of the MPM program, as presented by Liebe.

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James M. Galm (S'82) was born in Chardon, OH, on April 12, 1962. He received the B.S. degree in electrical engineering and applied physics in 1984, and the M.S. degree in electrical engineering in 1987, both from Case Western Reserve University, Cleveland, OH. He is currently a Ph.D. candidate in electrical engineering at CWRU.

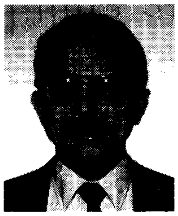
His primary research interests involve the improvement of manufacturing inspection techniques. Specifically, he is involved in the application of optimal filtering and estimation techniques to industrial metrology and inspection of machined parts. He is also working on the fusion and integration of multisensory data into the inspection process. His previous work has included atmospheric metrology, millimeter wave propagation studies, and high frequency antenna design.

Mr. Galm is co-founder and chief executive officer of PGM Diversified Industries, Inc., a manufacturing company currently producing innovative industrial sensors and automation systems. He is a member of the Machine Vision Association of the Society of Manufacturing Engineers.

Francis ("Frank") L. Merat (S'73-M'77) was born in Frenchville, PA. He received the B.S., M.S., and Ph.D. degree in electrical engineering from Case Western Reserve University, Cleveland, OH, in 1972, 1975, and 1978, respectively.

He is Associate Professor of Electrical Engineering and Applied Physics and a member of the technical staff at the Center for Automation and Intelligent Systems Research at Case Western Reserve University. His research is concentrated in the integration of tactile and visual information for assembly and inspection tasks and the application of computer vision and image processing to industrial inspection and measurement. His previous work has been in the areas of electronic holography, three-dimensional holographic displays, and imaging through turbulent media.

Dr. Merat is a member of the Society of Photo-Optical Instrumentation Engineers, the Association for Computing Machinery, the Machine Vision Association of the Society of Manufacturing Engineers and the Optical Society of America. He is a past Chairman of the Cleveland Section of IEEE.



Paul C. Claspy (S'70-M'70-SM'82) received the B.S. degree in physics from Kent State University, Kent, OH, in 1957, the M.S. degree in physics from The Ohio State University, Columbus, in 1960, and the Ph.D. degree in electrical engineering from Case Institute of Technology, Cleveland, OH, in 1970.

Following duty with the U.S. Army from 1964 to 1968 he was with Harshaw Chemical Co., where he was engaged in the characterization of optical and nonlinear optical crystalline materials. From 1970 to 1973 he was with Laser Communications, Inc., where he was involved in the development of a HeNe laser-based video communication system. Since 1973 he has been on the faculty of Electrical Engineering and Applied Physics at Case Western Reserve University, where his research has been directed toward the application of lasers and optics to communications. In 1980 he was Guest Professor at the Hochschule Bundeswehr, Muenchen, in West Germany, and at present he is a National Research Council Senior Research Associate at the National Aeronautics and Space Administration's Lewis Research Center. His current research activity is in devices and systems for high speed optical interconnects in microwave systems.

Dr. Claspy is a member of SPIE, OSA, ASEE, Eta Kappa Nu, and Sigma Xi.