Measurement of Atmospheric Attenuation at Millimeter Wavelengths

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A frequency-modulation radar technique especially suited to measurement of atmospheric attenuation at millimeter wavelengths is described. This two-way transmission method employs a single klystron, a single antenna and a set of spaced corner reflectors whose relative reflecting properties are known. Since the method does not depend on measurements of absolute antenna gains and power levels, absorption data can be obtained more readily and with greater accuracy than by the usual one-way transmission methods.

Application of the method is demonstrated by measurements in the 5-mm to 6-mm wave band. The results have made it possible to assign an accurate value for the line-breadth constant of oxygen at atmospheric pressure; the constant appropriate to the measurements lies between 600 and 800 MCS per atmosphere.

INTRODUCTION

It is well known that certain bands in the microwave region are attenuated considerably due to absorption by water vapour and oxygen in the atmosphere. A theory of absorption for both gases was given by Van Vleck.[1] Numerous measurements have been made on the gases when confined to waveguides or cavities[2] and several when unconfined in the free atmosphere.[3] Nevertheless, there is some uncertainty regarding the line-breadth constants which should be used in calculating water vapour and oxygen absorption. In particular, at atmospheric pressure there is doubt as to the amount of absorption on the skirts of the bands where the absorption is small. The present work was undertaken to test a new method of measurement and to improve the accuracy of experimental data measured in the free atmosphere.

The method of measurement is one of comparison of reflections from spaced corner reflectors whose relative reflecting properties are known. The free-space attenuation is readily calculated and any measured attenuation in excess of this represents absorption by the atmospheric gases.

A description of the method and the apparatus is followed by a discussion of data taken in the wavelength range 5.1 to 6.1 mm (which includes the long wavelength skirt of the oxygen absorption band centered at 5 mm). These data, when compared with the theory,[1] indicate that the line-broadening constant of oxygen at atmospheric pressure is of the order of 600 mc. Some rain and fog attenuation measurements at a wavelength of 6.0 mm are included.

METHOD

The experimental setup is shown in Fig. 1. It consists of a high-gain antenna for both transmitting and receiving and a pair of spaced corner reflectors. Corner reflectors can be built to have good mechanical and electrical stability, and their reflecting properties are relatively insensitive to slight misalignments. The reflectors are mounted well above the ground to ensure free-space propagation conditions.

At the outset, the relative reflecting properties of the corner reflectors are measured by placing them side by side at a convenient distance (d_1 for example) from the antenna. By alternately covering one and the other with absorbent non-reflecting material and measuring the reflected signals, the relative effective areas are determined. The reflectors are then separated as shown and consecutive measurements are made of the signals returned from each reflector. From these measurements, knowing the distances d_1 and d_2 and the calibration of the reflectors, one determines the attenuation over the path d_2-d_1 in excess of the free-space attenuation.* This excess, in the absence of condensed water in the air, represents absorption by the atmosphere.

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* The power received from the reflector at distance d_1 is,

$$P_1 = P_T \frac{A^2 A_1^2}{\lambda^4 d_1^4} Q(\lambda, d_1)$$

where A and A_1 are the effective areas of the antenna and corner-reflector respectively, and P_T is the transmitted power; $Q(\lambda, d_1)$ is a loss factor which accounts for atmospheric absorption. A similar relation holds for the power received from the reflector at distance d_2. The ratio of the received powers is then,

$$\frac{P_1}{P_2} = \left(\frac{A_1}{A_2}\right)^2 \left(\frac{d_2}{d_1}\right)^4 Q[\lambda, (d_2 - d_1)]$$

The accuracy of the measurements will be affected, of course, by spurious reflections in the neighborhood of the corner-reflectors. The sites for the experiment were chosen to minimize such reflections and checks were made by observing the decrease in the return signals when the corner-reflectors were covered by absorbent material. In all cases, the background reflections were at least 30 db below the signal from the corner-reflector.

The method of measuring the reflected signals is illustrated in Fig. 2. The transmitted signal is frequency modulated in a saw tooth manner with a small total frequency excursion, F. The signal reflected from the near corner-reflector is delayed with respect to the transmitted signal by a time, τ_1, equal to twice the distance to the reflector divided by the velocity of light. During a portion, $T_1 - \tau_1$, of the sawtooth cycle, there is a constant frequency difference, f, between the transmitted and received signals, ($f/F = \tau_1/T_1$). Power at this frequency is produced by mixing the initial source signal with the delayed received signal and amplifying the difference frequency in a narrow-band amplifier centered at frequency f. The output of this amplifier is, therefore, a pulse at frequency f, of length $T_1 - \tau_1$ and repetition rate $1/T_1$.

To measure the signal returned from the far corner-reflector it is necessary merely to increase the period of the sawtooth modulation proportionate to the increase in distance. The frequency excursion, F, remains the same; hence the average power output of the transmitter is unchanged. As may be seen in Fig. 2, the frequency difference, f, between the transmitted and received signals is unchanged; thus the same amplifier and output meter can be used for the two cases. Another advantage in changing only the sawtooth repetition rate is that the delay is the same fraction of a period in both cases; therefore the duty cycle is unchanged and the intermediate frequency pulses can be detected by either an average or a peak measuring device.

Since the beat frequency, f, is not affected by slow changes in the fre-

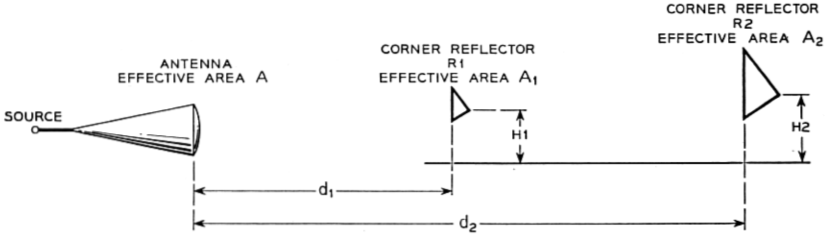

Fig. 1 — Siting arrangement for the atmospheric absorption measurements.

quency of the transmitter, the bandwidth of the intermediate frequency amplifier need be only wide enough to take care of non-linearity in the sawtooth modulation. A signal-to-noise advantage is obtained by the use of the narrow-band amplifier.

Table I gives the distances, heights and effective areas of the reflectors as well as the sawtooth repetition rates that were used in the experiment. The frequency excursion of the sawtooth modulation was 5.8 mc.

It will be noted that three reflectors were used; this was done to provide a long path (comparison of reflections from $R1$ and $R3$) for wavelengths at which the absorption was relatively low, and a short path (comparison of $R1$ and $R2$) for wavelengths at which the absorption was high. The small reflector, $R1$, was one foot on a side; the large reflectors, $R2$ and $R3$, were about 5.6 feet on a side. Fig. 3 is a set of side-by-side measurements showing the reflecting properties of the large reflectors relative to the small one for the wavelengths at which they were used.

APPARATUS

A schematic diagram of the waveguide and electronic apparatus is shown in Fig. 4; Fig. 5 is a photograph of the waveguide equipment so mounted that it moves as a unit with the horn antenna. The antenna is adjusted in azimuth and elevation by means of the milling vise at the bottom of the photograph. The box at the left contains the transmitting tube, a low voltage reflex klystron* which has an average power output of about 12 milliwatts over its 5.1- to 6.1-mm tuning range. About 2 milliwatts of the klystron output is fed through a 6-db directional coupler to a balanced converter that contains two wafer-type millimeter rectifier units.† The remainder of the power proceeds into a 3-db coupler which

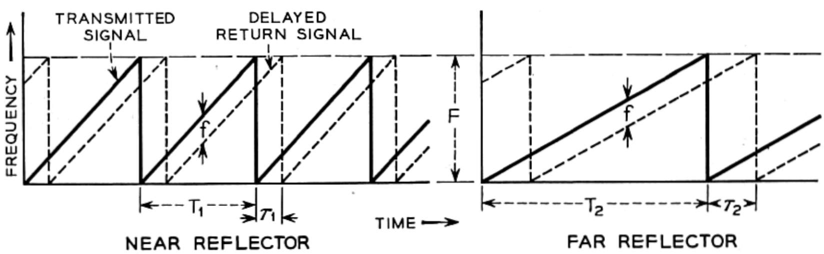

Fig. 2 — Transmitted and reflected frequency-modulated signals.

* This klystron was developed by E. D. Reed, Electron Tube Development Department, Murray Hill Laboratory.

† These millimeter-wave rectifiers were developed by W. M. Sharpless, Radio Research Department, at the Holmdel Laboratory.

TABLE I

Reflector	Distance	Height	Effective Area (Average)	Sawtooth Rep. Rate	Intermediate Frequency-f
	km	*m*	m^2	*kc*	*kc*
R1	$d_1 = 0.59$	6.7	0.05	33	750
R2	$d_2 = 1.36$	21.5	0.67	14.4	750
R3	$d_3 = 2.87$	75	0.79	6.8	750

has the antenna on one arm and an impedance composed of an adjustable attenuator and shorting plunger on another arm. This impedance is adjusted to balance out reflections from the antenna so that a negligible amount of the power flowing toward the antenna enters the converter which is on the remaining arm of the coupler. The delayed energy that re-enters the antenna after reflection from a corner reflector passes through the 3-db coupler to the converter.

The intermediate frequency amplifier shown in Fig. 4 operates with a bandwidth of 300 kc centered at $f = 750$ kc. The output of the amplifier is fed to a square law detector and meter for accurate measurement and to an oscilloscope for checking operation of the equipment. Oscillograms of the pulses obtained from the three corner reflectors are shown in Fig. 6; these are all on the same time scale. The gap between the pulses is the delay, τ, shown schematically in Fig. 2.

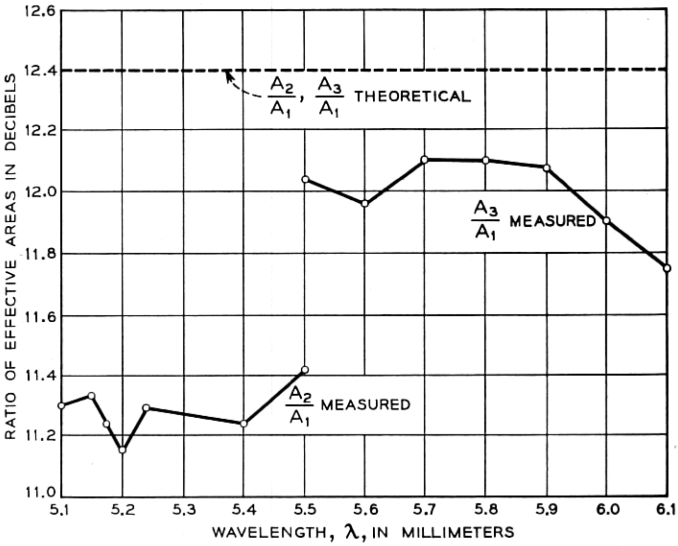

Fig. 3 — Calibration of corner-reflectors R2 and R3 using R1 as a standard.

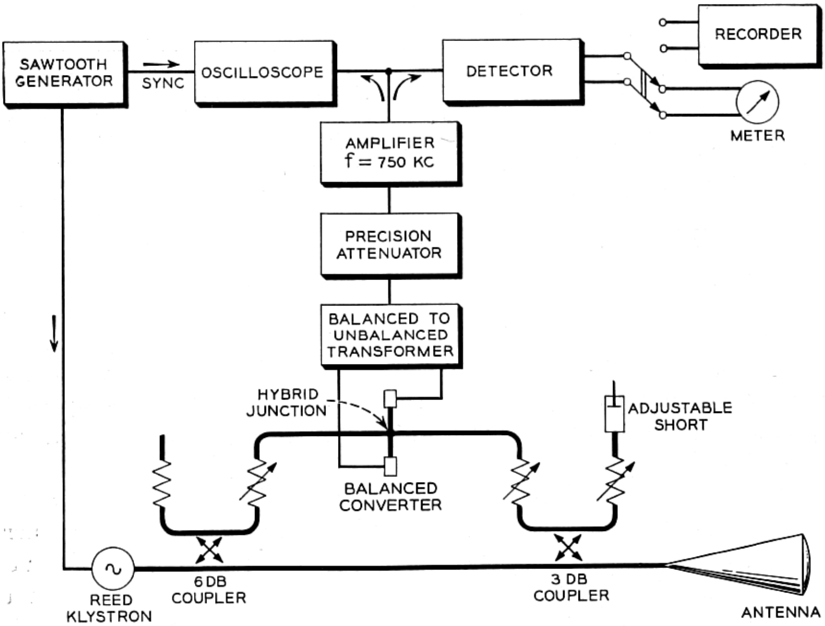

Fig. 4 — Schematic diagram of frequency-modulation radar.

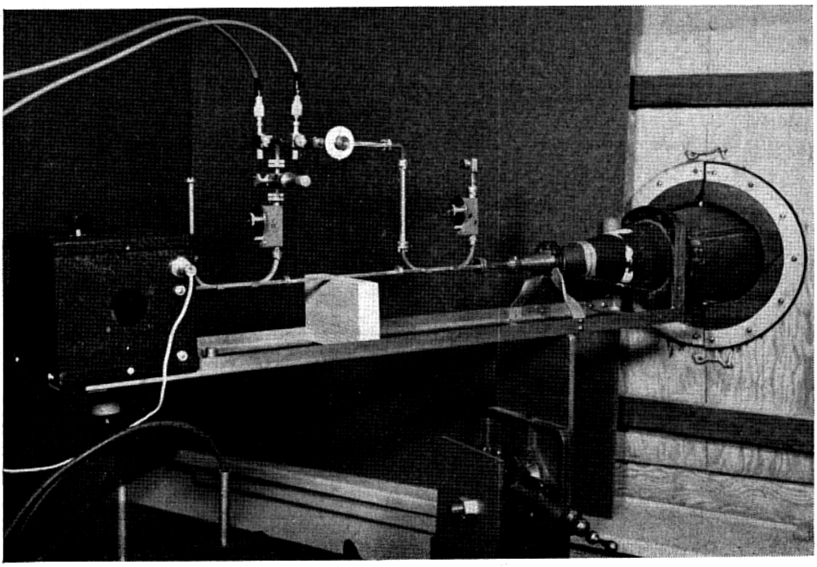

Fig. 5 — Waveguide apparatus and antenna.

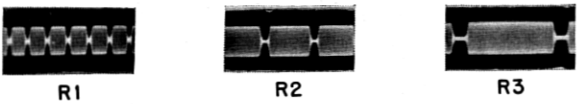

Fig. 6 — 750-kc pulses corresponding to the data in Table I.

Fig. 7 shows the conical horn-lens antenna supported by two bearings to allow adjustment of azimuth and elevation angles. The aperture of the antenna is fitted with a polyethylene lens 30 inches in diameter. The antenna has a gain of about 51 db and a beam width of about 0.5 degrees in the middle of the 5- to 6-mm wave band. This narrow beam, together with well-elevated reflectors, essentially eliminated ground reflections from the measurements.

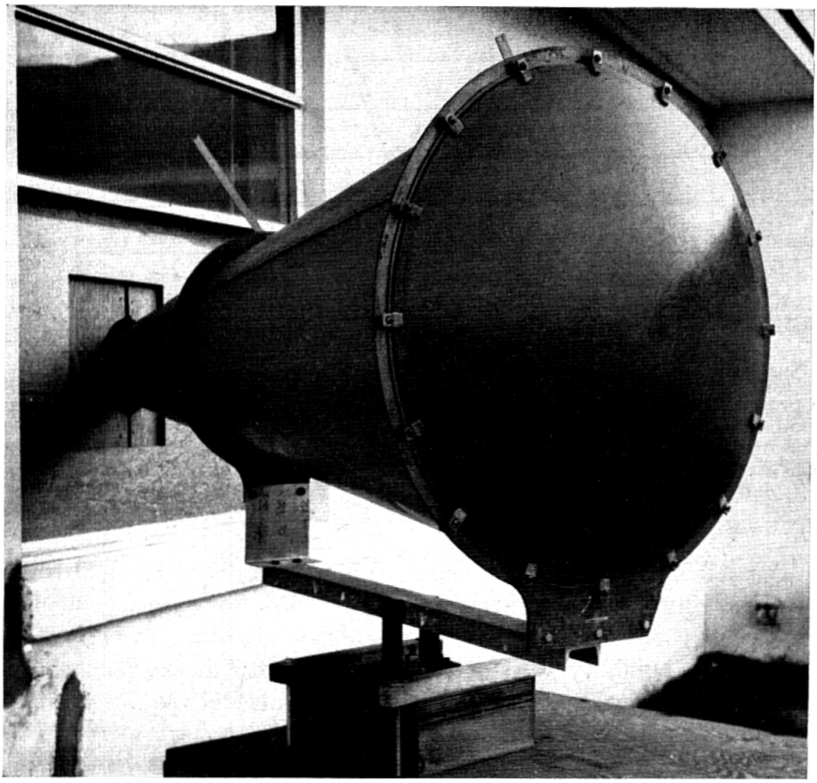

Fig. 7 — Conical horn-lens antenna and mount.

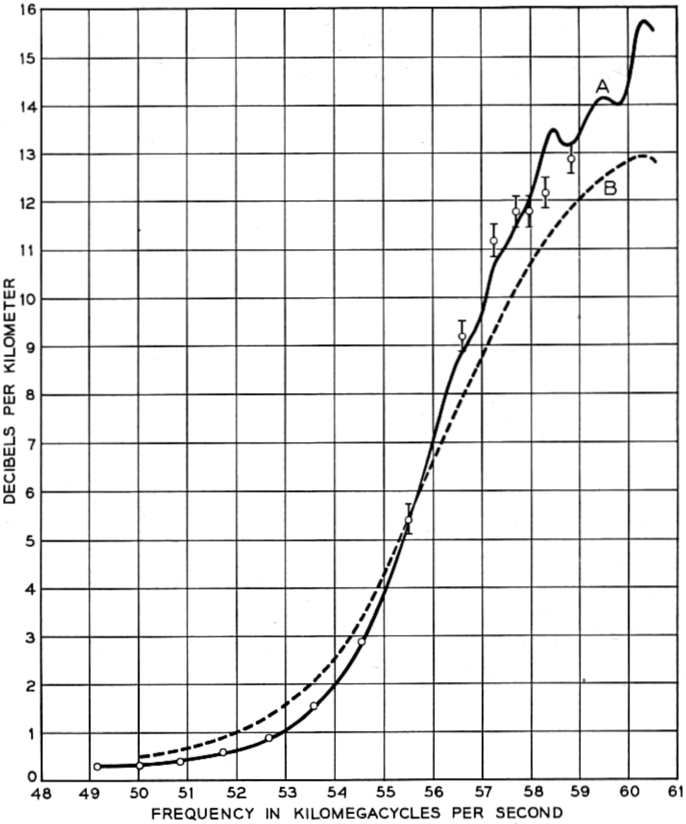

Fig. 8 — Calculated and measured absorption by air at sea level. The dots represent the experimental data; the vertical lines indicate the spread in the measured values. Curves A and B are calculated curves of oxygen absorption using line-breadth constants of 600 and 1200 mc, respectively, and a temperature of 293° K. (Courtesy of T. F. Rogers, Air Force Cambridge Research Center.)

RESULTS

The data to be discussed are shown in Fig. 8; they were taken at Holmdel, N. J., during the months of December, 1954, and January, 1955, on days when the temperature was between 25 and 40 degrees Fahrenheit; the absolute humidity was less than 5 grams/meter^3 during the measurements. It is believed, therefore, that the resonance of the oxygen molecule is the main contributor to the absorption.

The spread in the measurements is indicated by vertical lines through the average values. Each point represents an average of six or more measurements taken on different days. In the range 49 to 54.5 kmc, (5.5 to

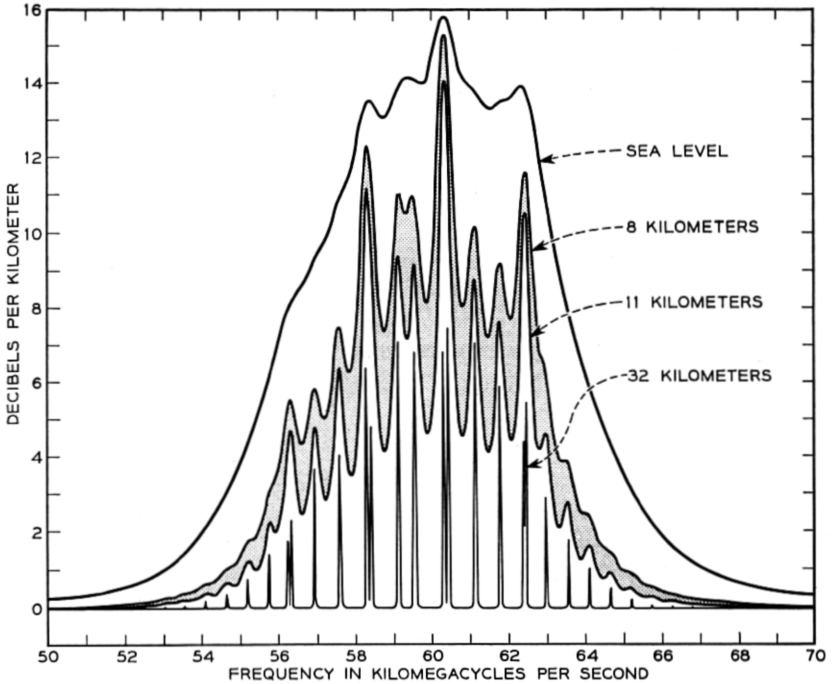

Fig. 9 — Calculated curves of oxygen absorption at various altitudes for a line-breadth constant of 600 megacycles and a temperature of 293° K. (Courtesy of T. F. Rogers, Air Force Cambridge Research Center.)

6.1 mm) the measurements were highly consistent, due mainly to the longer path that was used. Errors in the absolute values of the absorption are estimated not to exceed ±0.05 db/km in the 49 to 54.5 kmc region, ±0.25 db/km in the 55.5 to 59 kmc region. The errors in absolute absorption are governed mainly by the structural and thermo-mechanical stability of the corner reflectors.

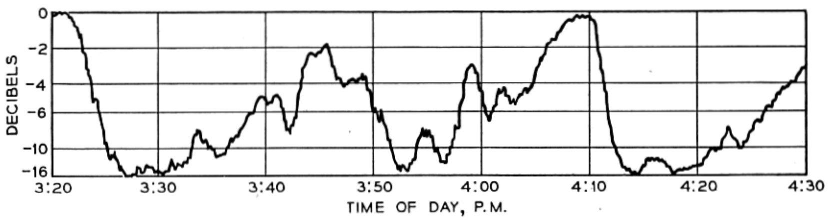

Fig. 10 — Attenuation of 6.0-mm radiation caused by a light rain.
Round-trip path length = 2.72 kilometers
Average rainfall rate = 5 millimeters per hour

TABLE II

Approximate Optical Visibility (miles)	Attenuation due to Land Fog DB/KM
1½	0.06
½	0.13
¼	0.22

In Fig. 8, measured values are compared with the theory of Van Vleck as calculated by T. F. Rogers using line-breadth constants of 600 mc and 1200 mc per atmosphere. The fit with the 600-mc curve is good from 49 to 55.5 kmc, but discrepancies are evident between 56.5 and 59 kmc. For completeness, Rogers' calculations for the absorption at higher altitudes are reproduced in Fig. 9.

A few continuous recordings of rain attenuation have been made at a wavelength of 6.0 mm; a record taken during a light rain is shown in Fig. 10. The median value of the signal is −6.7 db which corresponds to an attenuation of 2.5 db/km for this 5 mm per hour rainfall. During more intensive rainfalls, short-term attenuations in excess of 25 db/km have been observed.

On one occasion, it was possible to measure attenuation by land fog. The measurements given in Table II were made at a wavelength of 6.0 mm. No information regarding water content or drop size was available for this fog.

CONCLUSION

A frequency-modulation, two-way transmission technique has proven reliable for measurement of atmospheric attenuation at millimeter wavelengths. Prerequisite to the success of the method are corner reflectors with good mechanical, thermal and electrical stability.

The frequency-modulation method has been demonstrated by absorption measurements in the free atmosphere in the 5.1- to 6.1-mm band. The data thus obtained are in good agreement with Van Vleck's theory of oxygen absorption; the line-breadth constant appropriate to the measurements lies between 600 and 800 mc per atmosphere.

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