Measurements of Earth–Space Attenuation at 230 GHz

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Abstract—Measurements of attenuation at 230 GHz through the total atmosphere due to the presence of oxygen and water vapor molecules, clouds, and rain are presented and discussed. The measurements were carried out using a specially designed superhetrodyne receiver mounted on a sun tracker. Simultaneous measurements were also carried out at 13 GHz. For a measuring site close to sea level at Holmdel, NJ, the "clear-sky" zenith attenuation was found to be given by $A(\text{dB}) = 0.35\ \rho$, where ρ was the measured ground water vapor density in g/m^3. When the ground temperature was below about 7°C, most cloud and overcast gave <0.5-dB attenuation, whereas with a ground temperature greater than 13°C, cloud attenuation was 8–10 times greater. Calculations of zenith attenuation in the 230-GHz atmospheric window were also made using the Gross analytic line shape, Schulze–Tolbert empirical line shape, and an empirically modified Gross line shape. These calculations were based on determinations of water vapor density and temperature made at the measurement site, and on radiosonde measurements made at a distance of 80 km away. Measured and calculated results are graphically compared. It is concluded that either the modified Gross line shape or the Schulze–Tolbert line shape gives conservative estimates of zenith attenuation at 230 GHz for clear days, while the Gross line shape gives fair agreement with measured results.

I. Introduction

With the continuing improvement of millimeter- and submillimeter-wave sources and detectors, the atmospheric transmission windows lying above a frequency of about 200 GHz are becoming increasingly important for the purposes of radio astronomy, remote sensing, and communications. Potentially usable windows attainable with present technology are centered at frequencies of 230, 340, and 420 GHz, and possibilities exist of making use of higher frequency windows by using optically pumped laser technology [1]. Unfortunately, the strong water vapor absorption lines, beginning at 183 GHz and extending into the infrared portion of the optical spectrum, make the use of these windows subject to the amount of water vapor in the atmosphere, which may in many cases make transmission marginal. In addition, unexplained anomalies in transmission measurements, initially thought to be caused by water vapor dimers [2] but now thought to be caused by other effects [3], have caused measured values of attenuation in these windows to be consistently higher than predicted, and to vary in an unpredictable manner as atmospheric conditions change. Furthermore, the theory of absorption by collision-broadened spectral lines, due to Van Vleck and Weisskopf [4], has been modified several times [5], [6] to achieve better agreement with measured data, and has been changed lately by adding empirical corrections [7], [8] in attempts to correlate calculated and measured results.

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Absorption in the atmospheric window centered around 230 GHz, though dominated primarily by the water vapor lines at 183.3 and 325 GHz, also includes the effects of the tails of numerous submillimeter lines. Liquid water, when present in the form of rain, cloud, or fog also causes much attenuation in this frequency region. Measurements of attenuation through the total atmosphere are of importance in helping to decide the feasibility of earth–satellite communications in this atmospheric window.

Up to now, because of a lack of sensitive narrow-band receivers, measurements of atmospheric opacity in this frequency region were made using broad-band bolometric type devices (i.e., [9]). The consequent lack of frequency resolution makes it difficult to predict attenuation near the center of the window around 230 GHz. Since it is presumable here that any earth–space communications in this frequency range would be centered, it is important that we know with greater precision the effects of atmospheric attenuation at 230 GHz.

In addition, a number of astrophysically interesting molecular transitions occur with frequencies close to 230 GHz; it is thus quite likely that, in the future, this frequency region will become quite important for radio astronomical observations.

This paper presents the results of measurements of total atmospheric zenith attenuation in the 230-GHz atmospheric window. These measurements were made at various zenith angles using the sun as a source, and vertical attenuation was determined by extrapolating the measured attenuation as a function of angle to zenith angle zero. Attempts to fit these results with calculated results based on the Gross analytical line shape [5], the Schulze–Tolbert empirical line shape [7], and an empirically modified Gross line shape [8] were made. The range of frequencies covered by these calculations is 190–270 GHz. Since the skirts of the water-vapor absorption lines extend to frequencies far removed from their center frequencies, a total of 24 of the strongest lines, extending from 183.3 to 916 GHz were considered in the calculations. The effect of the 118.6-GHz oxygen line was also included, but ozone absorptions were not included because the contributions from this molecule are considered to be negligible over the frequency range of interest for ground-based observations. Furthermore, absorptions due to the water dimer were not treated because there exists

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no firm analytical basis for their inclusion in a calculation of this sort.

II. Absorption Calculations [10]

Van Vleck and Weisskopf [4] have shown that the attenuation coefficient α_0, at frequency ν, for a collision-broadened absorption line centered at frequency ν_0, with linewidth parameter $\Delta\nu$, is given by

$$\alpha_0 = \frac{8\pi^2 Nn|\mu|^2\nu_0\left[\exp\left(-E_i/kT\right)-\exp\left(-E_f/kT\right)\right]}{3hcG}F(\nu) \tag{1}$$

where the other parameters are determined as discussed below. The parameter N is the number of molecules per unit volume and is

$$N = \frac{N_A \rho}{M} \tag{2}$$

in which N_A is Avogardo's number, ρ is the density of molecules, and M is the number of grams in a gram molecular weight. For water, this number is $N = 3.346 \times 10^{16}\,\rho$, where ρ is measured in g/m^3. The factor $|\mu|^2$ is the square of the dipole matrix element between transition states and is equal to $\Sigma|\phi|^2\mu_0^2$, where μ_0^2 is the electric dipole moment. The factor $\Sigma|\phi|^2$ is the line-strength parameter determined by King *et al.* [11], and μ_0^2 is 3.39×10^{-36} ESU from Van Vleck [12]. The statistical weighting factor n which accounts for nuclear spin is unity [13] for even rotational states and 3 for odd rotational states. In the exponential terms, E_i is the energy of the lower transition state, E_f is the energy of the upper state, k is Boltzmann's constant, and T is the absolute temperature at which the attenuation is measured. The partition function G has been calculated by Van Vleck [12] to be 170 at 293K and varies with temperature as

$$G = KT^{3/2}. \tag{3}$$

Evaluation of the constant K from the previous values gives $G = 0.0339T^{3/2}$.

The line shape factor $F(\nu)$ derived by Van Vleck and Weisskopf is given by

$$F_{VV-W}(\nu) = \left(\frac{\nu}{\nu_0}\right)^2\left[\frac{\Delta\nu}{(\nu-\nu_0)^2+\Delta\nu^2}+\frac{\Delta\nu}{(\nu+\nu_0)^2+\Delta\nu^2}\right] \tag{4}$$

where the parameters are defined as before. Another analytical line shape factor was derived by Gross [5], who took account of the fact that the duration of collision of the molecules is short compared to the resonant period of the line, which is the case for foreign-gas broadening. This factor is given by

$$F_G(\nu) = \frac{4\nu^2\Delta\nu}{\left(\nu_0^2-\nu^2\right)^2+4\nu^2\Delta\nu^2}. \tag{5}$$

Although there is little difference in the millimeter-wave spectral region between results obtained using (4) and (5), the latter result will be used for some of the calculations discussed in this paper, because of its more general nature.

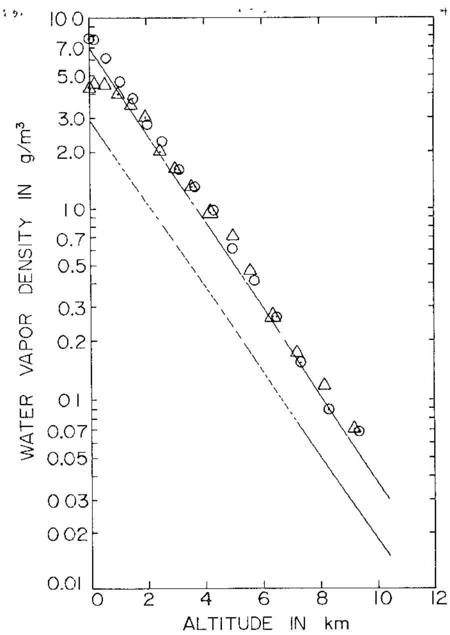

Fig. 1. Water vapor density profiles used in these calculations. The circles and triangles represent averages of radiosonde data for the months of October and November 1973, respectively, taken at the John F. Kennedy Airport. The solid lines represent extremes of distributions, based on on-site density measurements, actually used in the calculations.

Unfortunately, neither of the above analytical line shapes gives good agreement with experiment in the atmospheric transmission windows, giving generally lower attenuation values than have been observed. In an effort to fit calculations to experimental data, at least two empirical corrections to the above line shapes have been proposed. Schulze and Tolbert [7] have used the expression

$$F_{S-T}(\nu) = \left(\frac{\nu}{\nu_0}\right)^2\frac{\Delta\nu^{0.65}}{|\nu-\nu_0|^{1.65}+\Delta\nu^{1.65}} \tag{6}$$

to fit calculated and observed absorption values for the 118.6-GHz oxygen line. This expression has the same value at the center of the line as the Van Vleck–Weisskopf and Gross line shapes, but gives greater absorption in the skirts of the lines. A modification to the Gross line shape, based on the assumption of a continuum absorption, has been proposed by Gaut and Reifenstein [8], who use the expression

$$\Delta\alpha = 1.08 \times 10^{-11}\rho\left(\frac{300}{T}\right)^{2.1}\left(\frac{P}{750.2}\right)\nu^2\text{cm}^{-1} \tag{7}$$

where P is the atmospheric pressure in millimeters of mercury and ν is in gigahertz. Note that this expression adds a continuum term proportional to the square of the frequency.

Since a calculation of zenith absorption must include the effects of altitude, the altitude dependence of terms in (1) must be considered. The water vapor density is assumed to vary as shown in Fig. 1, in which the plotted points are averages of water vapor density distributions for the months of October and November 1973, measured

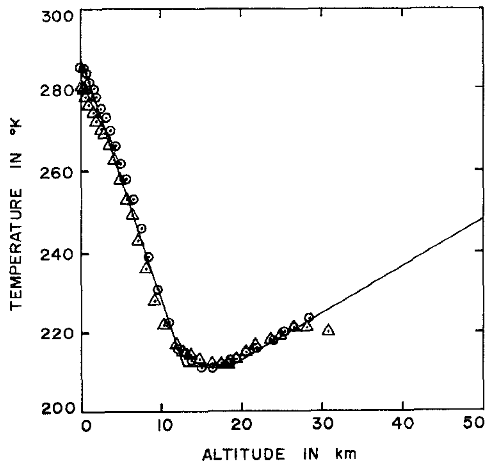

Fig. 2. Temperature profile used in these calculations. The circles and triangles represent averages for October and November 1973, and the solid line is the distribution used in the calculations.

by radiosonde at the John F. Kennedy Airport in New York, NY, which is 80 km from the measurement site. The solid lines indicate extremes of water vapor distributions used in these calculations which were varied according to on-site measurements of ground-level water vapor density. Since the radiosonde measurements were made only to a level of 10 km, the solid-line distributions were extrapolated to 50 km consistent with the 50-km upper limit of the calculations. This extrapolation ignores any possible contribution to attenuation caused by stratospheric water vapor, which has been treated by Croom [14], [15], and by Barrett and Chung [16]. This high altitude water vapor is expected to make a negligible contribution to attenuation in the 230-GHz window, however, because the low pressure makes the lines very narrow.

The temperature profile used in these calculations is also based on an average of the radiosonde data for the months of October and November, and is shown plotted in Fig. 2. Again, the indicated extrapolation to 50 km is made, and is considered valid because temperature at the higher altitudes is expected to have little effect on total zenith attenuation. The low-altitude slope of the temperature distribution curve was varied according to on-site measurements of ground-level temperature; otherwise, the same distribution was used for all calculations.

From Barrett and Chung [16], the pressure dependence at altitude Z is taken to be

$$P=760(10^{-3.05Z/50}) \tag{8}$$

and the linewidth parameter is

$$\Delta\nu=\frac{\Delta\nu_0(P/760)(1+0.0046\rho)}{(T/318)^{0.625}} \tag{9}$$

where $\Delta\nu_0$ is the linewidth parameter at $P=760$ mm and $T=318K$ for small ρ.

The total atmospheric attenuation γ measured looking upward from altitude h at zenith angle θ is given by

$$\gamma=\exp\left(-\int_h^\infty \alpha'(Z)\sec\theta\, dZ\right). \tag{10}$$

Three cases are now considered: 1) $\alpha'=\alpha_0$ and the Schulze–Tolbert line shape (6) is used for $F(\nu)$ to calculate γ, 2) $\alpha'=\alpha_0+\Delta\alpha$ and the Gross line shape (5), together with the continuum expression (7) for $\Delta\alpha$, is used to calculate γ, and 3) γ is calculated using the unmodified Gross line shape. In making these calculations, contributions due to the 24 strongest water vapor absorption lines up to a frequency of 916 GHz were considered. The attenuation due to the 118.6-GHz oxygen line was also added. The calculations covered a frequency range of 190–270 GHz, which includes the maximum transmission band of the 230-GHz window. Equation (10) was numerically integrated using the values of α' from the three cases discussed above with the maximum altitude taken to be 50 km. In order to get good accuracy and minimize computer time, the widths of the atmospheric strata ΔZ were varied from a minimum of 2.5 m at low altitude to a maximum of 50 m at high altitude, in performing the integration. These calculations will be compared to experiment in a later section.

III. Equipment

Partly for use in these measurements, a superhetrodyne receiver operating at 230 GHz was specially developed [17]. It consists of a mixer incorporating a low-noise GaAs Schottky-barrier diode mounted in a millimeter-wave integrated circuit, a varactor doubler pumped by a klystron at 115 GHz to supply the local oscillator signal, a cavity to couple the local oscillator into the signal waveguide, and a broad-band transistor amplifier operating at 1.3 GHz. The mixer DSB noise figure was 12.6 dB, and its performance was mainly limited by the low level of local oscillator power which was available at the output of the multiplier. The noise figure of the transistor amplifier was 4.5 dB.

The receiver was mounted on the sun tracker at Bell Laboratories, Holmdel, NJ [18], in such a way that it tracked the sun in hour angle all day and moved through a 2.8° peak-to-peak sinusoid in declination at a 1-Hz rate. The lower extremity of the sinusoid is at the declination of the sun. Normally, 30- and 13-GHz receivers are connected to the sun tracker. For this experiment, the 30-GHz receiver was removed and the circular waveguide feeding it was allowed to radiate directly into the feed horn of the 230-GHz receiver. With this arrangement, the dynamic range of the complete receiver was 23 dB when observing the sun. Fig. 3 shows the receiver connected to the sun tracker.

IV. Measurements

The measurements were carried out for a period of about three weeks in November 1973. During that time, the weather was mainly dry with daytime temperatures in the 3–15°C range. On about half of these days, some cloud was present and a completely overcast sky with some light rain was experienced on three of the days. The receiver was switched on every day, as one of the main

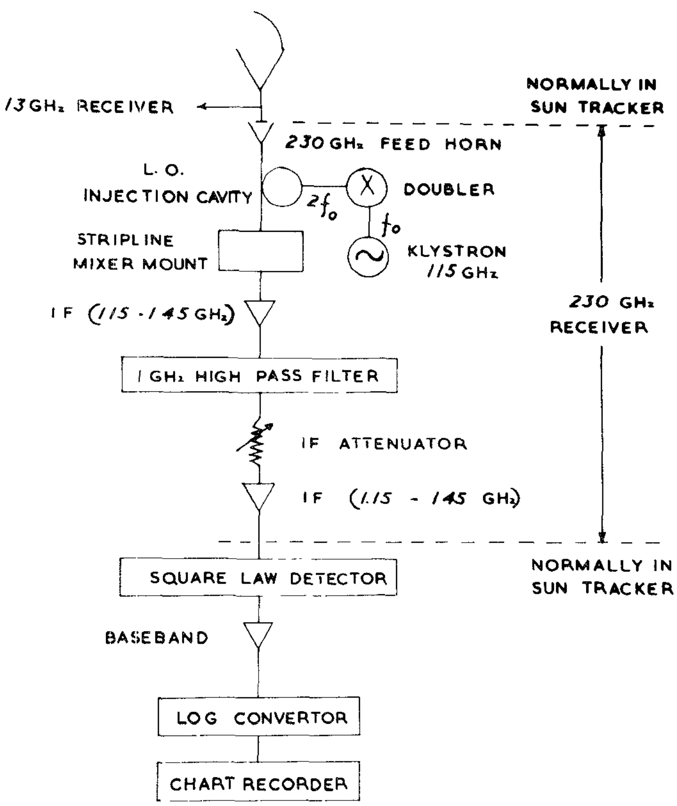

Fig. 3. Block diagram of the 230-GHz receiver in the sun tracker.

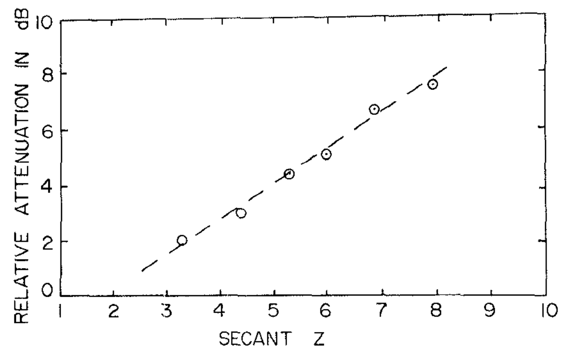

Fig. 4. Relative attenuation of solar signal on November 9, 1973, as a function of the secant of the solar zenith angle. The slope of the dashed line gives the attenuation per air mass.

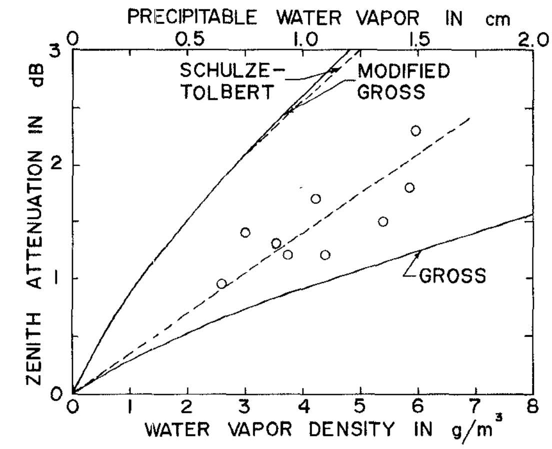

Fig. 5. Comparison of measured and calculated zenith attenuation for the three different line shapes as a function of surface water vapor density. The dashed line represents a best fit to the measured points as discussed in the text. If a linear decrease of H_2O vapor concentration with height can be assumed down to zero at 5 km (see text), the horizontal axis also represents the total precipitable water vapor.

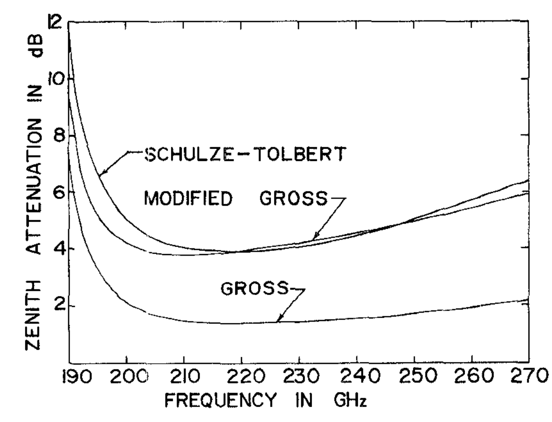

Fig. 6. Calculated zenith attenuation in the 230-GHz window for the three different line shapes as a function of frequency. The water vapor density is 7.0 g/m^3 and the surface temperature is 287.4K.

objectives of the experiment was to discover if a correlation existed between "clear-sky" attenuation and surface-water vapor density.

A. "Clear-Sky" Attenuation

The "clear-sky" attenuation was measured each day from the decrease in the intensity of the sun's signal as it traversed an increasing number of air masses throughout the afternoon.

Fig. 4 shows a typical day's data from which the zenith attenuation is determined. Fig. 5 is a plot of the zenith attenuation versus the surface density of H_2O vapor (obtained from surface temperature and relative humidity readings) and represents the results of measurements taken on nine days when neither overcast sky conditions nor rain contaminated the data. If one assumes a linear decrease of H_2O vapor concentration with height up to zero at 5 km (not too inaccurate for a near sea-level site such as Holmdel), the horizontal axis in Fig. 5 also represents total precipitable water vapor. The dashed line in Fig. 5, representing the best straight line fit to the experimental data, gives a "clear-sky" attenuation $A(\text{dB}) = 0.35\rho$, where ρ is the measured ground water vapor concentration in g/m^3.

The solid lines shown in Fig. 5 are the results of calculating the zenith attenuation using the modified and unmodified Gross line shapes and the Schulze–Tolbert line shape as discussed in Section II. Note that the measured data lie somewhat below that predicted by both the modified Gross and the Schulze–Tolbert models.

One may conclude from Fig. 5 that either the Schulze–Tolbert or the corrected Gross line shapes give a conservative value for zenith attenuation for clear weather. Fig. 6 shows the result of calculating the total zenith attenuation in the entire 230-GHz window region using each of the three line shape parameters.

At 90 GHz, with a surface H_2O vapor density of 2.75 gm/m^3, one of the authors has measured a value of 0.38 dB for the "clear-sky" zenith attenuation [21]. Fig. 5 shows that a value of 1 dB would be obtained at 230 GHz, giving a ratio of 2.6 for the attenuation at the two frequencies. This ratio would increase, however, as the water vapor density increased.

It should be emphasized at this point that, for a mountainous site, one does not expect the water vapor density as measured at the surface to be a good indicator of the *total* precipitable water vapor. This is because of turbulent atmospheric conditions normally associated with such sites. Consequently, a plot such as Fig. 5 of zenith attenuation versus surface water vapor density, would not be expected to show a linear relationship between the two variables. Measurements made at Kitt Peak, AZ, by one of the authors and by Goldsmith at Mount Hamilton, CA, at about the same frequency [22], demonstrate that this is in fact so—rather a large scatter being obtained when the zenith attenuation is plotted against the surface-water vapor density.

B. Clouds

Excess attenuation due to clouds was experienced on five days. On four of these days, the temperature ranged between 3 and 7°C, while on the fifth day the range was 13–15°C. Even though on all of these days the same types of clouds were present, the excess attenuation was very much greater on the warm day than on the colder ones. For instance, individual dark cumulus clouds on the colder days gave excess attenuations in the range 0.3–0.5 dB; however, the same type of cloud on the warmer day gave excess attenuation mainly in the range 1–2 dB, with occasional excursions to 5 dB. On the same day, a low lying storm front leading into very light rain, giving an attenuation of 0.2–1 dB at 13 GHz, gave 10 dB to greater than 23 dB at 230 GHz.

On the colder days, a light overcast gave no measurable excess attenuation, while a heavy overcast gave 0.5 dB with occasional increases ($\sim$ twice an hour) to $\sim$2–2.5 dB, lasting for a few minutes. On the warmer day, however, an overcast sky gave continuous fluctuations in the signal of magnitude 1.5–2 dB.

This difference in cloud attenuation between cold and warm days is due, presumably, to the fact that on the colder days the cloud water droplets have been mainly frozen into ice. This phenomenon is also noticeable at 90 GHz [21].

V. Conclusions

At 230 GHz for a site near sea level, the "clear-sky" attenuation was measured to be linearly related to the surface water vapor density. Excess attenuation due to cloud was found to be dependent on surface temperature, and for temperatures greater than 13°C, cloud attenuations of 2–3 dB are not uncommon. On the other hand, when the surface temperature falls below 6°C, cloud attenuation is reduced by a factor of 8–10. For clear, cool, dry days, either the Schulze–Tolbert or the modified Gross line shape factors give a conservative estimate of total zenith attenuation. For cloudy days, the agreement between theory and experiment is generally poor, but is much better on cold cloudy days than on warm cloudy days. For this latter case, an approach must be taken which accounts for the scattering and absorption of 230-GHz radiation by water droplets.

Acknowledgment

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Radio Communication in Tunnels

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Abstract—**The attenuation constant of radio waves in tunnels was obtained experimentally and theoretically. According to this study, the tunnel is a transmission channel of high-pass type. It is found that the higher the frequency, the smaller the attenuation constant. The experimental values of attenuation constants are similar to the theoretical values of the TE_{01} and EH_{11} modes when the tunnel is regarded as a circular waveguide with the same cross-sectional area as the tunnel. Radio communication using the tunnel was proven to be fully possible in spite of the standing wave effects due to the interference of the propagation modes.**

I. Introduction

At PRESENT, the increasing demand for underground streets and tunnels has generated a need for securing a communication system similar to those in deep mine shafts and tunnels. We can say that great interest is focused on the tunnel problem, and recent research in this area has been promising [1]–[8]. A communication system in such a place is a convenience for daily activities. However, in emergencies it may become vital for survival. In a disaster, i.e., fires, the conventional wire communnication system may become unreliable, necessitating a wireless radio system.

We have been searching for a place where radio and acoustic noise was minimal or nonexistent, in order to perform detailed experimental studies of the electromagnetic field surrounding the surface-wave transmission line [9]. The inside of a long tunnel fulfilled the necessary requirements. However, during the experiments, it was discovered that the tunnel itself was a transmission channel of high-pass type, similar to the circular waveguide. The meaurement of the Suikai and Sekiyama tunnels in Miyagi prefecture, Japan, revealed that, for 150–500 MHz, the attentuation constant of the guiding wave is proportional to the square of the free-space wavelength λ, and inversely proportional to the cube of the equivalent tunnel radius r [9]. The results obtained are in agreement with the waveguide theory of Marcatili and Schmeltzer [10] which is based on a characteristic equation given by Stratton [11].

The two main purposes for the present study were, first, to prove experimentally the possibilities of radio communication in tunnels and, second, to obtain an attenuation constant, theoretically and experimentally, to verify the tunnel as a circular waveguide.

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II. Experimental Communication and Results

A. Experimental Materials

A straight 1470-m long tunnel constructed of concrete was employed (for detailed compositions, see Fig. 1). The thickness of the tunnel wall is 0.9 m. The tunnel consisted of two lanes, with each lane 3.9 m in width. Further dimensions of the cross section are indicated in Fig. 1. At the time of this study, the tunnel was still under construction without obstacles, conductors, railroad tracks, cables, etc. This tunnel was not built specifically with a view to propagation. It was to fulfill a need of the Tohoku (Northeast) super express of the Japanese National Railways. But the effect of obstacles on the attentuation constant will be measured immediately after completion.

Yagi–Uda antennas or half-wave dipole antennas were used for both radio stations; the height of the antenna was 3.6 m above the road surface (Fig. 2). A wireless telephone system, as commonly found in taxicab radios, was used at a frequency of 470 MHz with a transmitting strength of approximately 1 W.

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