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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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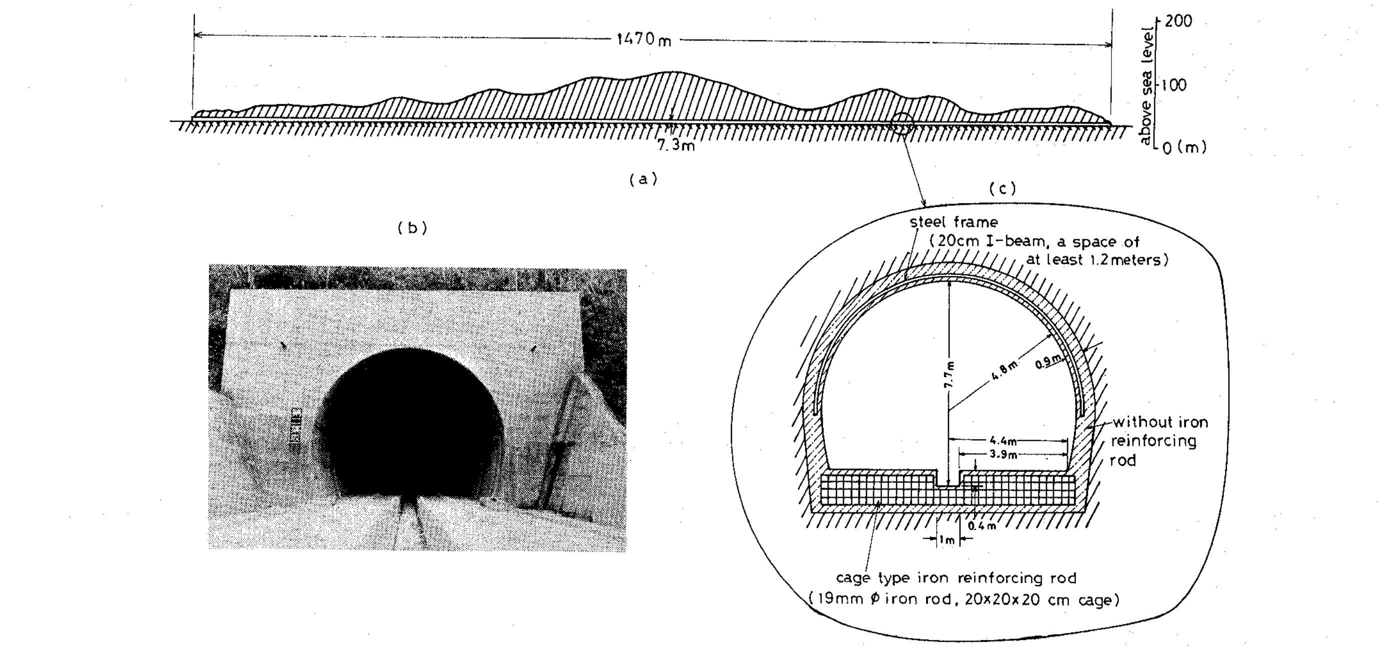

Fig. 1. The view of the tunnel in which measurements were made (all dimensions in meters).

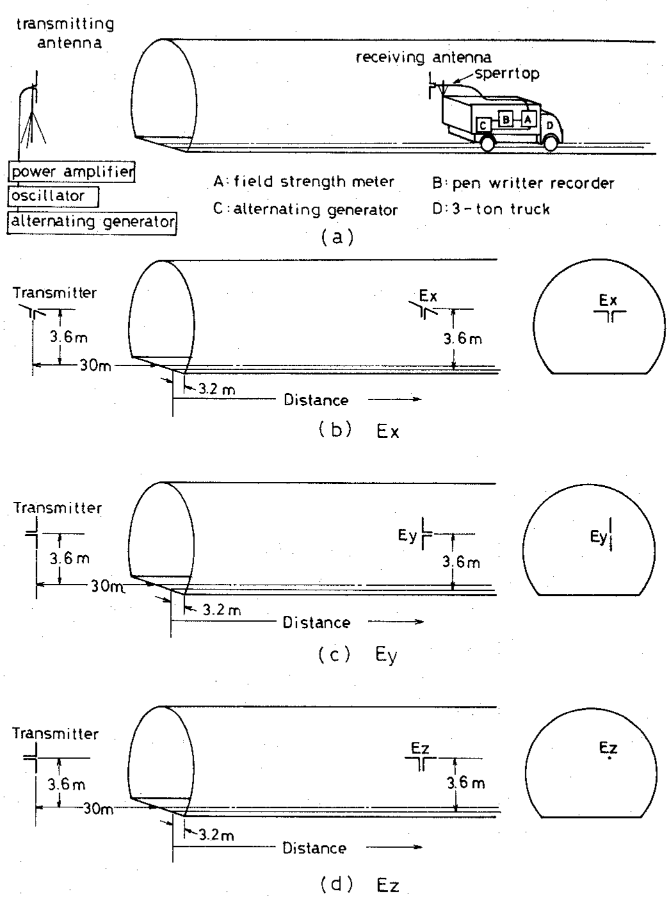

Fig. 2. Experimental setup.

B. Experimental Method

A fixed station with an antenna was set 30 m outside the entrance of the tunnel, and a mobile station with an antenna was placed on a track and moved along a solid line during the experiments (Fig. 2).

C. Experimental Results

Highly intelligible communications were achieved for the above mentioned conditions and also when the transmitting antenna was moved into the tunnel. Although the distance between the transmitting and receiving antennas was varied, large variations in field strength were not found. Hence, it is conceivable that even for longer tunnels, full communication is still possible.

III. Determination of Attenuation Constant By the Experiment

A. Experimental Method

A transmitter is set outside the tunnel, and a radio wave is sent into the tunnel (Fig. 2). While the reception equipment in the tunnel is moved on a truck along the tunnel, the output of field strength measurement is continuously recorded by a pen written recorder. In this manner, the variation of field strength against the distance in the tunnel is found and the attentuation constant is determined immediately. The method of least squares is used for data reduction.

B. Experimental Result

1) Attenuation Constant: The attenuation constant is shown in Fig. 3. Frequencies of 40, 60, 150, 470, 900, 1700, and 4000 MHz are used in the experiment. The resulting attenuation is found to increase monotonically with the inverse of frequency; e.g., at 4000 MHz, the attenuation becomes 0.7 dB/km. Furthermore, the experimental values of attentuation constants are closely correlated with the theoretical values for the corresponding TE_{01} and EH_{11} modes. According to these results, it becomes clear that the tunnel is a type of high pass transmission channel that is similar to a circular waveguide. Variations of field strength in the tunnel in Figs. 6–8 are used for experimental values in Fig. 3.

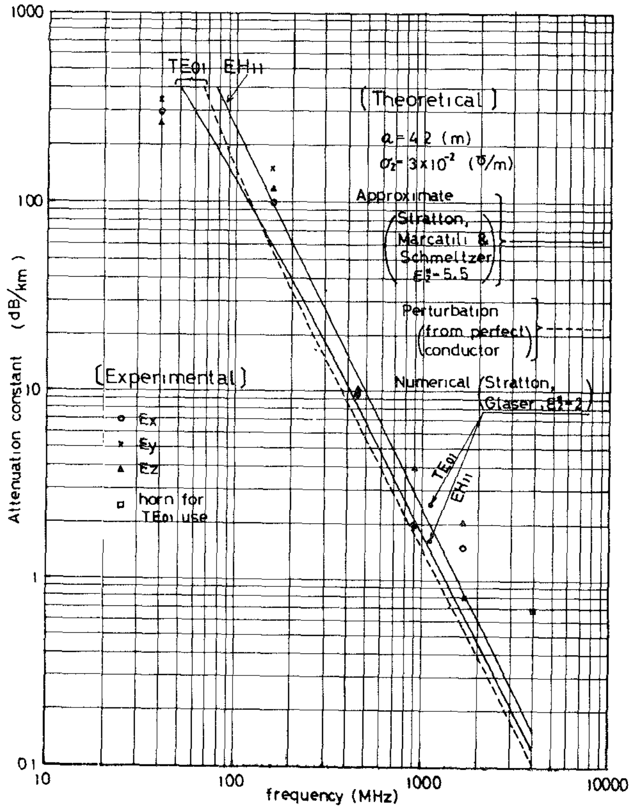

Fig. 3. The attenuation constants.

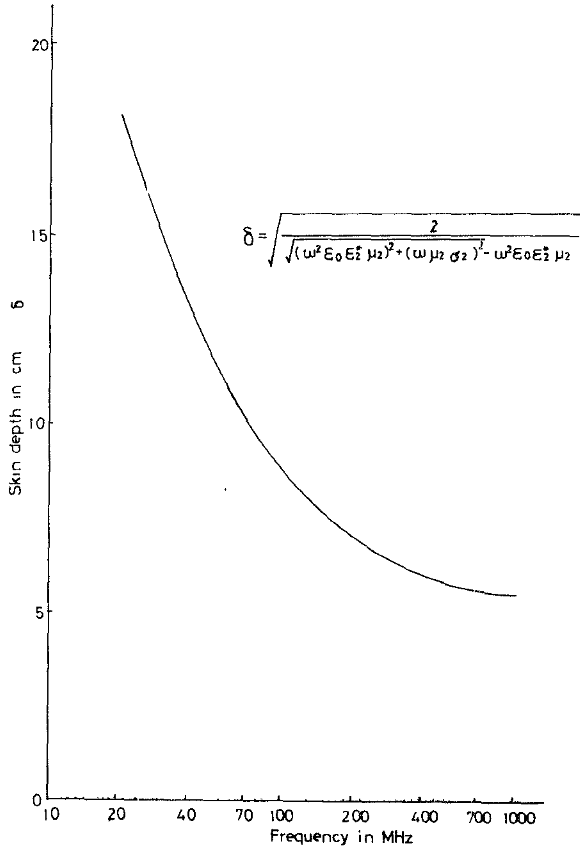

Fig. 4. Skin depth of the concrete tunnel wall.

2) Standing Wave Distribution in the Tunnel: The standing wave in the tunnel relates to the frequency, field components, and distance from the transmitting antenna.

a) Dependence against frequency: As a general tendency, the standing wave ratio (SWR) becomes smaller at low frequencies, and larger at high frequencies.

b) Dependence against field component: The SWR's of both E_x and E_y are almost identical in phase. The SWR of E_z is fairly larger in comparison with E_x and E_y. (But for the absolute value of field strength, E_z is smaller in comparison with E_x and E_y.)

c) Dependence against the distance from transmitting antenna: As a general tendency, the SWR becomes larger in places near the transmitting antenna (Figs. 6–8).

IV. Theoretical Consideration

A. Approximation to Circular Waveguide

In practice, the concrete tunnel wall is, of course, of finite thickness. At sufficiently low frequencies (below cutoff frequencies), the skin depth may exceed this thickness, in which case the field penetrates to the outside. However, an exhaustive discussion of such problems has no place here, for it is our purpose merely to experimentally prove the possibilities of radio communication in tunnels and to obtain the attenuation constant, theoretically and experimentally, to verify the tunnel as a circular waveguide. Fortunately, it is possible to make approximations in practical problems involving conducting walls which greatly simplify the problem.

When the transmission frequency is greater than the cutoff frequency, the skin depth is relatively small compared with the thickness of the concrete tunnel wall (Fig. 4) which, hence, can be assumed to be of infinite extent. Thus, to simplify theoretical considerations, the tunnel is substituted by a circular waveguide with a cross-sectional area equal to that of the tunnel.

The radius of an equivalent circular waveguide is $a=4.2$ m, as shown in Fig. 5: i.e., a waveguide consisting of a circular cylinder of radius a and free-space dielectric constant ϵ_0 embedded in another medium of dielectric having a complex dielectric constant ϵ_2. The magnetic permeability μ_0 is assumed to be that of free space for both media and wall conductivity $\sigma_2=3\times10^{-2}$ Ω/m (σ_2 measured according to Mitobe and Ito [12]).

B. Attenuation Constant

The propagation constants are the roots of the following characteristic equation for the general circular cylindrical structure [11]:

$$\left[\frac{J_n'(k_1a)}{J_n(k_1a)}-\frac{k_1}{k_2}\frac{H_n^{(1)\prime}(k_2a)}{H_n^{(1)}(k_2a)}\right]\left[\frac{J_n'(k_1a)}{J_n(k_1a)}-\frac{\nu^2k_1}{k_2}\frac{H_n^{(1)\prime}(k_2a)}{H_n^{(1)}(k_2a)}\right]=\left[\frac{n\lambda}{kk_1a}\right]^2\left[1-\left(\frac{k_1}{k_2}\right)\right]^2 \quad (1)$$

where $J_n(\ )$ denotes a Bessel function, $H_n^{(1)}(\ )$ denotes a Hankel function of the first kind, the primes denote differentiation with respect to the indicated argument, $k=\omega\sqrt{\epsilon_0\mu_0}=2\pi/\lambda$ is the free-space propagation constant $\omega=2\pi f$, f is the frequency, λ is the free-space wavelength $k_1^2=k^2-\gamma^2$, $k_2^2=\nu^2k^2-\gamma^2$, superscripts 1 and 2 refer to the internal and external media, respectively, γ is the

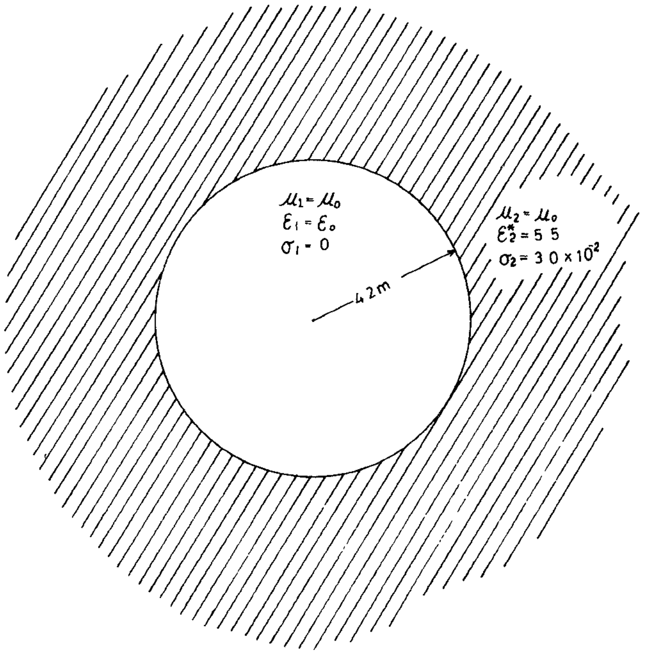

Fig. 5. Equivalent circular cylindrical waveguide for the tunnel.

TABLE I
SOME VALUE OF u_{nm}

n/m	1	2	3	4
1	2 405	5 52	8 654	11.796
2 or 0	3 832	7016	10 173	13 324
3 or −1	5 136	8.417	11.62	14.796
4 or −2	6 380	9761	13.015	16 223

complex propagation constant, $\nu = \sqrt{\epsilon_2/\epsilon_0}$ is the complex refractive index of the external medium, ϵ_2^* is the specific dielectric constant of the external medium, and n is an integer. The phase constant and attenuation constant of each mode are the real and imaginary parts of γ, respectively.

The solution of the Stratton's characteristic equation (1) was reported in two previous publications [10], [13]. The first one develops an approximate theory, (assuming that $ka = 2\pi a/\lambda \gg |\nu| u_{nm}$ and $k_2 a \gg 1$), and the second presents computer solutions; but in this case, rearrangement of (1) is necessary for calculation convenience [13]. According to Marcatili and Schmeltzer [10], the attenuation constants α_{nm} are

$$\alpha_{nm} = \left(\frac{u_{nm}}{2\pi}\right)^2 \frac{\lambda^2}{a^3} \begin{Bmatrix} \text{Re } 1/\sqrt{\nu^2 - 1}, \\ \quad \text{for TE}_{om} \text{ modes } (n=0) \\ \text{Re } (1/2)(\nu^2+1)/\sqrt{\nu^2-1}, \\ \quad \text{for EH}_{nm} \text{ modes } (n \neq 0) \end{Bmatrix} \tag{2}$$

where u_{nm} is the root of the equation $J_{n-1}(u_{nm}) = 0$; some values of u_{nm} are presented [10] in Table I.

Attenuation constants of the TE_{01} and EH_{11} modes ($8.686\alpha_{01}$ and $8.686\alpha_{11}$ in dB/km) have been plotted in Fig. 3 as a function of frequency.

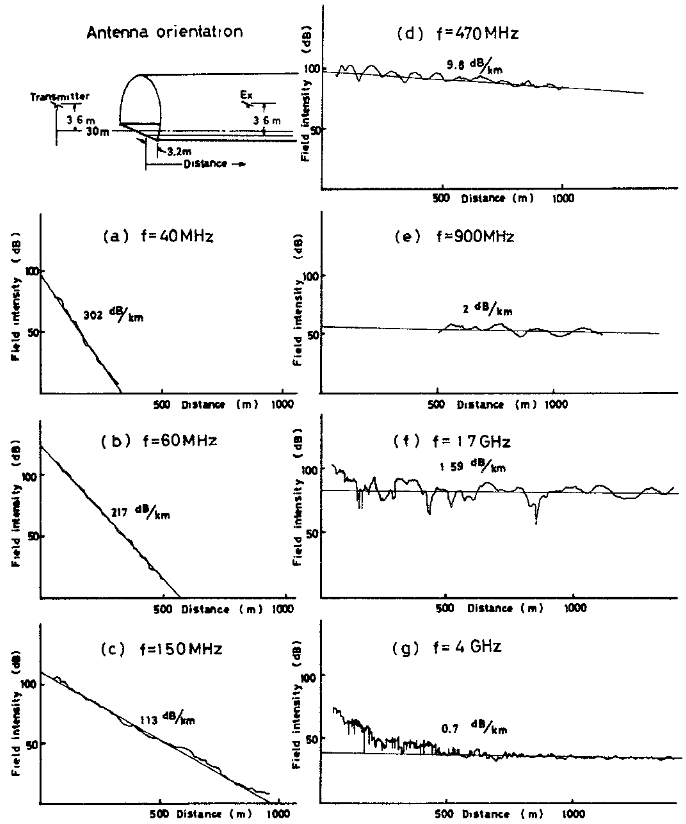

Fig. 6. Attenuation of the horizontal component E_x for various frequencies as a function of distance 1 μV/m = 0 dB.

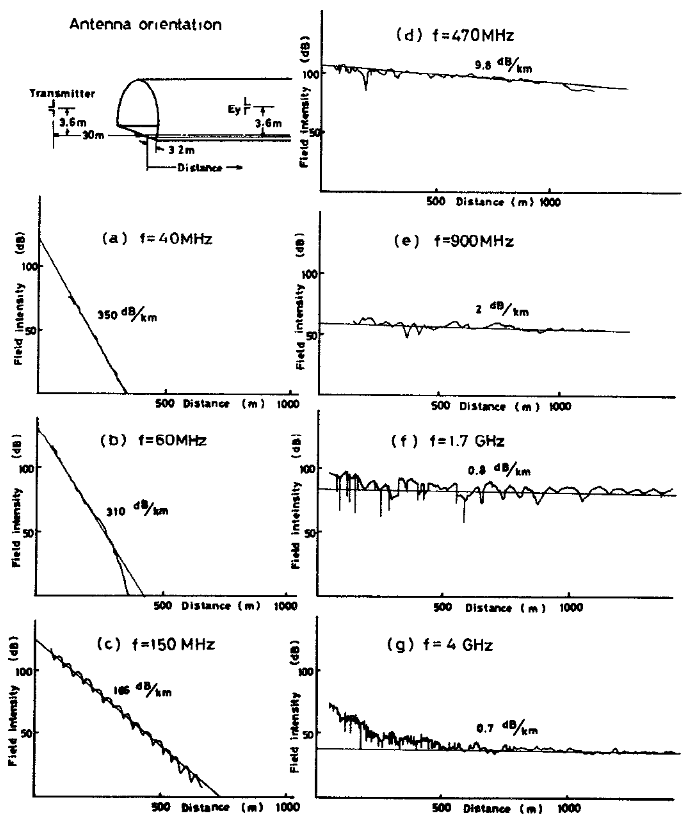

Fig. 7. Attenuation of the vertical component E_y for various frequencies as a function of distance 1 μV/m = 0 dB.

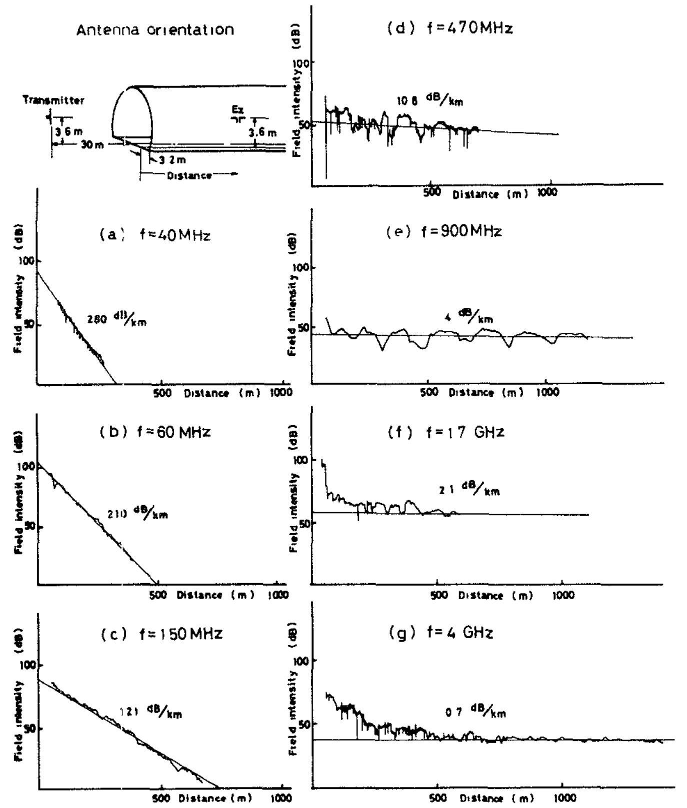

Fig. 8. Attenuation of the longitudinal component E_z for various frequencies as a function of distance 1 μV/m = 0 dB.

As pointed out by Marcatili and Schmeltzer [10] in the circular waveguide, comparing attenuation constants (2) of the different modes, we find that the mode with lowest attenuation is TE_{01} if $\nu > 2.02$ and EH_{11} if $\nu < 2.02$. In Fig. 3, numerical results are given according to perturbation method (result of high-order approximation, use Re $\sqrt{(jw\mu_2)/(\sigma_2 + jw\epsilon_0\epsilon_2^*)}$ for $\sqrt{\pi f \mu / \sigma_2}$ in [14], equation (5b-140)), and according to Glaser's curve (Glaser's Fig. 2 [13], only the $\epsilon_2^* = 2$ and one-point frequency), there is a certain difference in the TE_{01} mode, as expected. In case of the same calculation condition (electrical constants), numerical results of Marcatili–Schmeltzer's (2) agree with Glaser's numerical results. As the frequency becomes gradually higher, e.g., 1000, 1700, and 4000 MHz, the experimental value shifts from the theoretical curve to high attenuation (Fig. 3); this tendency is generally evident in the waveguide for use in the TE_{01} mode and the surface roughness is considered to be one cause.

V. Conclusion

It was shown that radio communication via the tunnel is possible and that the attenuation constants of the tunnel could be obtained. 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 circular waveguide, and when the cross-sectional area is equal to that of the tunnel. When the diameter of the tunnel is from several to ten times larger than the free-space wavelength, the tunnel can be used as a transmission channel for the wave in spite of the standing wave effects. However, the effect of obstacles in the tunnel is not yet understood. (See Figs. 6–8.)

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