THEORY OF THE PROPAGATION OF UHF RADIO WAVES IN COAL MINE TUNNELS

by

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ABSTRACT

This paper is concerned with the theoretical study of UHF radio communication in coal mines, with particular reference to the rate of loss of signal strength along a tunnel, and from one tunnel to another around a corner. Of prime interest are the nature of the propagation mechanism and the prediction of the radio frequency that propagates with the smallest loss. Our theoretical results are compared with measurements made by Collins Radio Co. This work was conducted as part of the Pittsburgh Mining and Safety Research Center's investigation of new ways to reach and extend two-way communications to the key individuals that are highly mobile within the sections and haulage ways of coal mines.

INTRODUCTION

At frequencies in the range of 200-4,000 MHz the rock and coal bounding a coal mine tunnel act as relatively low loss dielectrics with dielectric constants in the range 5-10. Under these conditions a reasonable hypothesis is that transmission takes the form of waveguide propagation in a tunnel, since the wavelengths of the UHF waves are smaller than the tunnel dimensions. An electromagnetic wave traveling along a rectangular tunnel in a dielectric medium can propagate in any one of a number of allowed waveguide modes. All of these modes are "lossy modes" owing to the fact that any part of the wave that impinges on a wall of the tunnel is partially refracted into the surrounding dielectric and partially reflected back into the waveguide. The refracted part propagates away from the waveguide and represents a power loss. This type of waveguide mode differs from the light-pipe modes in glass fibers in which total internal reflection occurs at the wall of the fiber, with zero power loss if the fiber and the matrix in which it is embedded are both lossless. It is to be noted that the attenuation rates of the waveguide modes studied in this paper depend almost entirely on refraction loss, both for the dominant mode and higher modes excited by scattering, rather than on ohmic loss. The effect of ohmic loss due to the small conductivity of the surrounding material is found to be negligible at the frequencies of interest here, and will not be further discussed.

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The study reported here is concerned with tunnels of rectangular cross section and the theory includes the case where the dielectric constant of the material on the side walls of the tunnel is different from that on top and bottom walls. The work extends the earlier theoretical work by Marcatili and Schmeltzer[1] and by Glaser[2] which applies to waveguides of circular and parallel-plate geometry in a medium of uniform dielectric constant.

In this paper we present the main features of the propagation of UHF waves in tunnels. Details of the derivations are contained in Arthur D. Little, Inc. reports.[3]

THE FUNDAMENTAL (1,1) WAVEGUIDE MODES

The propagation modes with the lowest attenuation rates in a rectangular tunnel in a dielectric medium are the two (1,1) modes which have the electric field $\vec{E}$ polarized predominantly in the horizontal and vertical directions, respectively. We will refer to these two modes as the E_h and E_v modes.

The main field components of the E_h mode in the tunnel are

$$E_x = E_0 \cos k_x x \cos k_y y \, e^{-ik_z z} \tag{1}$$

$$H_y = (k_z/\omega\mu_0)E_0 \cos k_x x \cos k_y y \, e^{-ik_z z} \tag{2}$$

where the symbols have their customary meaning. The coordinate system is centered in the tunnel with x horizontal, y vertical, and z along the tunnel. In addition to these transverse field components there are small longitudinal components E_z and H_z and a small transverse component H_x. For the frequencies of interest here k_x and k_y are small compared with k_z which means that the wave propagation is mostly in the z-direction. From a geometrical optics point of view, the ray makes small grazing angles with the tunnel walls.

In the dielectric surrounding the tunnel the wave solution has the form of progressive waves in the transverse as well as the longitudinal directions. The propagation constant k_z for the (1,1) mode is an eigenvalue determined by the boundary conditions of continuity of the tangential components of $\vec{E}$ and $\vec{H}$ at the walls of the tunnel. Owing to the simple form of the wave given by (1) and (2) these conditions can be satisfied only approximately. However, a good approximation to k_z is obtained. The imaginary part of k_z, which arises owing to the leaky nature of the mode, gives the attenuation rate of the wave. The loss L_{Eh} in dB for the (1,1) E_h mode is given by

$$L_{Eh} = 4.343 \, \lambda^2 \, z \left(\frac{K_1}{d_1^3 \sqrt{K_1 - 1}} + \frac{1}{d_2^3 \sqrt{K_2 - 1}} \right) \tag{3}$$

where K_1 is the dielectric constant of the side walls and K_2 of the roof and floor of the tunnel. The corresponding result for the (1,1) E_v mode is

$$L_{E_v} = 4.343\,\lambda^2\,z \left(\frac{1}{d_1^3\sqrt{K_1 - 1}} + \frac{K_2}{d_2^3\sqrt{K_2 - 1}} \right) \tag{4}$$

These results are valid if the wavelength λ is small compared with the tunnel dimensions d_1 and d_2. The same formulas are also obtained if one adds the attenuations for horizontal and vertical slot waveguides with dimensions d_2 and d_1, and dielectric constants K_2 and K_1, respectively. The losses calculated by (3) and (4) also agree closely with those calculated by a ray approach.

Figure 1 shows loss rates in dB/100 ft as functions of frequency calculated by (3) and (4) for the (1,1) E_h and E_v modes in a tunnel of width 14 ft and height 7 ft, representative of a haulage way in a seam of high coal, and for $K_1 = K_2 = 10$, corresponding to coal on all the walls of the tunnel. It is seen that the loss rate is much greater for the E_v mode. Figure 2 shows the calculated E_h loss rate for a tunnel of half the height. The higher loss rate in the low coal tunnel is due to the effect of the d_2^3 term in (3).

Two experimental values obtained by Collins Radio Co.[4] for horizontal-horizontal antenna orientations are also shown in Figure 1. These values agree well with theory for the E_h mode for 415 MHz, but not so well for 1000 MHz. The departure suggests that some additional loss mechanism sets in at higher frequencies.

It is also significant that the experimental values of the loss rates for all three orientation arrangements of the transmitting and receiving dipole antennas, namely, horizontal-horizontal, vertical-horizontal, and vertical-vertical, are surprisingly close to each other. The independence of loss rate with respect to polarization is not predicted by the theory discussed so far, as seen in Figure 1 for the E_h and E_v modes. Indeed, the theory predicts no transmission at all for the VH antenna arrangement.

PROPAGATION MODEL

The higher observed loss rate at the higher frequencies relative to the calculated E_h mode values, and the independence of the loss rate on antenna orientation can both be accounted for if one allows for scattering of the dominant (1,1) E_h mode by roughness and tilt of the tunnel walls. The scattered radiation goes into many higher modes and can be regarded as a diffuse radiation component that accompanies the E_h mode. The diffuse component is in dynamical equilibrium with the E_h mode in the sense that its rate of generation by scattering of the E_h mode is balanced by its rate of loss by refraction into the surrounding dielectric. Since the diffuse component consists of contributions from the (1,1) E_v mode and many higher order waveguide modes, all of which have much higher refractive loss rates than the fundamental E_h mode, the dynamical balance point is such that the level of the diffuse component is many dB below that of the E_h mode at any point in the tunnel.

Our propagation model, comprising the (1,1) E_h mode plus an equilibrium diffuse component, explains the discrepancy between theory and experiment in Figure 1, since the loss due to scattering of the E_h mode is greater at 1000 MHz than at 415 MHz owing to the larger effect of wall tilt at the higher frequency. The model accounts for the independence of loss rate on antenna orientation, since the loss rate is always that of the E_h mode, except for initial and final transition regions, no matter what the orientations of the two antennas may be. The transition regions, however, cause different insertion losses for the different antenna orientations.

Further strong support for the theoretical model is provided by the discovery by Collins Radio Co. that a large loss in signal strength occurs when the receiving antenna is moved around a corner into a cross tunnel; and that the signal strength around the corner is independent of receiving antenna orientation. This is exactly what our model predicts since the well collimated E_h mode in the main tunnel couples very weakly into the cross tunnel, whereas the uncollimated diffuse component couples quite efficiently. Since the diffuse radiation component is likely to be almost unpolarized, the observed independence of signal strength on receiving antenna orientation is understandable.

Another experimental result is that the initial attenuation rate in the cross tunnel is much higher than the rate in the main tunnel. This is also in accord with the model since the diffuse radiation component has a much larger loss rate than the E_h mode owing to its steeper angles of incidence on the tunnel walls.

THE DIFFUSE RADIATION COMPONENT

Scattering of the (1,1) E_h mode into other modes to generate the diffuse component occurs by two mechanisms: wall roughness and wall tilt.

Roughness is here regarded as local variations in the level of the surface relative to the mean level of the surface of a wall. For the case of a Gaussian distribution of the surface level, defined by a root mean square roughness h, the loss in dB by the E_h mode is given by the formula

$$L_{roughness} = 4.343\, \pi^2\, h^2\, \lambda(1/d_1^4 + 1/d_2^4)\, z. \tag{5}$$

This is also the gain by the diffuse component due to roughness.

Long range tilt of the tunnel walls relative to the mean planes which define the dimensions d_1 and d_2 of the tunnel causes radiation in the E_h mode to be deflected away from the directions defined by the phase condition for the mode. One can calculate the average coupling factor of such deflected radiation back into the E_h mode and thereby find the loss rate due to tilt. The result in dB is

$$L_{tilt} = 4.343\, \pi^2\, \theta^2\, z/\lambda \tag{6}$$

where θ is the root mean square tilt. Eq. (6) also gives the rate at which the diffuse component gains power from the E_h mode as a result of the tilt.

It is noted from (5) and (6) that roughness is most important at low frequencies while tilt is most important at high frequencies.

Figure 3 shows the effect on the (1,1) E_h mode propagation of adding the loss rates due to roughness and tilt to the direct refraction loss given in Figure 1. The curves are calculated for a root mean square roughness of 4 inches and for various assumed values of θ. It is seen that a value $\theta = 1°$ gives good agreement with the experimental values of Collins Radio Co. The effect of tilt is much greater than that of roughness in the frequency range of interest.

Having determined the value of θ, for the assumed value of h, we can now find the intensity ratio of the diffuse component to the E_h mode from the equilibrium balance equation

$$I_{d,\ \mathrm{main}} / I_{h,\ \mathrm{main}} = L_{hd} / L_d \tag{7}$$

where L_{hd} is the loss rate from the E_h mode into the diffuse component, and L_d is the loss rate of the diffuse component by refraction. To estimate L_d approximately, we take the loss rate to be that of an "average ray" of the diffuse component having direction cosines $(1/\sqrt{3}, 1/\sqrt{3}, 1/\sqrt{3})$. Then

$$L_d = 10\,(z/d_1 + z/d_2) \log_{10} 1/R \tag{8}$$

where R, the Fresnel reflectance of the average ray for $K_1 = K_2 = 10$, has the value 0.28. Then for $d_1 = 14$ ft, $d_2 = 7$ ft, $z = 100$ ft, we find that $L_d = 119$ dB/100 ft. This value has to be corrected for the loss of diffuse radiation into cross tunnels which we assume have the same dimensions as the main tunnel and occur every 75 ft. From relative area considerations we find that this loss is 2 dB/100 ft. The corrected value is therefore

$$L_d = 121 \text{ dB/100 ft.} \tag{9}$$

which is independent of frequency.

The loss rate L_{hd} is shown in Table I as a function of frequency for the 14 ft x 7 ft tunnel. The values are the sum of the roughness and tilt losses calculated by (5) and (6) for h = 4 inches rms and $\theta = 1°$ rms. The diffuse component level relative to the E_h mode, calculated by (7), is given in the fourth column of Table I. The diffuse component is larger at high frequencies owing to the increased scattering of the E_h mode by wall tilt.

PROPAGATION AROUND A CORNER

From solid angle considerations one finds that the fraction of the diffuse component in the main tunnel that enters the 14 ft x 7 ft aperture of a cross tunnel is 15% or – 8.2 dB. The diffuse level just inside the aperture of the cross tunnel, relative to the E_h mode level in the main tunnel is therefore obtained by subtracting 8.2 dB from the values in column 4 of Table I. The results are shown in column 5 of the table. A dipole antenna with either horizontal or vertical orientation placed at this point responds to one half of the diffuse radiation, and therefore gives a signal that is 3 dB less than the values in column 5 of Table I, relative to a horizontal antenna in the main tunnel.

If a horizontal antenna is moved down the cross tunnel the loss rate is initially 119 dB/100 ft (the value calculated above without correction for tunnels branching from the cross tunnel). Ultimately, however, the loss rate becomes that of the E_h mode excited in the cross tunnel by the diffuse radiation in the main tunnel. We determine the E_h level at the beginning of the cross tunnel by calculating the fraction of the diffuse radiation leaving the exit aperture of the main tunnel which lies within the solid angle of acceptance of the E_h mode in the cross tunnel. The result is

$$I_{h,\,cross}/I_{d,\,main} = \lambda^3/16\,\pi\,d_1^2\,d_2 \qquad (10)$$

This ratio, in dB, is given in column 2 of Table II.

Column 3 of Table II is the E_h level at the beginning of the cross tunnel relative to the E_h level in the main tunnel found by adding column 2 of Table II and column 4 of Table I. We find the corresponding ratio at 100 ft down the cross tunnel by adding the E_h propagation loss rates given in Figure 3 for $\theta = 1°$. The results are shown in the last column of Table II.

The foregoing theoretical results for the diffuse and E_h components in the cross tunnel allow us to plot straight lines showing the initial and final trends in signal level in the cross tunnel. These asymptotic lines are shown in Figures 4 and 5 for 415 MHz and 1000 MHz, in comparison with the cross tunnel measurements of Collins Radio Co. The agreement both in absolute level and distance dependence gives good support to the theoretical model.

EFFECT OF ANTENNA ORIENTATION

The theoretical model also allows us to predict the effect of antenna orientation when the transmitting and receiving antennas are far enough apart so that dynamical equilibrium between the E_h mode and the diffuse component is established. We start with both antennas horizontal (HH configuration) and consider this as the 0 dB reference. Then if the receiving antenna is rotated to the vertical (HV configuration) this antenna is now orthogonal to the E_h mode, and therefore responds only to one half of the diffuse component, so that the loss is 3 dB more than the values in Table I, column 4. The result is shown in Table III column 2. Now, by the principle of reciprocity, the transmission for VH is the same as for HV as shown in column 3 of Table III. We now rotate the receiving antenna to get the configuration VV. Again we incur an additional transmission loss of 3 dB more than the values in Table I, column 4. The VV values are shown in Table III, column 4.

ANTENNA INSERTION LOSS

Dipole or whip antennas are the most convenient for portable radio communications between individuals. However, a considerable loss of signal power occurs at both the transmitter and receiver when simple dipole antennas are used because of the inefficient coupling of these antennas to the waveguide mode. The insertion loss of each dipole antenna can be calculated by a standard microwave circuit technique for computing the amount of power coupled into a waveguide mode by a probe, whereby the dipole antenna is represented as a surface current filament having a sinusoidal current distribution along its length. The result is

$$C = \lambda^2 Z_0/\pi^2 d_1 \ d_2 \ R_r. \tag{11}$$

Z_0 is the characteristic impedance of the E_h (1,1) mode and R_r is the radiation resistance of the antenna, which are approximately 377 and 73 ohms, respectively, provided that λ is small compared with d_1 and d_2.

Formula (11) applies to antennas placed at the center of the tunnel and gives the results shown in Table IV, where the insertion loss L_i in dB is equal to $-10 \log_{10} C$. It is seen that the insertion loss decreases rapidly with increasing wavelength, as one would expect, since the antenna size occupies a larger fraction of the width of the waveguide. The overall insertion loss, for both antennas, is twice the value given in the table. A considerable reduction in loss would result if high gain antenna systems were used.

OVERALL LOSS IN A STRAIGHT TUNNEL

The overall loss in signal strength in a straight tunnel is the sum of the propagation loss and the insertion losses of the transmitting and receiving antennas. Table V lists the component loss rates for the (1,1) E_h mode due to direct refraction, roughness, and tilt; the total propagation loss rate; the insertion loss for two half-wave antennas; and the overall loss for five different distances. The overall loss for the HH orientation is also shown in Figure 6, where it is seen that the optimum frequency for minimum overall loss is in the range 500-1000 MHz, depending on the desired communication distance.

It is also of interest to combine the results in Table V with those in Table III to obtain the overall loss versus distance for the HH, HV (or VH), and VV antenna orientations. In order to compare the theoretical values with the experimental data of Collins Radio Co., which are expressed with reference to isotropic antennas, we add 4.3 dB to the overall loss calculated for half-wave dipoles. The theoretical results for the three different antenna orientations for frequencies of 415 MHz and 1,000 MHz are compared with the experimental data in Figures 7 and 8. It is seen that the theory agrees quite well with the general trend of the data.

OVERALL LOSS ALONG A PATH WITH ONE CORNER

Table VI gives the overall E_h mode loss for a path from one tunnel to another, including the corner loss involved in re-establishing the E_h mode in the second tunnel. The loss is the sum of the corner loss, given in column 3 of Table II and repeated in Table VI, and the straight tunnel loss given in Table V for various total distances. The results in Table VI are for the case of half-wave dipole transmitting and receiving antennas and are valid when neither antenna is within about 100 ft of the corner. The overall loss is less than the values in Table VI if the receiving antenna is within this distance, owing to the presence of the rapidly attenuating diffuse component that passes around the corner. From the principle of reciprocity, the same is true if the transmitting antenna is within 100 ft of the corner.

The results indicate that the optimum frequency lies in the range 400-1,000 MHz. However, if one installs horizontal half-wave resonant scattering dipoles with 45° azimuth in the important tunnel intersections, in order to guide the E_h mode around the corner, the optimum may shift to somewhat lower frequencies since a greater fraction of the incident E_h wave will be deflected by the longer low-frequency dipoles.

CONCLUSIONS

The kind of propagation model developed in this paper, involving the (1,1) E_h waveguide mode accompanied by a diffuse component in dynamical equilibrium with it, seems to be necessary to account for the many effects observed in the measurements of Collins Radio Company: the exponential decay of the wave; the marked polarization effects in a straight tunnel; the independence of decay rate on antenna orientation; the absence of polarization at the beginning of a cross tunnel; the two-slope decay characteristic in a cross tunnel; and overall frequency dependence. All of these effects are moderately well accounted for by the theoretical model. However, considerable refinement of the theory could be made by removing some of the present oversimplifications, such as: the assumption of perfectly diffuse scattering both in the main tunnel and immediately around a corner in a cross tunnel; the use of the "average ray" approximation; and the description of the propagation around a corner in terms of two asymptotes only.

The last item particularly deserves more attention since we have not included the conversion of the diffuse component in the transition region near the beginning of the cross tunnel into the E_h mode. For this reason we think that the good fit of the theory to the experimental data in Figures 4 and 5 may be somewhat fortuitous. More data at greater distances down a cross tunnel would be very desirable to settle this question. Data covering a wider frequency range in both main and cross tunnels would also allow a more stringent test of the theory.

REFERENCES

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3. Arthur D. Little, Inc., reports to U.S. Department of the Interior, Bureau of Mines, Pittsburgh, Pa.

4. Collins Radio Company, "Coal Mine Communications Field Test Report," December 29, 1972 prepared for U.S. Department of the Interior, Bureau of Mines, Pittsburgh, Pa.

FIGURE 1

REFRACTION LOSS FOR E_h AND E_v MODES IN HIGH COAL

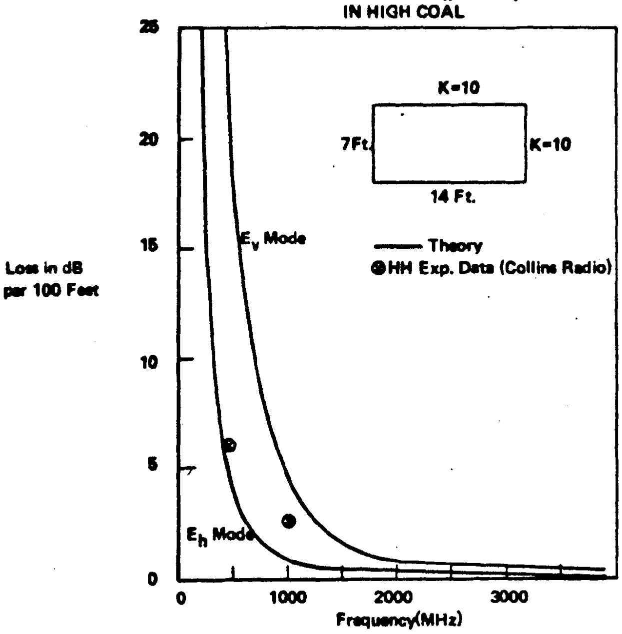

FIGURE 2

REFRACTION LOSS FOR E_h MODE IN LOW COAL

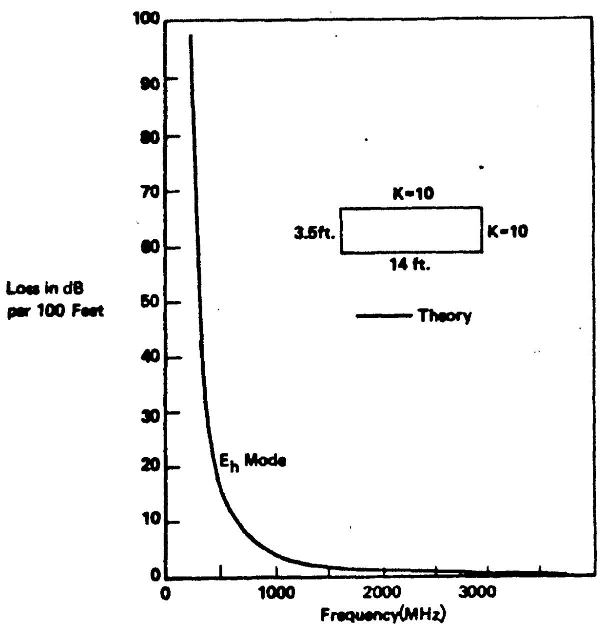

FIGURE 3

RESULTANT PROPAGATION LOSS FOR E_h MODE IN HIGH COAL

(Refraction, Wall Roughness and Tilt)

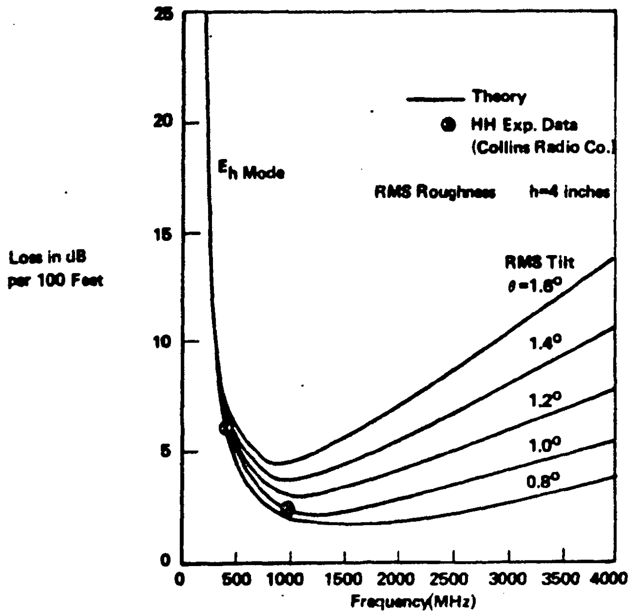

FIGURE 4

CORNER LOSS IN HIGH COAL

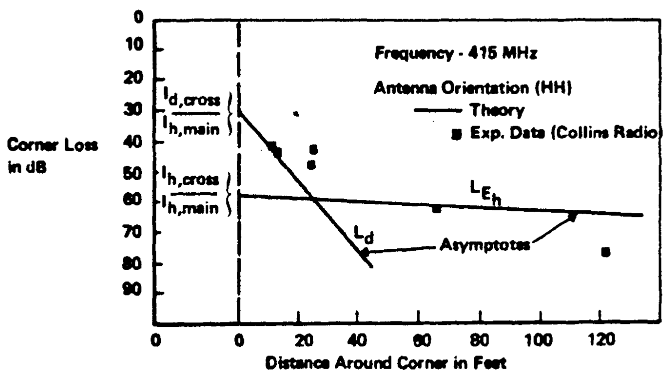

FIGURE 5

CORNER LOSS IN HIGH COAL

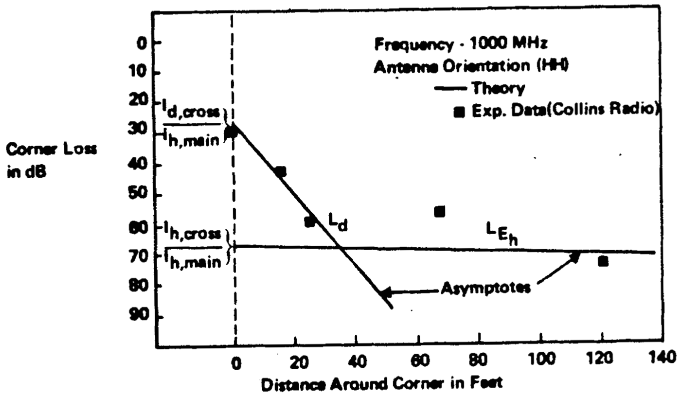

FIGURE 7

OVERALL LOSS IN A STRAIGHT TUNNEL IN HIGH COAL

(For Isotropic Antennas)

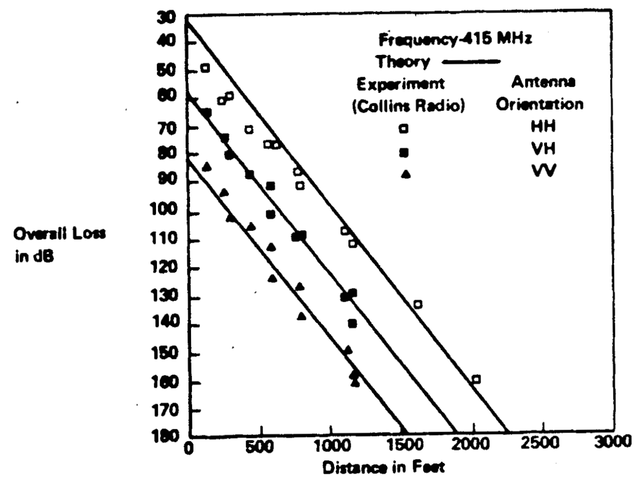

FIGURE 6

TOTAL LOSS FOR VARIOUS DISTANCES ALONG A STRAIGHT TUNNEL

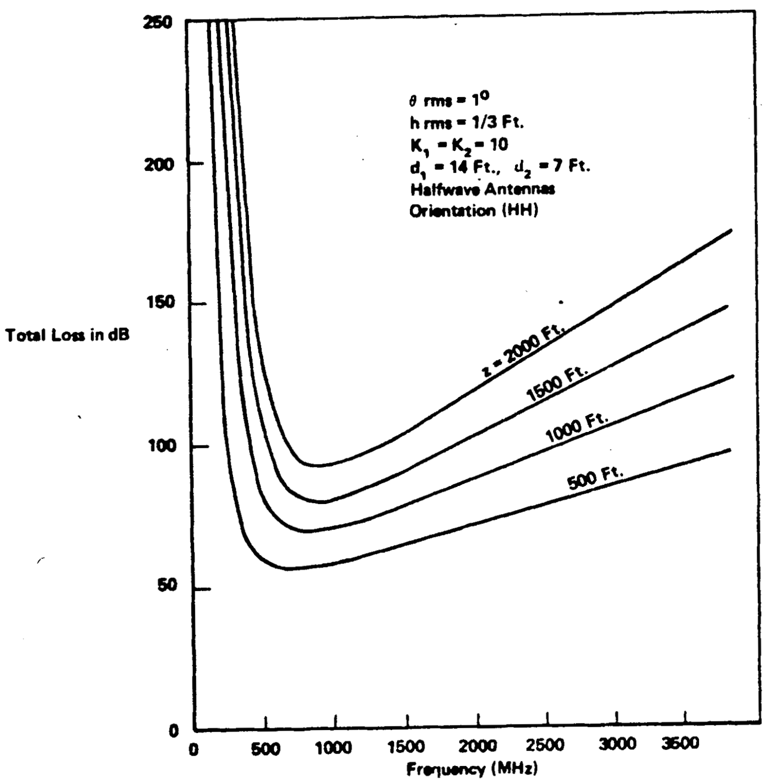

FIGURE 8

OVERALL LOSS IN A STRAIGHT TUNNEL IN HIGH COAL

(For Isotropic Antennas)

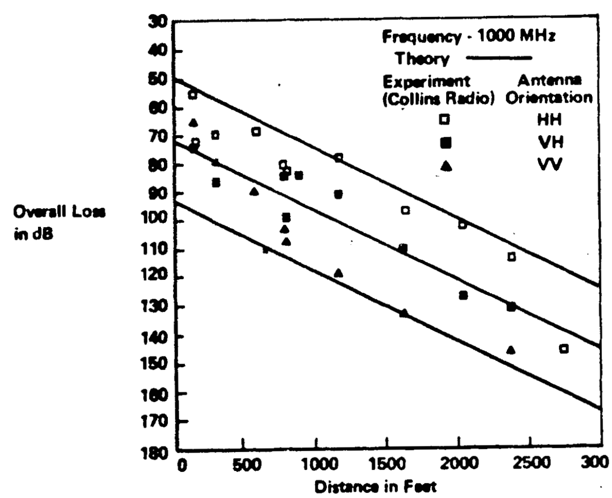

TABLE I

DIFFUSE RADIATION COMPONENT IN MAIN TUNNEL AND AT BEGINNING OF CROSS TUNNEL

f (MH$_z$)	λ (Ft.)	L_{hd} (dB/100 ft.)	$\frac{I_{d,\,main}}{I_{h,\,main}}$ (dB)	$\frac{I_{d,\,cross}}{I_{h,\,main}}$ (dB)
4,000	.245	5.4	-13.5	-21.7
3,000	.327	4.1	-14.7	-22.9
2,000	.49	2.8	-16.4	-24.6
1,000	.98	1.5	-19.0	-27.2
415	2.37	1.1	-20.6	-28.8
200	4.92	1.3	-19.7	-27.9

TABLE IV

INSERTION LOSS (L_i)

(For a Half-Wave Antenna)

F (MHz)	λ (Feet)	L_i (dB)
4000	0.245	36.0
3000	0.327	32.4
2000	0.49	28.9
1000	0.98	22.9
415	2.37	15.2
200	4.92	8.9

TABLE II

EXCITATION OF E_h MODE IN CROSS TUNNEL BY DIFFUSE COMPONENT IN MAIN TUNNEL

f (MH$_z$)	$\frac{I_{h,\,cross}}{I_{d,\,main}}$ (dB)	$\left(\frac{I_{h,\,cross}}{I_{h,\,main}}\right)_0$ (dB)	$\left(\frac{I_{h,\,cross}}{I_{h,\,main}}\right)_{100'}$ (dB)
4,000	-66.7	-80.2	85.6
3,000	-62.9	-77.6	81.8
2,000	-57.7	-74.1	77.1
1,000	-48.6	-67.6	70.1
415	-37.1	-57.7	64.1
200	-27.6	-47.3	71.6

TABLE V

CALCULATION OF OVERALL LOSS FOR E_h MODE WITH TWO HALFWAVE DIPOLE ANTENNAS

($h = 1/3$ Ft. $\theta = 1^\circ$, $K_1 = K_2 = 10$, $d_1 = 14$ Ft., $d_2 = 7$ Ft.)

f (MHz)	$L_{refraction}$ (dB/100')	$L_{roughness}$ (dB/100')	L_{tilt} (dB/100')	$L_{propagation}$ (dB/100')	$L_{insertion}$ (dB)	$L_{overall}$ (dB) 100'	500'	1000'	1500'	2000'
4000	.06	.05	5.33	5.44	69.90	75	97	124	152	179
3000	.10	.07	3.99	4.16	64.88	69	86	107	127	148
2000	.23	.10	2.66	2.99	57.86	61	73	88	103	118
1000	.91	.21	1.33	2.45	45.82	48	58	70	81	93
415	5.34	.50	0.55	6.39	30.48	37	62	94	126	158
200	23.00	1.04	0.27	24.31	17.80	42	139	261	383	504
100	92.00	2.08	0.14	94.20	5.80	100	477	948	1419	1890

TABLE III

EFFECT OF ANTENNA ORIENTATION

f (MHz)	HH (dB)	HV (dB)	VH (dB)	VV (dB)
1000	0	-22.0	-22.0	-44.0
415	0	-23.6	-23.6	-47.2
200	0	-22.7	-22.7	-45.4

TABLE VI

OVERALL LOSS ALONG A PATH INCLUDING ONE CORNER E_h MODE WITH HALFWAVE DIPOLE ANTENNAS

f (MHz)	E_h Loss per Corner (dB)	Overall Loss (dB) 500'	1000'	1500'	2000'
4000	80.2	177	205	232	259
3000	77.6	163	184	205	226
2000	74.1	147	162	177	192
1000	67.6	126	138	148	161
415	57.7	120	152	184	216
200	47.3	187	308	430	551