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SURVEY OF INDUCTIVE COMMUNICATION SYSTEMS

G.Y. Chin
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16. Abstract

A survey is made of various inductive systems proposed for low frequency train communication. It is found that thick dielectric jackets or coaxial and metallic shields may be required to reduce the environmental effects that lead to high attenuation. Twisted wire cables with inversely connected coupling antennas attain reduction of induced electrical noise and of radiated fields. External noise interference in various environments is discussed. Analysis is made of the coupling variation effect due to wire separation.

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PREFACE

This survey of the use of inductive systems for train communication was made by the staff of the Communication Branch of the Electromagnetics Technology Division, Transportation Systems Center. It is presented as part of a continuing program on ground-transportation communication sponsored by the Advanced System Division of the Federal Railroad Administration.

The objective is to gather information on various types of inductive cables which may be promising for use in train communication, to analyze their main advantages and shortcomings, and to present some of the measurements of their characteristics. The authors wish to thank the representatives of the Sumitomo Electric Industries, Ltd. and the Philco-Ford Corporation for helpful discussions and for providing useful information.

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1. INTRODUCTION

Inductive radio systems are receiving increasing attention as a means of communicating with trains and other ground transportation. In their most common forms, they offer advantages of low cost and non-critical installation, but, as low-frequency systems, they are subject to limitations of bandwidth and noise. The investigation of inductive systems has ranged from simple parallel wire systems to more complex configurations that offer protection from the electrical and physical environment.

Characteristics of parallel inductive cables based on measurements at frequencies up to 100 kHz were compiled by Fricke and Form.[1] Measurements on parallel circuits with cross-overs were also made by the Philco-Ford Corporation.[2] Sumitomo Electric Industries, Ltd., in cooperation with the Railway Technical Institute of the Japanese National Railways, has made further improvements on helical inductive transmission lines and recently conducted experimental studies on these lines. Much of the information which will be presented on advanced inductive systems, especially the helical cable and the partially shielded grooved metal frame line, has been obtained from Sumitomo, Ltd.

2. TYPES OF INDUCTION CABLES

In this section we shall briefly review different types of induction cables. Details of the electrical characteristics will be given in sections 3 and 4.

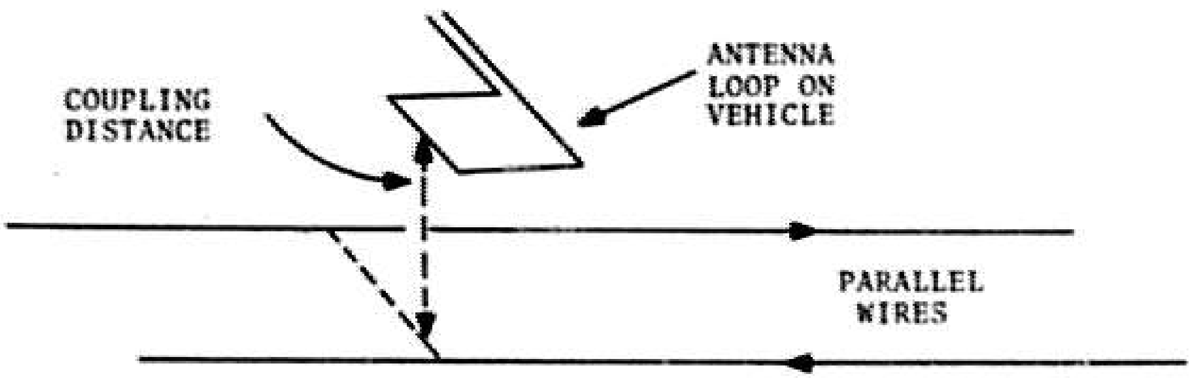
2.1 CONVENTIONAL CABLES

2.1.1 Parallel Lines

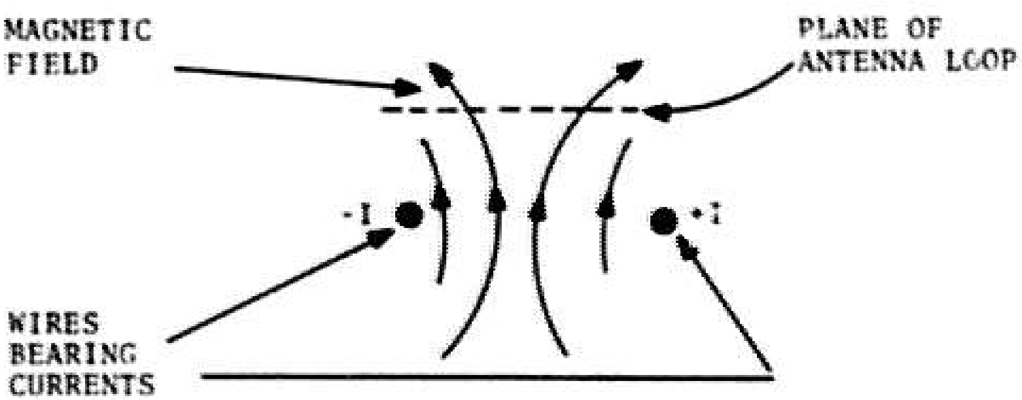
The most basic system consists of two long parallel wires terminated by a matched impedance and coupled inductively to the antenna, a wire loop, on the moving vehicle (Figure 1). As the currents generated in the parallel lines change, the associated inductive magnetic flux through the antenna loop changes and induces voltages and currents in the loop. Thereby the means are provided for transmitting signals from the wayside stations to the train.

Reciprocally, currents initiated in the vehicle loop induce, by means of a magnetic field currents and voltages in the parallel lines so that signals can be transmitted from the train to the wayside stations.

The steel rails of a roadbed may conveniently be used as inductive lines for the transmission of command data to moving trains.[1,3] However, the rails with their greater resistance have much higher attenuations than conventional aluminum or copper wires. Mellitt reported an attenuation of about 100 dB/km at 100 kHz for standard rails on a wet track (the attenuation for inductive wire lines at the same frequency is only about 3 dB/km).[3] These high losses are due to leakage currents between the rails which are not well insulated from each other. In contrast, inductive lines composed of wires or metallic strips are easily insulated by thick dielectric jackets from adverse effects caused by the environment. The details will be given in section 3. Since rail circuits have such high losses at low radio frequencies, we shall not discuss them further.



a. SIDE VIEW



b. LONGITUDINAL VIEW

Figure 1. Parallel Wire Inductive System

2.1.2 Planar Crisscrossed Parallel Lines

It is often desirable to reduce the susceptibility of a pair of lines to inductive and radiative noise and to minimize their radiated fields, which may exceed the FCC legal limitations. This can be accomplished by periodically alternating the positions of the lines or by twisting them.

Figures 2a and 3a show different wire arrangements for planar crisscrossed parallel lines. In common with the twisted helical cable (to be discussed in section 2.3) the crisscrossed cable must satisfy the following design criteria.

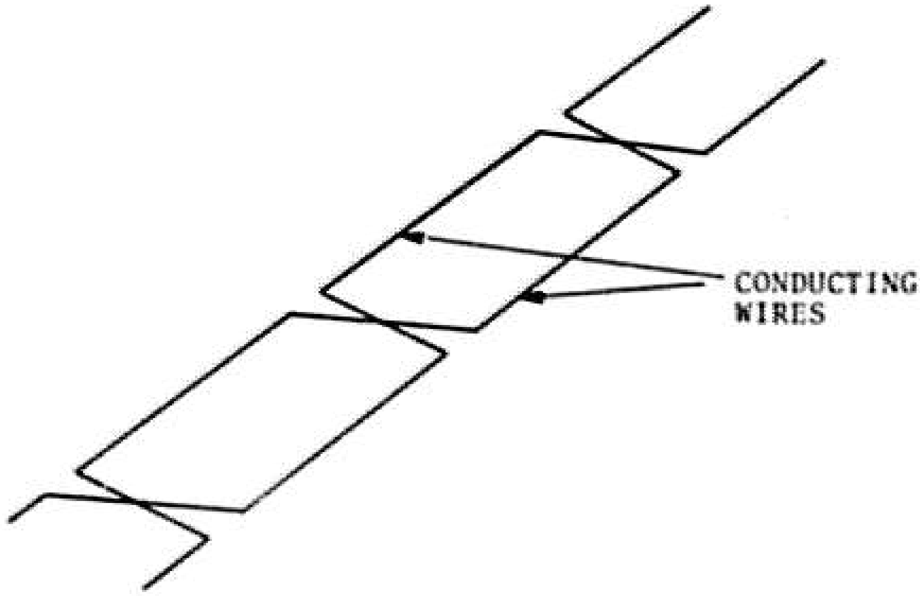
$$d \ll p \ll D \qquad (2\text{-}1a)$$

$$d \ll p \ll \lambda, \qquad (2\text{-}1b)$$

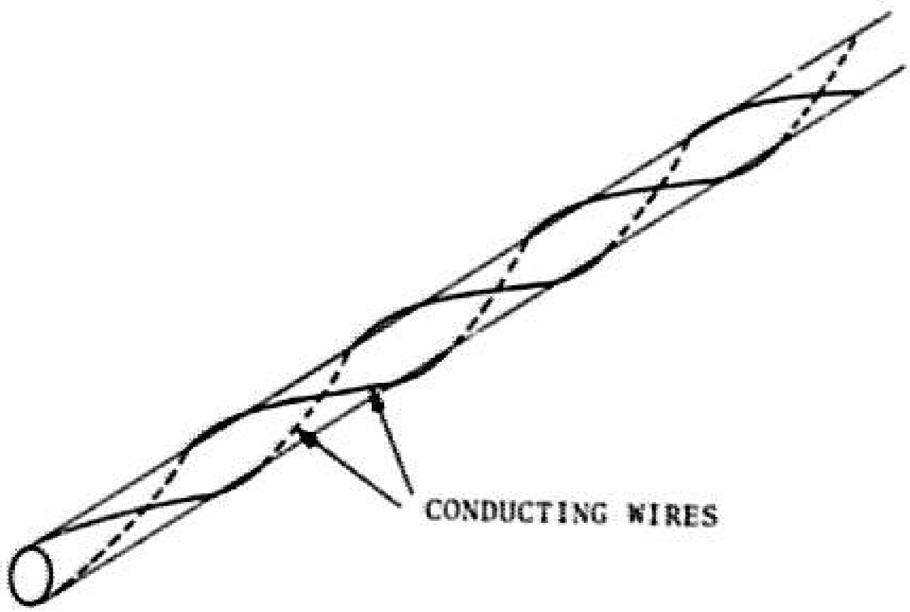
where d is the spacing between the wire pair, p is the periodicity interval (or pitch), D is the correlation length of the external noise along the line, and λ is the signal wavelength. The above conditions assure that when the phase and amplitude of the noise are uniformly distributed over several pitches along a transmission line, the noise induced at two points on the line at a distance of half a pitch has a phase difference of 180°. The unwanted radiation field from the transmission line is likewise suppressed since the field from a section of half a pitch is partially cancelled by the field from the adjactent half a pitch section. Inductive lines operate best in the low frequency region. For example at 200 kHz the wavelength would be about 4,500 feet. Therefore, the periodicity may be on the order of several hundred feet.

2.2 HELICAL CABLE[6,7,9]

Sumitono, Ltd. has developed a compact twisted line configuration, which is based on the helical geometry shown in Figures 2b and 3b. The cable is constructed from copper strips supported by dielectric, as sketched in the cross-section given in Figure 5. The cable is intended for the 50 kHz to 250 kHz region and rectangular loops with the dimensions 400 mm x 600 mm serve as the

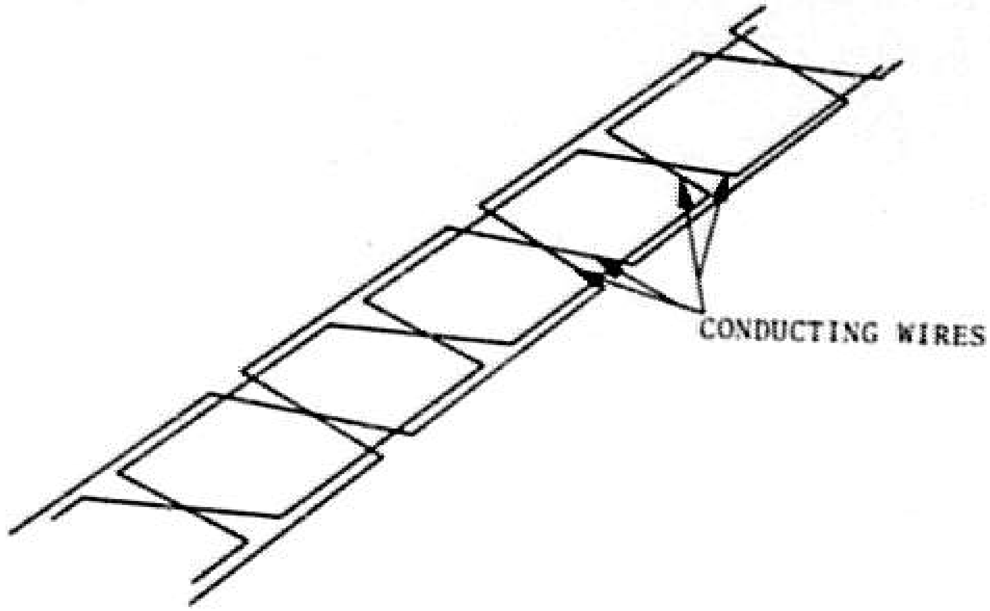


a. CRISSCROSSED PLANAR PAIR OF INDUCTIVE WIRES

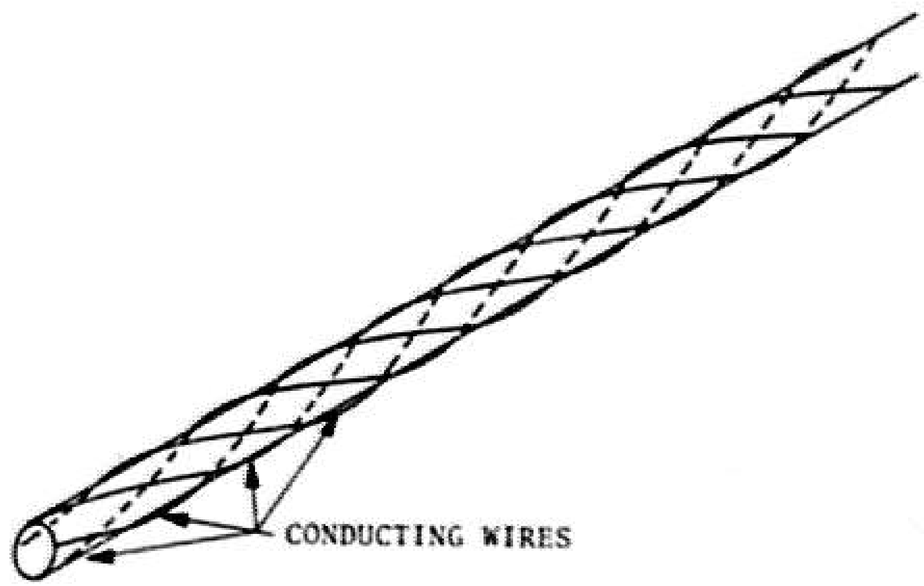


b. HELICAL PAIR OF INDUCTIVE WIRES

Figure 2. Pair of Inductive Wires (Courtesy Sumitomo Electric Industries, Ltd.)



a. CRISSCROSSED PLANAR QUADRUPLET OF INDUCTIVE WIRES



b. HELICAL QUADRUPLET OF INDUCTIVE WIRES

Figure 3. Quadruplets of Inductive Wires
(Courtesy Sumitomo Electric Industries, Ltd.)

coupler on the vehicle. Although some tests have been made, the helical cable is still in a developmental stage.

If a single antenna loop is used on the vehicle the amplitude coefficient of coupling changes non-uniformly with the twists of the wires. The situation is somewhat improved with the twisted quadruplet (Figure 3b). However, to resolve the problem completely, it is necessary to use multiple receiving (or sending) antennas with appropriate spacing combined with phase shifters (Figure 4).

2.3 SHIELDED LINES

The adverse influence of the environment may also be greatly reduced by shielding the inductive lines with conducting sheaths.

2.3.1 Coaxial Type

Figure 6 shows plan and cross-sectional views of a coaxially shielded line. Most of the electric field is confined within the shield. But by short-circuiting the outer shields, currents are allowed to flow on the outer shields so that magnetic fields still exist in the space outside the coaxial cables. Attenuation due to environmental conditions (such as wet snow) is virtually eliminated, but the presence of lossy magnetic material, such as steel rails, may still cause attenuation. The principal drawback of this line is the high cost.

2.3.2 Partially Shielded Grooved Metal Frame Type[9,10]

Figure 7 shows plan and cross-sectional views of a novel type of line developed by Sumitomo, Ltd. for a recently proposed system. The periodic length is about 5 feet, and the spacing between the parallel lines is about 8 inches. The effect of the metal frame is to reduce the change in characteristic impedance and attenuation due to environmental effects. For example, the transmission loss is below 3 dB/km in air and below 5 dB/km in wet sand condition for the frequency range from 50 to 250 kHz. A greater change in the loss is generally found in unshielded cable.

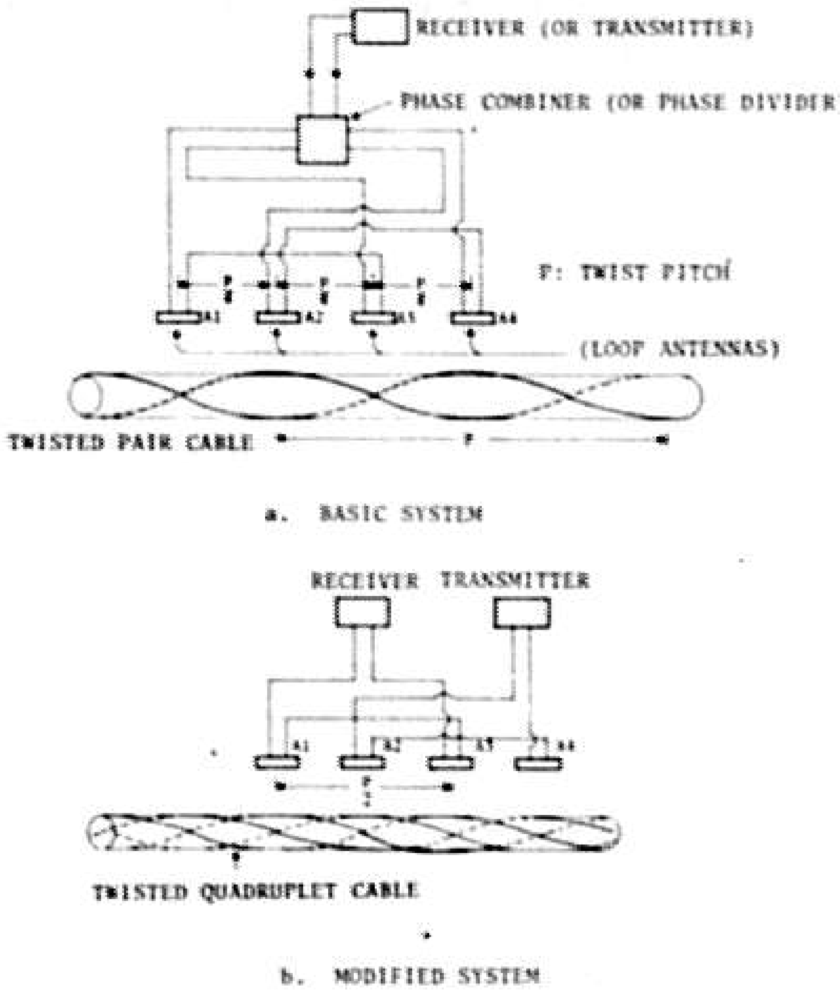


Figure 4. Multiple Antenna Arrangements for Twisted Inductive Lines (Courtesy Sumitomo Electric Industries, Ltd.)

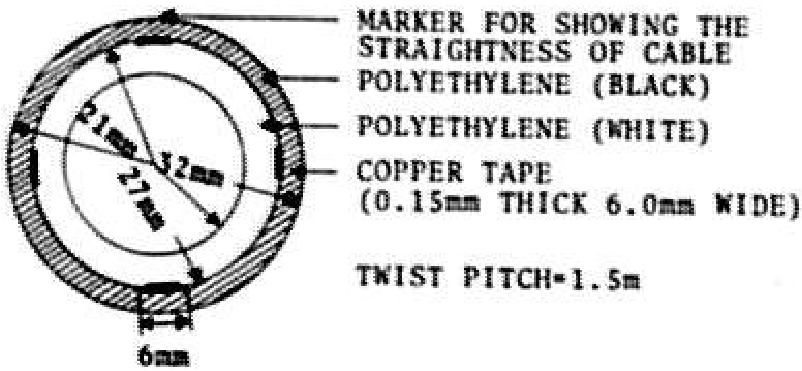
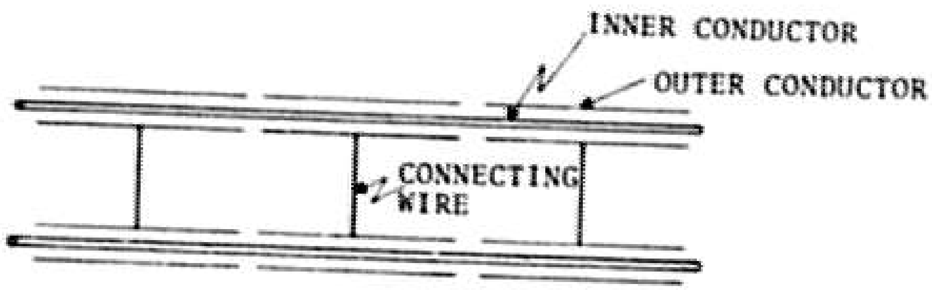
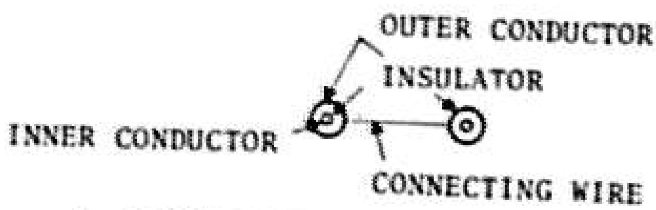


Figure 5. Cross Section of Sumitomo Helical Inductive Cable
(Courtesy Sumitomo Electric Industries, Ltd.)

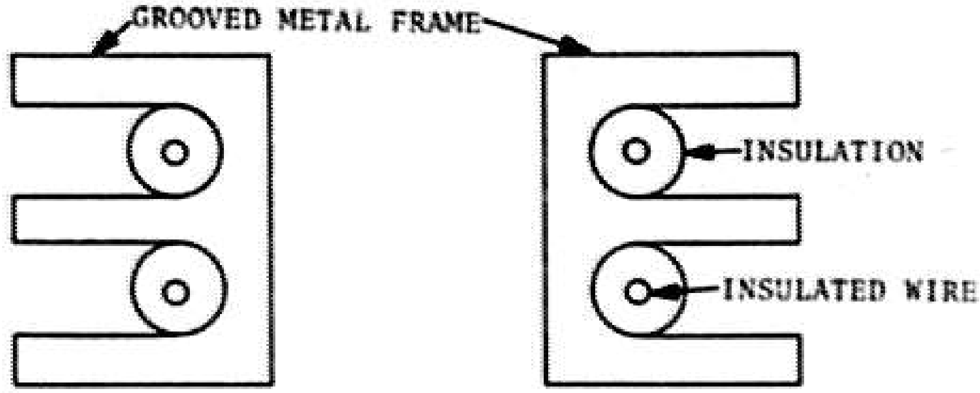


a. PLAN VIEW

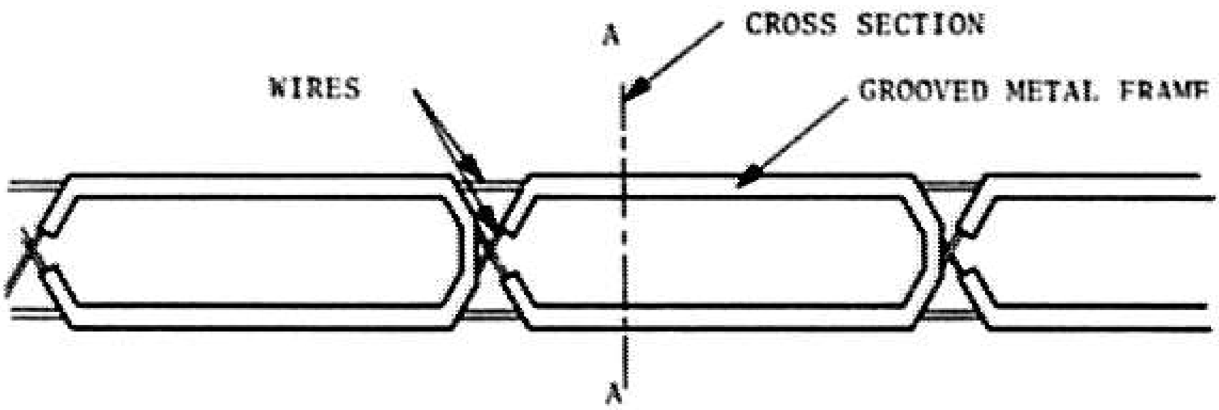


b. CROSS-SECTIONAL VIEW

Figure 6. Coaxially Shielded Inductive Wires
(Courtesy Sumitomo Electric Industries, Ltd.)



a. CROSS-SECTIONAL VIEW (A-A)



b. PLAN VIEW

Figure 7. Sumitomo Partially Shielded Inductive Lines with Grooved Metal Frame (Courtesy Sumitomo Electric Industries, Ltd.)

2.3.3 W-Line[12,14]

Figure 8 shows a cross-sectional view of this two-conductor transmission line investigated by the Wheeler Laboratories. One of the conductors forms a partial shield for the other. Lines of this type are still in a developmental stage, and extensive data is not available. Such structures promise to extend the range of use into the megahertz region. The design shown in Figure 8 suffers serious mechanical disadvantages due to its rigidity and unwieldy size, and designs have been proposed which may eliminate the mechanical problems while retaining desirable electrical characteristics. Because of the orientation of the line, the coupler detects the quadruple moment of the field rather than the dipole moment. Consequently, the detected field is somewhat more sensitive than other lines to variations in coupling distance. As the line is still in the preliminary stages of development, we shall not discuss it further.

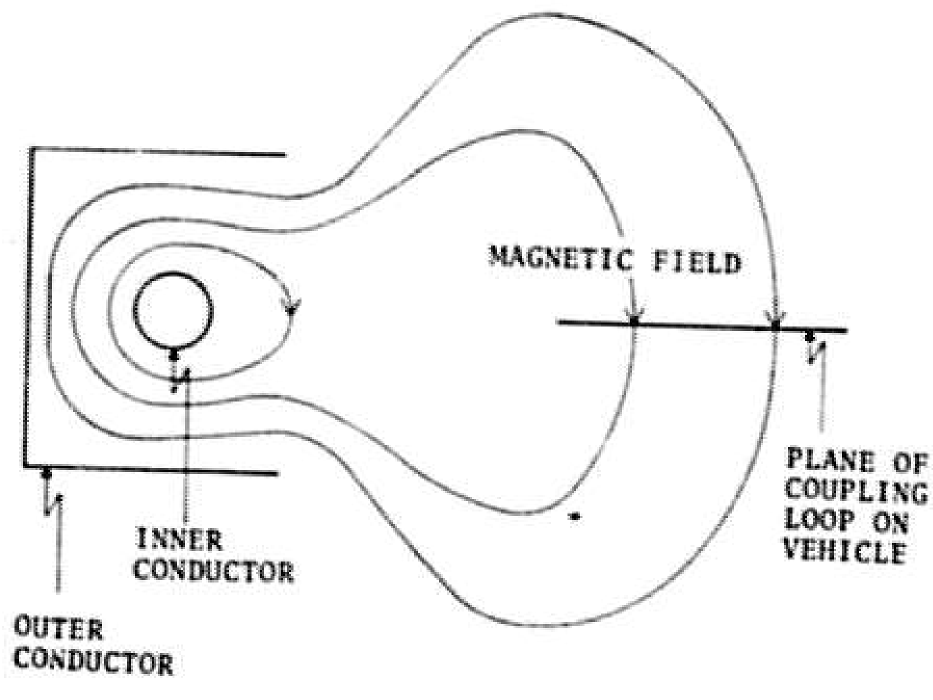


Figure 8. Cross-Section of W-Line System Investigated by Wheeler Laboratories

3. TRANSMISSION CHARACTERISTICS

3.1 ATTENUATION

3.1.1 General

For a parallel wire transmission line attenuation in dB per unit length is given by the low loss approximation

$$\alpha = 8.686(R/Z_c + GZ_c)/2$$

where Z_c is the characteristic impedance, R is the resistance per unit length of the line, and G is the shunt conductance per unit length. The resistance is inversely proportional to the skin depth.

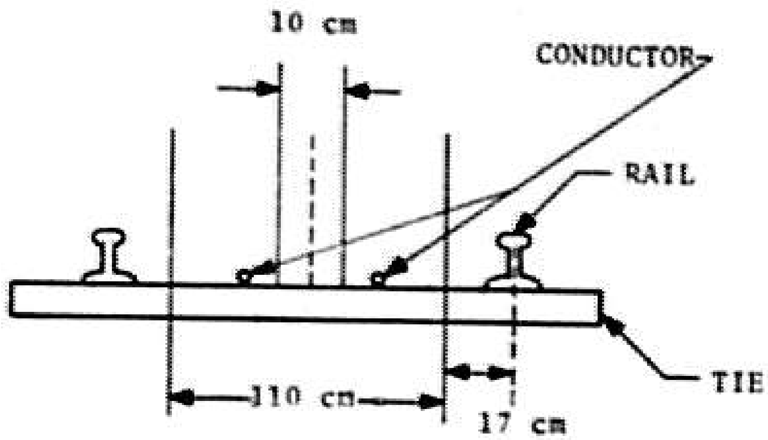
3.1.2 Railroad Bed Effect

If the line is placed on the ground the railroad bed effects must be considered. Fricke and Form have reported on measurements of these effects.(1) Figure 9a illustrates two positions of the conductors in the attenuation measurements. In position 1 the conductors are installed on the ties at least 17 cm from the rails. In position 2 the conductors are installed on the rail flanges.

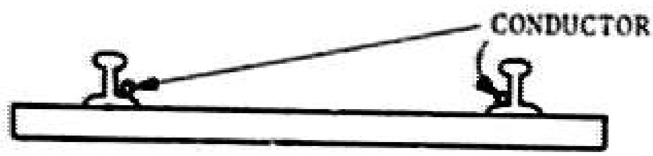
Figure 9b shows measured attenuation for linear conductors with a thin PVC dielectric sheath 0.65 mm in thickness. Curve (A) is for the conductors in free space. Curve (B) is for the conductors in position 1 on the ties. Curve (C) is for the conductors in position 2 on the rail flanges.

3.1.2.1 Ballast - The attenuation due to ballast leakage (corresponding to the shunt term in the formula given in 3.1.1) is the difference between curve (B) and (A) in Figure 9b.

3.1.2.2 Rail Induction - In Figure 9b curve (B) shows that the attenuation was virtually unchanged while the conductor spacing ranged from 10 to 110 cm. The conductors were not yet coupled



POSITION 1. INSTALLED ON TIES, SPACING RANGING FROM 10 TO 110 cm



POSITION 2. INSTALLED ON RAIL FLANGES, SPACING OF 143.5 cm

Figure 9a. Two Positions of Linear Conductors in Attenuation Measurements(1)

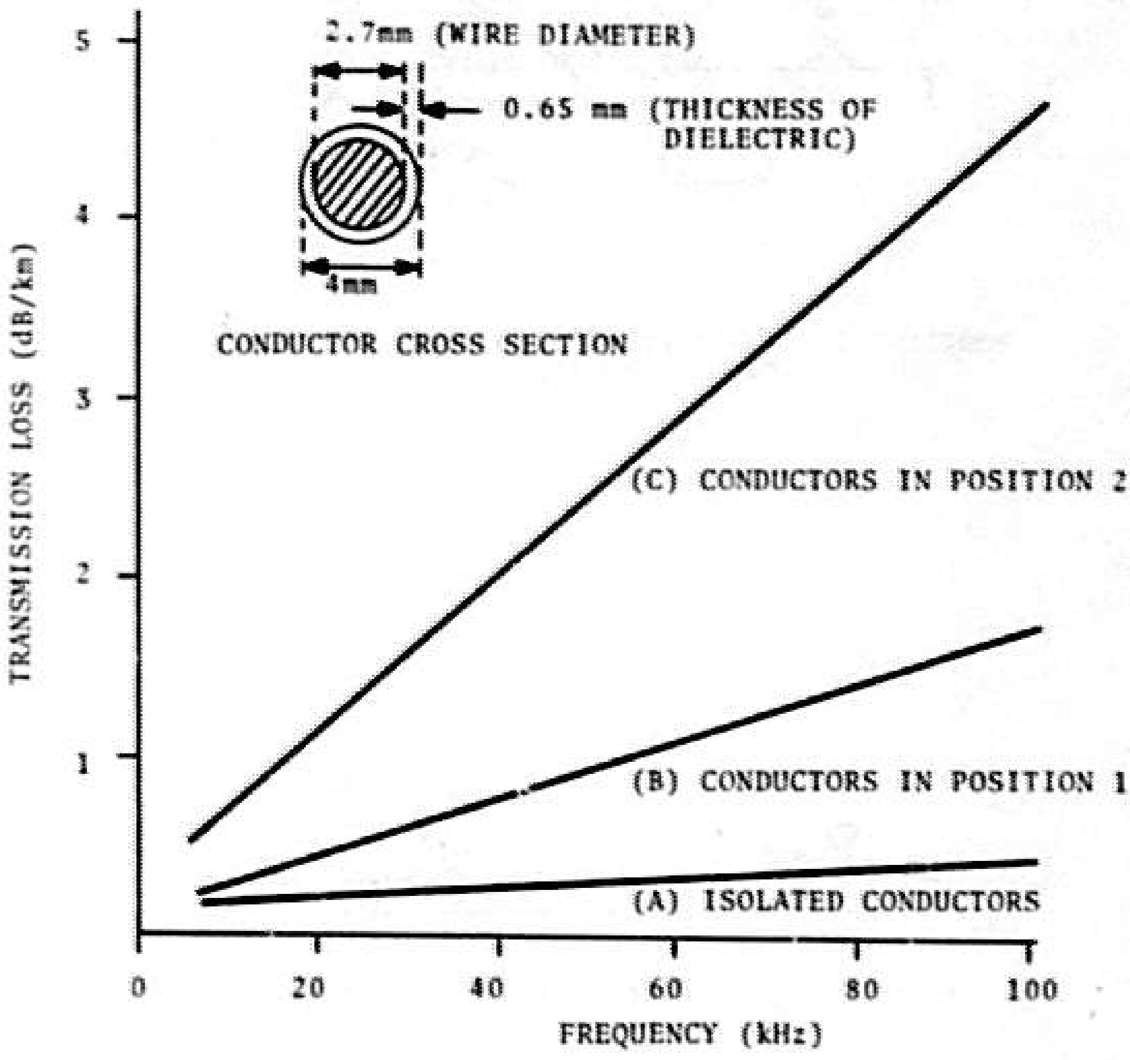


Figure 9b. Measured Attenuation vs. Frequency for Linear Conductors with Thin Dielectric Sheath

with the rails. The attenuation attained its highest value when the twin conductors were mounted on the rail flanges with a spacing of 143.5 cm, as shown by curve (C) in Figure 9b. Eddy currents were then induced in the iron rails. The figure shows the predominating influence of the rail attenuation. At 100 kHz the attenuation is 4.7 dB per km.

Similar high attenuations for wires attached to rail webs were measured by Philco-Ford Corp.(2) For wires 3000 ft long with cross-overs every 300 ft the attenuation was found to be 6.3 dB/km at 100 kHz which is comparable to the results reported by Fricke and Form.

By increasing the separation from the rail and by adding a dielectric sleeve around the conductor, the coupling between the conductor and the rail and therefore the attenuation can be considerably reduced. Figure 9c shows the measured attenuation for the conductors with a thick dielectric sheath (3.65 mm in thickness) installed on the rail flanges. As can be seen, the attenuation is reduced to one-third of the loss for the case of the thin sheath.

3.1.3 Environmental Effects

Sumitomo Ltd. has measured environmental effects on transmission loss for several inductive cables over the frequency range from 80 to 300 kHz.(9) The test conditions were chosen to simulate the ground between the steel rails of a railroad track, where the attenuation is most severely affected by the presence of snow, water, or wet sand. Since the electric field near the cable is the physical quantity most strongly perturbed by environmentally induced changes in the dielectric constant of the surrounding medium, various techniques of electric shielding were tried in an attempt to minimize moisture-induced attenuations. Environmental tests of this kind, as conducted by Sumitomo, Ltd. on different types of shielded and unshielded inductive cables, are summarized below.

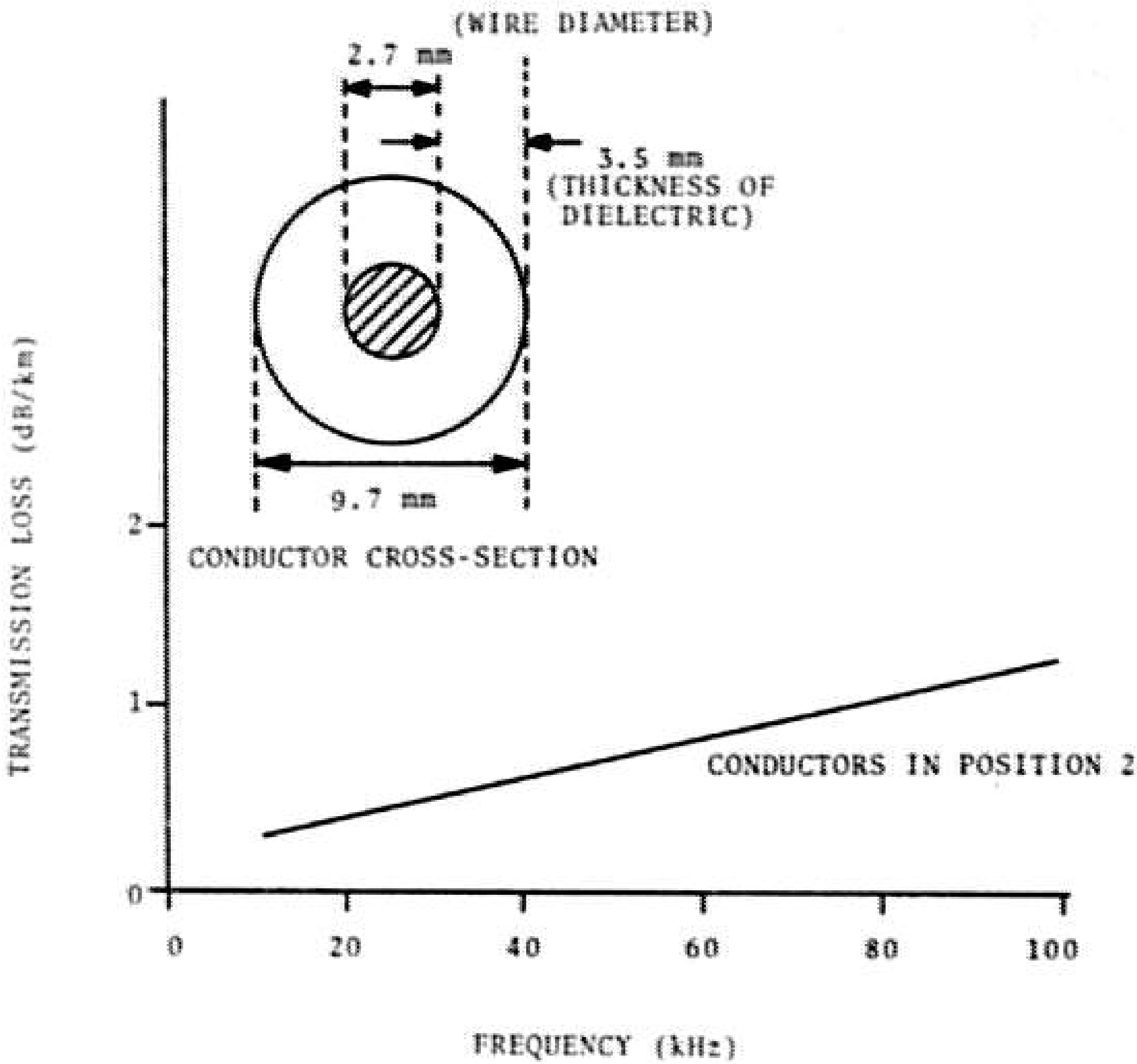


Figure 9c. Measured Attenuation vs. Frequency for Linear Conductors with Thick Dielectric Sheath

3.1.3.1 Helical Cable - Figure 10 shows a cross-sectional view of a helical cable with four conductors. The thickness of the polyethylene around the conductors can be changed to enclose a larger portion of the electric field energy. Figure 10 shows the transmission loss versus frequency for the cable with a 2.5 mm thick dielectric jacket, (a) when the cable was in dry air and (b) when the same cable was immersed in wet sand which is the environmental condition that caused the greatest transmission loss. At 250 kHz with the cable in free space the loss was 1.2 dB/km while in wet sand the loss reached 5.5 dB/km. Curve (c) of Figure 10 is for a cable enclosed in a polyvinylchoride jacket with overall diameter 55 mm (a jacket thickness of 14 mm) and embedded in very wet sand. The considerable reduction of loss can be clearly seen. At 250 kHz the loss is down to 1.6 dB/km.

3.1.3.2 Parallel Wires - With parallel wire transmission lines most of the electric field energy is concentrated near the surface of the conductors. Increasing the thickness of insulation around the wires would be expected to lead to a decrease in transmission loss for this case as well. Figure 11 shows the results of tests conducted on parallel wires of diameter 1.3 mm with various insulation thickness. The upper curve shows the loss for the thickness δ = 3.75 mm; at 250 kHz the loss in wet sand was 6 dB/km. The lower curve shows the loss for δ = 10 mm; at 250 kHz the loss was reduced to 3.75 dB/km.

3.1.3.3 Coaxially Shielded Wires - Takahashi et. al.[8] have studied the characteristics of a coaxially shielded line constructed from parallel coaxial cables. The outer conductors were cut at regular intervals and the resulting parallel segments short-circuited, as shown in Figure 6. The purpose of the design is to confine the electric field within the coaxial structure while allowing a magnetic field to exist in the external space. Consequently, the line is insensitive to the lossy dielectric effects of surrounding moisture but can still be coupled through the magnetic field. Figure 12 shows that the transmission loss was not at all affected by snow, as compared with an increase of more

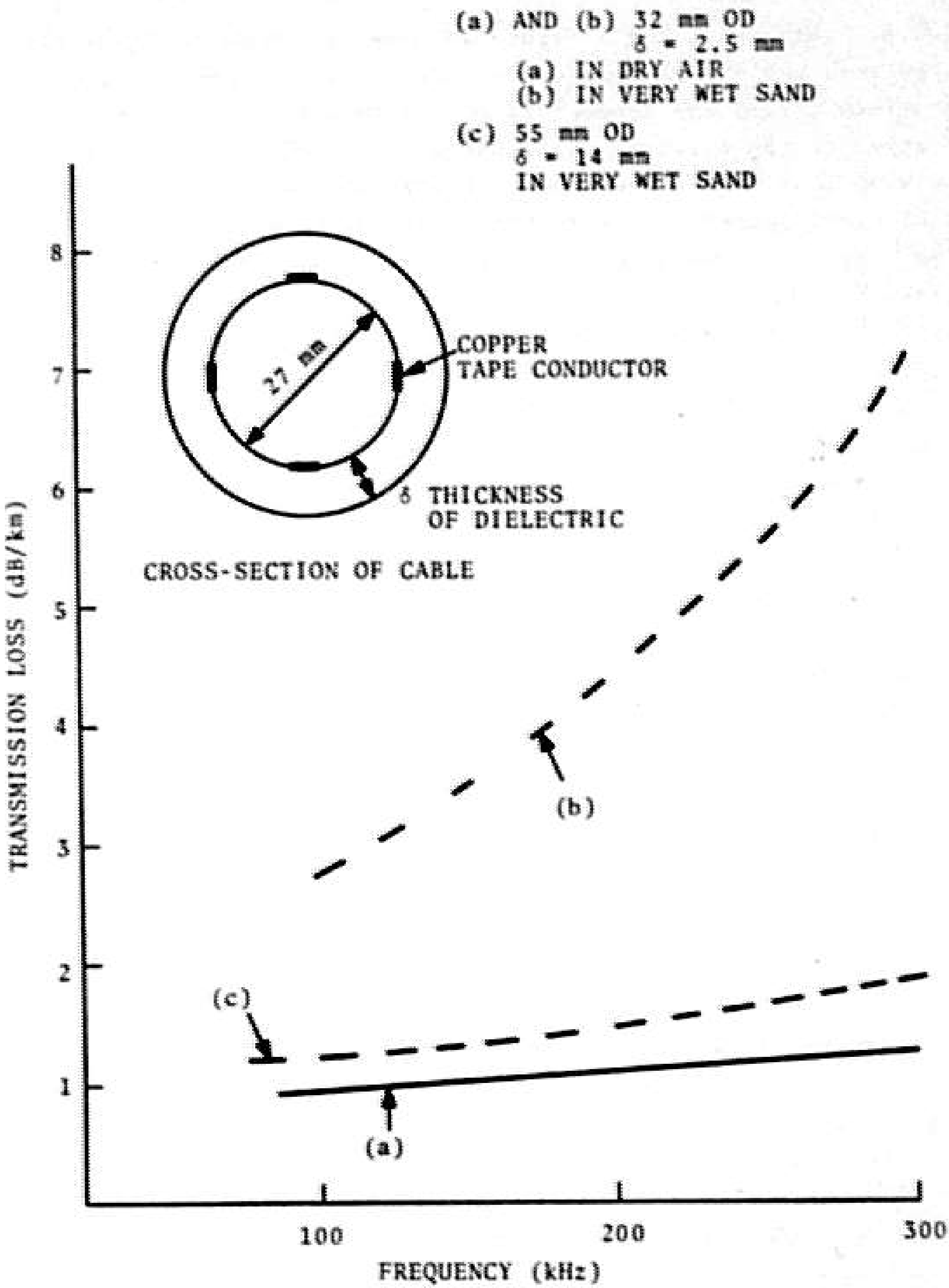


Figure 10. Measured Attenuation vs. Frequency of Twisted Helical Inductive Cable (Courtesy Sumitomo Electric Industries, Ltd.)

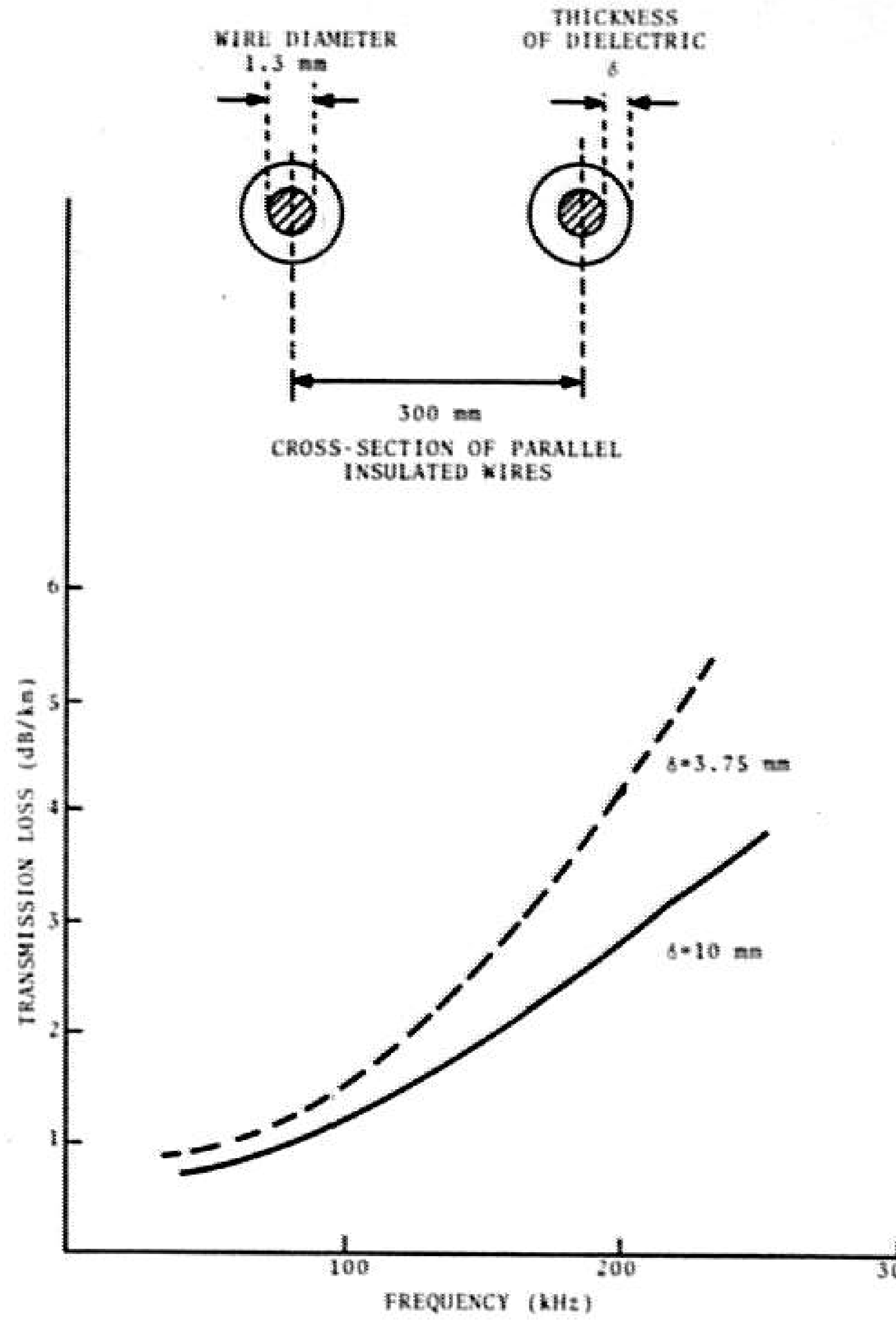


Figure 11. Measured Attenuation vs. Frequency of Parallel Insulated Wires in Wet Sand (Courtesy Sumitomo Electric Industries, Ltd.)

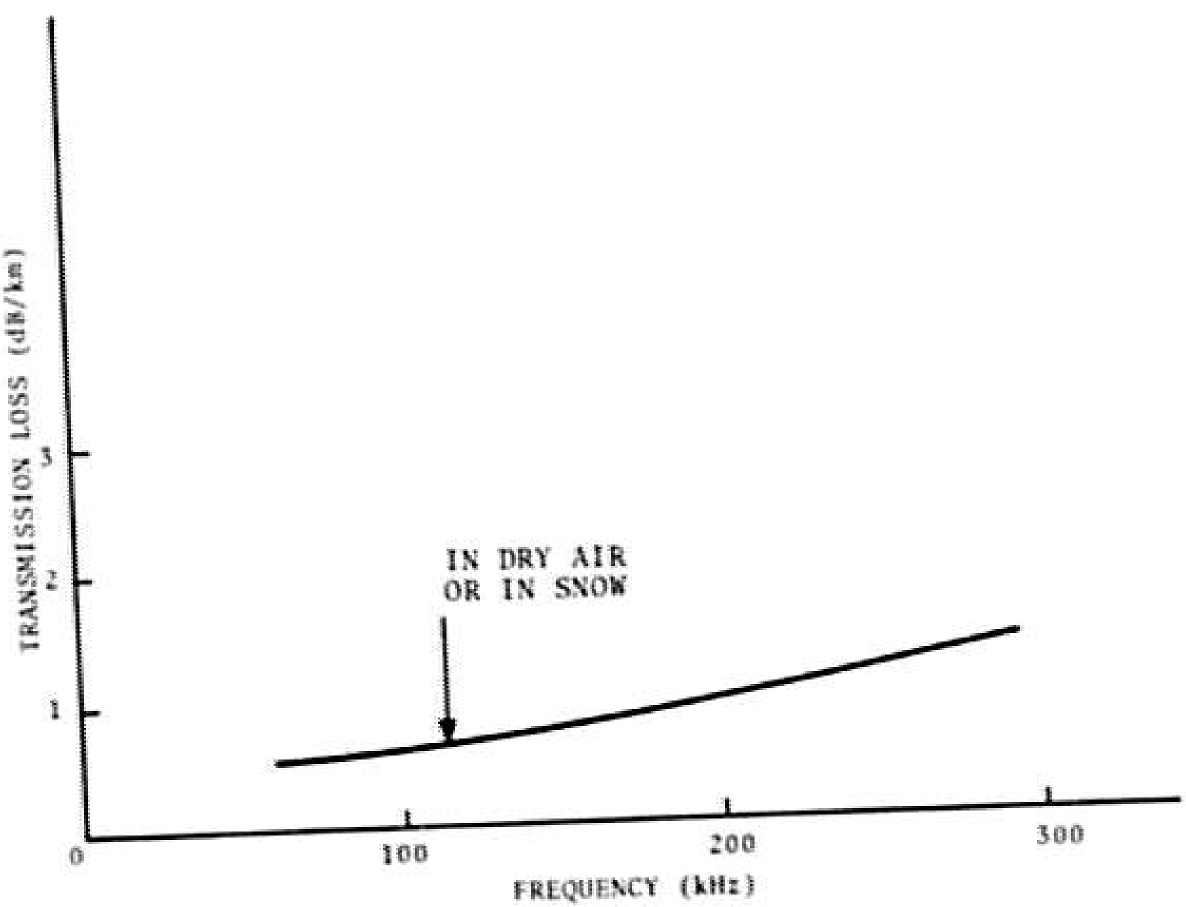


Figure 12. Measured Attenuation vs. Frequency for Coaxial Type of Inductive Lines (Courtesy Sumitomo Electric Industries, Ltd.)

than 10 dB/km for parallel bare wires under the same conditions.[9] Coupling loss for the shielded cable was reported to be the same as that for the unshielded cable in air, but no experimental data are shown.[8]

3.1.3.4 Partially Shielded Wires in a Grooved Metal Frame - In this type of cable the shielding principle discussed in the preceding section is applied to two or four insulated wires in a planar crisscross arrangement. Figures 2a and 3a show the unshielded cables, and Figure 7 shows the cable shielded by a grooved metal frame. In Figure 13 the attenuation versus frequency for the cable is given with the cable in dry air and in wet sand. In air, the cable with the metal frame has a higher loss than the unshieded wires, but the variation in loss due to the environmental effects is less for the framed cable, which exhibits a variation of only 1.75 dB/km at the frequency of 25 kHz. The metal frame also provides a rigid support for the wires when the transmission line is suspended in the air. In a recent memorandum Sumitomo, Ltd. has described a version of the framed cable with two wires and insulation thickness of 5 mm.[10]

3.2 CHARACTERISTIC IMPEDANCE

3.2.1 Environmental Effect on Various Types of Cables

Measurements of the characteristic impedance of various types of inductive lines were made by Sumitomo, Ltd.[9] According to their measurements, the characteristic impedance is in all cases practically independent of frequency for the range of frequencies considered. Table 1 summarizes the results of their measurements. The table shows that for the twisted helical cable of 35 mm overall diameter, wet sand can change the impedance by 45%. A thick PVC jacket (55 mm overall diameter) reduced the change to only 9%. Snow did not change the impedance of the coaxial type at all, and wet sand changed the impedance of the grooved metal type only slightly.

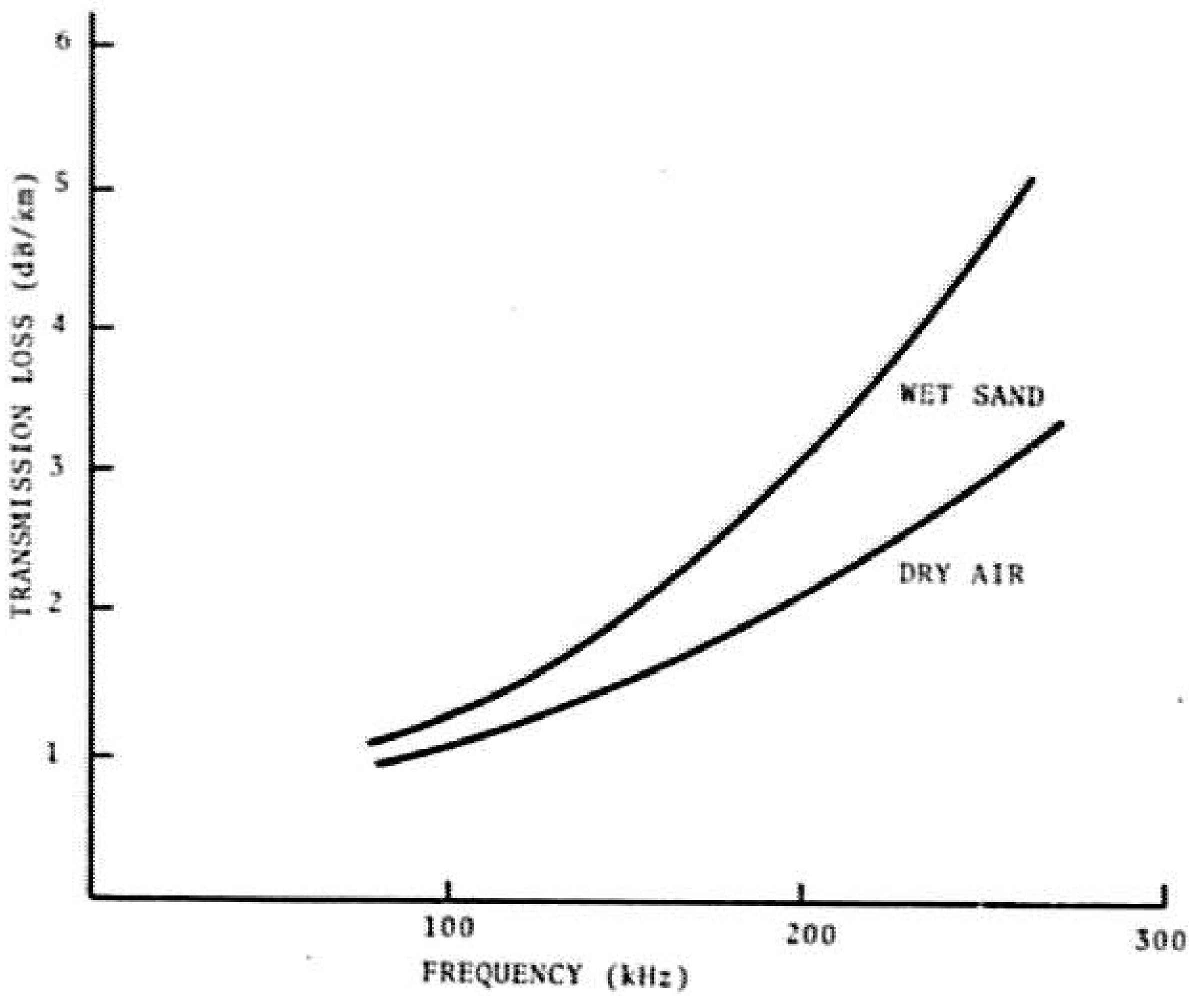


Figure 13. Measured Attenuation vs. Frequency of Partially Shielded Inductive Cable with Grooved Metal Frame (Courtesy Sumitomo Electric Industries, Ltd.)

TABLE 1. MEASURED CHARACTERISTIC IMPEDANCE FOR VARIOUS TYPES OF INDUCTIVE LINES (SUMITOMO, LTD.)

Type of Inductive Line	Frequency Range in kHz	Characteristic Impedance in Environment of		
		Dry Air	Wet Sand	Snow
Twisted Helical-overall diameter:	80 to 300			
35 mm		282 to 288	157Ω	-
55 mm		--	261Ω	-
Insulated Parallel Wires with Thickness of PVC Insulation:	40 to 280			
3.75 mm		--	300Ω	-
10 mm		--	340Ω	-
Coaxial	60 to 300	158Ω	-	158Ω
Partially Shielded with Grooved Metal Frame	60 to 300	245Ω	230Ω	-

3.2.2 Frequency Dependence as Measured by Philco-Ford Corp.

Measurements of the characteristic impedance of parallel wire inductive circuits with cross-overs every 300 feet were also made by Philco-Ford Corporation WDL Division of Palo Alto, California.[2] Three circuits were considered: #1 was 3,000 feet long, #2 was 1,400 feet long, and #3 was 900 feet long. The wavelength corresponding to the frequency of 200 kHz is about 4,500 feet, which is considerably larger than the cross-over intervals. Steel clips held #12 AWG insulated wires against the rail web. First with all circuits shorted and then with all circuits open the input impedances at a range of frequencies were measured by resistance substitution. Impedance null and peaks were determined, and characteristic impedances were calculated from the measurements. The following table shows the impedance for selected frequencies.

TABLE 2. MEASURED CHARACTERISTIC IMPEDANCE IN Ohms (PHILCO-FORD)

Circuit	50 kHz	100 kHz	150 kHz	163 kHz	200 kHz
#1	130	157	157	198	256
#2	199	232	219	234	270
#3	525	101	205	232	365

Thus, according to the Philco-Ford data, the characteristic impedance is frequency dependent. One notable difference in this test from that of Sumitomo, Ltd. is that Philco-Ford attached the inductive wires to the steel rails. The strong frequency dependence of the electromagnetic parameters of the ferromagnetic, lossy rails is probably the reason for the observed variations.

4. COUPLING CHARACTERISTICS

4.1 GENERAL DISCUSSION

An important quantity in communication between the vehicle and wayside station is the coupling loss, L_c, which is defined as the ratio of the power level in the transmission line and the received power level at the vehicular coil coupler. The coupling loss can be given by

$$L_c = 10 \, \text{Log}_{10} \frac{rZ}{\omega^2 m^2} \, . \qquad (4\text{-}1)$$

where Z is the characteristic impedance of the transmission line, r is the impedance of the antenna loop, ω is the angular frequency at the center of the band used for communication and m is the mutual inductance between the transmission line and the antenna loop.[6] By the reciprocity theorem, the coupling loss from the loop to the point on the transmission line opposite the loop has the same value as that from the line to the loop. The mutual inductance is obtained by dividing the product of the magnetic flux through the coil and number of turns of the coil by the current in the transmission line.

In the design of an actual system, the magnitudes of some of the parameters in the right-hand side of Equation (4-1) may be adjusted in order to reduce the coupling loss. In the case of the helical cable, for example, the characteristic impedance was reduced by adjusting the width of the conductive tapes.[6] The signal-to-noise ratio for the receiving system must, however, be taken into account. Multiple winding and ferrite cores can be employed to make the vehicle antenna more sensitive or to allow reduction of its physical size. However, there will be a corresponding increase of noise reception at the vehicle receiver, although not at the wayside station. Noise reduction by inversely connecting antenna pairs will be discussed in section 4.3. Transmission of a number of voice channels is possible through separate loops or by means of a wide band antenna.

In the case of twisted or crisscrossed inductive wires of short pitch, a single loop antenna leads to periodic changes of the coupling coefficient along the line.[6] In order to obtain uniform coupling, more than one loop antenna must be used and the signals from the loops combined through a phase shifter (see Figure 4a and b).

Measurements of the coupling losses for some of the transmission lines mentioned in section 2 were made by Sumitomo, Ltd. For the case of the twisted helical line of dimensions shown in Figure 5 (placed on the ground, with a loop antenna, 30 cm x 30 cm, separated from the cable by 28 cm) the measured coupling loss at resonance was 58 dB at 83 kHz and 56 dB at 194 kHz.[5] For the case of the proposed grooved metal frame transmission line (coupled to hybrid type of loop antennas and ferrite core antennas) the measured coupling loss was 55 dB at 200 kHz when the antennas were at 30 cm above the transmission line.

4.2 SPATIAL CHARACTERISTICS

In this section we shall discuss the variation of the coupling field intensity in the space around a parallel wire transmission line and the consequent restriction of cable location. A general formula for the vertical component of the magnetic field intensity, H_z, in the space surrounding two parallel conducting wires lying on a horizontal plane with currents of magnitude I flowing in opposite directions is given below:[1]

$$H_z = \frac{-I}{2}\left[\frac{(s-\frac{a}{2})}{h^2+(s-a/2)^2} - \frac{(s+\frac{a}{2})}{h^2+(s+a/2)^2}\right] \qquad (4\text{-}2)$$

where a is the spacing between the two conductors, h is the height of the observation point above the conductors, and s is the lateral distance between the field observation point and the mid-point between the conductors. Equation (4-2) can be expressed in the alternative form.

$$\left(\frac{\pi a}{2I}\right)H_z = \frac{1}{2}\left\{\frac{[1-2(s/a)]}{[2(h/a)]^2+[2(s/a)-1]^2} + \frac{[1+2(s/a)]}{[2(h/a)]^2+[1+2(s/a)]^2}\right\} \quad (4\text{-}3)$$

This form is convenient when the spacing between the conductors, a, is held constant, and h and s are varied. Figure 14a shows the calculated vertical component of the normalized magnetic field versus the lateral distance s/a for various values of height h/a. Figure 14b shows a plot of the contours of equal magnetic intensity (vertical component) in the space above the conductors. The contours are designated in dB to indicate coupling power relative to the maximum intensity at the mid-point between conductors.

When the observation point is above the mid-point between the conductors, s = o and Equation (4-3) reduces to

$$\left(\frac{\pi a}{2I}\right)H_z = \frac{1}{[2(h/a)]^2 + 1} \quad . \qquad (4\text{-}4)$$

Figure 15a shows $\left(\frac{\pi a}{2I}\right)H_z$ calculated as a function of h/a with s = o. We see that the maximum value of the intensity occurs at h = o and that the intensity decreases monotonically as h increases.

Equation (4-4) can be written in an alternate form which is convenient when the observation point is held at a constant height, h, and the conductor spacing, a, is varied.

$$\left(\frac{\pi h}{I}\right)H_z = \frac{\frac{1}{2}(a/h)}{1 + \left[\frac{1}{2}(a/h)\right]^2} \; . \qquad (4\text{-}5)$$

This relationship is shown in Figure 15b. A maximum of the normalized field $\left(\frac{\pi h}{I}\right)H_z$ occurs at a/h = 2, consequently, for a fixed value of h, maximum field intensity is achieved when the conductors are spaced as that a = 2h.

We see from Figure 15a that if h ≈ a then a variation of 3 dB in coupling power would correspond to a variation in receiver height of about 0.32 a. For the widely spaced induction lines (i.e., large a) the coupling is relatively insensitive to distance variation.

If h >> a, then the 3 dB limitation on variation with distance is quite strict. This is the case for the twisted helical cable being developed by Sumitomo, Ltd., where the spacing between

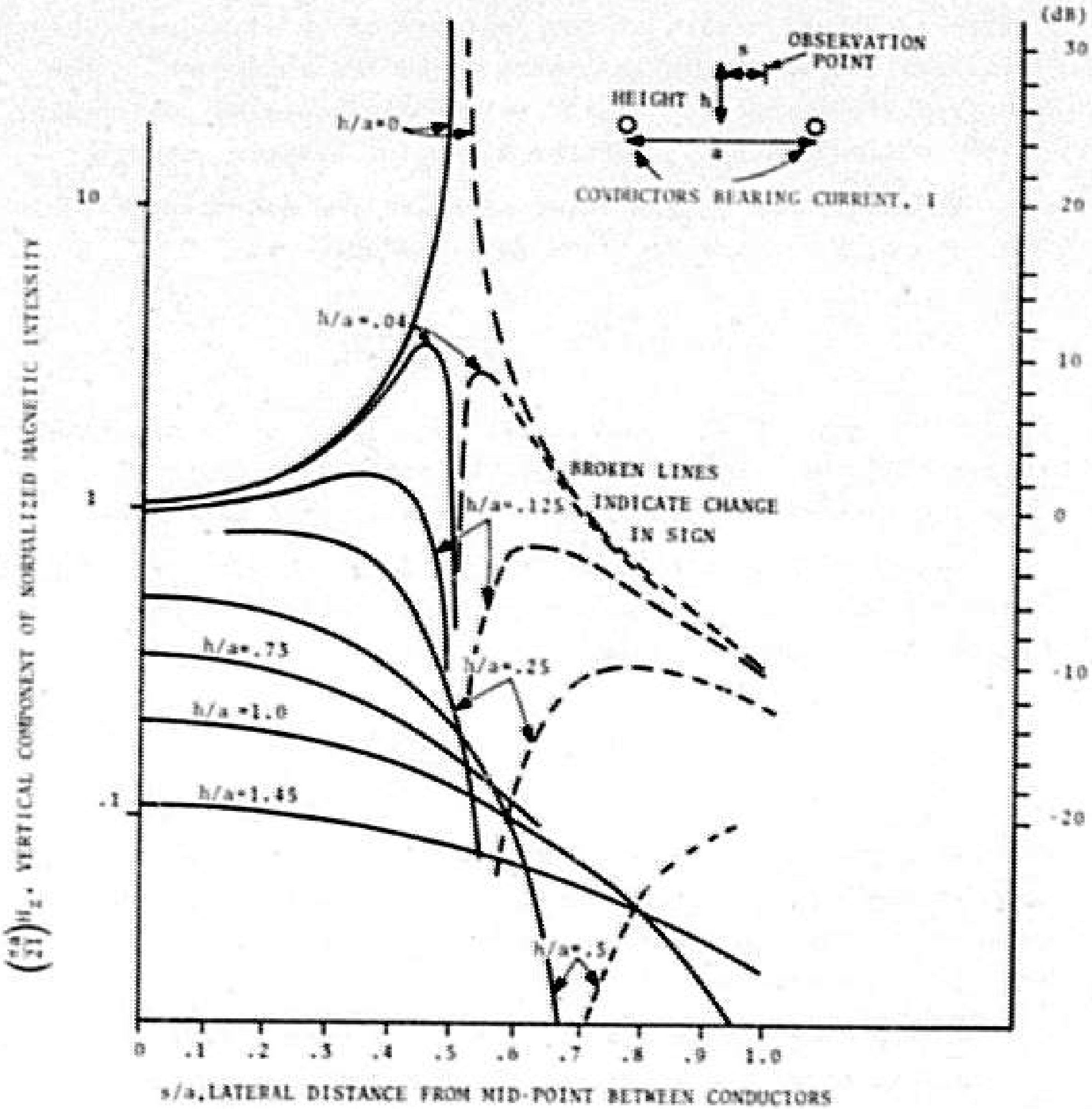


Figure 14a. Relative Vertical Magnetic Intensity vs. Lateral Distance

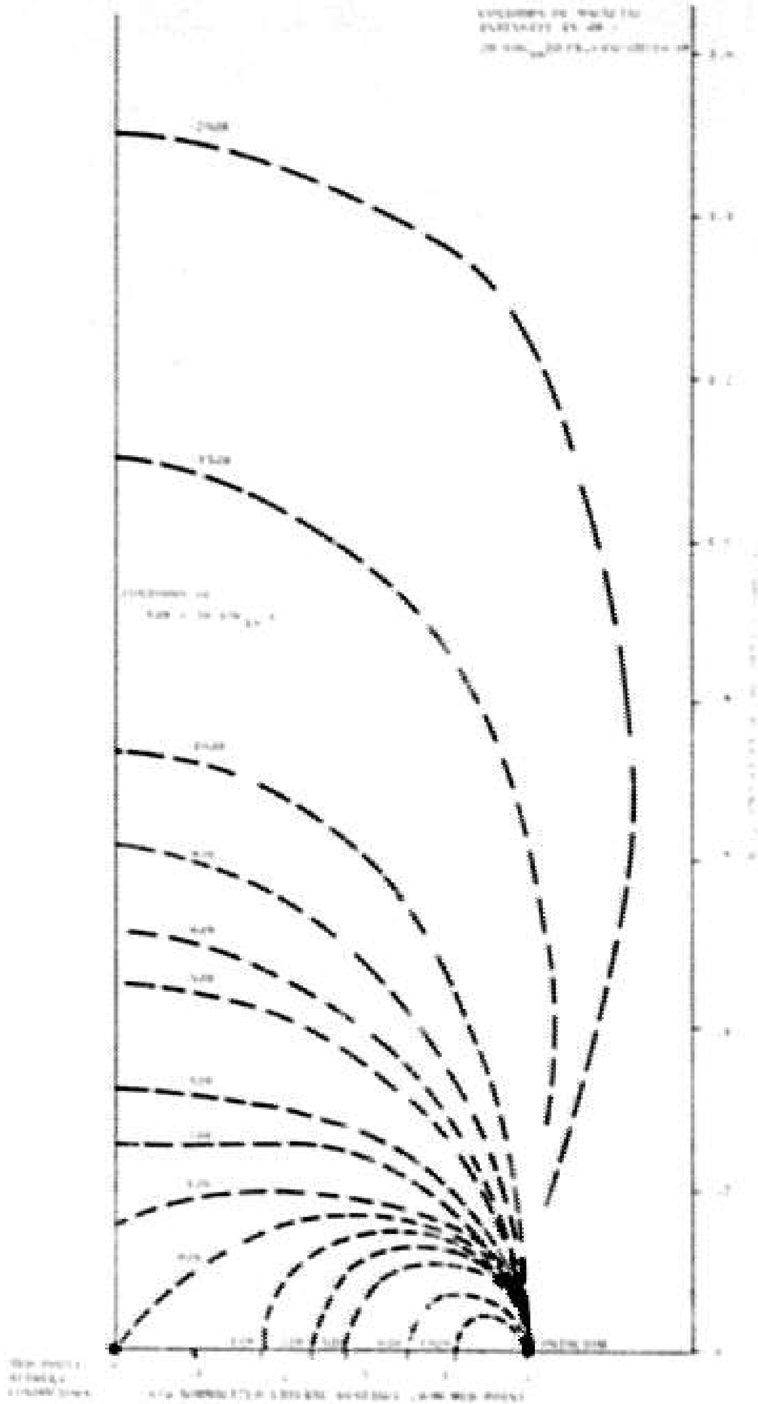


Figure 14b. Contours of Equal Magnetic Intensity (Vertical Component) in Space Above Conductive Lines

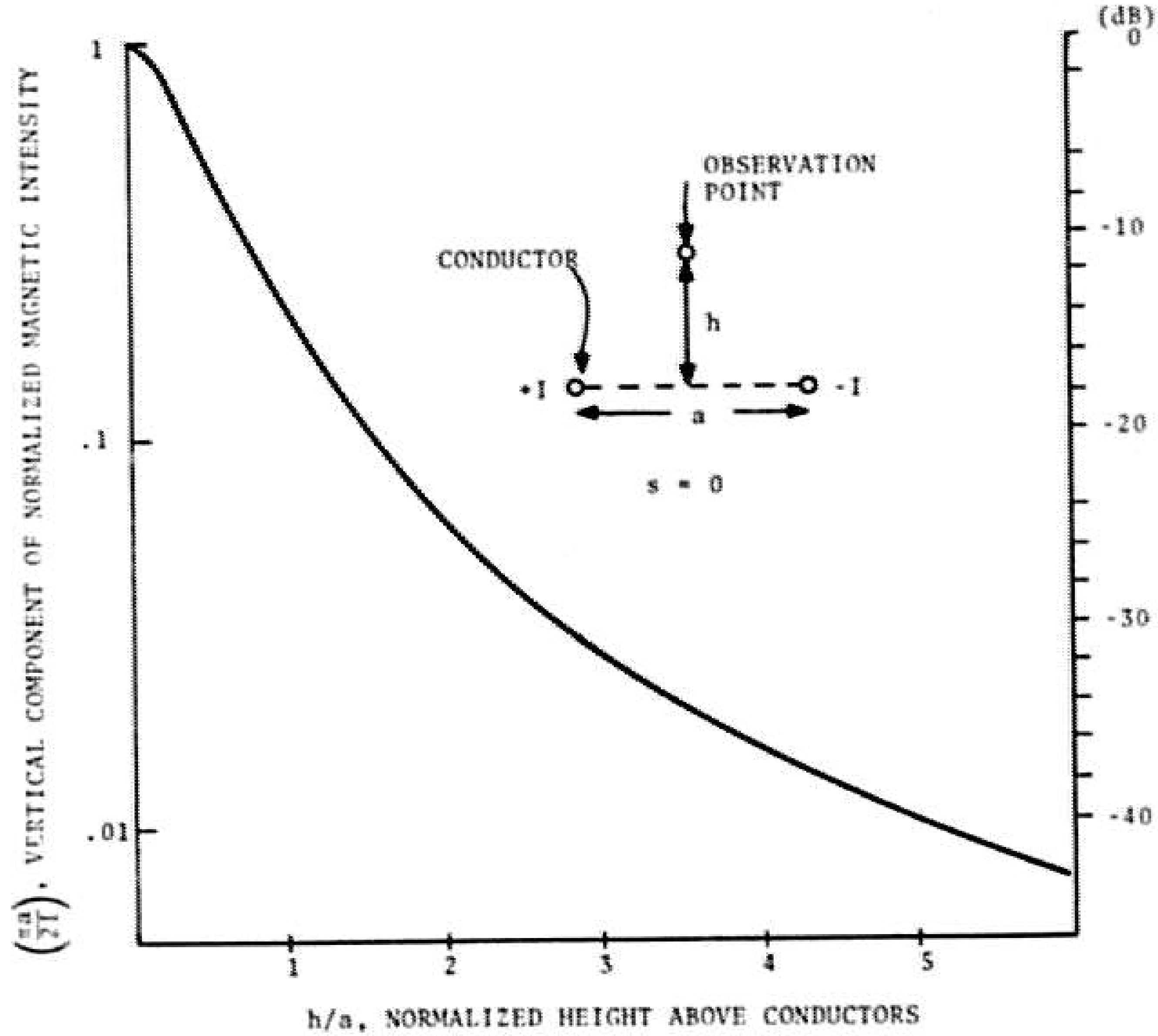


Figure 15a. Normalized Vertical Magnetic Intensity Over the Midpoint for Variable Height of Observation Point

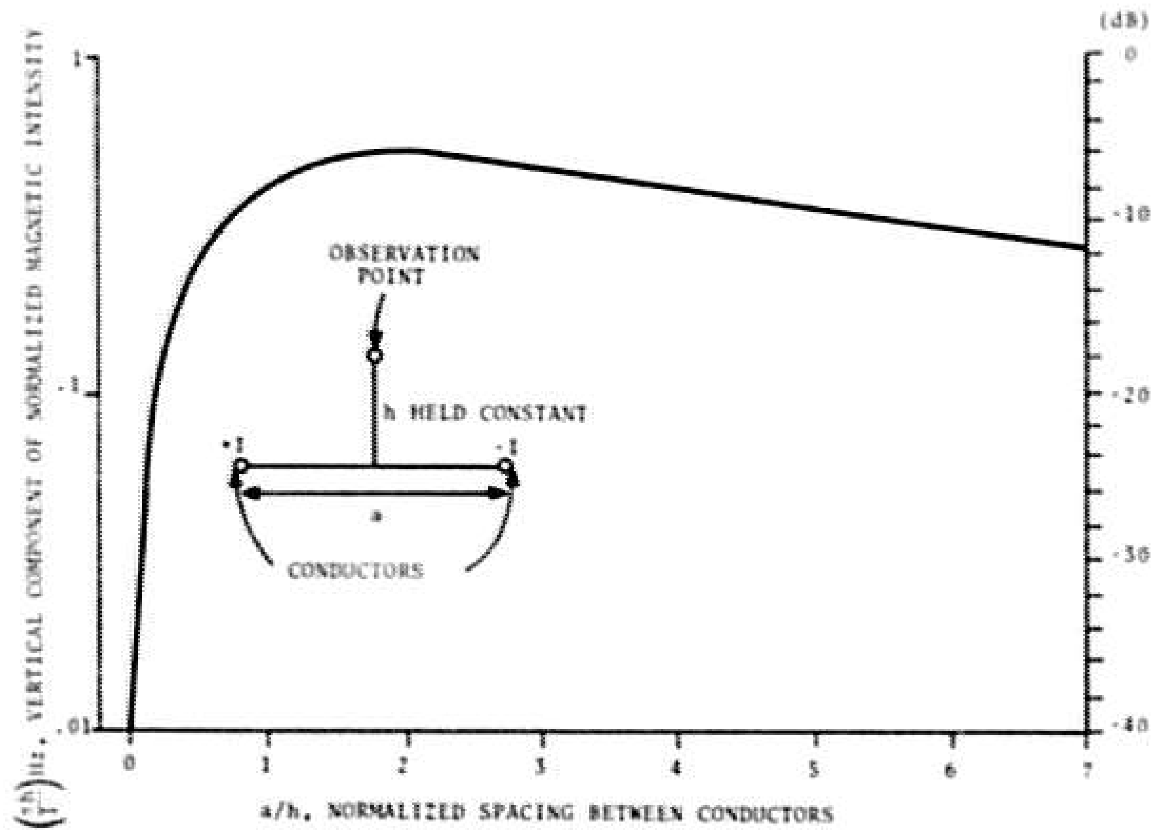


Figure 15b. Normalized Vertical Magnetic Intensity for Variable Spacing between Conductors

conductors is about 2.7 cm and the distance from the conductors to the coupler is proposed to be 30 cm. In that case, for a coupling power variation restriction of 3 dB, only a 5.7 cm increase and a 4.8 cm decrease in range are allowed. The physical location of this cable is consequently restricted. Cable sag may rule out suspension above the ground unless a rigid structure is employed to support the cable.

4.3 EFFECT OF NOISE

As discussed in section 2.2, twisting or crisscrossing the inductive wires suppresses the noise excited in the line by induction or radiation, and also reduces field intensities outside the useful coupling range. Likewise, noise induced in a pair of loop antennas is suppressed if they are inversely combined, and unwanted distant fields caused by the pair of antennas are also reduced. The results of experiments conducted by Sumitomo, Ltd. to investigate methods of noise suppression will be discussed in the following sections.

4.3.1 Measured Suppression of Noise for Twisted Wires

Figure 16a shows measurements of the suppression of induced noise in twisted quadruplet helical cable 100 m in length.[6] The relative reduction in comparison to a parallel line is about 40 dB from 50 kHz to 400 kHz.

Figure 16b shows the electric field intensity from the twisted helical cable with a transmitted power of 20 dBm. The regulation of the FCC is that the external electric field be less than 15μV/m, or 23.5 dB above 1μV/m, at the distance of $\lambda/2\pi$ from the transmitting component. The test frequency of the measurement (the results of which are shown in Figure 16b) is 220 kHz; in this case $\lambda/2\pi$ = 216.5 m. Further data of the helical cable should be obtained beyond that given in Figure 16a to determine the distance from the cable at which the electric field reaches 15μV/m. Measurements for parallel wires would be helpful for comparison with the helical cable. The electric field for perfectly uniform

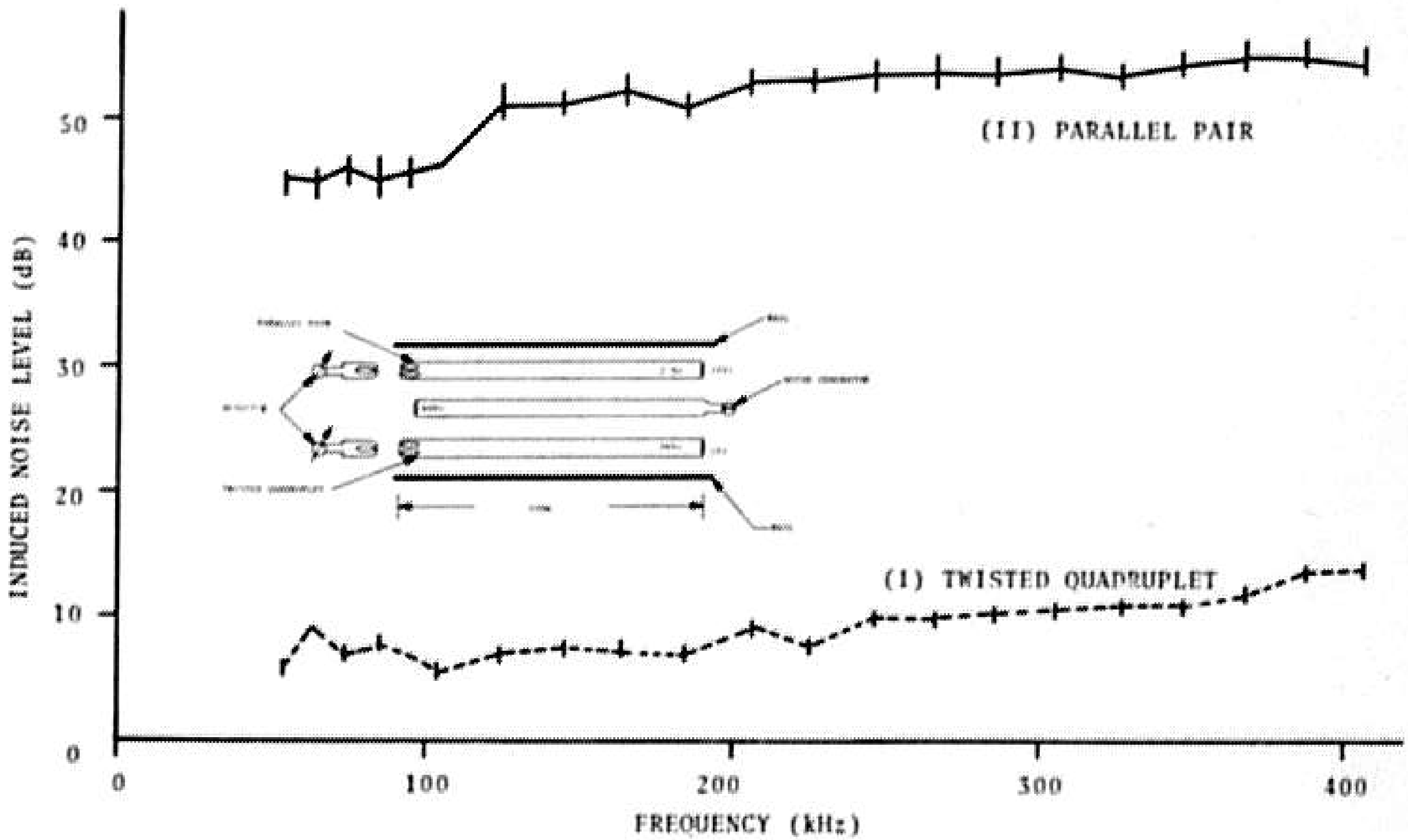


Figure 16a. Measured Suppression of Induced Noise in Twisted Helical Wires (Courtesy Sumitomo Electric Industries, Ltd.)

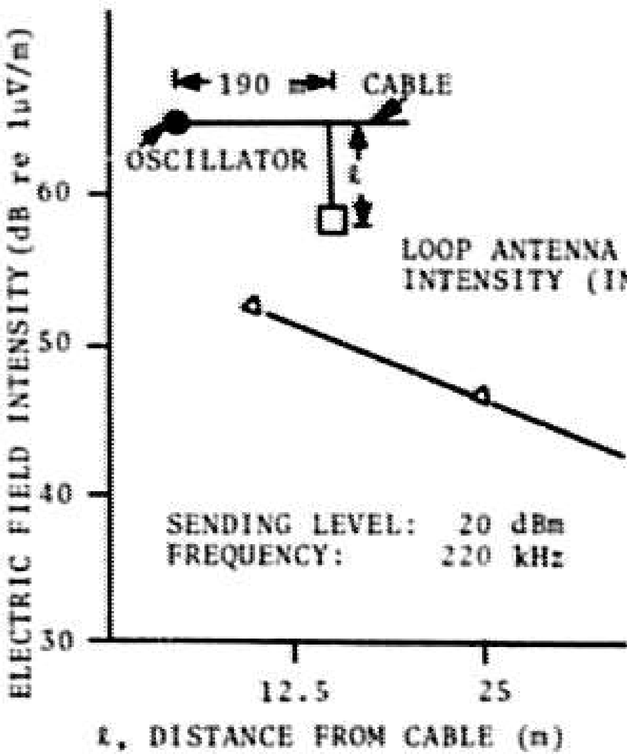


Figure 16b. Measured Electric Field Level from Twisted Helical Wires (Courtesy Sumitomo Electric Industries, Ltd.)

parallel wires in free space drops off as the square of distance at distances much larger than the separation of the wires. However, in practice, irregularities in the line and surroundings cause radiation and other deviations from predicted behavior.

Measured results on planar criss-cross wires would be helpful for comparison of noise suppression and unwanted field intensity.

4.3.2 Measured Suppression of Noise for Inversely Combined Loop Antennas

Figure 17a shows the measured reduction of induced noise in an antenna system consisting of two inversely combined loop antennas. It is apparent that suppression is greatest when the axis through the loop is perpendicular to the direction of incoming noise. As a function of direction there is a maximum reduction of 28 dB and a minimum reduction of 15 dB at 82 kHz.

Figure 17b shows suppression of unwanted external fields from the antenna system by inversely combining two loop antennas. For the arrangement shown there is a reduction of about 28 dB at 82 kHz.

4.3.3 External Noise Magnitude and Communication Between Wayside Station and Train Station

Information on measured external noise is given in the article on spectrum engineering, by the Joint Technical Advisory Committee of the IEEE and EIA.(15) Figure 3 on p.S 9-15 of Reference 15 shows the median operating noise factor, F_{am}, in dB above the thermal noise (kTB) from various noise sources. These values are the levels expected from an omni-directional, short "lossless" vertical antenna near the surface; these particular values of F_{am} may be converted to a free-space median rms field strength, E_n, expressed in decibels referred to 1 microvolt per meter by

$$E_n = F_{am} + 20 \log_{10} f + 10 \log_{10} b - 95.5289 \qquad (4\text{-}6a)$$

where f is the frequency in MHz and b is the bandwidth in Hz. The

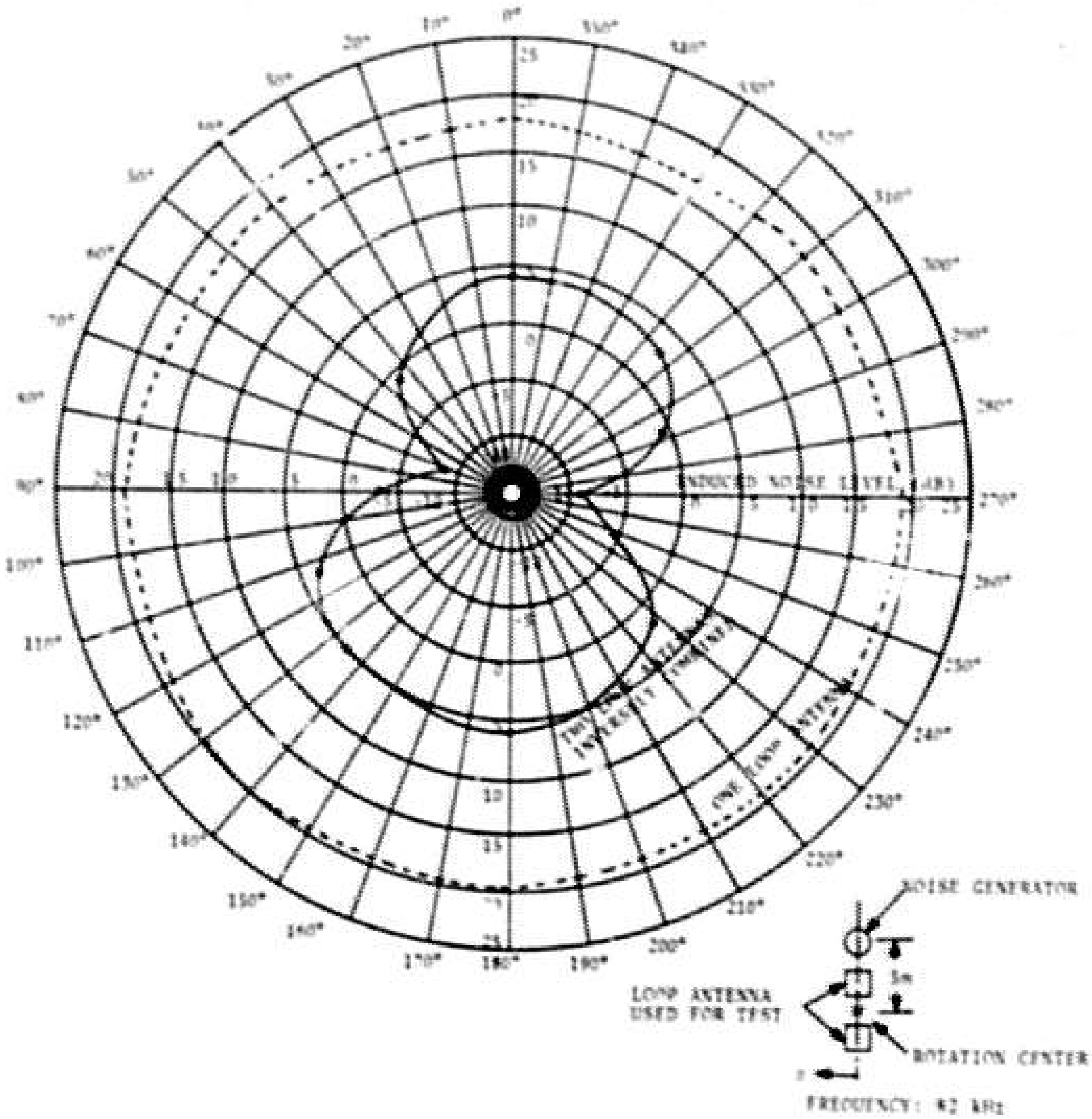


Figure 17a. Measured Suppression of Induced Noise in Two Inversely Combined Loop Antennas (Courtesy Sumitomo Electric Industries, Ltd.)

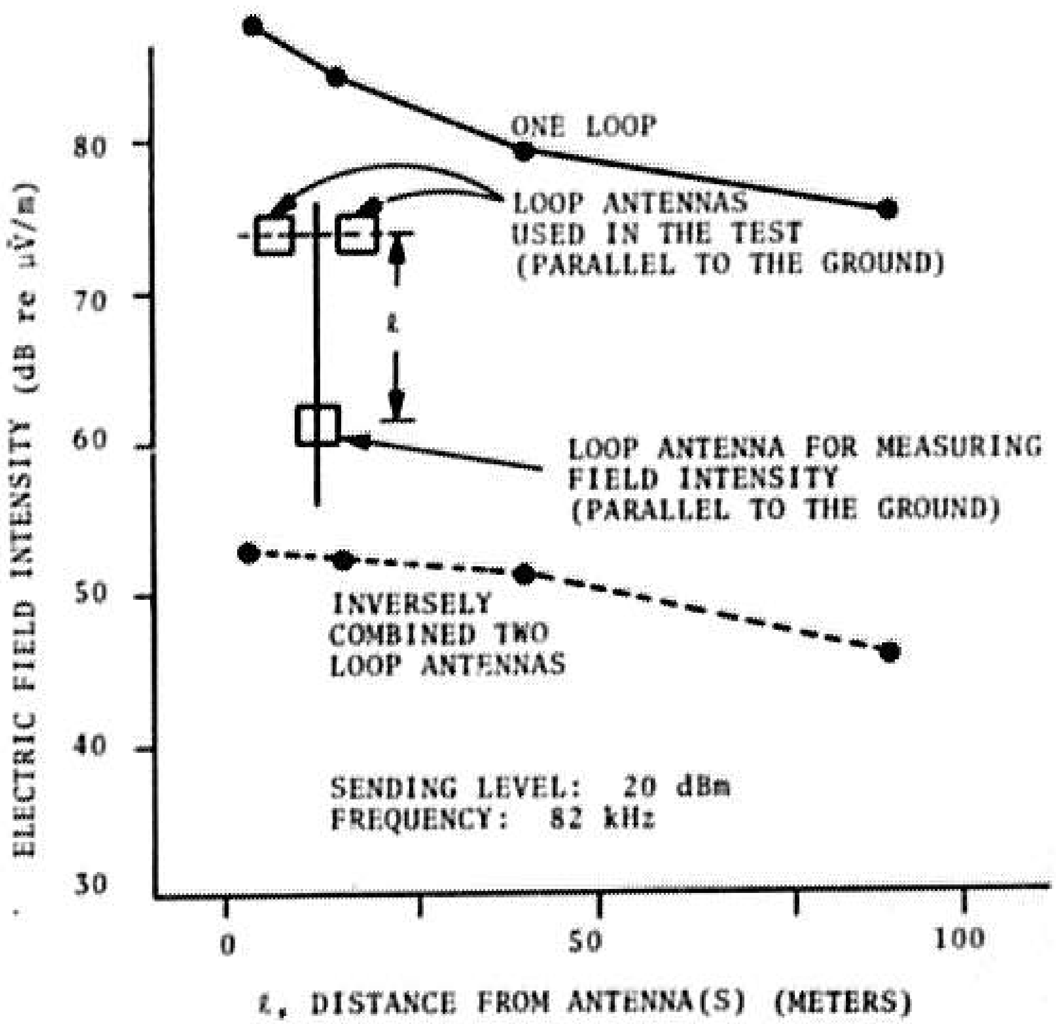


Figure 17b. Measured Suppression of Unwanted Radiation by Inversely Combining Two Loop Antennas (Courtesy Sumitomo Electric Industries, Ltd.)

above formula is derived theoretically using the capture area formula for the short antenna,

$$\text{CAPTURE AREA} = .12\ \lambda^2 \tag{4-6b}$$

Measurements of atmospheric radio noise and man made radio noise are shown in Reference 15. The atmospheric noise is for the location of Washington D.C. This type of noise is produced mostly by lighting discharges in thunderstorms. The noise level depends on frequency, time of day, weather, season of the year and geographic location.(16)

Table 3 gives the power budget requirement for communication from a point on the transmission line to the train.

TABLE 3. POWER BUDGET REQUIREMENT IN COMMUNICATION FROM TRANSMISSION LINE TO TRAIN

1.	Environmental noise at vehicle antenna.
2.	Add signal-to-noise ratio, 20 dB, to obtain signal requirement at antenna.
3.	Add coupling loss from vehicle to transmission line, 55 dB, to obtain power requirement at point on transmission line opposite the coupler.
4.	Add line loss, 4 dB/km, for power requirement at point separated from coupler point.

As the atmospheric noise is dependent on a number of seasonal variables we will consider only the man-made noise. The thermal noise (kTB) is -144 dBm/kHz. For a voice band of 4 kHz it is -138 dBm. From Reference 15 we find that at 100 kHz the man-made noise (urban) is 105 dB above the thermal noise or -33 dBm. Assuming the required signal-to-noise ratio is 20 dB, then the signal required at the antenna is -13 dBm. With a coupling loss of 55 dB the power required at the point on the transmission line opposite to the coupler is 42 dBm or 16 watts for the urban noise environment. For a suburban area about 1.6 watts is required and for a rural area about 0.16 watts is required. If we take the transmission loss to be around 4 dB/km we would add, for a length of ℓ km from the sender to the coupler, ℓ x 4 dB to the power at the point opposite the coupler. The estimation given above shows that the required sending powers at the launch point for urban and suburban areas are somewhat greater than the 1 watt launching power given in the Sumitomo tests.

4.3.4 Cross-Talk from Neighboring Circuits

Unwanted signals on cross-talk can be excited in an inductive line by other inductive circuits nearby. The extent to which neighboring circuits interfere is given by the cross-talk attenuation, which has been measured by Philco-Ford Corp. for a number of inductive circuits located close to one another (Figure 18). The inductive wires are attached to the track rails. The following table shows inter-circuit cross-talk measurements made at 100 kHz.

TABLE 4. MEASURED INTER-CIRCUIT CROSS-TALK ATTENUATION

Applied Circuit	Applied Voltage	Read Circuit	Read Voltage	Cross-talk Attenuation, db
#1&#2 Parallel	51	#3	0.8	36.1
#1	71	#2	2.5	29.1
#2	52	#1	1.75	29.4
#1	68	#2	2	30.6
#1	68	#3	2.6	28.4
#3	42	#1&#2 Parallel	1.15	31.2

The coupling loss from an inductive line to the vehicular antenna is typically around 55 dB, as compared with measured values of cross-talk attenuation around 30 dB, and consequently the question of interference is raised. Excessive interference can be reduced by operating nearby circuits at different frequencies to provide additional isolation.

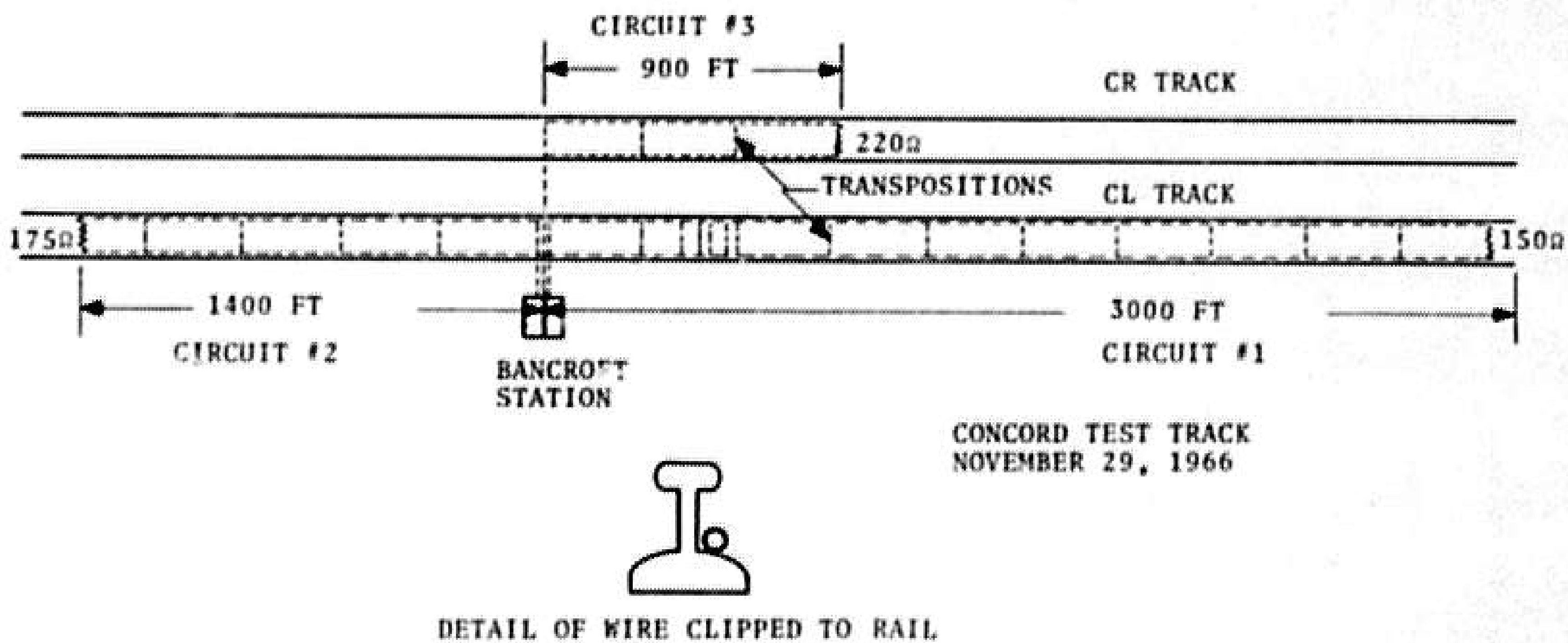


Figure 18. Inductive Wire Circuits in Philco-Ford Measurements(2)

The spacing dependence of the mutual inductance, m, between two pairs of parallel inductive lines, the pairs in the same plane and parallel, can be obtained from Equation (4-2):

$$m = \frac{a^2}{s^2 - (a/2)^2} \qquad (4\text{-}7)$$

where a is the spacing between the wires of each pair and s is the separation between pairs. The coupling loss which is inversely proportional to the square of the mutual inductance is then given by

$$L_c = 10 \log_{10}\left\{\frac{\left[s^2 - (a/2)^2\right]^2}{a^4}\right\} + \text{constant} \qquad (4\text{-}8)$$

From this relation, it is seen that decreasing the spacing, a, by a half result in an increase of the coupling loss by 12 dB.

5. MECHANICAL CHARACTERISTICS

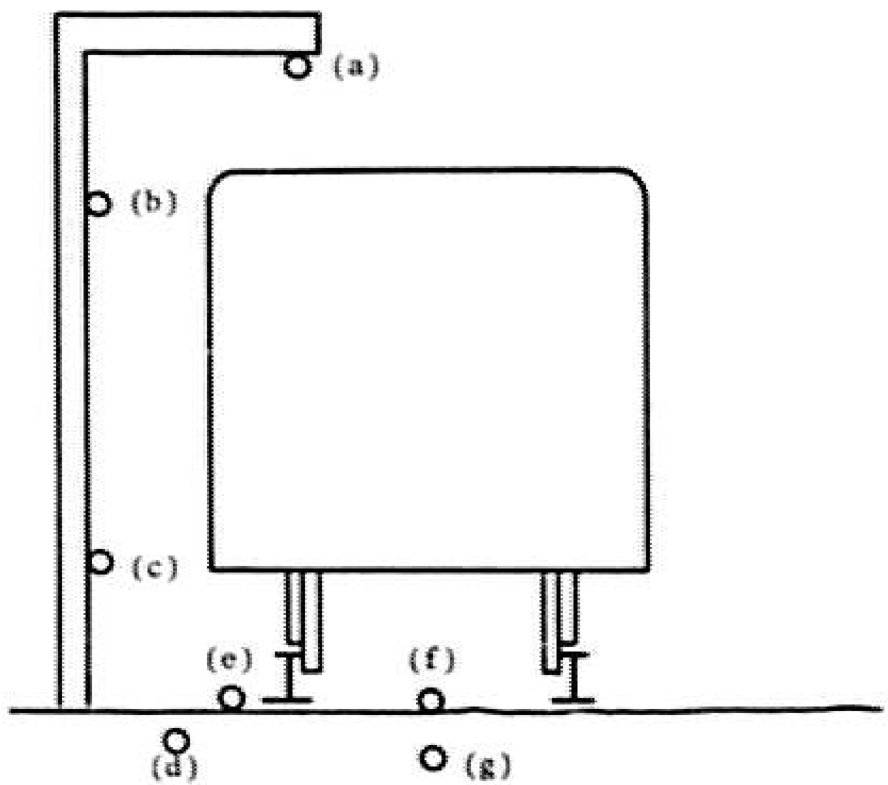
5.1 INSTALLATION

We shall consider the installation possibilities for two types of cables, the helical and the planar "criss-crossed" cable. Figure 19 shows representative locations for the helical transmission line. In Section 4.2 we pointed out that, for this cable with narrow spacing between the wires, the coupling is rather sensitive to variations in distance from the cable. If the cable is in the air the sag must be restricted so as to limit the coupling variation. In locations as (c), (e), and (f) of Figure 19 there is greater chance of damage because of vandalism or accidental breakage. For new railroads the cable may be buried just below the surface of the roadbed.

Figure 20 shows possible locations for installation of the planar criss-cross wires (see Figure 2). If the line is suspended in the air, some rigid framework is necessary. The line with the grooved metal frame already provides such a rigid framework. The grooved metal frame type of line provides some immunity from environmental change and from breakage. The German Federal Railway, in co-operation with Siemens and Halske, have opted for placing conductors in the rail flange-case (f).[1] The magnetic field may be assumed approximately perpendicular to the plane of the transmission line. This determines the orientation of the antenna loops and hence the orientation of the antenna patterns.

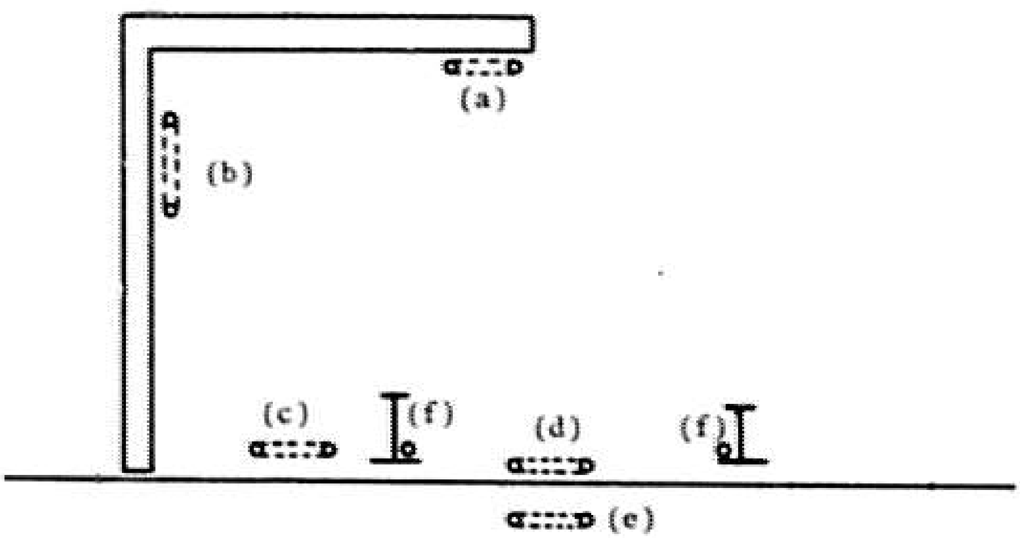
5.2 REPAIR

The helical cable is relatively more difficult to repair in case of breakage because of the difficulty in correct phasing of the replacement section. Repair of the crisscrossed type of wires is somewhat easier, because the broken cable may be joined by inserting a short piece of the same cable.



(a) HUNG ABOVE ROOF OF TRAIN
(b) ON SIDE POST AT HIGHER HEIGHT
(c) ON SIDE POST AT LOWER HEIGHT
(d) BURIED IN THE GROUND OUTSIDE THE TIES
(e) ON TIES NEAR A RAIL
(f) ON TIES BETWEEN THE RAILS
(g) BURIED IN THE GROUND BETWEEN THE RAILS

Figure 19. Possible Locations for Installation of Helical Twisted Wires (Courtesy Sumitomo Electric Industries, Ltd.)



(a) HUNG OVER ROOF OF TRAIN
(b) ON SIDE POLES
(c) OUTSIDE THE RAILS
(d) ON TIES BETWEEN THE RAILS
(e) BURIED IN THE GROUND BETWEEN THE RAILS
(f) FASTENED TO RAIL FLANGES

Figure 20. Possible Locations for Installation of Planar Crisscrossed Wires
(Courtesy Sumitomo Electric Industries, Ltd.)

6. CONCLUSIONS AND RECOMMENDATIONS

Inductive systems are simple in structure and relatively inexpensive. They are low band systems employed most commonly below 300 kHz. If inductive wires are placed on rail flanges, induced eddy currents in the rails will cause high attenuation. This attenuation can be reduced by increasing the separation of the wire from the rail (Figure 9a, b and c).

Electrical characteristics (as attenuation and characteristic impedance) of inductive wires with thin insulation are affected adversely by certain environmental substances of which wet sand causes the largest increase in attenuation (Figures 10 and 11). These adverse effects can be reduced by either increasing the thickness of the dielectric jacket around or by shielding each wire with a metallic shell, thus keeping the strongest electric field intensities within a controlled region of space (Figures 6, 7, 10, 11, 12, and 13). Coaxial lines and partially shielded lines have been developed specifically for environmental shielding purposes.

The characteristic impedance of inductive cables is nearly constant within the frequency band of interest (see Table 1). However, the measured characteristic impedance reported by Philco-Ford shows significant variations that were probably caused by the proximity of the wires to the steel rails (see Table 2). It is suggested that measurements of the characteristic impedance should be conducted for the same cable configurations with the cables laid on the ground and with the cables clipped to the rails.

The cross-sectional magnetic field intensity distribution of a pair of inductive cables was studied (Figures 14a, b, and 15a, b). The results of the study show:

1. The intensity decreases monotonically as coupling distance between the probe and the plane of the cables increases (Figure 15a).

2. There is an optimum cable spacing for a given coupling distance, i.e., the spacing being twice the coupling distance (Figure 15b).

3. If the coupling distance is much smaller than the cable spacing (i.e., less than 0.2), then the field intensity varies slowly with distance (Figure 14b).

4. If the coupling distance is greater than 0.4 of the cable spacing then the field intensity is quite sensitive to the change of the coupling distance (Figure 14b).

In order to prevent large coupling distance variations, it is recommended that a rigid frame be provided for the inductive cables where they are suspended in mid-air.

In order to reduce the noise field effect, the inductive cables can be designed either with alternating wi.e positions or with twisted helical wires. The periodicity should be much shorter than the intended operating wave length. The same alternating position configurations can also reduce the unwanted radiation field. In the case of the vehicular loop coupler, two loops connected in series with phase reversal can achieve the same effect. Noise on a system with two-phase reversal loop couplers has been reduced 20 dB as compared with a single loop coupler (Figure 17a). Similarly, the radiated field is equally reduced for the same system (Figure 17b).

The measured coupling loss is typically on the order of about 55 dB. The required transmitted power for a voice communication (4 kHz bandwidth) has been estimated. The minimum power required to maintain 20 dB S/N, is 1.6 watts, 0.16 watts, and 0.016 watts for typical urban, suburban, and rural areas, respectively. Additional power will be required for long inductive cables. The additional power can be calculated by the following relation:

$$\text{Additional Power} = 4\,\ell\ \text{dB}$$

where ℓ is the length of inductive cables in kilometers.

Cross-talk measurements made by Philco-Ford show that there is only 30 dB attenuation between two adjacent inductive cables at the same frequency (Figure 19). Since a typical coupling loss is 55 dB, the effect of the cross-talk should be seriously investigated. A series of measurements should be conducted with various different inductive cable configurations and combinations.

In the aspects of maintenance, it is much easier to replace a section of a cable pair than the helical cable.

Finally, a qualitative summary of different types of cable is given below in Table 5. The heading "electrical immunity from environment" indicates immunity from the effects of the immediate environment as snow, wet sand, etc. and not the noise fields.

TABLE 5. PROPERTIES OF VARIOUS INDUCTIVE CABLES

Cable	Electrical Immunity from Environment	Installation	Coupling with Antenna	Material Cost
Helical Twisted type with intermediate insulation thickness	good	very easy	good	moderate
Thick insulation for parallel lines and 'criss-cross' type	good	easy	better	low
Coaxial Type	best	difficult	best	high
Partially Shielded type:	good	easy	better	moderate
a) with grooved metal frame				
b) with thick insulation	better	easy	better	moderate

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