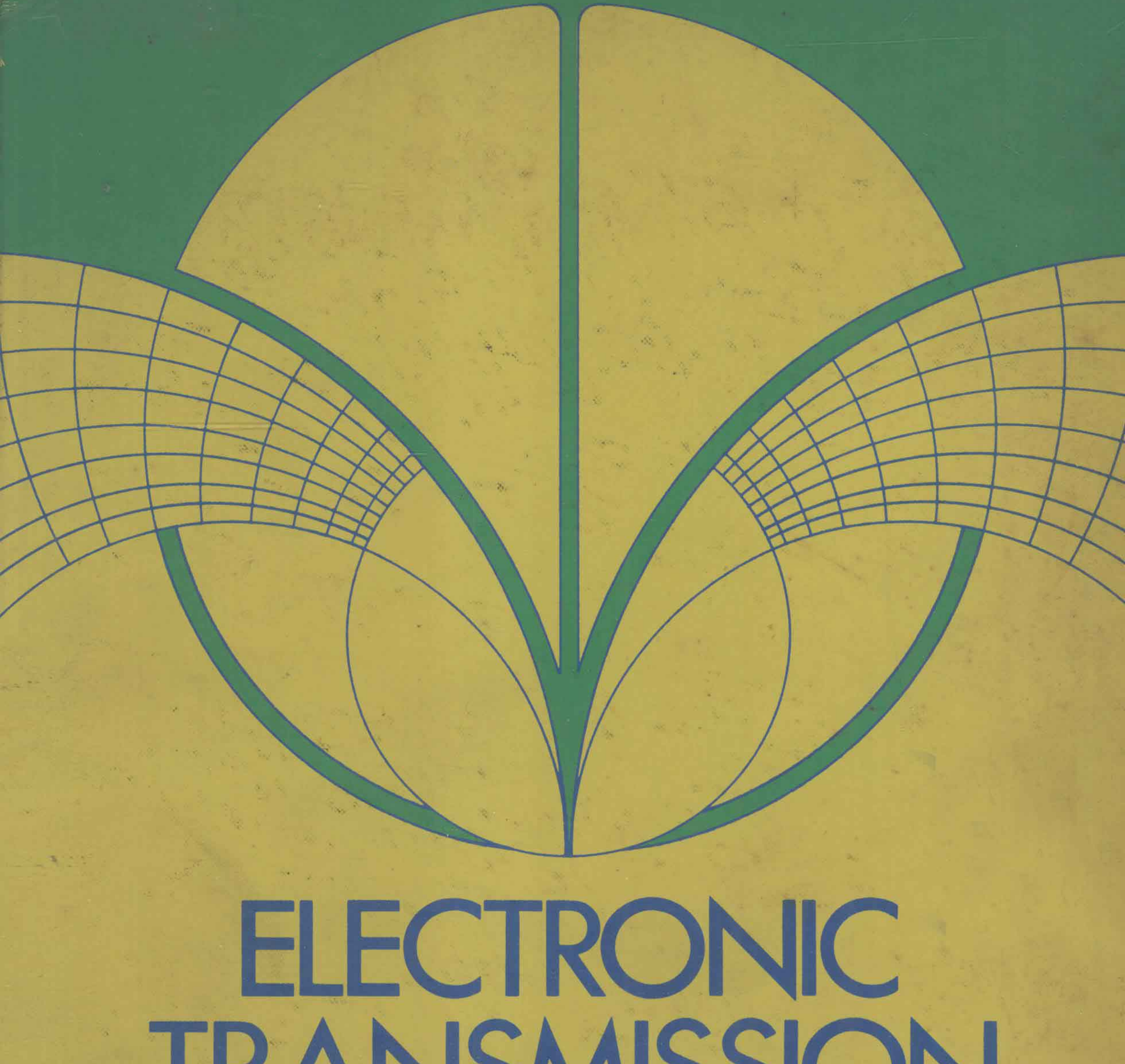

ELECTRONIC TRANSMISSION TECHNOLOGY

lines, waves, and antennas

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PREFACE

The purpose of this textbook is to provide a strong background to technologists in the fundamentals of traveling waves on guided structures and in free space. A student using this book should have a knowedge of algebra and circuit theory; an acquaintance with differential equations would be helpful although not essential.

The text initially describes the physical configurations of various types of transmission lines and gives a clear picture by way of examples of how voltage or current transients behave on such lines. This greatly stimulates student interest in the phenomenon of traveling waves and gives them a good physical understanding for their behavior on the structures discussed in the rest of the text. The steady-state solutions on a uniform transmission line are fully developed mathematically and are later applied by analogy to hollow guides and free space transmission. Some of these derivations in Chapter Three may be skipped over, but the conclusions are significant and should be thoroughly understood.

The Smith Chart and applications to both lossless and lossy lines are covered in Chapter Four. The following two chapters are devoted to the impedance measurement and the matching techniques that are employed at high frequencies.

Plane waves and moding in hollow waveguides are covered in Chapter Seven. This chapter also includes the promising low loss helical waveguide and optical fibers.

Chapter Eight, in mainly a descriptive manner, discusses the various types of radio wave propagation used in radio and microwave systems. The final chapter is devoted to antennas and concludes with the design of a Master Antenna Television System.

I wish to express my appreciation to many of my associates and students for helpful suggestions. In particular I must thank Mr. Ben Wentzell for his encouragement in the completion of this text.

WILLIAM SINNEMA

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CHARACTERISTICS OF STANDARD TRANSMISSION LINES

1-1 INTRODUCTION

The central purpose of this text is to communicate an understanding of the traveling-wave phenomenon. Although ignored in some applications, a finite time always elapses before a change at one point reaches another point. In basic circuit theory we neglect the effects of the finite time of transit of changes in current and voltage and the finite distances over which these changes occur. We assume that changes occur simultaneously at all points in the circuits. But there are situations in which we must consider the finite time it takes an electrical wave to travel and the distance it will travel. It is in these situations that we must employ traveling-wave theory.

Although this text will deal primarily with electric waves, it may be worthwhile to note some other types of waves. Sound waves in air, for instance, form a "longitudinal" wave where the particle motion (air) is in the direction of wave travel. It forms rarefractions and condensations of the air particles, which propagate at a velocity of 330 m/s at standard temperature (0°C) and pressure (14.7 lb/in.^{2}). This velocity increases with an increase in the air pressure or with a reduction of the mass density of the medium.

Heat conduction in solids also propagates as a wave. Thermal waves correspond to a very lossy type of transmission line, and therefore experience a high attenuation. The velocity of thermal propagation increases with the conductivity but decreases with the specific heat and mass density of the medium. For many other examples one may wish to refer to the book by R. K. Moore.[1]

Traveling-wave concepts must be used whenever the distance is so great or the frequency so high that it takes an appreciable portion of a cycle for the wave to travel the distance. The meaning of "appreciable portion of a cycle" depends upon the application. In some devices, phase shifts of less than a degree (0.3% of a period) are significant. In other cases, a quarter-cycle delay may be permitted.

To obtain a feeling of where or when traveling-wave theory should be employed, we should obtain an expression for the wavelength (λ) of a wave. For sinusoidal signals we define a *wavelength* as that distance which a wave travels in one cycle, or period. In free space electric waves travel at the velocity of light, c, which is equal to

$$\begin{aligned} c &= 3 \times 10^8 \text{ m/s} \\ &= 186{,}000 \text{ mi/s} \end{aligned}$$

In one period, therefore, the distance a wave travels (1 wavelength) is

$$\begin{aligned} \lambda &= \text{velocity} \times \text{period} \\ &= v \times T \\ &= v \times \frac{1}{f} \end{aligned} \tag{1-1}$$

where f is the frequency of the signal. In free space the wavelength will be equal to

$$\lambda = \frac{c}{f} \tag{1-2}$$

Wavelengths in free space can now be found for some typical frequencies. Some of these are tabulated in Table 1-1. If we assume that the traveling-wave technique must be employed for distances greater than $\frac{1}{10}$ wavelength, a distance of 3 mm at 10 GHz would require the use of this technique, whereas the same distance at 100 MHz would not. On the other hand, a distance of 1 mi is insignificant at power-line frequencies but not in the broadcast band.

In this text the various forms of propagation are divided into the following main divisions:

1. *Transmission lines:* two conductors.
2. *Waveguides:* single, hollow conductors.
3. *Antennas:* no conductors in the propagation medium.

[1]Richard K. Moore, *Traveling-Wave Engineering* (McGraw-Hill Book Company, 1960).

TABLE 1-1 Free Space-Wavelengths at Various Frequencies

Application	*Frequency*	*Wavelength*
Power transmission	60 Hz	3000 mi
Voice	1000 Hz	300 km
Broadcast band	1 MHz	300 m
FM, TV	100 MHz	3 m
X-band radar	10 GHz	3 cm

Each mode has its own application and advantages. Both transmission lines and waveguides have an exponential type of attenuation, with the waveguide having a lower attenuation than a transmission line of equal length. The waveguide however, becomes excessively large at lower frequencies (less than 2 GHz). Antennas have an inverse-square-law type of attenuation characteristic, which is an advantage for longer distances. However, they become very inefficient at low frequencies, where the physical size limitations of an antenna are encountered.

Figure 1-1 shows the relative input power required for the three modes of transmission if a fixed received power is needed. A solid-dielectric coaxial line having a loss of 10 dB/100 ft, a waveguide having a loss of 0.5 dB/100 ft, and

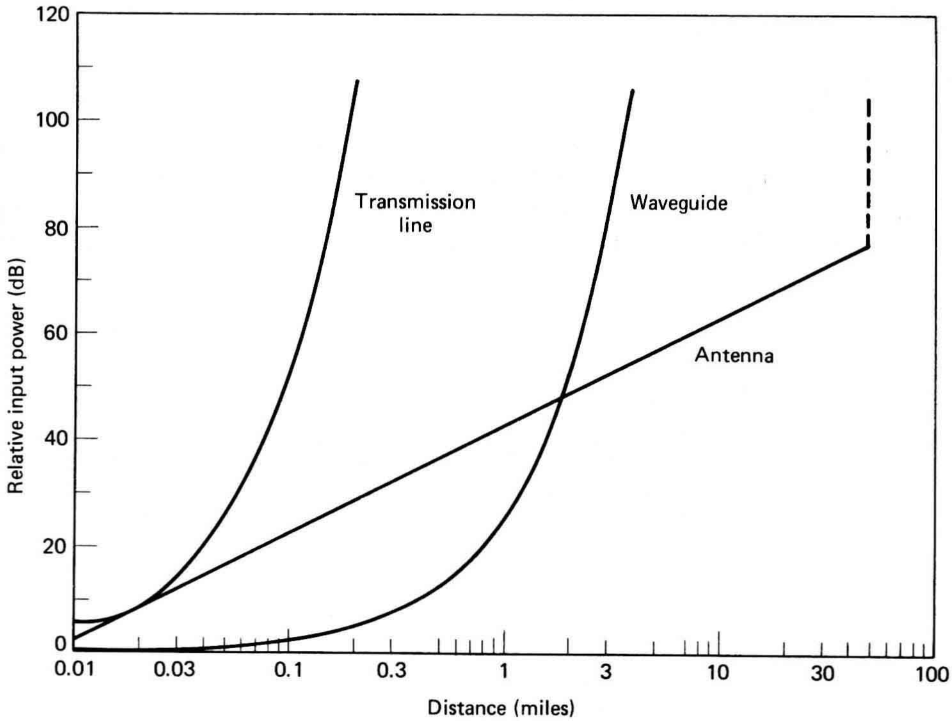


FIG. 1-1 Relative input power required for a fixed receiver power.

transmitting and receiving antennas having a gain of 1000 (30 dB) are assumed at a 2-GHz operating frequency. The antenna has a typical line-of-sight distance. From observation of the figure it is clear that for short transmission distances, waveguides and transmission lines are more efficient, whereas for longer distances, antennas have a clear advantage in efficiency.

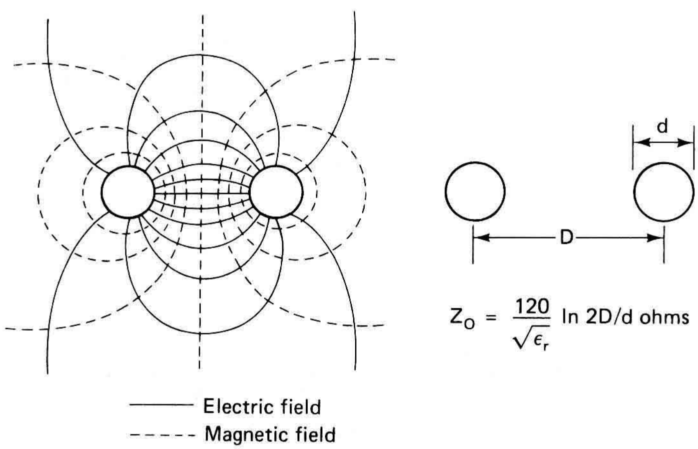
1-2 STANDARD TRANSMISSION LINES

Two of the most common wave-guiding structures are the two-wire open line and the coaxial line. These lines generally propagate the "principal mode," which is called the *transverse electromagnetic wave* (TEM). Very simply, this means that the electric (E) and the magnetic (H) fields are always transverse to the direction of wave propagation. If these lines are operated at frequencies that cause the transverse dimensions to become an appreciable portion of a wavelength in size, other, "higher modes" can be set up. These generally are undesirable and are avoided.

Some of the more common types of transmission lines are discussed in this section. The characteristic impedance is also given for each configuration, assuming a lossless transmission line. The significance of this impedance will become evident later. Suffice it to say at this time that it represents the input impedence of a line of infinite length.

Two-Wire Open Line

The *two-wire open line* (Fig. 1-2) is easy to construct and has been extensively used in the telephone industry in the past, and still is very much used in the 60-Hz power industry. Its characteristic impedance (Fig. 1-3) is easy to adjust by changing the spacing. Typical impedances for air-dielectric lines range from about 200 to



$$Z_0 = \frac{120}{\sqrt{\epsilon_r}} \ln 2D/d \text{ ohms}$$

FIG. 1-2 Transverse views of the fields of the open two-wire transmission line.

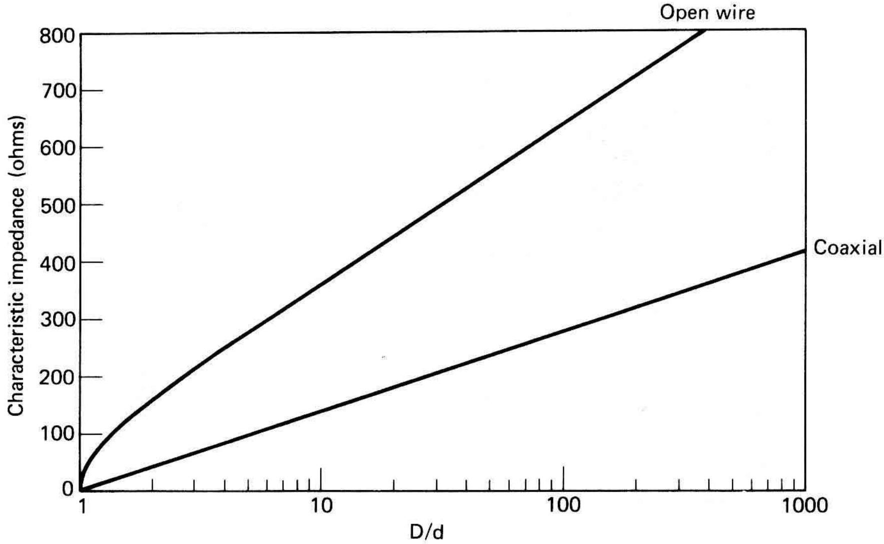


FIG. 1-3 Characteristic impedance of open-wire and coaxial transmission line.

600 Ω. The "twin-lead" transmission lines used commonly in connecting TV receivers to an antenna has a polyethylene supporting structure, resulting in an overall characteristic impedance of 300 Ω.

The two-wire line is a balanced line in that both lines have equal impedances with respect to ground. This differs from the coaxial line, where usually the outer shield or conductor is at ground potential. The real disadvantage of the open-wire line is that its fields extend far beyond the line. This results in excessive radiation losses at the higher frequencies. These lines are seldomly used at frequencies above a few hundred megacycles.

Coaxial Cable

The *coaxial line* (Fig. 1-4) is an unbalanced line (the outer conductor is normally at ground) and probably the most commonly used transmission line. It has no radiation loss but does have a loss depending upon the dielectric used. If air dielectric is used, only slight losses are encountered with the dielectric spacers. The maximum continuous wave power ratings depend upon the size of the conductors and the breakdown voltage of the dielectric in the transmission line.

The *dielectric* commonly used in coaxial lines is polyethylene and more recently polytetrafluorethylene (Teflon). The dielectric constants of some dielectrics are given in Table 1-2. Teflon has superior mechanical strength and melts at higher temperatures but is much more expensive and less pliable.

The *dielectric constant* ϵ is very closely related to a capacitance and for this reason is frequently called *capacitivity*. The units are farads per meter and it has a value in free space of $1/36\pi \times 10^{-9}$ F/m, which is generally symbolized by ϵ_0. The

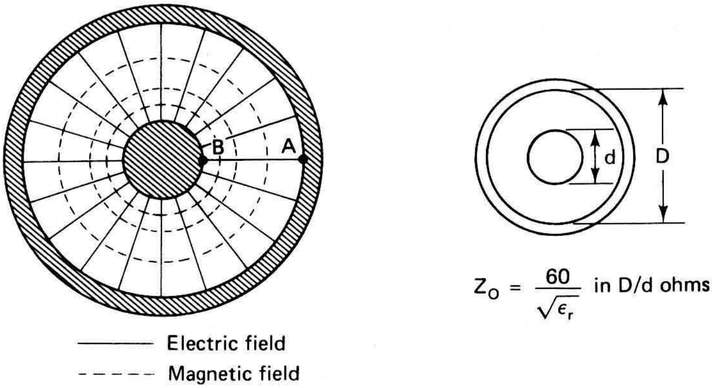


FIG. 1-4 Transverse views of the fields of the coaxial transmission line.

TABLE 1-2 Dielectric Constants of Some Dielectrics

Material	*Frequency (MHz)*	*Loss tangent,* τ	*Relative dielectric constant,* ϵ_r	*Comments*
Polystyrene	100	0.00007	2.6	Plastic. Moderate strength. Brittle but machinable. Melts at high temperatures.
	1000	0.0001	2.6	
	10,000	0.0004	2.5	
Polyethylene	10,000	0.0004	2.3	Plastic. Easily cut, but not machinable; usually molded to shape. Melts at high temperatures.
Teflon	10,000	0.0004	2.1	Tough, machinable, surface has lubricant properties, good high-temperature characteristics.

dielectric constant indicates the amount of charge that can be stored in the dielectric for a given voltage.

The *relative dielectric constant* (ϵ_r) of a material is defined as the ratio of the dielectric constant of the material to the dielectric constant of free space:

$$\epsilon_r = \frac{\epsilon}{\epsilon_0} \tag{1-3}$$

The *power loss* in an insulating material is related to the *conductivity* (σ) of the insulator. To make this a little more meaningful, an insulator can be considered electrically as a large resistance in shunt with a capacitance, as shown in Fig. 1-5. The conductivity (σ) is the inverse of the *resistivity* (ρ).

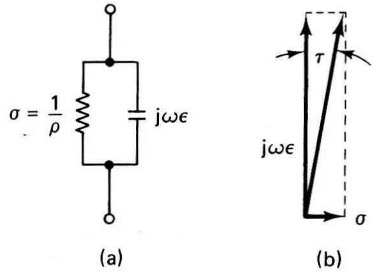


FIG. 1-5 Equivalent circuit of an insulator.

For a good insulator the conductivity will be small. The admittance phase diagram appears in Fig. 1-5(b), where the loss phasor is defined as

$$\tan \tau = \frac{\sigma}{\omega\epsilon}$$

which for small σ reduces to ($\tan \tau \longrightarrow \tau$)

$$\tau = \frac{\sigma}{\omega\epsilon} \tag{1-4}$$

The lower the conductivity (the higher the resistivity), the less the attenuation that will be experienced by the signal passing through it.

All lines also experience a resistance loss due to the finite conductivity of the conductors. This loss is generally less than that of the dielectric. All common types of transmission lines experience an increased attenuation with frequency due to skin effect. The attenuation characteristics of one of the better types of coaxial lines are given in Fig. 1-6. This line has the insulating support in the form of a helical ribbon of dielectric material.

These *air-dielectric lines* are often put under slight pressure with nitrogen gas to prevent entry of moisture and other contaminants and to increase the voltage breakdown level. This type of line is used in power transmitter operations, where the power loss must be kept to a minimum. In general, the larger-diameter cables are used for the higher-power applications (see Fig. 1-7), to avoid voltage breakdown under the greater voltages. Great care must be taken when installing or handling these types of lines to avoid crushing, which produces variations in the characteristic impedance of the line. Some lines use a corrugated conductor to improve both flexibility and resistance to crushing, while slightly increasing the attenuation.

For low-power and receiver application, *solid-dielectric lines*, the nominal 50-Ω coaxial cable RG8A/U and RG58A/U, are more common, where the higher attenuation losses are acceptable. Table 1-3 gives the characteristics of some of the coaxial lines that are generally used in communication systems. Solid-dielectric lines are more flexible than air-dielectric lines and also have a higher breakdown voltage.

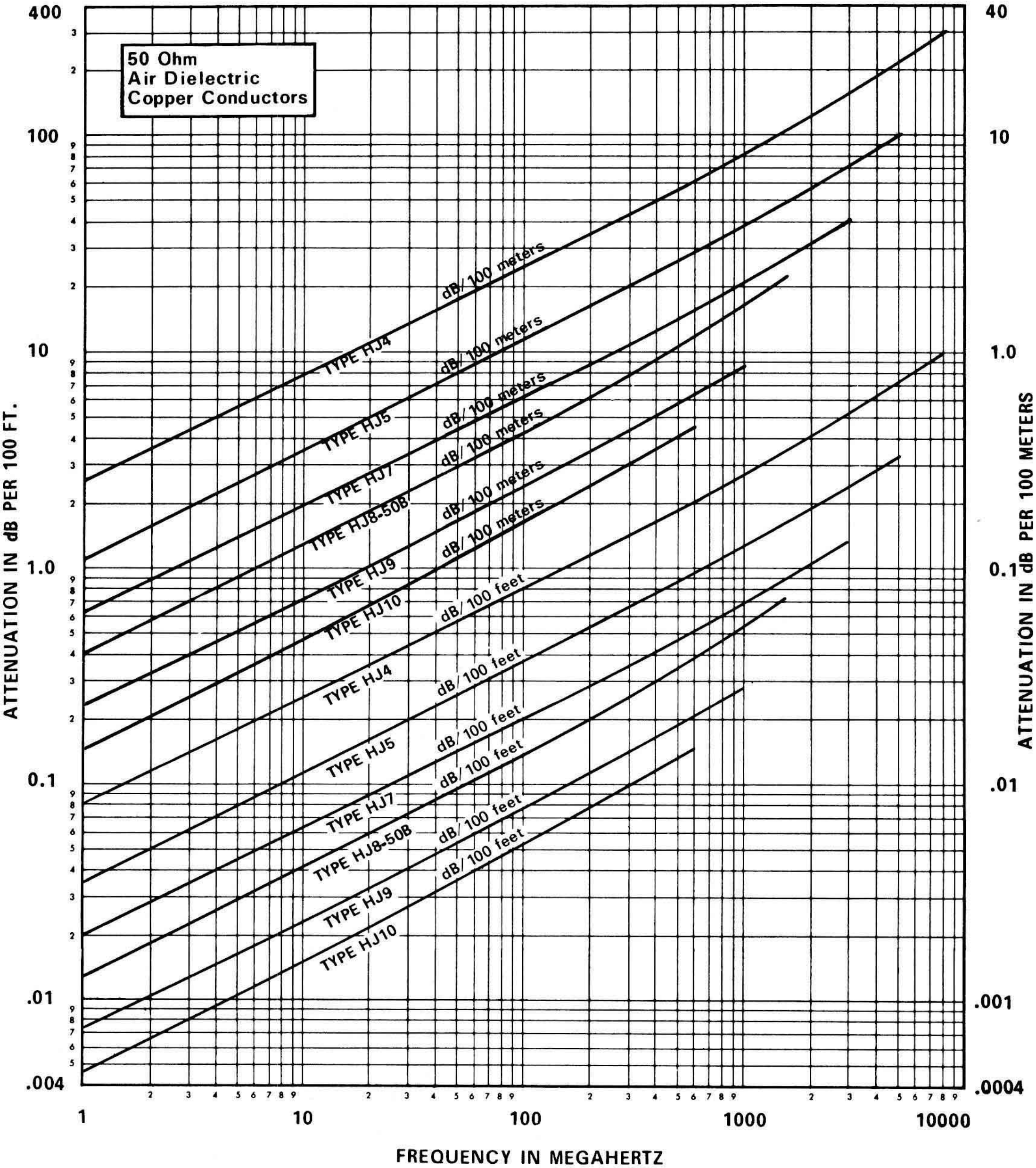


FIG. 1-6 Attenuation of Andrew HELIAX coaxial cable. (From Andrew Catalog 27, containing complete specifications.)