The following paper was first published in the April, 1981, issue of QST Magazine. It was recently edited to include fresh data. At the time of original publication, the co-authors were employees of Times Wire & Cable Co., now Times Microwave.

COAXIAL CABLE - The Neglected Link

Is a better grade of coaxial cable worth the price difference? This analysis of the importance of shielding in coaxial lines explains why the answer is "Yes!"

By Ken Smith and Charles Brainard - KA1PM

When energy is transmitted through a coax cable, some of this energy may escape. Conversely, the cable may be in a field of energy and some of that energy can penetrate into the cable. The transformation of the energy out of, or into, the cable is called radiation, and the associated transducer is termed an antenna. The cable is a transmitting antenna when the energy escapes (egressive signals) and a receiving antenna when the energy penetrates into the cable (ingressive signals). This phenomenon has many names associated with it such as leakage, radiation, isolation, shielding, shielding effectiveness, screening and screening efficiency.

Energy must pass through the cable shield for either egressive or ingressive signals. Obviously, for the most common use of coaxial cable, high attenuation of the energy passing through the shield is essential. There are cables that are designed for controlled leakage, and they are used when a highly controlled radiation of signals is desired. The following discussion, however, will be directed toward shields that are designed to prevent this leakage.

In 1960, a development program was established to investigate methods of construction of flexible coaxial cable to reduce cost, decrease attenuation and to improve RF shielding. It was found that test methods used to measure the radiated energy were quite difficult and were not sufficiently repeatable to evaluate different cables. This method measured the energy external to the cable resulting from a known energy level within the cable. Hence, a new test method was developed which gave relative ratings in decibels. This method was found to be useful for evaluation of different cables even though these ratings could not be directly interpreted in radiation. The repeatability of the test was in the neighbor of 3 to 5 dB, and it was found that relative ratings varied from 20 to 100 dB for various cables.

The theoretical development of electromagnetic field coupling through the shields of coaxial cable began many years ago and the general theory was presented in an article by Schelkunoff in 1934. He represented the coupling by a transfer impedance and developed formulas for calculating the characteristics of solid shields. He also analyzed multi-layer shields. Co-author Ken Smith developed the Radiometer, an instrument that uses the triaxial test method for measurement of the electromagnetic field coupling through the shield. He developed this instrument for the Times Wire and Cable Co. in 1978.

The purpose of this dissertation is to show the transfer impedance and capacitive coupling impedance and, therefore, shielding effectiveness of different types of coaxial cables. The theory of electromagnetic field coupling and method of measurement will be reviewed, as will the measurement data of different types of cables.

MEASUREMENT

The Radiometer measures the absolute value of the transfer impedance and the capacitive coupling impedance of the coaxial shield. An artist's sketch of the test setup is given in FIG. 1, showing

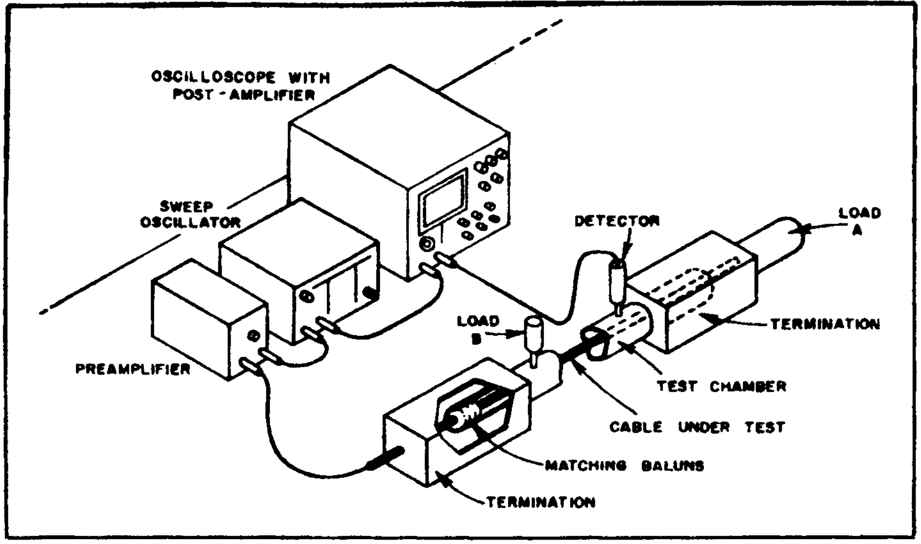

Fig. 1 — A setup for using a triaxial-test method for measuring the electromagnetic-field coupling through the shield.

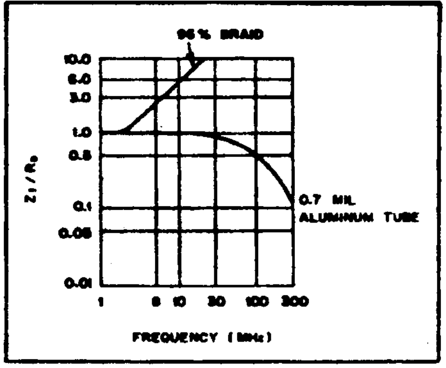

Fig. 2 — Coaxial-cable transfer impedances (Z_t) divided by the dc resistance of the shield (R_o) vs. frequency.

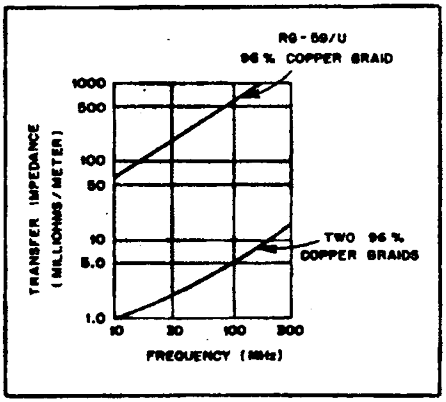

Fig. 3 — The relationship of transfer impedance vs. frequency for braided shields is shown by this graph.

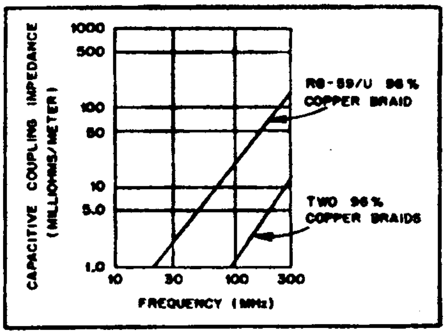

Fig. 4 — A graph representing capacitive coupling impedance vs. frequency for braided shields.

that the cable is coaxially supported by a dielectric in the test chamber, creating a triaxial transmission system. The inner coaxial-transmission system is inside the test specimen and the outer coaxial-transmission system center conductor is the shield of the specimen. Its outer conductor is the test chamber. The specimen is terminated in its characteristic impedance by load A and the combination of the sweep oscillator and preamplifier. Load B and the detector are connected to the outer system by coaxial terminals. The rectangular termination on the ends of the chamber have ferrite toroids surrounding the test sample. These toroids minimize current flow along the shield of the test specimen to the end of the rectangular termination where the shield of the specimen is grounded. These rectangular terminations form baluns, creating high impedance, allowing load B and the detector to match the impedance of the chamber. Errors are not introduced by leaky conductors; the shield of the specimen is unbroken through the entire length of the fixture. The connectors on the sample are connected to the ends of the rectangular terminations and are not critical since the baluns isolate the connector leakage from the signal in the test chamber.

When the equipment is set up as shown in FIG. 1, an analysis (neglecting attenuation and assuming the cable shield is uniform) shows that the magnitude of the output voltage in the triaxial system is:

$$Vf = \frac{(Zt - Zf)\, Vj\, \mathrm{Sin}\,\{(Bs - Bc)\, L/2\}}{Zs\,(Bs - Bc)} \qquad \text{Eq. 1.}$$

Where

Vf = the detector voltage with set up of Fig. 1.
Vj = the specimen input voltage.
Zt = the transfer impedance in ohms per meter.
Zf = the capacitive-coupling impedance in ohms per meter.
L = the distance between the coaxial terminals of the test Chamber in meters.
Zs = the specimen characteristic impedance in ohms.
Bs = the specimen phase constant in radians per meter.
Bc = the test chamber phase constant in radians per meter.

An analysis of the output voltage with load B and detector shows:

$$VR = \frac{(Zt + Zf)\ Vj\ \text{Sin}\ \{(Bs + Bc)\ L/2\}}{Zs\ (Bs + Bc)} \qquad \text{Eq. 2}$$

where

VR = the detector voltage with load B and detector swapped.

Zt and Zf may be calculated since ratios Vf/Vj, VR/Vj, Bs, Bc, L and Zs can be measured. The test procedure provided with the Radiometer includes tables which can be used to convert the voltage ratios measured in dB to transfer impedance and capacitive-coupling impedance. The minimal specimen attenuation is neglected but the chamber attenuation is accounted for. The tables were obtained from the following equations:

$$Zt = \frac{1}{L}\sqrt{Zs\ Zc}\left(\frac{\phi}{\sin\phi}\ e^{x} + \frac{\theta}{\sin\theta}\ e^{y}\right) \qquad \text{Eq. 3}$$

$$Zf = \frac{1}{L}\sqrt{Zs\ Zc}\left(\frac{\phi}{\sin\phi}\ e^{x} + \frac{\theta}{\sin\theta}\ e^{y}\right) \qquad \text{Eq. 4}$$

where

Zt = the transfer impedance in ohms per meter.
Zf = the capacitive coupling impedance in ohms per meter.
Zs = the specimen characteristic impedance in ohms.
L = the chamber length in meters.
ϕ = (Bs + Bc) L/2 in radians.
θ = (Bs – Bc) L/2 in radians.
Zc = the chamber characteristic impedance in ohms.
Bs = the specimen phase constant in radians per meter.
Bc = the chamber phase constant in radians per meter.

$$x = \frac{DBR - \alpha c/2}{8.68} = \text{Ln}\ VR/Vj \qquad \text{Eq. 5} \qquad c = \text{chamber attenuation}$$

$$y = \frac{DBF - \alpha c/2}{8.68}\ \text{Ln}\ VF/Vj \qquad \text{Eq. 6}$$

αc = chamber attenuation

NOTE: X, Y, DBR, DBF and αc are negative quantities.

DISCUSSION and ANALYSIS of TRANSFER-IMPEDANCE TEST RESULTS

Transfer impedance in an elementary length of coaxial cable is defined as the ratio of the potential gradient (voltage) in the disturbed circuit to the current flowing in the interfering circuit. When the cable is acting as a receiving antenna (ingressive signals) the disturbed circuit is within the cable and the interfering circuit is the environment around the cable. A lower transfer impedance reduces the electromagnetic coupling (radiation).

The transfer impedance of a braided shield has two components – a diffusion component caused by current diffusing through the metal and a mutual-coupling component caused by penetration of the magnetic field through the openings in the braid. The mutual-coupling component can be represented by a mutual inductance. (Figs. 2, 3 & 4 are related to this discussion.)

The transfer impedance is the vector sum of these two complex quantities, and its magnitude is:

$$Zt = \sqrt{(Zd\ \cos\phi) + (Zd\ \sin\phi + Zm)^2} \qquad \text{Eq. 7}$$

where

Zf = the capacitive coupling impedance in ohms per meter
p = the electric polarizability of the holes in the braid.
M = the magnetic polarizability of the holes in the braid.
Zm = the mutual-coupling component of Zt in ohms per meter.
r = the relative dielectric constant of the insulation in the external circuit.
r = the relative dielectric constant of the insulation within the cable.

The capacitive-coupling impedance will be zero if there are no openings in the shield. If openings exist, then the capacitive-coupling impedance should vary directly with the frequency. The test data plotted in Fig. 4 follows this characteristic reasonably well.

THE BOTTOM LINE

Measurements of the transfer impedance and capacitive-coupling impedance of coaxial shields can be made and the results of these measurements agree with the theoretical equations. Since the theory of transfer of energy through shields is known, an engineer can analyze and design coaxial cable theoretically. Because of the different types of coaxial cables in use today, the design engineer should be aware of the large variation in the coupling of electromagnetic fields through the shields.

The information in Table 1 gives an idea of the relative isolation of coaxial cable in accordance with the percent and type of shielding. We have also indicated the losses in dB per 100 feet at 15 and 150 MHz (near two very popular Amateur Radio bands) for each construction in the table. While Table 1 deals with RG-59/U cable, the isolation characteristics are applicable to any solid-dielectric cable while the losses per 100 feet can be interpolated to other coaxial lines.

Down-line attenuation of cables is controlled by (1) the type and material of the center conductor; (2) the velocity of propagation and type of material of the center dielectric; and (3) the type and material of the outer conductor. An examination of the loss curves of Fig. 5 shows that RG-58A/U exhibits loss characteristics from 11% to 12% greater than for that of RG-58/U. The only difference between these two cables is the nature of the center conductor, RG-58A/U has a 19-strand tinned-copper center conductor while RG-58/U has a solid bare copper center conductor. Tinned copper is very popular with manufacturers because it simplifies soldering. But, considering attenuation tinned-copper shields generate seriously detrimental effects above 500 MHz.

Another example that can be drawn from Fig. 5 is loss differentials (approximately 33%) between RG-8/U and FM-8 (Flexifoam by Times). RG-8/U utilizes a 7-strand bare-copper center conductor and a 66% velocity core dielectric as opposed to a solid bare-copper center conductor and a 79% velocity center core dielectric. It should be noted that in order for the FM-8 to possess a 50-ohm characteristic, the center conductor must be enlarged to 0.102 inches (2.59mm) or, No. 10 gauge v. 0.0808 inches (2.05mm) or, No. 12 gauge for the center conductor on RG-8/U. As the velocity of propagation is increased while maintaining the same diameter inside of the shield, the center conductor must be increased in size in order to maintain the same cable impedance. Some of the new cables offer velocities a bit above 92% and with the required attendant increase in the size of the center conductor, serious reduction of cable attenuation characteristics is available. Beware, however, of making these cables into tightly wound coils for choke purposes, the cables are mechanically more fragile and may not be able to handle the very small bend radiuses required for this application. Pay close attention to the specifications, namely bend radius, as stated by the cable manufacturer. Some of the filament-wound ultra-flexible center conductors can be prone to kinking which can cause the characteristics of the cable to wander drastically.

Braided-shield coaxial cables are, to varying degrees, impacted by their environment. That is, mounting a poorly shielded cable direct to a tower leg, as is so common, can drastically alter the attenuation characteristics of the cable. This change in characteristics is often in excess of 10 times with degradation increasing with frequency. Placing poorly shielded cables into any conducting environment such as when attached to a tower leg or even buried in the ground can cause adverse results.

where

ϕ = 0.785 – tan (cot d/δ d/δ)
Zd = the diffusion component of Zt
Zm = the mutual-coupling component of Zt in ohms per meter.
d = the diameter of the braid wire in meters.
δ = the skin depth in meters.

The approximate diffusion component and mutual-coupling component for braided cable is obtained from an extension of Vance's equation and Schelkunoff's.[1]

The diffusion component is:

$$Zd = Rdc \frac{(\sqrt{2})\ d/\delta}{\sqrt{\mathrm{Sin\,h}^2(d/\delta) + \sin^2(d/\delta)}} \qquad \text{Eq. 8}$$

$$\delta = \frac{\rho}{\pi f \mu'}$$

The mutual-coupling is:

$$Zm = \frac{\omega v \mu m}{\pi^2 D^2}$$

where

ρ = the resistivity of the shield in ohms per meter.
f = the frequency in hertz.
μ' = the absolute magnetic permeability of the shield in henrys per meter.
d = the diameter of the braid wire in meters.
Rdc = the dc resistance of the shield in ohms per meter.
ω = the angular frequency in radians per second = 2 f.
v = the number of holes per meter in the braided shield.
μ = the absolute magnetic permeability of the insulation between the conductors in henrys per meter.
D = the mean inside diameter of the shield in meters.
m = the magnetic polarizability of the holes in the braid.
Zm = the mutual-coupling component in ohms per meter.
Zd = the diffusion component in ohms per meter.
δ = the skin depth in meters.

ANALYSIS OF CAPACITIVE-COUPLING IMPEDANCE TEST RESULTS

The openings in the shield also allow the electric filed to penetrate, creating electric coupling. This coupling can be represented by a capacitive coupling between the center conductor of the coaxial cable and the return path external to the cable. The capacitive-coupling impedance is derived from the definition accepted by the International Electrotechnical Commission Working Group I (Screening Efficiency)[7] and Vance's equation for transfer admittance.[5]

$$Zf = \frac{p}{m} Zm\sqrt{\varepsilon r_c / \varepsilon r_j} \qquad \text{Eq. 11}$$

Table 1

Relative isolation characteristics of RG-59/U coaxial cable vs. percentage and type of braid coverage/shielding.

Shield	*Relative Isolation (dB)*	*Ratio of Power Radiated from Cable*	*Losses in dB per 100 ft. (30.48 m)*	
			15 MHz	*150 MHz*
40% bare copper	17	1:50	1.72	5.55
51% bare copper	18	1:63	1.72	5.55
59% bare copper	26	1:398	1.39	4.51
79% bare copper	34	1:2500	1.13	3.67
98% bare copper	52	1:160,000	0.98	3.20
96%/96% bare copper	83	$1{:}2 \times 10^8$	1.01	3.31
Solid sheath (alum.)	282	$1{:}17 \times 10^{28}$	0.89	2.91

Note: Isolation capabilities of coaxial cable at 20 meters is roughly 10 times as good as at 2 meters.

Table 2

Formulas Common to All Coaxial Cable

Capacitance (C) = $\frac{7.36E}{\text{Log}(D/d)}$ picofarads/ft

Inductance (L) = 0.140 Log (D/d) microhenrys/ft

Impedance (Z_o) = $10^3\sqrt{\frac{L}{C}} = \frac{138}{\sqrt{E}}$ Log (D/d) ohms

Velocity of propagation as % of speed of light = $\frac{100}{\sqrt{E}}$

Time delay = $1.016\sqrt{E}$ nanoseconds/ft

Cutoff frequency = $\frac{7.50}{\sqrt{E}(D+d)} = F_{co}$ (GHz)

Magnitude of Reflection Coefficient =

$$(1) = \left[\frac{Z_r - Z_o}{Z_r + Z_o}\right] = \frac{VSWR - 1}{VSWR + 1}$$

$$VSWR = \frac{1+\Gamma}{1-\Gamma}$$

Peak voltage = $\frac{1.15Sxd\,(\log D/d)}{K}$

$$\alpha = \frac{0.435}{Z_o(D)}\left[\frac{D}{d}K_1 + K_2\right]\sqrt{F} + 2.78\,\sqrt{E}(P.F.)(F)$$

where

α = attenuation in db/100 ft

d = outside diameter of inner conductor in inches

D = inside diameter of outer conductor in inches

S = maximum voltage gradient of the cable insulation in volts per mil

E = relative dielectric constant of the insulation of cable

Log = Logarithm to base 10

K = safety factor

K_1 = strand factor and material

K_2 = braid factor and material

F = frequency in MHz

P.F. = power factor

Feet x 0.3048 = meters

Properties of Wire and Cable Insulating Materials

Material	*Dielectric Constant*	*Power Factor*	*Volume Resistivity (ohms-cm)*	*Normal Operating Temperature Limits (°C)*
TFE	2.1	0.0003	10^{19}	−75 + 250
Polyethylene	2.3	0.0003	10^{16}	−75 + 80
Cellular polyethylene	1.40-2.10	0.0003	10^{12}	−75 + 80
Polyvinylchloride	3.00-8.00	0.0700-0.1600	2×10^{12}	−55 + 105
Nylon	4.60-3.50	0.040-0.030	4×10^{14}	−60 + 120
Kel-F	2.37	0.0270-0.0053	1.2×10^{18}	−40 + 150
Silicone rubber	2.08-3.50	0.007-0.016	10^{13}	−70 + 250
Ethylene propylene	2.24	0.00046	10^{17}	−40 + 105
FEP	2.10	0.0003	10^{18}	−75 + 200
Perforated TFE	1.50	0.0002	10^{19}	−75 + 250
Cellular TFE	1.40	0.0002	10^{19}	−75 + 250
Cellular FEP	1.50	0.0002*	18^{18}	−75 + 200
Polyimide	3.00-3.50	0.002-0.003	10^{13}	−75 + 300

*Varies with frequency

From the formulas in this paper, transfer impedance and capacitive-coupling impedance can be calculated. As these impedance values rise, the outer conductor (shield) has larger openings and, consequently, higher-impedance cable is more affected by its environment.

There is much more to coaxial cable than meets the eye. Since the cost of this type of transmission line is usually relatively small in proportion to other station costs, it's difficult to reason the use of a poor grade of cable. A properly shielded line should be a must for all installations.

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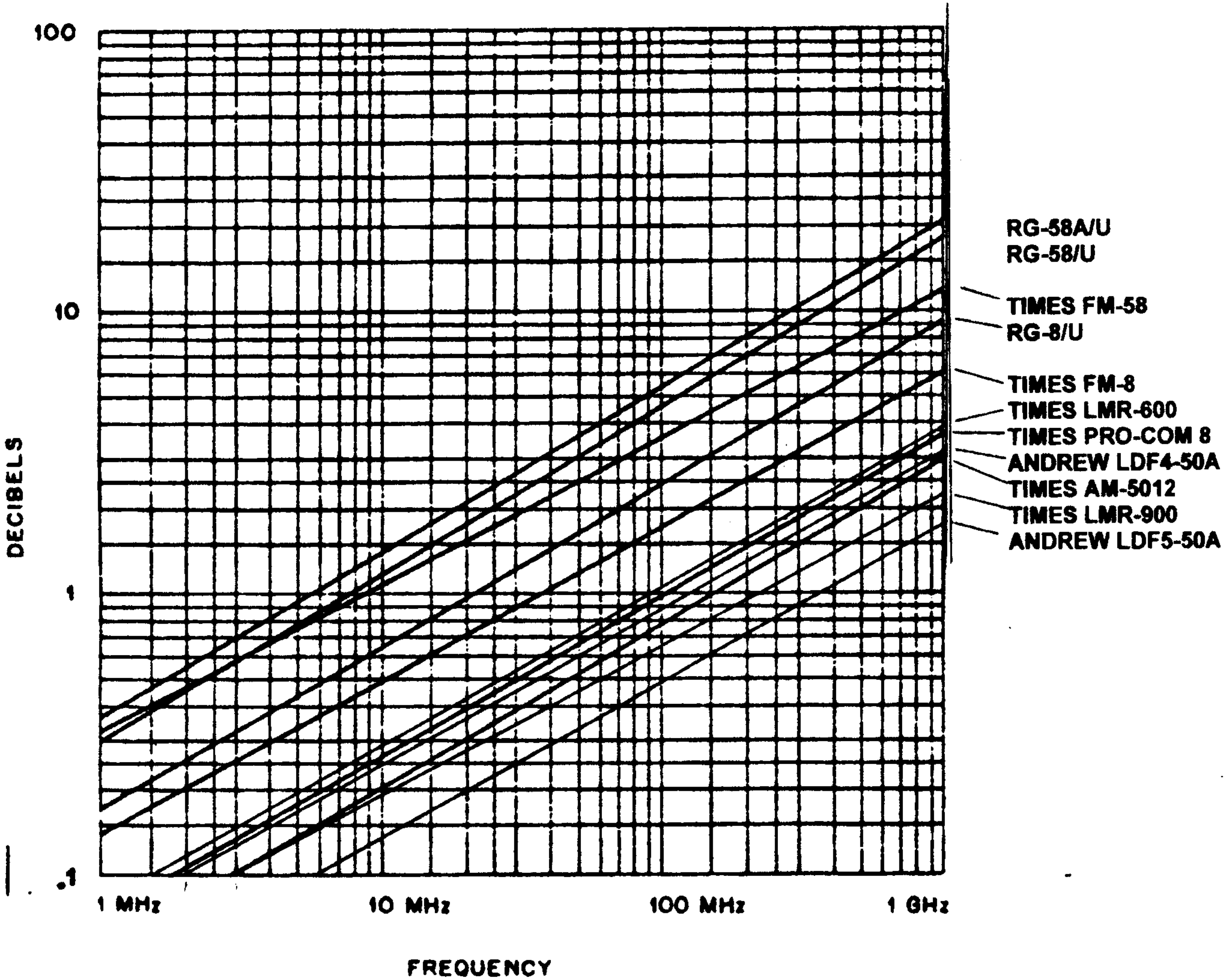

Fig. 5 — Nominal loss characteristics per 100 ft (30.48 m).