Coaxial Cable Theory

Welcome to the 2nd Quarter 2013 CSEI Technical Report.

In the case of this report, I'll willingly confess that in part, I'm strapped for time, and am therefore (re)issuing a technical article issued MANY years ago by a company no longer in existence. However, in saying this I'll also state that the Texscan Technical Tips of the (I believe) 1970's were some of the best ever issued – in terms of excellent treatises on basic electronics, video theory, and CATV theory and practice.

Beyond this cover page, the remainder of this article is simply a scan of a series of three (3) Tech Tips issued by Texscan on coaxial cable theory sometime in the 1970's. I also plan to re-issue several other Texscan Tech Tips in the coming year; as again, I consider them to be some of the best 'theory' articles written during that time period or since.

As near as I can determine, the intellectual property rights 'lineage' is as follows:

- Article originally written by unknown person or persons at Texscan.
- Texscan then combined with Antec for several years.
- Texscan/Antec sold to Scientific Atlanta.
- SA then sold to Motorola.
- Motorola has since sold 'portions' of the SA line to Arris; with Arris now a composite company owning all or portions of the following older companies: C-COR, Phillips, ADC, and Motorola/SA.

So, if a 'company' does indeed own intellectual rights to the following article, it's likely Arris and I'm therefore giving them full credit at this time.

Now read on for an excellent treatise on the cable that we work with each day, but often don't understand as well as we should regarding theory of operation.

Be sure to contact me if you have questions regarding the following article.

Take care and best regards.

Mark Bowers
VP of Engineering
Cablesoft Engineering, Inc.

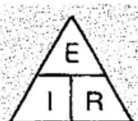
Coaxial Cable

The next few issues of Texscan technical topics will deal with a very important portion of the system; the cable itself. In order to properly understand what happens in the cable, we must first understand some of the more basic AC terminology.

RESISTANCE

Resistance, as stated by Ohm's Law, is simply the characteristic of a circuit that limits the flow of current. Resistance may be the given value of a circuit component called a resistor, or the quantity of resistance in wire, cable or other circuitry. Resistance, by definition, gives us a value in ohms at zero frequency (DC).

Stated in equation form:



$$E = I \times R,$$
$$I = E \div R$$
$$R = E \div I$$

When dealing with frequencies greater than zero (AC), we find that resistance is no longer sufficient to give a complete picture. An additional term known as "reactance" must be employed.

REACTANCE

Inductive Reactance

Inductive reactance (X_L) is that portion of total circuit reactance which is provided by coils, chokes, and transformer windings. Any device in which wire is wound circularly around some type of core is an inductor. Inductors are current devices. Inductive reactance (X_L) increases as frequency increases — thus, an inductor passes low frequencies more easily than high frequencies. The reason for this is due to the fact that current flowing through the wire in an inductor generates a magnetic field about the inductor; the intensity of the magnetic field determined by the value of current, and the direction of the field determined by the direction of current flow. For a **constant** (DC-zero frequency) value of current, the intensity and direction of the magnetic field are **constant.** As a result, current flows easily through the inductor, since the inductor appears, to the current, to be nothing more than a length of wire. Magnetic fields, by nature, do not like to change, and when they do change, they do so slowly. Thus, in order for an inductor to conduct a **changing** (alternating) current, the magnetic field **must change** as the magnitude and direction of current change. Clearly, the magnetic field can change more easily at low (slow rate of change) frequencies than at high (high rate of change) frequencies. Therefore, the inductive reactance, X_L, in ohms, of a circuit, increases with both frequency and the value of the inductor (value of inductor given in "Henrys").

Expressed in Equation form:

$X_L = 2\pi FL$, where
X = Reactance in ohms
F = Frequency in cycles
L = Inductance in Henrys
$\pi = 3.14159\ldots$

Capactive Reactance

Capactive Reactance (Xc) is that portion of total circuit reactance caused by capacitance. Any time that two conducting surfaces are placed parallel to each other and are separated some small distance by a non-conducting substance — the result is capacitance. This is exemplified by the circuit component known as a capacitator. Capacitators are voltage devices. Capactive reactance (as opposed to inductive reactance) decreases as frequency increases. Therefore, a capacitator tends to pass high frequencies more easily than low frequencies. To understand this, remember that a capacitator is simply two parallel conductors separated by a non-conductor. Therefore, it is basically an open circuit, current cannot flow through it. At DC (zero frequency) capacitor acts simply as an open circuit and consequently blocks a DC current or voltage level.

When voltage is applied to a capacitator, an electric field is generated between the two conducting surfaces — this is what occurs when a capacitator "charges." Electric fields, like magnetic fields, do not like to change in intensity, but will do so slowly. Thus, if a changing voltage (frequency greater than zero) is applied to one side of a capacitator, the electric field in the capacitator resists change and in order to maintain a constant intensity between the two conducting surfaces, pulls the other side of the capacitator along with the first side. Thus, a changing voltage applied to one side of a capacitator appears on the other side and causes a corresponding current to flow in the far side of the circuit (no current flows through the capacitator). Since the electric field has more time to change at low frequencies, the output of a capcitator follows the input better when frequency is high. Thus, we say that as frequency increases, Xc decreases. The actual value of Xc, in ohms, is inversely proportional to the value of capacitance (measured in "Farads") and the frequency.

Expressed as an equation;

$$X_C = \frac{1}{2\pi FC}$$

Where X_C = Capacitive Reactance in Ohms
F = Frequency in cycles
C = Capacitance in Farads
$\pi = 3.14159\ldots$

IMPEDANCE

The AC Counterpart to DC resistance is Impedance. Impedance is denoted by the symbol Z, and is equal in series circuits, to $Z = \sqrt{R^2 + X_T^2}$

Where Z = Impedance in ohms
R = Resistance Component in Ohms
X_T = Reactance in Ohms
Note: $X_T = X_L - X_C$

for Parallel Circuits

$$Z = \frac{RX_T}{\sqrt{R^2 + X_T^2}}$$

in The parallel circuit case,

$$X_T = \frac{X_L \times X_C}{X_L - X_C}$$

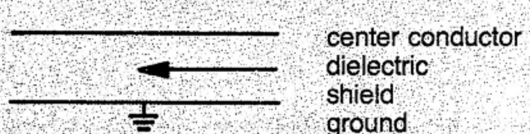
also:

Ohms law applies to impedance as it does to resistance

$$E = I \times Z; \quad I = E \div Z; \quad Z = E \div I$$

CABLE AS A CAPACITOR

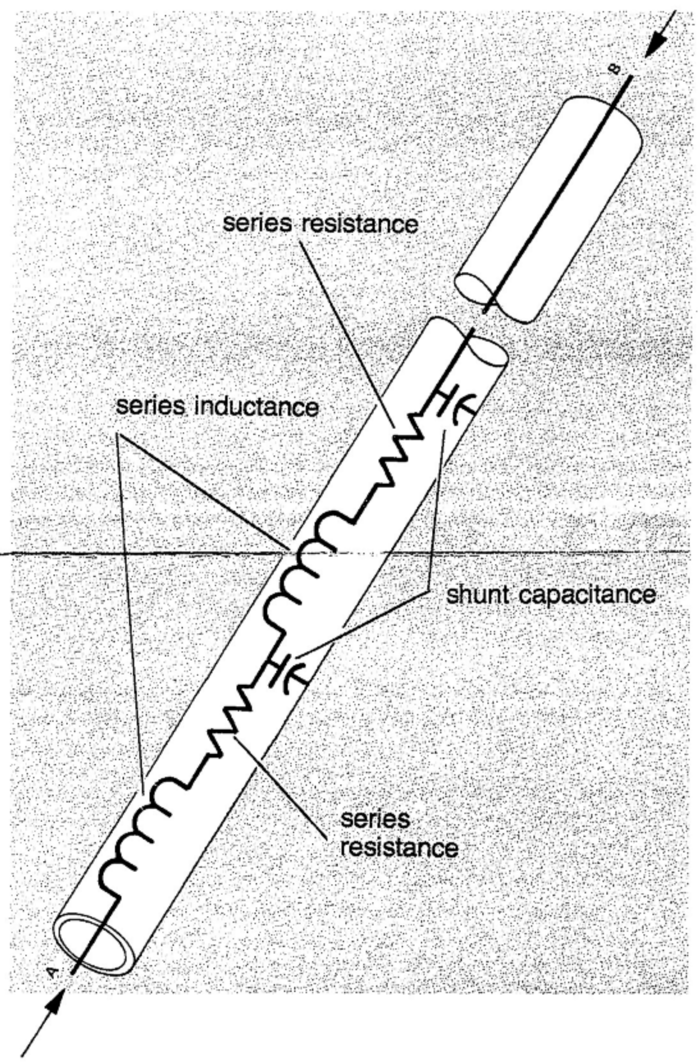
Since the outer shield is at ground potential, and the center conductor is at some potential other than ground, we can now display the components of a cable as a capacitor with the shield at ground potential, the center conductor at some other potential, and the two separated by a dielectric.



When we charge this capacitor from some voltage source, remove the voltage source, and check the voltage at some time after the removal, we will find that there is some voltage still remaining, but a lesser quantity than that with which we started. This indicates that there was some leakage between one plate (the center conductor) and the other plate (the shield). This particular leakage is called dielectric [illegible]s.

CABLE AS AN INDUCTANCE

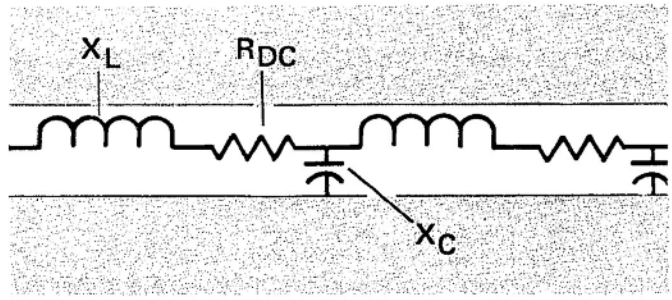
The conventional symbol for an inductance is a coil. If we straighten it out into a single line, it will still have inductance because of the flow of current through it. In the cable, then, we have such a single line in our center conductor. When we go from point A to point B, the center conductor is a series inductance, but it is not a single series inductance, and therefore, in any transmission line going from point A to point B, there will be an infinite number of inductances. As we have shown before, the center conductor and outside shield, with the dielectric material between them, will form a capacitor. This capicator is a shunting capacitor from center conductor to ground. Hence, we can add to our electrical equivalent of a piece of coaxial cable a series of shunting capacitors from the center conductor to ground, so that the representative picture becomes a capacitor at one end of a cable followed by an inductance, another shunting capacitor, another inductance and so on to the shunting capacitor at the other end of the cable.



Coaxial Cable

The impedance of the cable may now be determined from the following

$$Z\ cable = R_{DC} \times X_L + X_C$$
$$= R_{DC} + 2\pi FL + \frac{1}{2\pi F_C}$$



Next month we will examine the effects of these reactances in respect to varying frequencies applied.

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Technical Topics

Coaxial Cable
PART TWO

Coaxial Cable

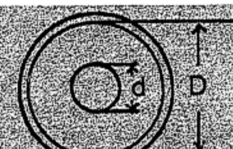
In the last issue we examined a section of coaxial cable as to its component inductance and capacitance. To this point the math is rather straightforward. Beyond what has been presented, things get somewhat more complicated and the derivation of the following from the foregoing requires an understanding of differential equations and is beyond the scope of this series. Rather I will state without proof that the characteristic impedance of a coaxial cable is also defined as:

$$Z_o = \sqrt{\frac{L}{C}}$$

Where L = Inductance in Henrys/unit length
C = Capacitance in Farads/unit length

Since these parameters are entirely dependent upon physical construction, we can also express the impedance of coaxial cable as:

$$Z_o = \frac{138}{\sqrt{E}} \log_{10} \frac{D}{d}$$



Where E = Dielectric coefficient
D = Inside diameter of the outer conductor
d = outside diameter of the inner conductor

As a result, Coaxial Cable of 75 ohms impedance may have various center conductor diameters and outside diameters.

Coaxial Cable

ATTENUATION IN COAXIAL CABLE

As an RF signal propagates along a coaxial line, its level is reduced. This attenuation is a FREQUENCY dependent phenomena. Since the attenuation is a function of frequency, the attenuation per length *must* be stated at the HIGHEST frequency at which the cable will be used. A given cable may be specified as 1.8dB/100ft at 216 MHz. The frequency dependence of the cable is expressed as:

$$\Delta A_O = \sqrt{\frac{F_2}{F_1}}$$

Where ΔA_O = Attenuation change factor
F_1 = Highest frequency
F_2 = lowest frequency (or frequency of interest)

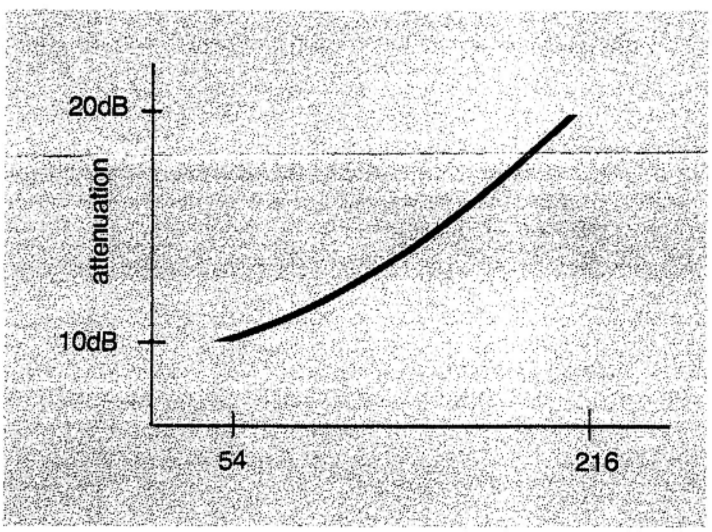
In our example: if the cable is 1.8dB/100 ft at 216 MHz; what is the attenuation at 54 MHz?

$$\Delta A_O = \sqrt{\frac{F_2}{F_1}} = \sqrt{\frac{54}{216}} = \sqrt{\frac{1}{4}} = \sqrt{\frac{1}{2}}$$

Multiply $\Delta A_O \times$ by the given attenuation
Attenuation 1.8dB $\times \Delta A_O$ (½) = .9dB/100 ft.

From the above equations, the attenuation at any frequency can be determined.

This frequency dependence causes system "TILT". In a "20dB" span, only the highest frequencies are attenuated by 20dB. In a 12 channel system, this would be Channel 13. The low frequency signals, traveling the same distance are attenuated only 10dB or one-half as much.



TEMPERATURE EFFECTS

The previous section of information is correct at any given temperature. Cable attenuation is also a function of temperature. The attenuation change is .125%/F°. To see the effects of temperature on a system, let's assume 50 miles of trunk only. Trunk cable will typically have 1dB/100 ft attenuation at 216 MHz. In this 50 miles of trunk there is:

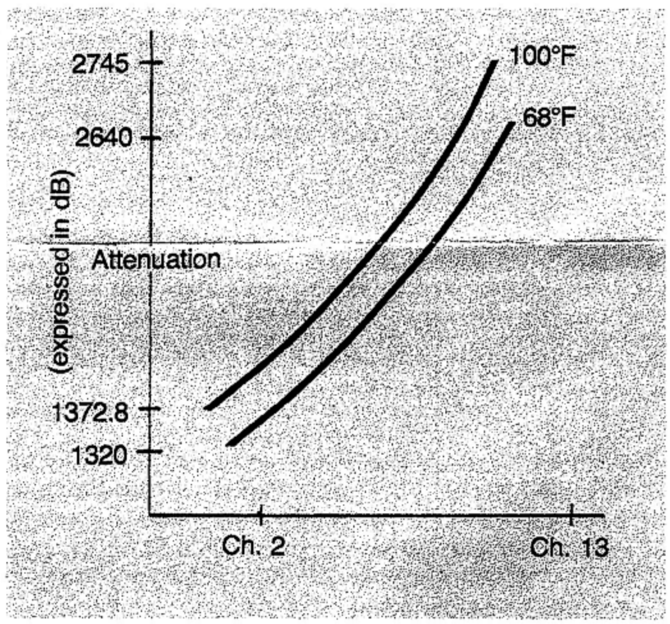
$$50 \text{ mi.} \times 5280 \frac{\text{Ft.}}{\text{Mi}} \times 1 \frac{\text{dB}}{100 \text{ Ft.}}$$

= 2640dB of cable (Channel 13)

If the mean temperature is 68°F, then the system should function well. But . . . if the temperature rises to 100° F, the attenuation increases by:

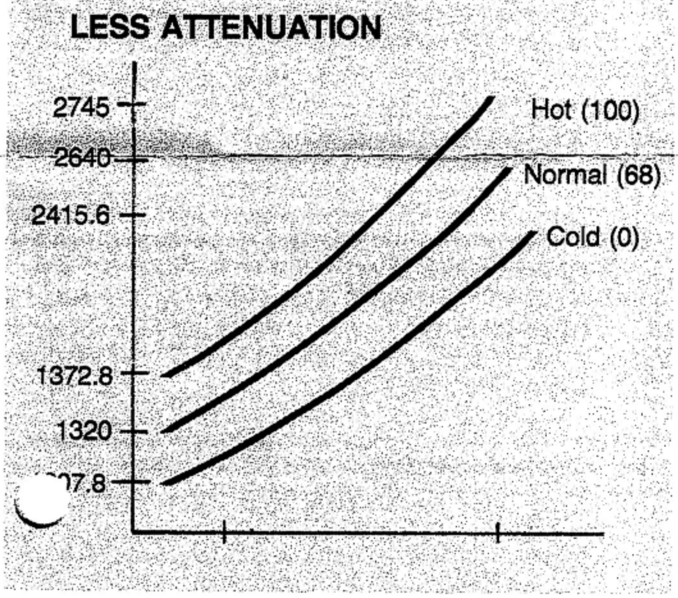
(100°F − 68°F) × .125%/°F = 4%

4% × 2640dB = 105.6dB More Attenuation (Channel 13) for a total of 2745.8dB. At Channel 2 the original attenuation was 1320dB and the same 4% change affects this attenuation. The Channel 2 change is 52.8dB.



As we encounter cold temperature, the attenuation *decreases* by the same .125%/°F. In our 50 mile system, the change at a temperature of 0°F is (+68-0) × .125% = 8.5%.

(Channel 13) 2640dB × 8.5% = 224.4dB
(Channel 2) 1320dB × 8.5% = 112.2dB

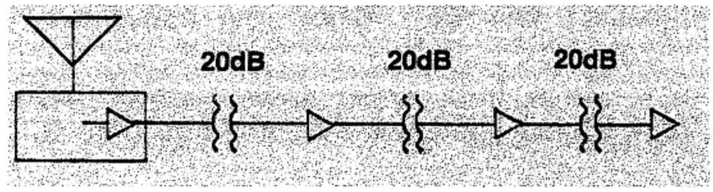


But notice that not only did the total attenuation change dramatically; the slope or tilt changed as well.

	Attenuation Channel 13	Attenuation Channel 2	Tilt
100°F	2745 dB	1372.8dB	1372.8dB
68°F	2640 dB	1320 dB	1320 dB
0°F	2415.6dB	1207.8dB	1207.8dB

Note that the tilt changed 52.8dB from normal to hot and 112.2dB from normal to cold and a total change from cold to hot of 165dB.

We can reduce these to smaller segments quite easily. In a system spaced at 20dB, the amplifiers will be about 2000 ft apart. In our 50 mile trunk, there will be 131 amplifiers. To find the net effect per amplifier, divide each element calculated above by 131.



	Ch. 13	Ch. 2	Tilt	Ch.13	Ch.2	Tilt	Ch.13	Ch.2	Tilt
100°	20.8	10.4	10.4						
68°	20	10	10						
0°	18.3	9.15	9.15		etc.			etc.	
ΔA 100°	2.5dB	1.25dB	1.25dB						
0°									

So the net change PER SPAN is 2.5dB of attenuation and 1.25dB of Tilt.

This means that in hot weather, amplifier INPUT LEVELS will be lower than normal, and in cold weather, these input levels will be higher than normal. If the system were constant gain (all manual stations), then the output levels would fluctuate with the input levels. At the end of our small example above (3 amplifiers), the output change would be 7.5dB at Channel 13 and 3.75dB at Channel 2.

In the winter then, the system would be driven into cross modulation and triple beat, and in the summer, the system would have carrier to noise problems. . . . UNLESS we go to each amplifier and adjust its gain to compensate for the cable changes. This is a rather laborious task as temperatures may vary sufficiently from daylight to dark to cause serious problems. Some means then needs to be discovered to compensate the system gain to temperature automatically; hence the AGC amplifier. But AGC at a single point only partially solves the problem. It does nothing to change the slope. AGC alone without slope control only delays the buildup in terms of cascade length. . . . It's like the commercial . . . "sooner or later we're gonna getcha!" Modern amplifiers utilize both automatic gain and automatic slope control circuitry. Since this segment is directed to cable and its parameters, we will not pursue AGC/ASC further at this time.

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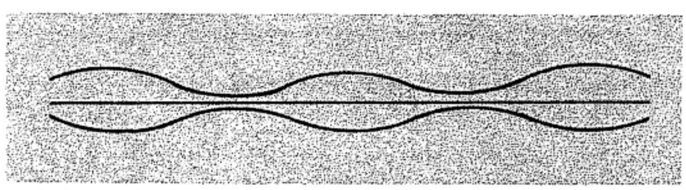
Coaxial Cable
PART THREE

Coaxial Cable

REFLECTIONS

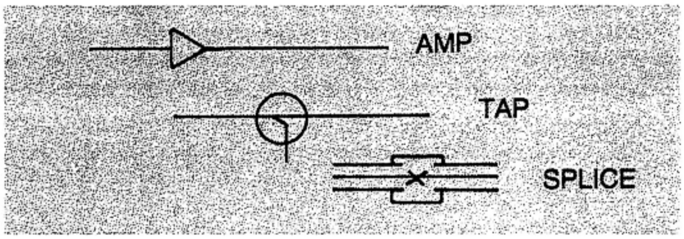
PERIODICITY

If in any CATV transmission line, some type of discontinuity appears at regular intervals, a condition known as periodicity arises. A discontinuity can arise in a cable during manufacture if the cable machine causes a slight compression in the cable. Since the dimensions of the cable have been changed at that point, the characteristic impedance is changed.



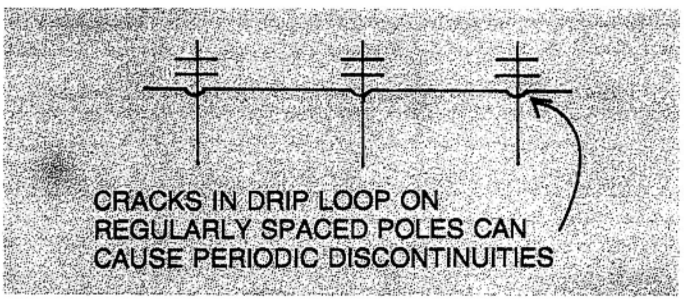
A discontinuity also occurs whenever an amplifier is inserted into the transmission line and also whenever a tap is inserted. Thus, any time there is any interruption of any sort in a transmission line, a discontinuity or characteristic impedance change (of some magnitude) occurs at the point of interruption.

Coaxial Cable



Due to the sudden change in characteristic impedance, some of the signal power in the transmission line is reflected. Reflected power creates what is known as standing waves along the transmission line.

If the discontinuities occur at regularly spaced intervals, then clearly, this distance between discontinuities is a half-wavelength for some frequency.



Thus, for this frequency and for all integral (1,2,3,4. . .) multiples of this frequency, the standing waves caused by reflected power are in phase and, therefore, add. The result is that most of the power at these frequencies is reflected and, therefore, any signals at these frequencies are greatly attenuated. If, for example, these discontinuties occured at a distance which was half an electrical wavelength for television Channel 6, then Channel 6 could very well "mysteriously" disappear from a CATV system even before the first subscriber location was reached.

Periodicity can be prevented by careful inspection of all cable before installation, and by locating amplifiers and taps at random (rather than regular) distances from each other. Sweep testing of cable prior to installation will detect structural problems by means of bad return loss readings. For a more complete discussion of this subject review T.T.T. issues on Return Loss, Part I and Part II.

VELOCITY OF PROPAGATION

The electrical wavelength of any sinusoidal wave is the physical distance travelled by an increment of electromagnetic energy during the time taken to complete one sinusoidal cycle. As frequency (cycles per second) increases, the time taken to complete one cycle decreases, and, therefore, the electrical wavelength decreases. Thus, the electrical wavelength (in feet) of a signal equals the velocity of the energy (in feet per second) divided by the signal frequency (in cycles per second). The velocity at which the energy travels is known as the "velocity of propagation."

In free space, the velocity of propagation for electromagnetic energy is the speed of light. In all other transmitting media, the velocity of propagation is less than the speed of light. Clearly, as the velocity of propagation decreases, the electrical wavelength decreases.

The velocity of propagation (Vp) is different for different types of transmission lines. Vp is expressed as a percentage of the velocity of light. Thus, for free space Vp is 100%, Vp for twinlead is considerably less, and Vp for coaxial cable is considerably less still.

$$\text{Wavelength in free space (ft.)} = \frac{984}{f\ \text{MHz}}$$

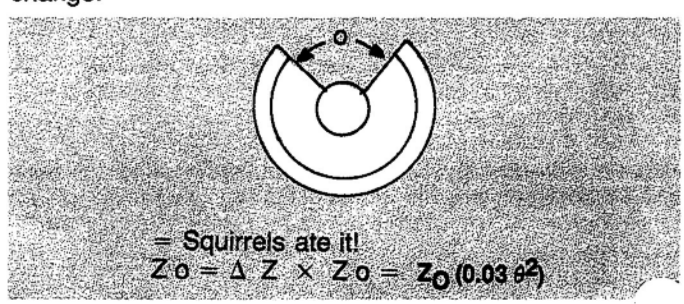
$$\text{Wavelength in cable (ft.)} = \frac{984\ (Vp)}{f\ \text{MHz}}$$

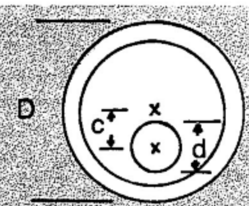
Typical Vp for various types of cable

Cable	Dielectric	Vp
RG 59	.66	Polyethelyene
RG 59	≈ .84	Polystyrene
RG 6	.66	Polyethelyene
RG 11	.66	Polyethelyene
.5 dia	≈ .84	Polystyrene
.5 dia	≈ .87+	Gas injected
.5 dia	≈ .90	Air dilution

THE IMPORTANCE OF GOOD CABLE INSTALLATION PRACTICES

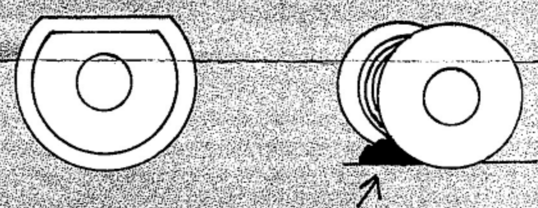
It is very important to maintain care in the construction of a cable system. As an example, during the course of construction, if we lay a cable along the ground, and a vehicle runs over the cable, it will flatten out the bottom of the cable. Thereupon, the space from center conductor to the outside shield will be changed, which will change the C without changing the L, and therefore, will change the 75-ohm impedance. Or we may kink the cable, in which case, the same thing will happen since distance from center conductor to outside shield will be reduced and the capacity will change without any change in L. Therefore the impedance will change.





= too sharp bend or faulty dielectric

$$Zo = \frac{60}{\sqrt{E}} \text{Cosh}^{-1} \frac{1}{2}\left[\frac{D}{d} + \frac{d}{D} - \left(\frac{4C^2}{dD}\right)\right]$$



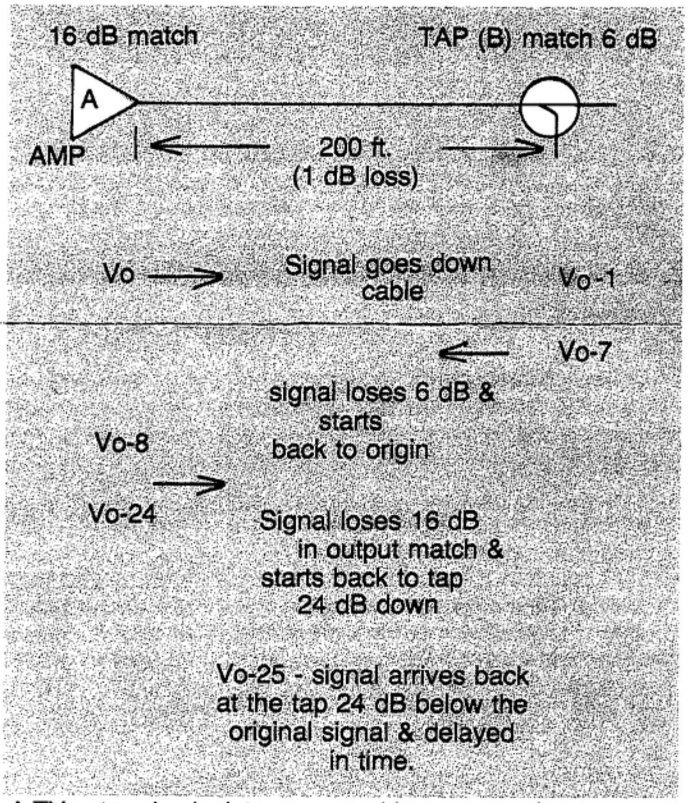
= Bad lashing machine! Car ran over it!
Bad spool handling
Zo = ?

THE EFFECT OF MOISTURE IN A CABLE

The presence of moisture in the cable is one of the things that the entire cable industry fights. The presence of moisture inside the cable will actually change the K (dielectric constant) of the cable and, therefore, the capacity will change once again without any change in L. Again, this will change the impedance. It is apparent, then, that it is quite easy to change the C of the cable but very difficult to change its L. Therefore we have to be very careful in maintaining the relationship between the L and the C in order not to upset our 75 ohm impedance. This becomes important in our consideration of the cable, because, every time we produce a mismatch in the cable, we find that some of the power which we normally would expect to continue down the lines does not, but instead, returns from the point of mismatch in the direction from which it came. We define the returning signal at point of mismatch by the term "return loss." As an example, if the return loss from the mismatch were 20 dB, this could indicate that the signal being reversed in direction and returning from whence it came, would be 20 dB below the signal that arrived at the mismatch in the first place. It becomes obvious, then, that the amount of signal available to continue down the line must be reduced by the amount of the signal reflected. The presence of mismatches, then, robs us of signal power. We may find it necessary to add additional amplifiers to our cascade in order to make up for this accumulation of mismatch losses. This is a minor problem compared to the problem which arises because of the presence of two mismatches in a single length of cable.

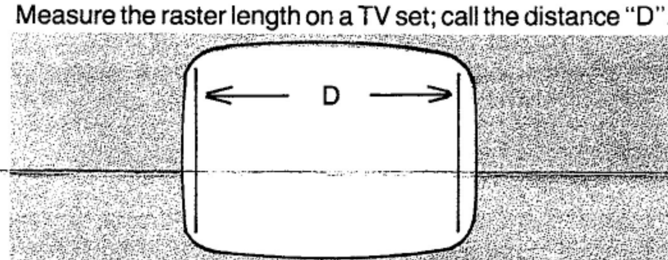
GHOSTS

If a cable has more than one mismatch or if the mismatch is physically close to even a moderate match, ghosts can be generated. Consider the following example:

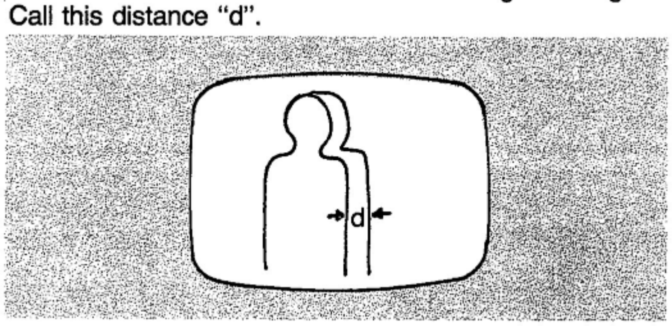


A TV set and calculator can provide an approximate space for the ghost producing discontinuties.

Measure the raster length on a TV set; call the distance "D".



Measure the distance from the desired image to the ghost. Call this distance "d".



Since the horizontal rate for colorcast is 15,734 KHz., the line time is 63.35 s. The retrace is about 11 s, so the active time per line is 52.55 μs or so. Measuring the "d" and "D" distances and solving the following equation gives the ghost *round trip time! – Subtracting 11 μs for the invisible retrace,*

$$\frac{D}{d} = \frac{52.55}{X} \quad \text{or} \quad X = \frac{d}{D} \times 52.55$$

X is time in μs. To convert to distance we need to know the signal velocity in cable. The signal propagates at 186,292 mi/sec. in free space, and at less velocity in cable. The units of mi/sec. are somewhat unwieldy, so let's convert to ft./ s as follows:

$$\frac{186{,}292\ \text{mi}}{1\ \text{sec}} \times \frac{5{,}280\ \text{ft}}{1\ \text{mi}} \times \frac{1\ \text{sec}}{1{,}000{,}000\ \mu s} = 983.62\ \frac{\text{ft}}{\mu s}$$

To find the speed in cable, multiply by the velocity of propagation (Vp) of the cable your system uses.

$$\text{Example: } Vp = .94 \times \text{speed} = .94 \times 983.62 = 924.60\ \frac{\text{Ft}}{\mu s}\ \text{in cable}$$

Now we know the number of feet the signal travels, and the amount of time for the ghost (round trip). Multiply the found numbers and divide by 2 to get the one way distance. In the example given, if the screen were 20″ wide, and the ghost image spaced 1/6″ inches, the distance in cable would be 200 ft. See example given above. Once the distance is found, consult the system maps for devices which are spaced the appropriate distance apart. And remember, ghosts do not propagate "upstream around amplifiers, only downstream." This system yields approximations only and should not be considered as exact.

Next month we begin a cable dictionary.