Broadband Library Winter 2020
Full Version

Coaxial Cable Testing
In my summer and fall columns we reviewed some of the research conducted by Oliver Heaviside (1850 to 1925), an English physicist, engineer, and mathematician whose research helped define our industry. If you've not read those two columns you may wish to before proceeding. They addressed the following transmission line characteristics: resistance, reactance, impedance, series resistance and conductance, shunt capacitance and conductance, dielectric loss, RF attenuation, and characteristic impedance.

Before we can review testing procedures for coaxial cable (transmission lines) we have a few remaining parameters to address. They are velocity factor, wave motion, reflections and standing waves.

Velocity Factor
Velocity factor (V_F) of a cable is the speed at which an electrical signal can propagate through the cable (transmission line) relative to the speed of light. In a vacuum the V_F would be 1. If the V_F is 0.7 the signal travels through the cable at .7 times the speed of a light as compared to a cable with a vacuum dielectric.

The V_F of a cable can be calculated by the formula $V_F = 1/\sqrt[2]{\varepsilon}$ where ϵ is the dielectric constant of the dielectric material used in the cable. The velocity factor in a coaxial cable is therefore determined by the dielectric material in use. There are a number of materials that are used as a dielectric. Each of these dielectrics has a different dielectric constant and thus a different velocity factor. Common values for the dielectric constant depending on the dielectric material are 2.3 for polyethylene (PE) yielding a V_F of .66, and 1.3 for modern foam polyethylene yielding a V_F of .87.

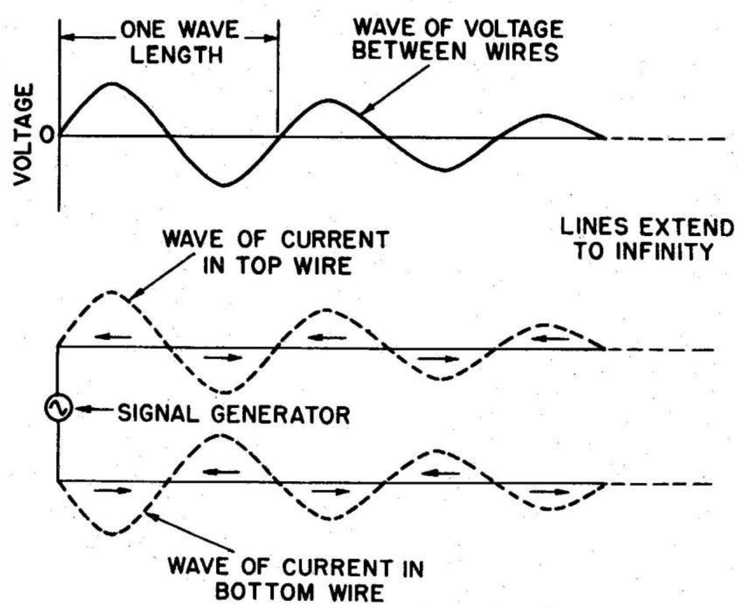


Figure 1 Traveling Waves

Before we review standing waves, we need to examine wave motion on a perfect transmission.

Wave Motion on an Infinite Line
Figure 1 shows sine waves of voltage and current that travel at high speed along a two-wire transmission line of infinite length. Because this is a line of infinite length, no reflections occur; therefore, the voltage and the current are in phase with each other everywhere along the line. Because of line losses, the curves diminish in amplitude as the waves progress along the line. If a voltage is impressed on a line such as this, an electric field will be established between the wires. Likewise, current will flow in the wires, and a magnetic field will be established around each wire. These two fields constitute an electromagnetic wave that travels down the wire at a velocity somewhat less than that of light. Figure 1 illustrates what would happen if the voltage and current were stopped for an instant in time. An instant later all waves would have moved to the right a slight amount. In this figure the waves are stopped at the instant when the alternating source voltage has just reached zero.

Traveling waves exist on the line because it takes a finite amount of time for them to propagate down the line. The characteristics of a theoretically infinite line are helpful and can be summarized as follows.

1. E and I are in-phase along the entire length of line.
2. The ratio of E to I is constant along the entire length, and relates to the characteristic impedance (Z_O).
3. The input (source) impedance is equal to the line characteristic impedance (Z_O).
4. Since E and I are in-phase, the line operates at maximum efficiency.
5. Any line length can be made to *appear* as infinite if it is terminated in its characteristic impedance.

Line Reflections
A signal traveling along an electrical transmission line will be partly (or wholly) reflected back in the opposite direction when the traveling signal encounters a discontinuity in the characteristic impedance of the line, or if

the far end of the line is not terminated in its characteristic impedance. This can happen, for instance, if two lengths of dissimilar transmission lines are joined together.

Reflections cause several undesirable effects including inefficient signal power transfer and modified frequency response. Reflections cause standing waves to be set up on the line. Conversely, standing waves are an indication that reflections are present. There is a relationship between the measures of reflection coefficient and standing wave ratio.

In telecommunications and transmission line theory, the reflection coefficient is the ratio of the *complex* amplitude of the reflected wave to that of the incident wave. The voltage and current at any point along a transmission line can (always) be resolved into forward and reflected traveling waves given a specified reference impedance $Z_{0,}$, usually the characteristic impedance of the transmission line involved. The reflection coefficient (using a Greek capital gamma) is defined as the complex ratio of the voltage of the *reflected* wave ($E^{reflected}$) to that of the *incident* wave ($E^{forward}$).

$$\Gamma=\frac{E_{refl}}{E_{fwd}}$$

The voltage standing wave ratio (VSWR) is determined solely by the absolute magnitude of the reflection coefficient:

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

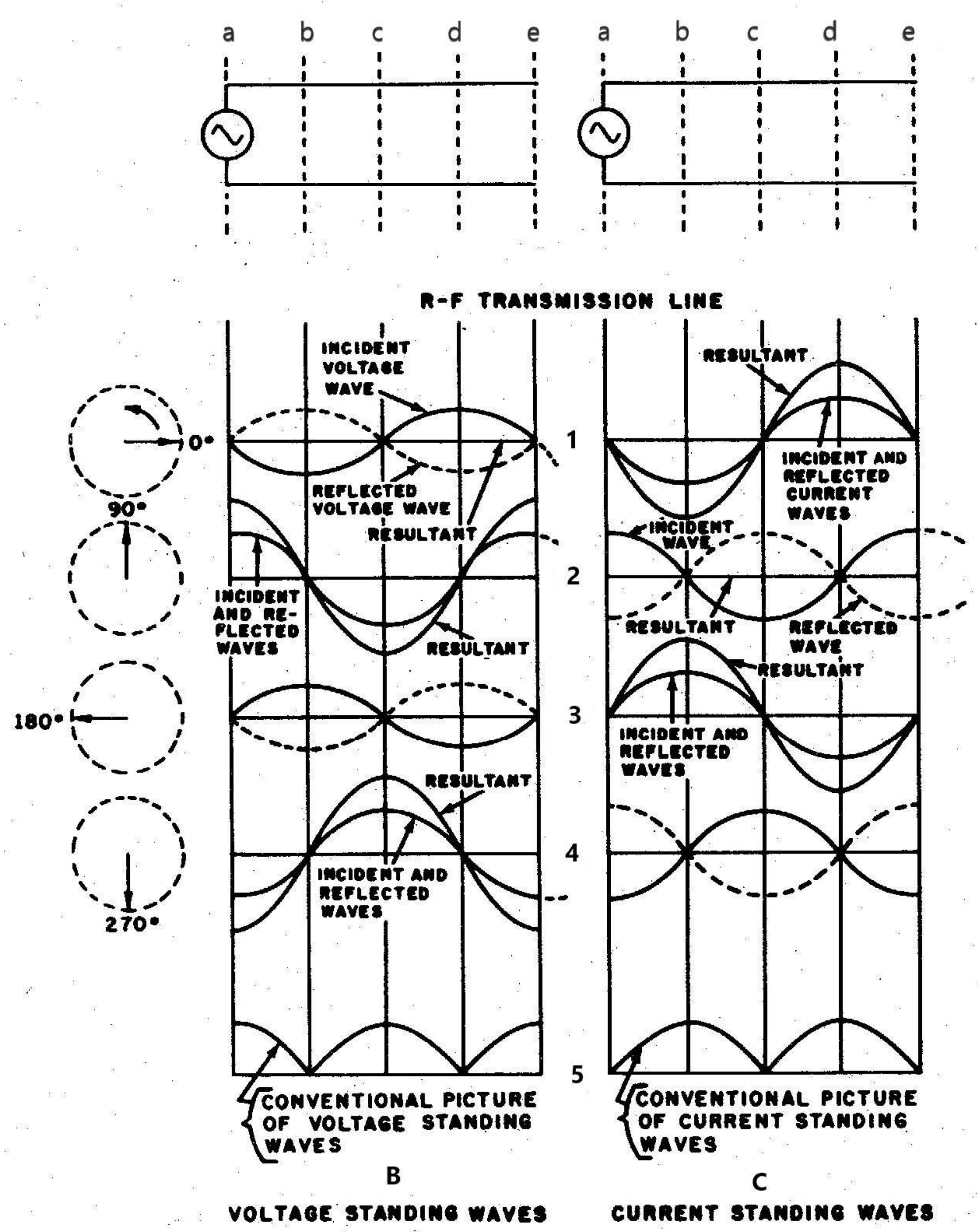
Along a lossless transmission line of characteristic impedance Z_0, the SWR signifies the ratio of the voltage (or current) maxima to minima (or what it would be if the transmission line were long enough to produce them). The above calculation assumes that Γ has been calculated using Z_0 as the reference impedance. Since it uses only the magnitude of Γ, the SWR intentionally ignores the specific value of the load impedance Z_L responsible for it, but only the magnitude of the resulting impedance mismatch. SWR remains the same wherever it is measured along a transmission line (looking towards the load) since the addition of a transmission line length to a load Z_L only changes the phase, not magnitude of Γ.

Return loss is the loss of power in the signal returned/reflected by a discontinuity in a transmission line. This discontinuity can be a mismatch with the terminating load or a device inserted in the line. It is usually expressed as a ratio in decibels (dB);

$$RL=10\log 10\left(\frac{Pi}{Pr}\right)$$

where RL is the return loss in dB, Pi is the incident power and Pr is the reflected power. Return loss is related to both standing wave ratio (SWR) and reflection coefficient (Γ). Increasing return loss corresponds to lower SWR. Return loss is a measure of how well devices or lines are matched. A match is good if the return loss is high, and results in lower insertion loss. Return loss is normally used in modern practice in preference to SWR because it has better resolution for small values of reflected (standing) waves.

Figure 2 illustrates the formation of standing waves on *an open end transmission line one wavelength long*. The left and right sides of Figure 2 are divided vertically, with the left side depicting the formation of *voltage standing waves* (**B** at the bottom), and the right side the formation of *current standing waves* **C**. The letters **a** through **e** along the top mark quarter wavelength sections of the incident and reflected waves, and the numbers **1** through **4** down the middle mark the 0, 90, 180 and 270 degree phase rotation points of the incident and reflected signals. Number **5**, bottom left center, depicts the resultant voltage standing wave.



It should be noted that all of the waveforms shown in Figure 2 are instantaneous values that exist along a transmission line. These curves are unlike conventional sine waves in which distance along the X axis represents the time domain, proceeding from left to right. Instead, these curves represent instantaneous values of current or voltage as they exist all along the line *at the same instant in time*.

Voltage Standing Wave Formation

Assume that part of Figure 2-**B** (voltage standing waves), the generator voltage vector has gone through at least two complete revolutions so that the voltage wave has had time to travel down the line and return to the generator end.

Figure 2: Formation of standing waves

The waveforms are stopped in time in this figure at the instant that the generator voltage vector is at the zero position.

It can be observed that the initial voltage wave is reflected at the output end of the line in phase with the voltage wave that would have continued along the line in the original direction of travel if the line had been longer. For example, the dotted waveform extending slightly beyond the end of the line in row **1** indicates that the incident wave would have started going negative. Therefore, the reflected wave will start back as a negative value. At the instant in time being considered here the incident and reflected wave add vectorially to give a zero value resultant wave.

Ninety degrees later (in row **2**) the incident and reflected waves are in phase and add vectorially to give the resultant voltage wave, as shown. At 180° (row **3**), the resultant voltage is again zero; and at 270° (row **4**), the incident and reflected waves are once again in-phase and add (as vectors) as shown.

Next, consider the voltage variations across the (one wavelength) line that occurs with respect to position at certain locations along the line. At column **a** (along the top of the figure), the voltage is zero (row **1**), then maximum in one direction (row **2**), then zero again (section **3**), and finally maximum in the other direction (row **4**). A suitable voltage detection device (beyond the scope of this article) located at **a**, **c**, or **e** will indicate voltage peaks (points of maximum voltage); and at **b** and **d** the device will indicate voltage nodes (points of minimum voltage).

Standing waves of voltage are shown in row **5** of Figure 2 (bottom waveforms). This curve represents effective values of voltage at the various points along the line. These values are actually the *effective values* of the sinusoidal voltage variations occurring across the line at points where the measurements are being made. Thus, at column **c** the voltage will be zero at one instant of time (row **1**), then it will build up to a maximum with one polarity (row **2**), then it will become zero (row **3**), and finally it will build up to a maximum with the opposite polarity (row **4**).

Common Coaxial Testing Methods

Common coaxial testing methods include use of a time domain reflectometer (TDR), RF loss measurements at specific or multiple frequencies, DC resistance, adaptive equalizer activity (in QAM signals), return loss and standing waves. Only return loss and standing waves will be addressed in the remainer of this article.

Actual Measurements

For my measurements I used a medium quality Siglent spectrum analyzer (50 ohm input impedance) with an internal precision tracking generator, along with an external return loss bridge of 'fair' quality. If you wish to know more about the methodology behind frequency response and return loss measurements, you'll need to seek other articles by others or myself. My website contains several past articles on this subject.

The following measurements were performed on a length of RG-6U cable with a unknown discontinuity (measures as a partial short using resistance) towards the end of the run. I built a new home last fall (2019), and this partially shorted RG-6U cable run has remained unused since then. I've tried a TDR and a high quality leakage detector in an attempt to locate, to some degree of precision, the location of the damage so that I could open the ceiling for repairs. The TDR and leakage measurement methods both proved inaccurate. In my second measurement we'll use standing waves to attempt to pinpoint the location of the damage.

Return Loss Measurements.

See Figure 3. Here I have my tracking generator and spectrum analyzer linked using a return loss bridge. I normalized the trace to the top graticule to account for jumper cable and connector loss, matching pad loss, along with any small discontinuities at the source. I then attached a 75 ohm termination to the DUT (device under test) port on my RL bridge to establish a baseline for the cable test. Dynamic range is somewhat limited due to the required use of a matching pad (6 dB of loss in dynamic range) plus the limited quality of the return loss bridge in use. It is, however, adequate for these tests.

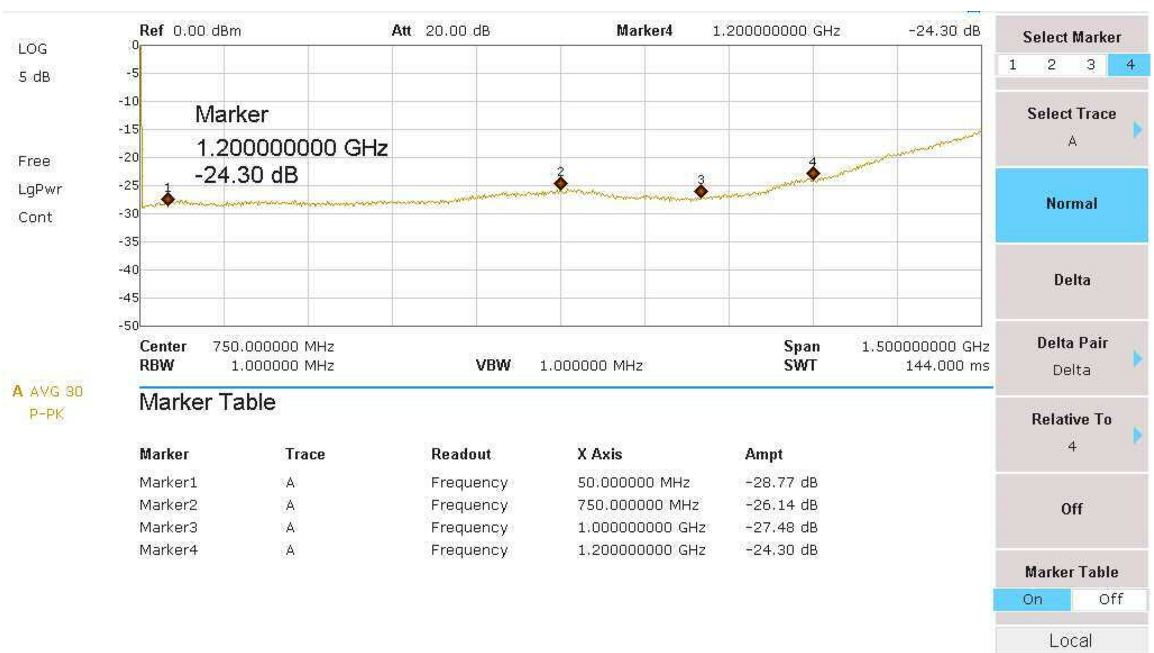


Figure 3: Return Loss with a 50–75 ohm matching pad on the DUT port

Note that the marker table values above show return loss as negative values; however return loss is always positive, assuming the incident wave is of greater value than the reflected wave.

Now examine Figure 4. We noted earlier that a higher return loss is desirable as it indicates less reflected power. The 24 to almost 29 dB return loss measured with a 75 ohm terminator has now dropped to 4 to 16 dB depending on frequency. Clearly there is a problem with this cable, and one that affects the entire frequency range.

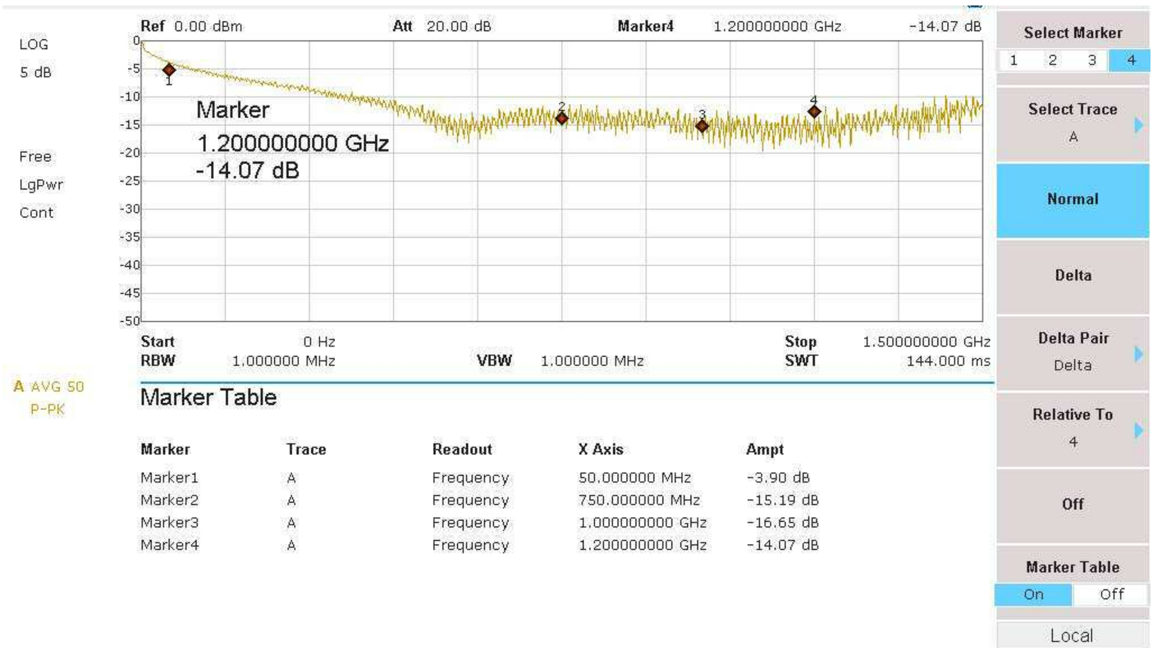


Figure 4: Return Loss on defective RG-6U cable run

Standing Wave Measurements.
As already stated, standing waves are created by the addition and subtraction of the incident and reflected waves at a given point on our transmission line. In Figure 5 we see the results of feeding my tracking generator output coupled through a 50 to 75 ohm matching pad into the defective cable, using a directional coupler to measure the forward and reflected signals. Peaks every 5.2 MHz can be clearly seen on the waveform. The relationship between the frequency between successive peaks, velocity factor, and distance to {the} fault are stated in the formula: $DTF = \frac{492 * Vp}{Dp}$ where DTF is distance to fault, V_P is the velocity factor, and D_P is distance between standing wave peaks in MHz. Using 5.2 MHz for the distance between peaks and .87 for V_P yields a DTF of 83.32 ft. I have that location marked on my basement ceiling and will provide feedback as to how well this method worked.

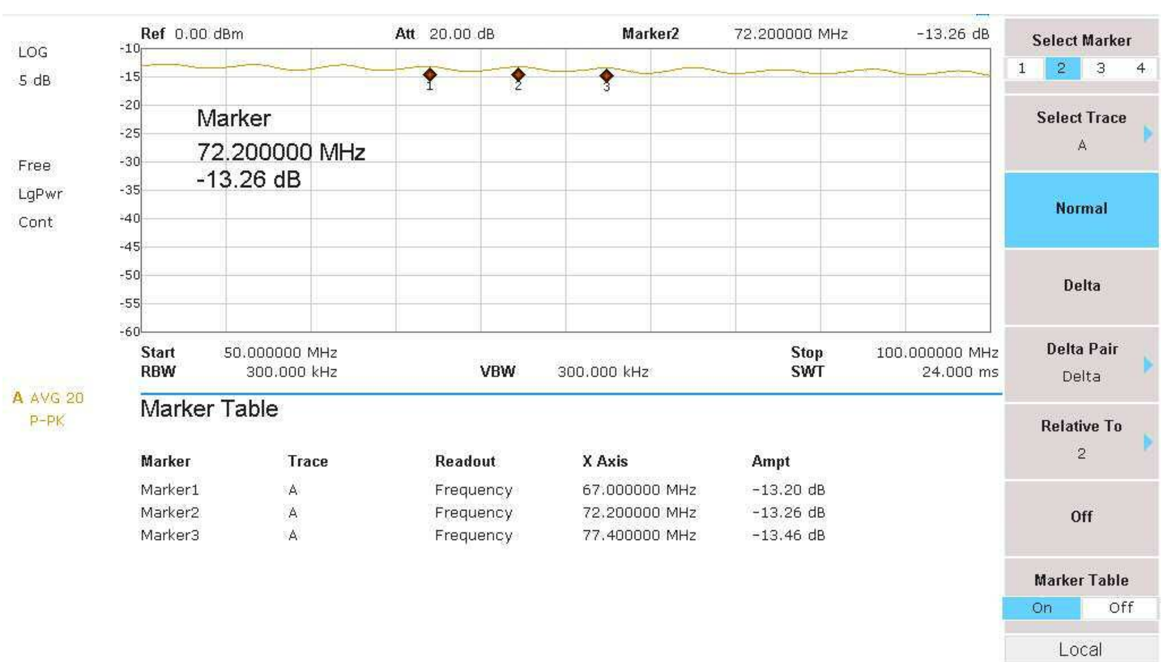


Figure 5: Standing waves on defective RG-6U cable run

Final Thoughts
In my past three articles I've sought to address many of the parameters associated with signal transport on transmission lines in general and coaxial cable more specifically. It is far more complex that one might expect at the onset, and we've only briefly addressed many of these concepts and parameters.

As a final observation, the standing wave method to measure distance-to-fault can be quite accurate, especially if successive peaks are measured at very low frequencies, especially in the return path. Using this method some years back during a return plant proof of performance led the local tech to within 6 ft of a buried cable fault (defective splice). He was duly impressed.