# TDR (Time Domain Reflectometry)

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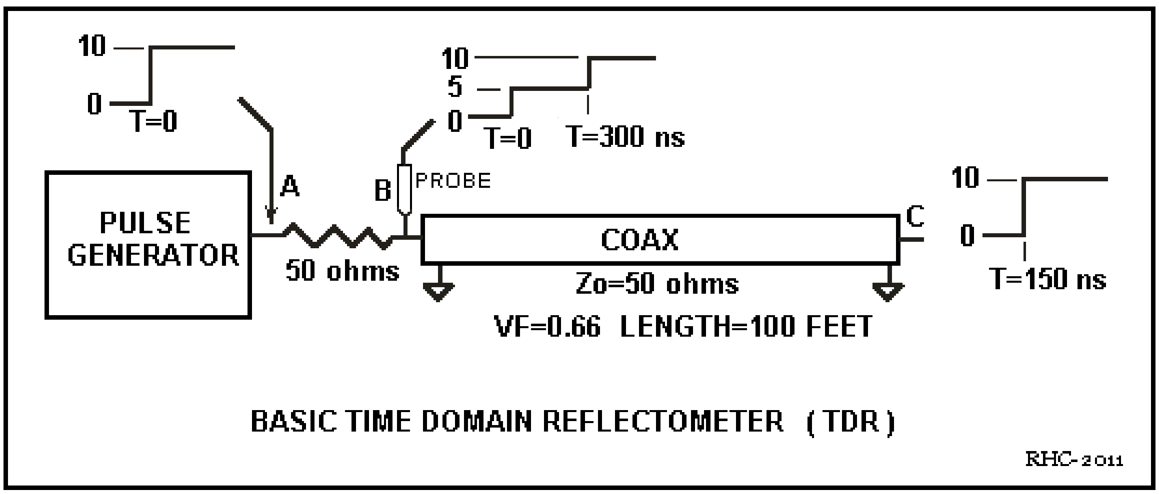
The TDR feature enables measurement of transmission line impedances and lengths even when they are not open or shorted at the far end. This is also very useful when two or more different types of transmission line are connected in series. For example, 50 ohms and 75 ohms. The distance to the antenna can be measured without having to disconnect the line from the antenna.

For many years TDR's have been built with analog pulse generators and oscilloscopes. This requires a wideband scope (or a sampling scope) but basically the system is straightforward. This was the only practical way to implement TDR before low cost powerful computers became available.




This diagram shows the basic components of a TDR. The test pulse has a rise time that is short compared to the times to be measured. Typically the pulse has a sharp leading edge and it is much wider than any time to be measured. The trailing edge of the pulse is not used. This is called a **step function**. The amplitude of the pulse is not critical since the measurements involve ratios. In this figure the amplitude is 10 volts. (It could be a low amplitude pulse too.)

The output of the pulse generator is a voltage source. The leading edge of the pulse steps up to 10V at time T=0 and the voltage seen at point A is always the same regardless of the load that is connected.

There is a resistor in series with the output of the pulse generator, typically this is 50 ohms. For this example, a piece of coax is connected to the output which has a characteristic impedance, Zo, of 50 ohms. This test coax is 100 feet long and it has a velocity factor of 0.66.

The scope is connected to point B. Keep in mind that at T=0, the coax looks like a 50 ohm resistor to the wave that is starting to travel down it. During the initial transient stage this value of Zo will apply until the wave has time to travel all the way to a discontinuity in the system and be reflected back. If there is no discontinuity and the wave travels down the line forever or is absorbed by a load resistor at the end, then the impedance at point B will continue to be Zo forever. In a typical case, a ideal 50 ohm coax terminated with an ideal 50 ohm resistor looks like 50 ohms at DC and at all RF frequencies. *In actual practice, loss in the coax and skin effect complicate things somewhat but we won't worry about that for now.*

The 50 ohm resistor in series with the generator output and the Zo of the transmission line form a voltage divider of 50 ohms and 50 ohms, so one half of the voltage appears at point B at T=0.

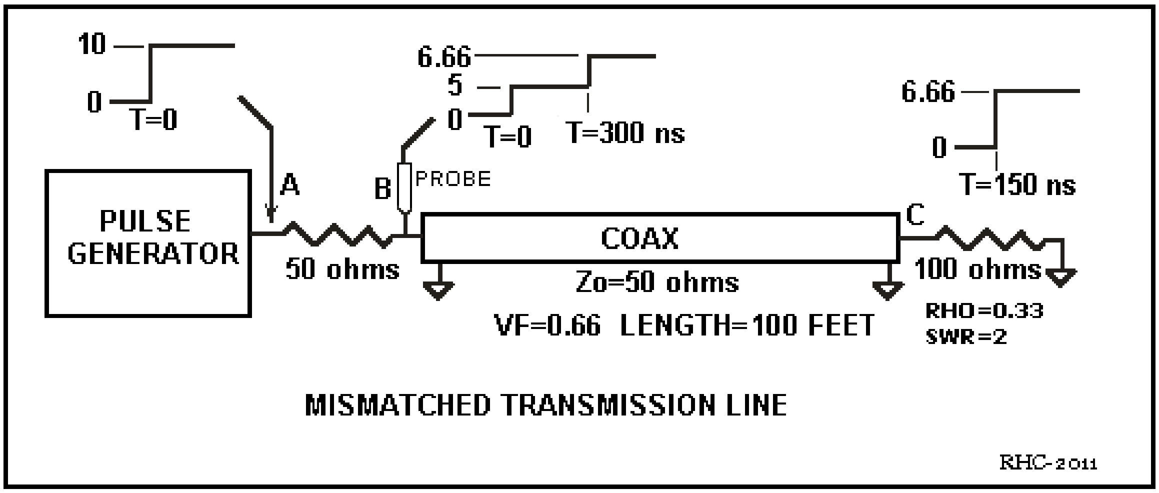
The wave would travel down the coax at the speed of light, which is about 1 foot per nanosecond, but the dielectric material in the coax slows it down. The **velocity factor** is the actual velocity of the wave through the dielectric divided by it's velocity if the coax did not have a dielectric (that is, the speed of light in air) . Typically this is in the range of 0.66 to 0.9, depending on the material used for the dielectric. The dielectric makes the line appear to be longer than it really is, that's why a quarter wave coax stub is shorter than a quarter wave length of the signal in air.

The voltage step in this example takes 150 nsec to travel down the coax to the open end. A scope probe at point C will see a step that is 10 volts high but it's delayed by 150 nsec with respect to the step seen at point A (the 50 ohm series resistor has negligible delay).

*Wait a minute, the voltage at point B was only 5 volts and now we have 10 volts at point C. How did that happen?* In fact, a scope probe placed anywhere along the coax will see the 5 volt step traveling down the line for the first 150 nsec. When it gets to the open end of the coax, the wave is reflected in phase and the 5 volt step now becomes 5 + 5 volts to form the 10 volt step seen at point C. Now, as we watch the signal travel back down the line, its amplitude is 10 volts. When the reflected wave reaches point B, the probe at point B sees 10 volts. It takes 300 nsec for the wave to travel down the line and back. The scope can measure this time which is two times the electrical length of the coax. If the velocity factor is known, then the physical length of the line can be calculated by multiplying the electrical length by the velocity factor.

The 50 ohm resistor in the generator is the same as the Zo of the test line, so there is no reflection at the generator and the final value seen at point B is 10 volts. It takes a short time (usually nanoseconds or microseconds) for the voltage to reach its final value. This time delay usually isn't a factor for ordinary radio communication . *For high speed data communication, it can be a factor when the delay is comparable to or even greater than the time interval between data bits.*

In this example, the wave at the open end of the coax was reflected in such a way that it was positive and it added to the incoming wave. The ratio of the reflected signal to the incoming signal is called the reflection coefficient. **Anytime there is a change in the impedance, there will be a reflection.** In this special case the reflection is equal to the incoming signal so the reflection coefficient is **+1**. Another interesting case is when the end of the coax is shorted. In this case the reflected signal will be inverted and it subtracts from the incoming signal so the wave that travels back toward the generator has an amplitude of 5-5=0 V. The reflection coefficient is **-1**. In this case, the voltage at point B will drop to zero after 300 nsec, which is what you expect since an ohmmeter at point B will read zero ohms due to the short circuit. In summary, the reflection coefficient is always in the range of **+1 to -1**. It can't be greater than one because the reflected wave cannot be greater than the incident wave.




Here's a practical example where the coax is terminated in a 100 ohm resistor which does not match the characteristic impedance of 50 ohms. The line is said to be mismatched. To help visualize what is going to happen, let's look at the final state of the voltage after a long time has elapsed. The generator is outputting 10V, there is a voltage divider of 50 ohms and 100 ohms, so the final value at point B has to be 6.66 V after things have settled down. *The question is how long does it take for this steady-state result to be reached?*

In the previous examples with an open circuit and a short circuit, the reflection coefficients were +1 and -1 respectively.

The general formula for the reflection coefficient, RHO, is:

**RHO = ( Zload - Zo )/( Zload + Zo )**

where Zload is the load at the far end of the line and Zo is the characteristic impedance of the line. We can check this for the two extreme cases, one when Zload is infinite (open circuit):

RHO= (infinity - Zo)/(infinity + Zo) = +1

When Zload=0:

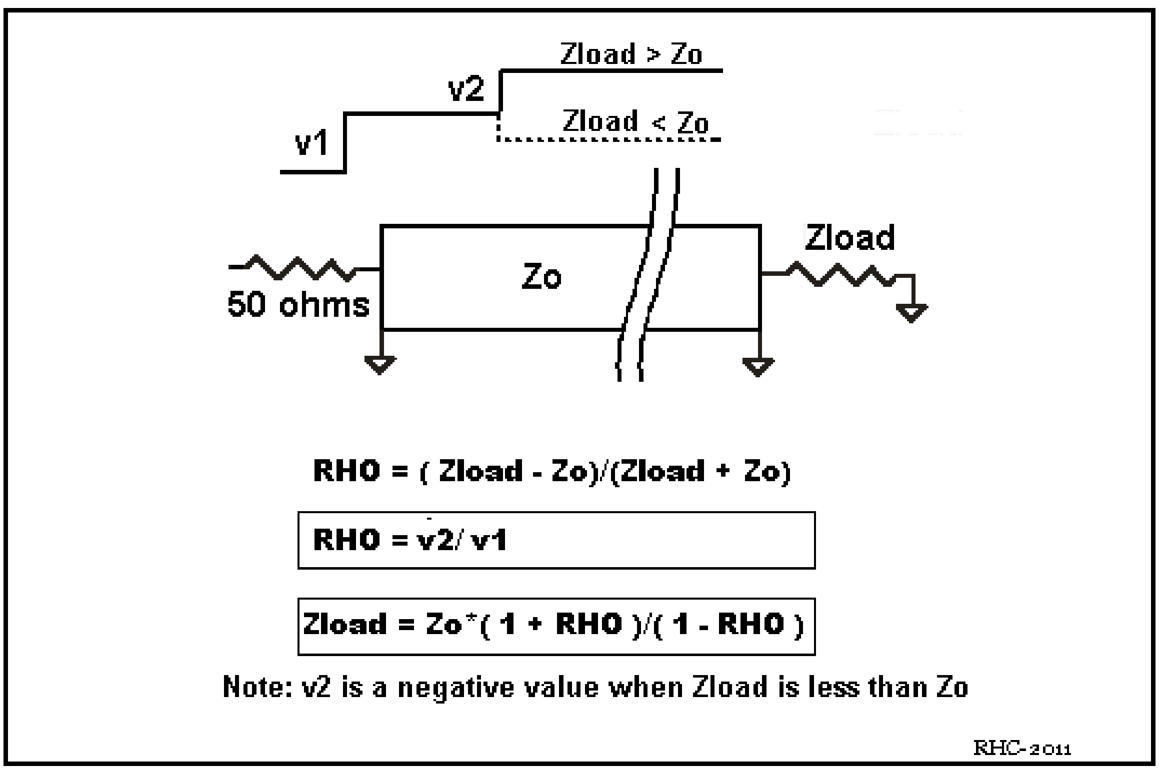
RHO=(0 - Zo)/(0 + Zo) = -1

**For values of Zload between zero and infinity, RHO varies between -1 and +1.**

Therefore, for the above diagram, RHO = (100 - 50)/(100+50) = +0.33

This means that if the incoming signal has an amplitude of 5V, the reflected wave will have an amplitude of 5*0.33 = 1.66V and it will add to the incoming wave so the final value at point C at T=150 nsec is 5+1.66 = 6.66V. This reflection of 1.66 V travels back down the line and after another 150 nsec it arrives back at point B and the voltage at point B jumps up to 6.66V. Thus the final voltage at B and C is 6.66V just as we expected from the preliminary analysis when we treated the circuit as a simple voltage divider.

By measuring the reflected wave at Point B, we can <u>work backward</u> and calculate what Zload must be to cause this reflection. The following diagram shows the measurement point B expanded.




The reflection coefficient is the value of the second step, **v2**, divided by the value of the first step, **v1**. Note that v2 is a negative number when Zload is less than Zo.

**Zload = Zo* ( 1 + RHO)/( 1 - RHO)**

**Let's check some special cases for measured values of RHO:**

V1 and V2 can be measured with a scope.

If the line is open: v2 = v1
Then RHO = v1/v1 = +1
Then Zload = Zo * ( 1 + 1)/( 1 - 1) = infinity

If the line is shorted: v2 = -v1
Then RHO = -v1/v1 = -1
Then Zload = Zo * ( 1 - 1 )/( 1 + 1 ) = 0

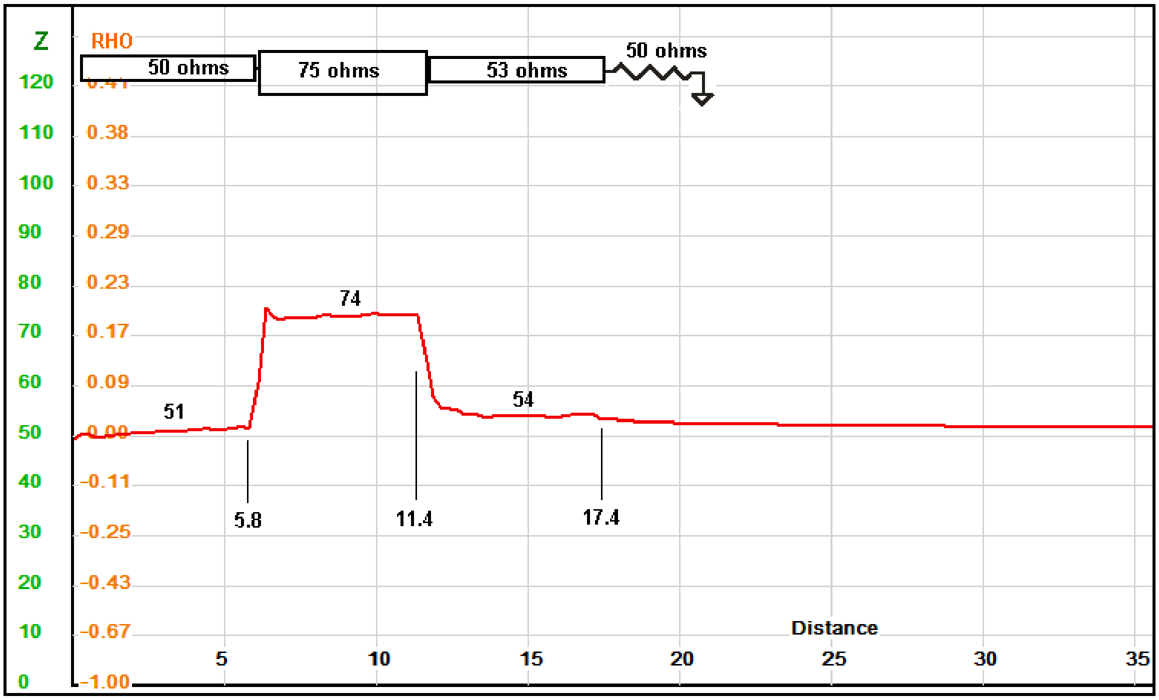
If the line is terminated with 100 ohms: v2 = 0.33*v1
Then RHO = 0.33v1/v1 = 0.33
Then Zload = Zo * ( 1 + 0.33)/( 1 - 0.33) = 50 * 2 = 100 ohms

If the line is terminated with 50 ohms: v2=0 (no reflection)
Then RHO = 0/v1 = 0
Then Zload = Zo * ( 1 + 0 )/ ( 1 - 0) = Zo = 50 ohms

If the line is terminated with 30 ohms: v2 = - 0.25*v1
Then RHO = -0.25v1/v1 = - 0.25
Then Zload = Zo * ( 1 - 0.25)/( 1 + 0.25) = 50 * 0.60 = 30 ohms

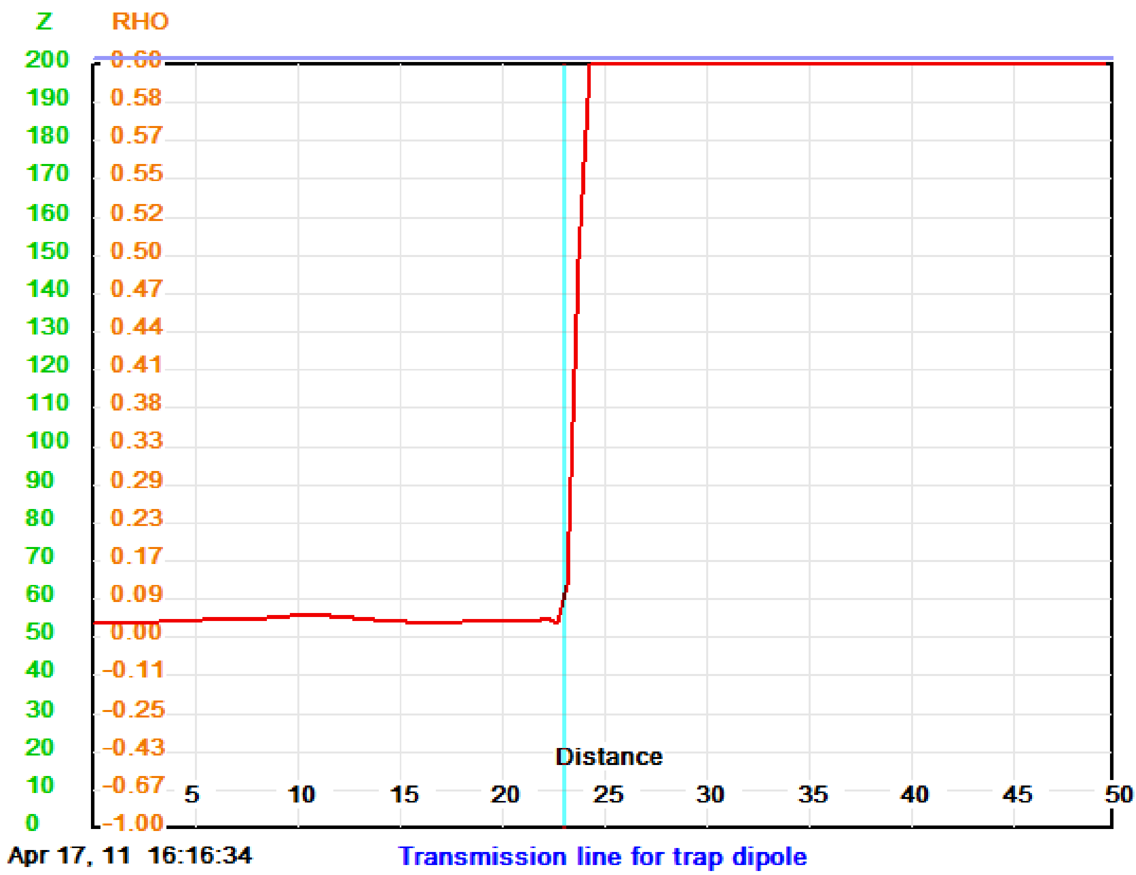
This is a brief introduction to the basic principles of TDR. In recent years the increased power of low cost computers has made it possible to create a TDR in software using the data from a frequency scan of a circuit. The vector network analyzer first collects data for the reflection coefficient at a number of frequencies. Then mathematical operations convert the frequency data to the corresponding time data. In this way the analyzer, which is basically a frequency domain instrument, does double duty by providing both frequency and time domain data with no extra cost in hardware.

An interesting thing that can be done with a TDR is determine the impedance and lengths of several different cables in series. This diagram shows data from an AIM for a transmission line made up of three lengths of coax with nominal impedances of 50, 75 and 53 ohms. The composite line is terminated with 50 ohms. The numbers along the horizontal axis are distance.




The first section of line has a measured impedance of 51 ohms and it's 5.8 feet long. The second section has a measured impedance of 74 ohms and it is (11.4 - 5.8)=5.6 feet long. The third section is (17.4 - 11.4) = 6.0 feet long.

Multiple reflections quickly complicate the interpretation of a TDR scan.
This web page has an excellent presentation on a technique for the [Analysis of reflections]




This picture shows the TDR picture of a simple trap dipole antenna feed with a 53 ohm coax that is 23 feet long (indicated by the vertical cyan cursor). Since the antenna is a relatively narrow band circuit, its impedance is very high over most of the frequency range scanned by the TDR. This causes a large jump in the reflection coefficient at the far end of the coax, so it's possible to determine the length of the transmission line without disconnecting it from the antenna.

In this case the antenna is an open circuit for DC, so the impedance is very high at the feed point. If the antenna has a DC path to ground at the feed point, the TDR trace will go to zero ohms at the end of the transmission line.

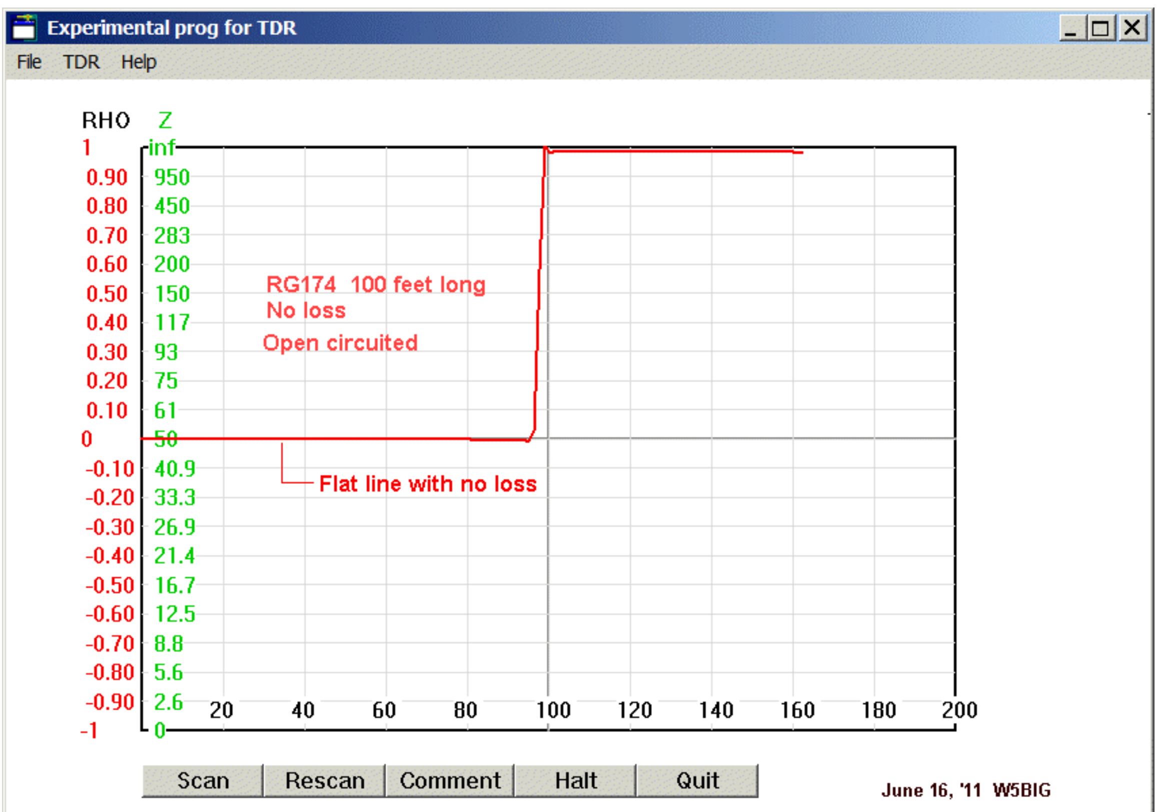
The final steady state impedance displayed by the TDR is the same impedance that would be measured at DC. Depending on the horizontal scale, this final value may not be reached because of multiple reflections in the system.

The resolution in distance is approximately 0.25% of full scale for the AIMuhf and 0.5% of full scale for the AIM4170 and the PowerAIM. For distances greater than 200, the three instruments have essentially the same resolution.

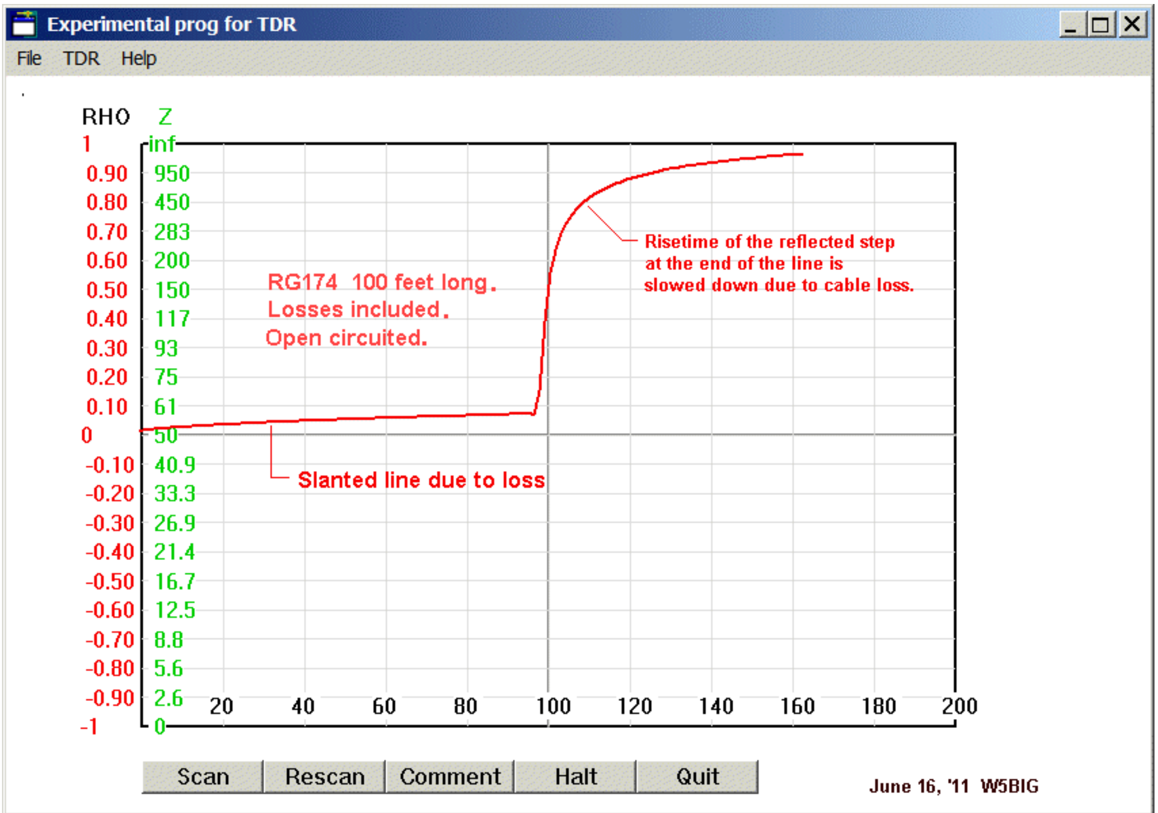
# Effect of Cable Loss

When the cable has **loss**, the TDR trace can be more complex due to reflections that are scattered all along the cable. Each increment of cable length looks like a discontinuity with respect to the ideal Zo and there appears to be a reflection at every point. This causes an upward slope to the trace that <u>looks</u> like an increase in impedance as a function of distance. This is not a real increase in cable impedance and the Y-coordinate of the trace cannot be simply interpreted as an impedance value. It can be used as a qualitative indication how the cable differs from the ideal Zo. Experiments have shown that ladder line gives a trace that appears to vary quite a bit from a flat line. Even though ladder line has very low loss in free space, it's proximity to structures in the path, like buildings or trees may affect the loss in a complex way. They may also affect the line impedance. Unfortunately, the TDR trace does not distinguish which effect is taking place at each point along the line.

Here are examples showing a length of RG174 simulated with and without loss:



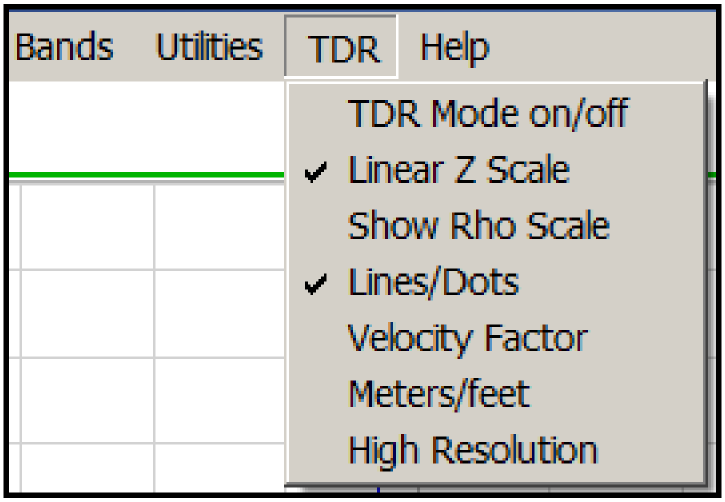

**RG174 without loss**




**RG174 with typical value of loss**

Experiments with various cables yield similar results, showing more slope when the cable has greater loss.

# TDR Operation




**TDR Mode on/off** - alternates between the normal Frequency mode and the TDR mode.

**Linear Z Scale** - If this is checked, the vertical Z display is a linear scale. If it is not checked the vertical scale shows RHO on a linear scale and Z is a function of RHO.

**Show RHO Scale** - If this is checked, RHO will be displayed on the vertical axis along with Z.

**Lines/Dots** - Plot the trace with continuous lines or dots at each measurement point.

**Velocity Factor** - Enter the velocity factor used for calculating distance based on electrical length. The same value is used for the whole transmission line system when multiple cables are involved. The typical value is 0.66 to 1.0. The electrical length can be displayed on the graph by setting the Velocity Factor = 1.

**Meters/feet** - Display distance data in meters or in feet. (meters can be selected as the default in the config file)

**High Resolution** - Increases the resolution along the distance axis by approximately 2x.

**In the TDR mode, these functions work similarly to the way they do in the frequency mode:**

**Scan** - clear the screen and do a TDR scan. The AIM takes a series of impedance readings, converts these readings to the reflection coefficient at each frequency and then transforms the frequency data to time data using the inverse Fourier transform.

**Rescan** - do a TDR scan without erasing the screen. The color of the plot cycles through five different colors.

**Scales** - enter the distance and Zmag scales.

**Halt** - stop a scan

**Quit** - exit the program

The buttons at the bottom of the screen that are not used in the TDR mode are grayed out.

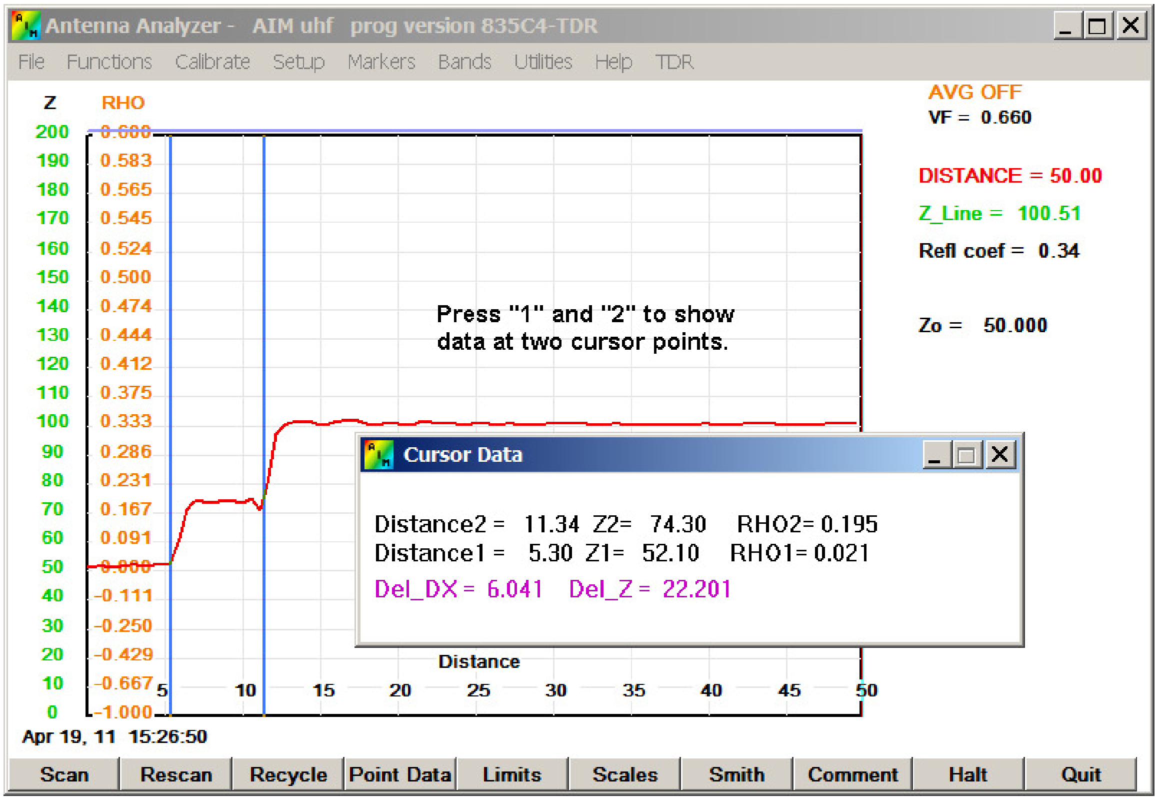
On the **Files Menu** (upper left corner of the screen), the same menu items are used for saving TDR graphs and recalling them from memory.

The AIM uses the same calibration file and config file in both the frequency mode and the TDR mode.

**Setup -> Ruler 1 and Ruler 2** - Rulers for Zmag can be used.

**Setup -> Average Reading** - The averaging is normally set to zero (no averaging) but it can be turned on while in the TDR mode.

## CURSOR DATA




This figure show how data at two points can be displayed along with their differences by moving the cursor to the first point and pressing a **1**, then move the cursor to the second point and press **2**. This action can be repeated by moving to other points and pressing 1 or 2. Data in the small window will be updated each time. The two selected distances are indicated by blue vertical lines on the graph. Close the data window by clicking the **X** in the upper right corner.

The data at the cursor position is displayed in the upper right corner of the main window just like it is for the frequency mode. In this diagram, the mouse cursor is all the way to the right side of the graph at Distance=50 and the line impedance is 100.51 ohms. The value of Zo (Zref ) is used for calculating the reflection coefficient. This can entered by using the **Setup** menu.

## REFERENCES

1. Excellent power point presentation by Ian, G3NRW, on all aspects of the AIM, including the TDR feature:
http://homepage.ntlworld.com/wadei/aim4170.htm

2. Good article on the fundamentals of TDR measurements:

http://materias.fi.uba.ar/6644/info/reflectometria/basico/55W_14601_0%20tdr%20Z%20measurements.pdf

3. App Note on how transmission line loss affects the TDR presentation:

http://www.polarinstruments.com/support/cits/AP156.html