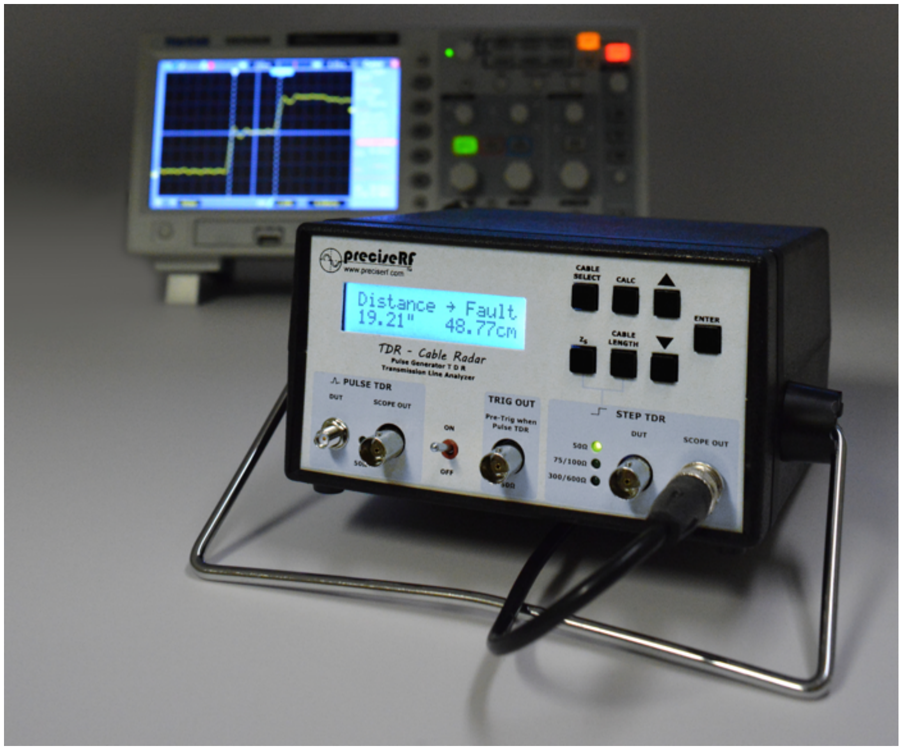
Using TDR for Measuring Transmission Lines in Ham Radio Installations



Roger M. Stenbock W1RMS

This application note reviews the elements of transmission line measurement in the ham radio environment. It demonstrates how you can measure line impedance, return loss, SWR, velocity factor, distance to fault and line losses using pulse interrogation techniques. It focuses on the new preciseRF *TDR-Cable Radar®* pulse generator as a companion accessory to an oscilloscope.

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Precision Ham Radio Measurements

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1. Transmission Lines

Virtually all ham radio installations require some type of transmission line. The purpose of a transmission line is to efficiently transfer RF energy from the transmitter to the transmitting antenna, or conversely, efficiently transfer RF energy from the receiving antenna to the receiver.

Ideal Transmission Line

The ideal transmission line matches the transmitter and antenna impedance precisely and delivers all input energy without losses. This usually occurs when all the power is transmitted without reflections and or resistive losses. Real-world transmission lines always have losses because either the source impedance (Zs) of the transmitter, the load impedance (Z_L) of the device receiving the energy (usually the antenna) or the line impedance (Zo) of the transmission lines are not matched.

Line Losses

There are other losses such dielectric, resistive and reactive losses which affect the performance of the transmission line. Many times these losses are due to manufacturing defects, poor quality, inferior connectors, environmental damage to the line such as UV radiation, moisture, physically kinked or broken cables, miss-matched cable types or excessive cable length.

The goal is to insure that the transmission line meets the expected performance requirements. In the ham radio applications, overall transmission lines performance is usually measured with SWR meters, return loss bridges or RF samplers with station monitors. These techniques work well and are low cost. They provide an overall check of the transmitter, transmission line and antenna (or resistive load) quality. Their main disadvantage is that they do not provide information as to where the fault is located, nor do they indicate the fault type, such as defective cables loose, connectors or other problems. Fortunately, time domain reflectometry (TDR) provides more information. Wikipedia defines a transmission line as:

> *"In communications and electronic engineering, a transmission line is a specialized cable designed to carry alternating current of radio frequency, that is, currents with a frequency high enough that their wave nature must be taken into account. Transmission lines are used for purposes such as connecting radio transmitters and receivers with their antennas, distributing cable signals, and computer network connections."*

2. TDR Basics

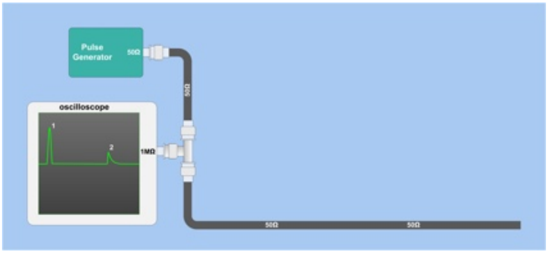


Figure 1. Simple TDR set-up

See figure 1. TDR principles are fairly easy to master. Think of it as cable radar. A pulse generator is connected via a “T” connection to an oscilloscope’s high impedance input and a pulse or step is injected (incident pulse) into the cable. The pulse and any reflections are then displayed on the oscilloscope for analysis.

Properly Terminated Line

See figure 2. If the conductor is of a uniform impedance and is properly terminated, the entire transmitted pulse will be absorbed in the far-end termination and no signal will be reflected toward the TDR. Any impedance discontinuities will cause some of the incident signal to be sent back towards the source. This is similar in principle to radar.

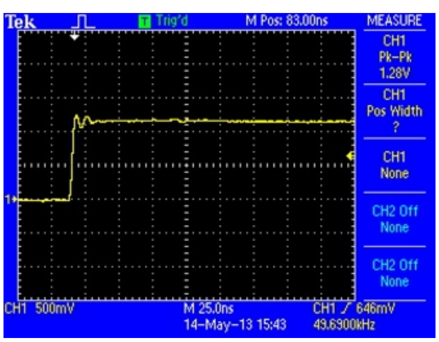


Figure 2. Terminated line

Since the pulse in transmission lines travels at a certain speed (.66 to .90 times the speed of light) depending on the cable type, it is possible to locate the reflection (fault) by measuring the round trip time and thus, locate the distance to the fault.

Open Line

See figure 3. The scope displays the incident pulse and any reflections. With an open

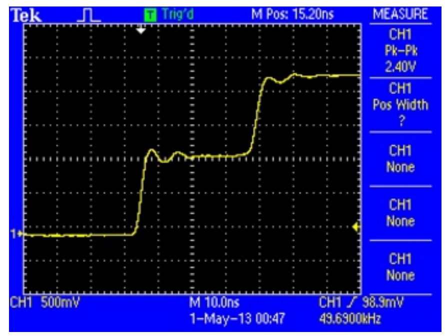


Figure 3. Open cable

cable for example, which is a very high impedance, increases in the impedance create a reflection that reinforces the original pulse.

Shorted Line

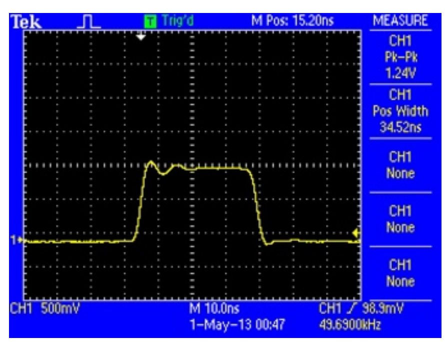


Figure 4. Shorted cable

See figure 4. A shorted cable, for example, has very low impedance, it creates a reflection that opposes the original pulse.

TDR Sensitivity

Because of TDR's sensitivity to impedance variations, it may be used to verify cable impedance characteristics, splice and connector locations, associated losses, and measure cable lengths.

Figure 5. Reflections

See figure 5. By analyzing the pulse amplitude, shape, and time, one can analyze the likely cause of the fault. In this example, the first reflection is negative going, indicating a decrease in impedance (most likely caused by a kinked cable). The second reflection is positive going, indicating an increase in impedance (most likely caused by a defective connector or braided shield failure).

Incident Pulse

See figure 6. The incident pulse is the pulse applied to the device under test (DUT). The amplitude is measured from the most negative level (generally ground) to the most positive level (excluding any aberrations not caused by reflections from the DUT).

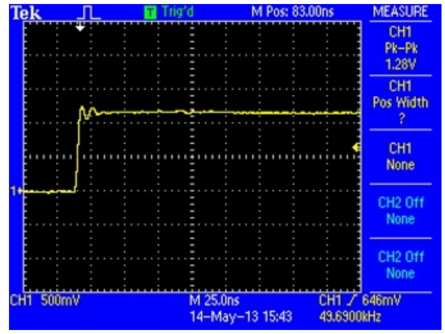


Figure 6. The incident pulse

Reflected Pulse

The reflected signal, also called the reflected pulse, contains signals which are made of reflections caused by the line impedance (Zo) not matching the pulse generator source impedance (Zs). The amplitude is measured as a deviation from the most positive level of the incident pulse. This level can be either positive or negative.

See figure 7. This multiple exposure waveform shows the incident pulse (the first half of the screen), and the reflected signal of positive and negative values.

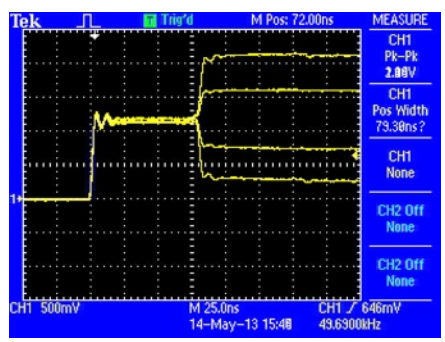


Figure 7. Multiple exposure of Zo variations

3. TDR Equipment

The commercial communications industry has long adopted TDR techniques to analyze transmission lines. A TDR measurement of a transmission line provides precise quantitative data of the line performance and identifies any faults.

Specifically, TDR measurements provide information such as distance to fault (DTF), reflection coefficient (p), transmission line impedance (Zo), return loss (RL), voltage standing wave ratio (VSWR), line length, line velocity factor (Vf), cable dielectric and resistive losses at specific frequency and cable length. While the measurement capability is impressive, the equipment costs are high and generally beyond the reach of ham radio operators.

Up until now, ham radio operators wanting to make TDR measurements either had to spend considerable money on a commercial TDR oscilloscope and pulse generator with integrated samplers and TDR computers, or compromise and use an ordinary oscilloscope and pulse generator and accept the limitations provided by this solution.

Equipment Choices

The electronic practitioner who wishes to make TDR transmission line measurements basically has these options:

1. If you have the money, buy a new TDR system such as the Mohr CT100, a Tektronix TDR scope or Angilent TDR scope. Starting at $18,000, these solutions are expensive, but they have the latest software and work well and have factory support.
2. Buy a used TDR system from eBay. Good price, but they may be difficult to get calibrated or serviced.
3. Compromise and use your scope, pulse generator and your trusty calculator. This works pretty well depending on your pulse generator performance. This choice is low cost, uses “T” connection, but has no low impedance scope input capability (needed for speed). All calculations must be done manually.

4. The TDR-Cable Radar ®

Recognizing the cost and performance limitations of the available choices, we created the *TDR-Cable Radar* ®. It was designed to be affordable, yet provide laboratory level accuracy and utility. *TDR-Cable Radar* ® takes advantage of the fact that low cost, high performance oscilloscopes are available from many sources. When used with an oscilloscope of sufficient bandwidth, measurements can be made rivaling those of commercial TDR systems at a fraction of the cost.

The *TDR-Cable Radar* ® includes a TDR computer because these scopes, while high enough in bandwidth (about 200MHz) do not have a TDR computer. This requires the user to make all the calculations manually. While not difficult to do, they are nevertheless tedious. Conventional pulse generators do not have the very fast rise time, selectable Zs and duration rates best suited for TDR work.

TDR for Ham Radio

The *TDR-Cable Radar* ® gives hams the means to analyze transmission lines and circuit board strip lines. Line impedance from 50 Ω to 600 Ω can be measured with 25 ps resolution. It features isolated high speed samplers and separate device under test (DUT) outputs. This design allows a direct, fast Tr 50 Ω connection to the oscilloscope for accurate TDR measurements without the inconvenience and lower performance that the “T” connector solution offers.

A transmission line library is included. It contains data for velocity factor (Vf), line impedance (Zo) and line loss data. The integrated TDR measurement computer takes the work out of TDR measurements, such as time to fault (TTF), reflection coefficient (p), cable length, velocity factor (VF), line impedance (Zo), return loss (RL), SWR and cable loss.

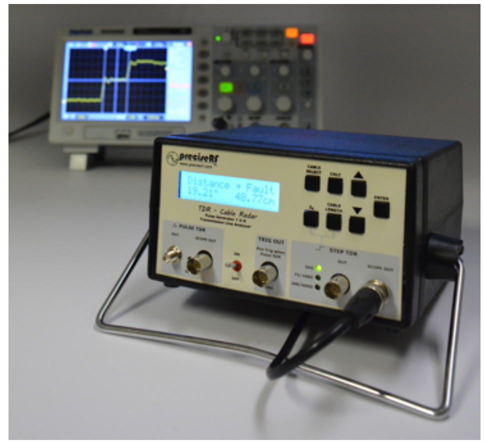
The *TDR-Cable Radar* ® features both pulse and step TDR. The step TDR has a maximum range of 15 KM and time resolution of better than 1 ns. The pulse TDR features a ≤ 400 ps pulse width and ≤ 150 ps Tr.

The resolution is under 5mm, which is well suited for analyzing circuit board strip lines. A dedicated trigger output features a 100 ns pre-trigger to allow viewing of the TDR pulse leading edge when using sampling scopes without a delay line such as the 7S11 and 7T11 installed in legacy Tektronix 7000 scopes.

TDR-Cable Radar ® Method

The TDR measurement set-up consists of the *TDR-Cable Radar* ® pulse generator and an oscilloscope. The pulse generator provides all required TDR pulses with the proper amplitude and transition time (Tr) and source impedance (Zs). The scope displays the resultant TDR waveform and provides a means of measuring time and amplitude of these pulses.

The user inputs voltage and time values observed on the scope, and the pulse generator computer provides measurement results. The scope option shown above includes a 200 MHz Hantek DSO oscilloscope especially selected for TDR measurements.



The *TDR-Cable Radar* ® *with scope*

Rise Time

The scope should have a calibrated vertical amplifier and calibrated time base. See figure 8. Three bandwidths displays created with a bandwidth limiter are shown. The scope bandwidth should be sufficiently high to identify reflections at the resolution needed for the application.

For short line distances and circuit board TDR, finer time resolution is required. Resolution is a function of the scope's rise time (Tr). Bandwidth is directly related to Tr and the commonly accepted mathematical relationship is BW=.35/Tr. While some users have used scopes with bandwidth as low 20 MHz, 100-200 MHz bandwidth scopes will work for most ham radio applications.

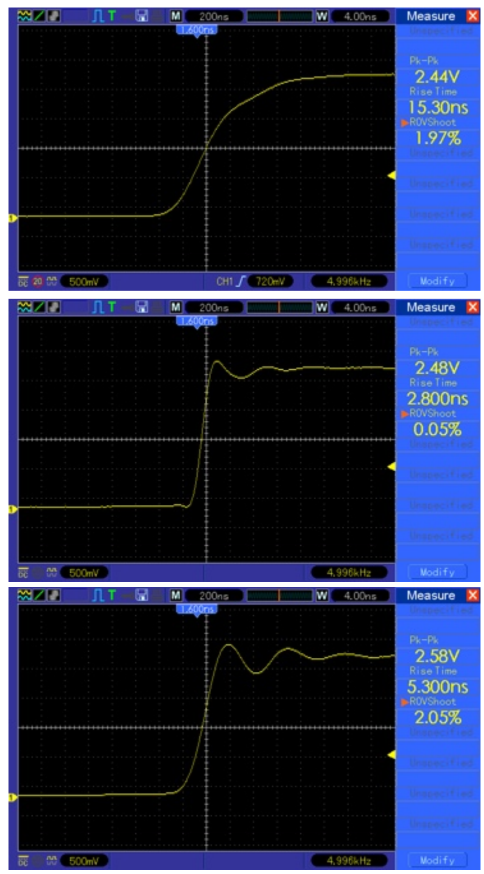


Figure 8. Tr displays of 20, 100 and 200 MHz BW scopes

Effects of Rise Time on TDR Resolution

The scope's rise time has a significant effect on TDR measurements are shown in figure 9. The example is a TDR measurements of a 12 foot piece of RG 58 coax with a published velocity factor (Vf) of .66 with the end open.

It demonstrates that this is about the shortest cable that can be tested with a 20 MHz scope. Note that impedance variations are clearly visible in the 100 MHz and 200 MHz scope.

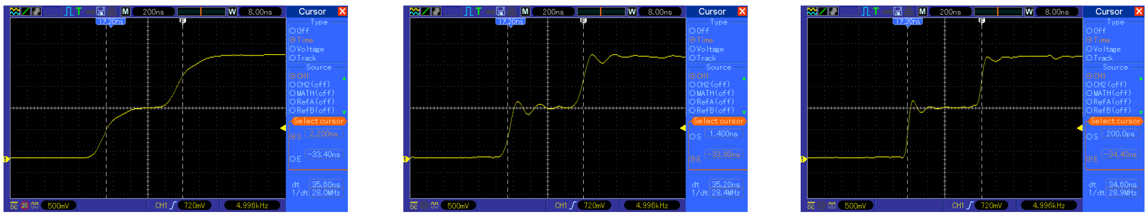


Figure 9. Scope rise time and bandwidth effects on TDR Measurement resolution

5. *TDR-Cable Radar* ® Controls

See figure 10. Here is a depiction of the *TDR-Cable Radar* ® pulse generator front panel and controls. Black is used for labels, blue is for outputs and green is for trigger functions. Green LEDs indicate the state of the current TDR mode and output impedance. The controls are grouped into five sections, see tables 1 and 2.

Figure 10. The *TDR-Cable Radar* ® *front panel*

Button	Table 1. Key Description
CABLE/Vf	Provides a cable selection from the library. Each cable includes the nomenclature, cable loss per 100 feet at 100 MHz, cable impedance (Zo) and velocity factor (Vf). A selection of a cable is used as a preset value for calculations performed by the TDR computer.
Zo	Sets the source impedance Zs and step or pulse TDR selection. Zs impedance is 50 Ω, 75 Ω and 300 Ω suitable for line impedance measurements ranging from 50 Ω to 600 Ω.
CABLE LENGTH	Selects TDR range and duration ranging from 15 KM (100 us pulse width) to 75 Meter (500 ns pulse duration) in four ranges. Maximum resolution is 10 ps (using pulse TDR).
CALC	Selects calculation of distance to fault (DTF), cable length, velocity factor (Vf), reflection coefficient (p), return loss (RL), SWR, and line loss per 100 ft at 100 MHz.
UP	Use the UP and DOWN key to scroll increasing or decreasing numerical data or selectable items.
DOWN	Use the UP and DOWN key scroll increasing or decreasing numerical data or selectable items. Also used to display additional calculation results.
ENTER	Completes a data entry or sub calculation or function.

Table 2 Displayed Prompt Convention

	Whenever prompted by the return symbol press the **ENTER** key to advance.
	Whenever prompted by the down arrow, press the **DOWN** key for additional measurement results.

Display

The display is a high contrast two line sixteen digit backlit LCD display. See figure 11. It provides the state of the current TDR function and shows various input and output conditions. It also indicates TDR measurement results.

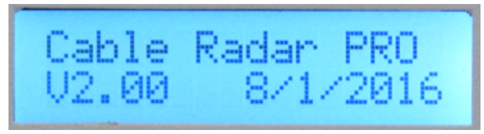


Figure 11. LCD display

Step TDR Output

See figure 12. The Step TDR output consists of the DUT output and the scope output. The pulse waveform duration and frequency is settable from 5 KHz to 1 MHz. They are accurately set by a crystal oscillator timebase.

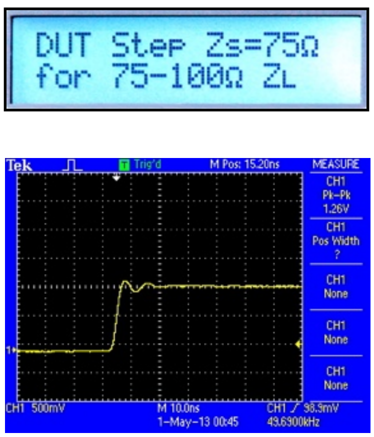


Figure 12. Step TDR

This allows for TDR range measurements from a few centimeters to 15 KM. Step TDR is most useful for measuring reflection coefficient, cable impedance (Zo), return loss (RL), voltage standing wave ratio (VSWR) and distance to fault. The source impedance (Zs) is calibrated and selectable from 50 Ω, 75 Ω and 300 Ω, using high speed SMA microwave relays set by the on-board microprocessor.

Pulse TDR Output

See figure 13. The DUT pulse output. The very fast pulse TDR is used to measure circuit board traces and line losses.

The SMA outputs a pulse to the device under test (DUT) with a 400 ps pulse width, a Tr of ≤ 150 ps and an amplitude of 2 V Pk-Pk. When PULSE TDR is enabled the green LED next to the DUT connector illuminates. The maximum range is 1.5 KM, pulse width is 10 us and the frequency is 50 KHz.

When using pulse TDR, the SMA connector is intended for the DUT and the BNC connector for the scope's vertical input. To preserve the high frequency detail, the scope vertical should be terminated into 50 Ω.

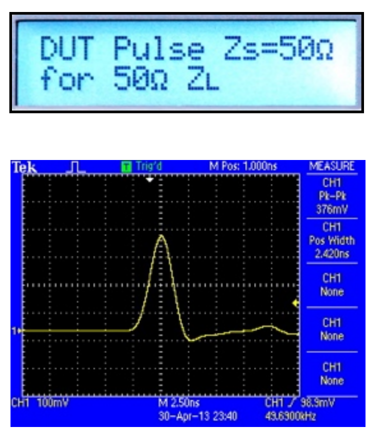


Figure 13. Pulse TDR

6. TDR Concepts and Terms

There are a number of primary TDR measurements concepts terms. These are the reflection coefficient (ρ), distance to fault (DTF), velocity factor (Vf) and line loss or cable loss. Some of these measurements also provide return loss (RL), line impedance (Z_0), VSWR and other parameters. What follows are the mathematical relationships governing these measurements:

The Reflection Coefficient

TDR measurements are based on a series of impedance ratios. TDR measurements are described in terms of a reflection coefficient, ρ (rho). The coefficient ρ is the ratio of the reflected pulse amplitude to the incident pulse amplitude:

$$\rho = V\ reflected \div V\ incident$$

For a fixed termination Z_L, ρ can also be expressed in terms of the transmission line characteristic impedance, Z_O and the load impedance Z_L.

$$\rho = V\ reflected \div V\ incident$$
$$= (Z_L - Z_0) \div (Z_L + Z_0)$$

Representing a matched load, a short circuit and an open load, ρ has a range of values from +1 to —1, with 0 representing a matched load. When ZL is equal to Zo, the load is matched. V reflected, the reflected wave, is equal to 0 and ρ is 0. There are no reflections:

$$\rho = V\ reflected \div V\ incident$$
$$= 0 \div V = 0$$

A Z_L reading of zero (0) implies a short circuit. The reflected wave is equal to the incident wave, but opposite in polarity. As seen below, the reflected wave negates part of the incident wave. The ρ value is -1.

$$\rho = V\ reflected \div V\ incident$$
$$= -V \div V = -1$$

When Z_L is infinite, an open circuit is implied. The reflected wave is equal to the incident wave and of the same polarity. The reflected wave reinforces part of the incident wave. The ρ value is +1.

Transmission Line and Load Impedance

The characteristic impedance Z_0, or the load impedance Z_0 can be calculated with the value of ρ:

$$Z_L = Z_0 * (1+ \rho)\div(1-\rho)$$

Return Loss of the Transmission Line

The return loss (RL) of a transmission line is a conversion of the reflection coefficient (ρ) to dB. Return loss is expressed as a positive number and can be calculated by the equation as follows:

$$RL = -20 \log 10 (\rho)$$

VSWR of the Transmission Line

The voltage standing wave ratio (VSWR) represents the ratio between the maximum and minimum amplitude of the standing wave. VSWR can be calculated by the equation as follows:

$$VSWR = (V\ max \div V\ min)$$
$$= 1+ \rho \div 1 - \rho$$

Cable Losses of the Transmission Line

Cable losses in the ham radio installation are caused by several factors. While both conductor loss and dielectric loss occur, conductor loss usually dominates. Conductor loss is caused by the finite resistance of the metal conductors in the cable which, due to the skin effect, increases with frequency. The result of this incremental series resistance is an apparent increase in impedance as you look further into the cable. So, with long test cables, the DUT impedance looks higher than it actually is.

The second problem is that the rise time and settling of the incident pulse is degraded by the time it reaches the end of the cable. This affects resolution and accuracy since the effective amplitude of the incident step is different than expected. This amplitude inaccuracy does not cause much error when the DUT impedance is close to 50 Ω, but for a larger or smaller impedance, the error can be significant.

Loss per unit of length is generally provided by the manufacturers. For example, RG 58 might be specified as 4.1 dB/100 feet. Given a constant amplitude sine wave generator and a known length of transmission line, one can measure the actual loss per unit of length and compare that to a specified cable length usually given as dB/100 feet.

Gaussian Pulse Loss Measurements

One can make loss measurements using a TDR pulse generator with a fast enough pulse Tr output by comparing the incident pulse amplitude to the reflected pulse amplitude.

Losses in a transmission line due to changes in frequency are proportional to the square root of the frequency. Thus, if the attenuation per unit length is known for a particular frequency f1, the loss of any other frequency f2 can be calculated from the following equation:

$$a_{f2} = a_{f1} \left(\sqrt{f2 \div f1}\right)$$

where a is loss in dB

Since the *TDR-Cable Radar* ® makes loss measurements using a very fast gaussian pulse, we can apply the above equation using a 200 MHz scope for our measurements.

See figure 14. The *TDR-Cable Radar* ® generates a pulse with a Tr of ≤ 150 ps and a pulse width of ≤ 400 ps. When the pulse is displayed on a Tektronix 6 GHz DSO, the incident pulse Tr of ≤ 150 ps Tr is clearly evident.

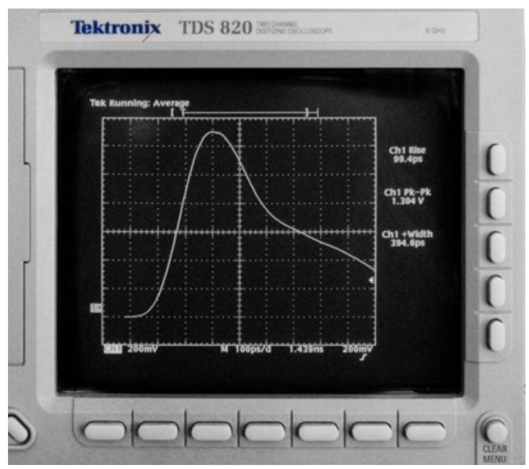


Figure 14. Gaussian pulse displayed on 6 GHz DSO

Given the relationship of BW=.35/Tr, we see that .35 ÷ 150ps = 2.3 GHz. The maximum FFT frequency is about 2.3 GHz.

See figure 15. When the same pulse is viewed on a 200 MHz scope, the displayed pulse Tr and pulse width will be stretched and the amplitude is decreased. However, the *generated* Tr, width and amplitude are unchanged, it's just that the scopes lower BW limit can't display them.

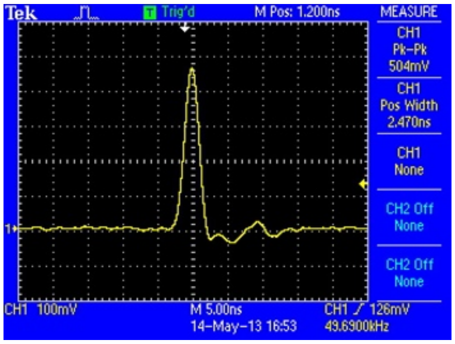


Figure 15. Gaussian pulse displayed on 200 MHz DSO

According to the ARRL on-line calculator, the Tandy RG 58 coax is specified to have a cable loss of 4.068 dB/100 feet, and at 2.2 GHz the calculated loss is 26.66 dB /100 feet.

Using a Rigol DSA1030 laboratory spectrum analyzer, we measured an actual cable loss of 5.2 dB/100 feet. At 2.2 GHz the measured loss was 21.3 dB /100 feet. The calculated results are pretty close when compared to real-world cables measurements.

Fundamentally, the *TDR-Cable Radar* ® makes the loss measurement at 2.2 GHz and then calculates the loss at 100 MHz, using the equation previously discussed:

$$af2 = af1 (\sqrt{f2 \div f1})$$

where a is loss in dB

Summary

Understanding the frequency contents of gaussian pulses allows for measurements of cable losses using pulses with equivalent results as a constant amplitude sine wave generator measurement. This holds true as long as the measurement scope's bandwidth is ≥ 2 times the measurement parameter (loss @ 100 MHz). So, a 200 MHz scope will give reliable results.

Not all secondary factors affecting cable loss are taken into account using the gaussian pulse cable loss measurement method. For this reason, when making cable loss measurements a normalized cable length gives the most accurate result. Sample cable lengths of 25-50 feet give the best accuracy. However, for comparative cable loss testing, cables with identical length of just a few feet can be tested and high measurement certainty can be achieved.

7. Step-by-step TDR Measurements

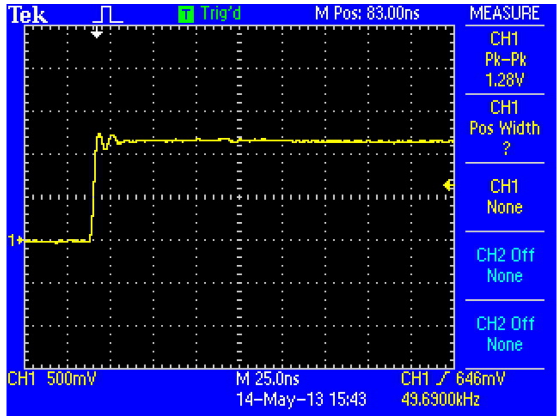
This section explains how to make TDR measurements using the TDR-Cable Radar ® measurement computer (accessible by using the **CALC** key). In each example you will be shown how to connect the scope and the DUT to the TDR-Cable Radar ®. Examples of the TDR-Cable Radar ® display and scope display are shown. Since the DUT transmission lines and cables you will be using are most likely different than the examples shown, your measurement results will reflect the actual cables you will be testing. The following examples are covered:

1. Reflection Coefficient, Return Loss, SWR and Zo Measurements.
2. Distanced to Fault (DTF) Measurements.
3. Velocity Factor Measurements.
4. Line Loss Measurements.

Reflection Coefficient, Return Loss, SWR and Zo Measurements

Hams worry about VSWR, and for good reason. Most transmitters do not tolerate a mismatched load with a VSWR > 2:1, and power that is supposed to go to the antenna is lost as heat. As previously discussed, VSWR is directly related to the reflection coefficient (ρ), return loss (RL), and line impedance (Zo). Using TDR to measure ρ, we get all four parameters in one measurement. See the step-by-step instructions below:

Reflection Coefficient Measurements Steps	Scope Display
 1. Using the **Zs** key, set the *TDR-Cable Radar ®* to **STEP TDR** and the appropriate Zs (Usually 50 Ω).	

<table>
<tr><th>Reflection Coefficient
Measurements Steps</th><th>Scope Display</th></tr>
<tr><td>2. Connect the Step TDR SCOPE OUT to the scope input, use a 50 Ω feedthrough terminator. Set the scope for the display shown.</td><td>
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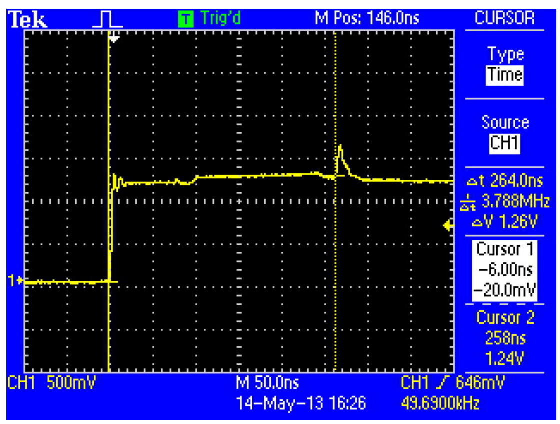
3. Using the CALC key, select the Calc. Reflection Coefficient (p) function.</td><td></td></tr>
<tr><td>4. Connect the cable to be tested to the DUT output. Adjust the scope to show both the incident pulse and the reflected pulse.</td><td>
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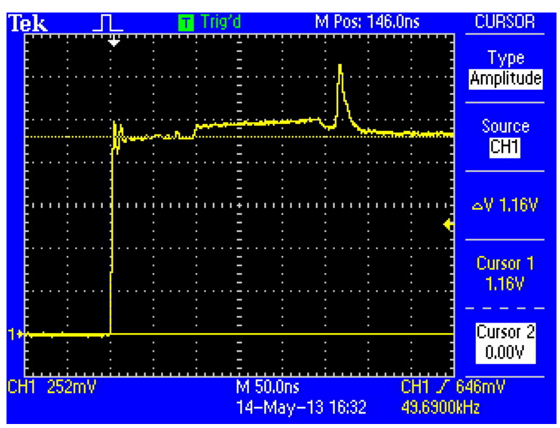
5. Adjust your scope for about 6 divisions amplitude. Measure the incident pulse Pk-Pk amplitude.</td><td>
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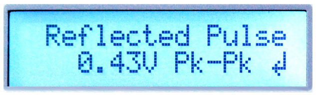
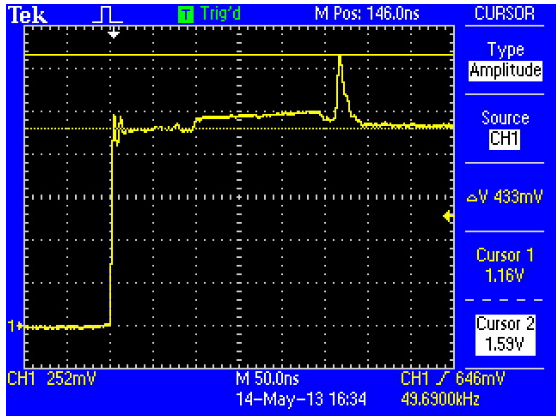
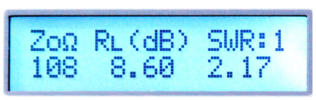
Reflection Coefficient Measurements Steps	Scope Display



6. Measure the reflected pulse Pk-Pk amplitude.



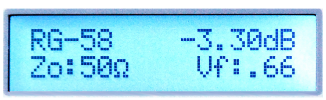
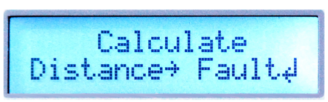
7. Press the **ENTER** key. The reflection coefficient will be displayed. Press the down key for additional results.

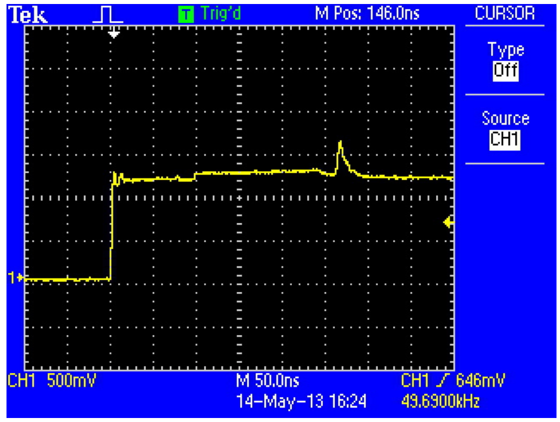


8. Results for Zo, return loss and SWR will be displayed.

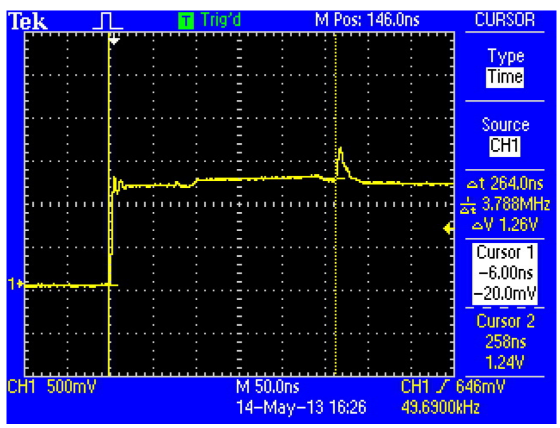
Distanced to Fault (DTF) Measurements

While it is good to know the reflection coefficient, return loss and VSWR, if there is a problem, it would be helpful to know where in the line the problem is located. Fortunately, if we know the cable type and its velocity factor (Vf), we can locate the fault quite easily. The Vf is a part of the cable specification. If you don't know the Vf, it can also be measured with the *TDR-Cable Radar*®. See the step-by-step instructions below:

Distance to Fault Measurements Steps	Scope Display
 1. Using the **Zs** key, set the output to **STEP TDR** and the appropriate Zs (usually 50 Ω).	
 2. Select the cable from the cable library using the **CABLE/Vf** key. If the cable is not found, set the Vf during the DTF measurement.	
 3. Using the **CALC** key, select the Calc. Reflection Coefficient (p) function.	
 4. Confirm the Vf of your cable or set the desired value.	

<table>
<tr><th>Distance to Fault Measurements Steps</th><th>Scope Display</th></tr>
<tr><td>5. Connect the cable to be tested to the DUT output. Adjust the scope to show both the incident pulse and the reflected pulse.</td><td>
</td></tr>
<tr><td>

6. If the reflected pulse is not displayed, change the range with the RANGE/DURATION key.</td><td></td></tr>
<tr><td>

7. Press the ENTER Key. Measure the delta time from the incident to the reflected pulse. Enter this value into TDR-Cable Radar®.</td><td>
</td></tr>
<tr><td>

8. The distance to fault is displayed</td><td></td></tr>
</table>

Velocity Factor Measurements

The velocity factor (Vf), also called wave propagation speed or velocity of propagation (VoP) of a transmission medium is the speed at which a wavefront of an electromagnetic signal or a change of the voltage on a wire passes through the medium, relative to the speed of light.

See table 3. The speed of radio signals in a vacuum, for example, is the speed of light and so the velocity factor of a radio wave in a vacuum is unity (1) , or 100%. In electrical cables, the velocity factor mainly depends on the insulating material.

Vf	**Transmission line**
0.95 - 0.99	Open-wire “ladder” line
0.80	Belden 9085 twin lead
0.82	RG-8X Belden 9258 coaxial cable (foamed polyethylene dielectric)
0.66	RG-213 RG-58 coaxial cable (solid polyethylene dielectric)

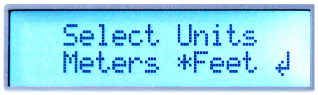
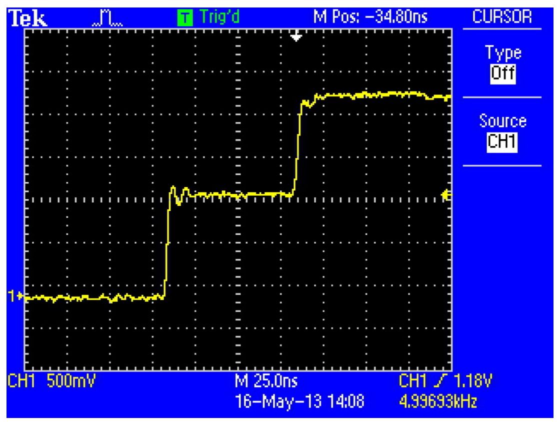
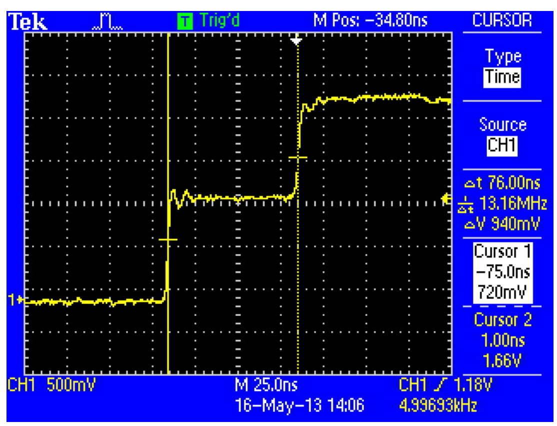
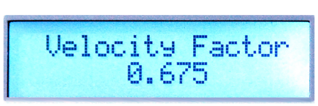
Table 3. Typical velocity factors (Vf) of transmission lines

The use of the terms velocity of propagation and wave propagation is confined to transmission lines and cables. In a ham radio and engineering context, these terms would be understood to mean a true speed or velocity in units of distance per time. Since Vf affects the accuracy of distance to fault measurements, a means to measure Vf is provided. See the step-by-step instructions below:

<table>
<tr><th>Velocity Factor Measurements Steps</th><th>Scope Display</th></tr>
<tr><td>

1. Using the Zs key, set the TDR-Cable Radar® to STEP TDR and the appropriate Zs (usually 50 Ω).</td><td></td></tr>
<tr><td>

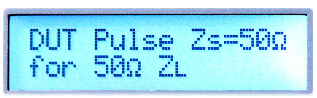
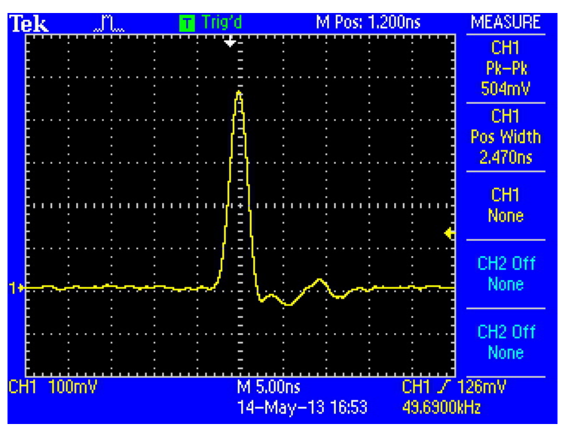
2. Select the measurement choice for Vf using the CALC key.</td><td></td></tr>
</table>

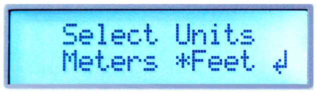
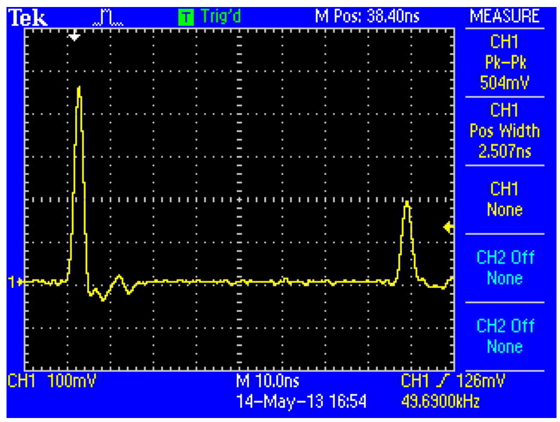
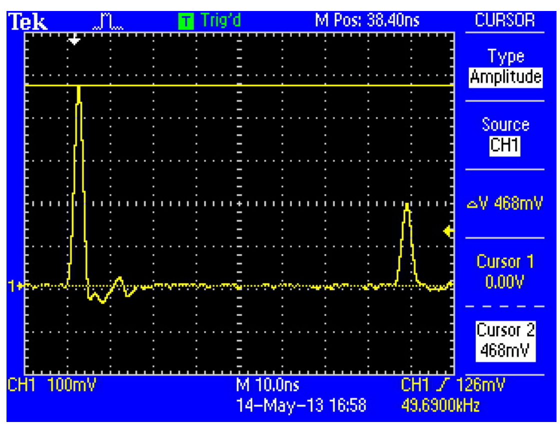
Velocity Factor Measurements Steps	Scope Display
 3. Select Units, Meters or Feet.	
 4. Set the known cable length using the up and down keys.	
5. Connect the cable to be tested to the **DUT** output. Make sure the cable is open at the other end. Adjust the scope to display both the incident pulse and the reflected pulse.	
 6. Measure the delta time from the incident to the reflected pulse. Enter this value into the *TDR-Cable Radar* ®	
 7. Press **ENTER.** The velocity factor (Vf) is displayed - in this case it is .675. That's pretty close to the published value of .66.	

Line Loss Measurements

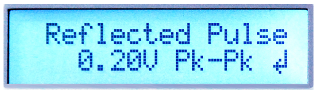
Line loss or cable loss is a function of frequency and the length of the cable. It is expressed in dB loss for a given length at a specific frequency. Doubling the length doubles the loss in dB. However, doubling the frequency does not double the loss as the losses in a transmission line due to changes in frequency are proportional to the square root of the frequency. The greater the frequency and length, the greater the loss.

Line loss is a published specification provided by the cable manufacturer. A fundamental contributor to line loss is the dielectric. Dielectric quality and condition can change over time due to environmental conditions such as moisture and mechanical stress. It is not uncommon for cables that have been in service a number of years to have increased line losses. If you want to transfer the maximum power from your transmitter to the antenna, a measurement of line loss is important. See the step-by-step instructions below:

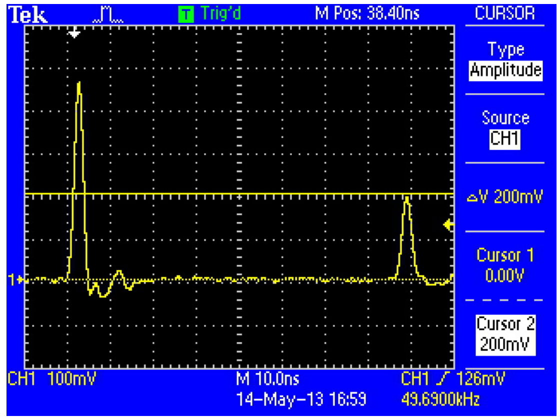
Line Loss Measurement Steps	Scope Display
 1. Using the **Zs** key, set the *TDR-Cable Radar* ® to pulse TDR.	
 2. Using the **CALC** key, select Cable Loss measurement.	
3. Connect the **PULSE TDR SCOPE OUT** to the scope input using a 50 Ω feedthrough terminator. Set the scope for the display shown.	

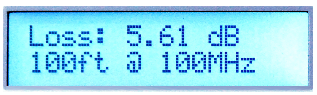
Line Loss Measurement Steps	Scope Display
 4. Select Units, Meters or Feet.	
 6. Set the Cable Length.	
5. Connect the cable to be tested to the **PULSE TDR DUT OUT.** Adjust the scope to show both the incident pulse and the reflected pulse.	
 7. Using your scope cursors, measure the incident pulse Pk-Pk amplitude. Enter this value into the *TDR-Cable Radar*®.	

Line Loss Measurement Steps	Scope Display



8. Using your scope cursors, measure the reflected pulse Pk-Pk amplitude. Enter this value into the *TDR-Cable Radar*®.





9. The cable loss is shown on the display.

8. Common Transmission Line Faults

In this section we'll take a look at common line faults and what they look like on the oscilloscope. This will help you pin-point the source of the problem and how to fix it.

Common transmission line problems are:

1. Defective shield
2. Pinched cable
3. Line mismatches
4. Faulty connectors
5. Circuit board trace mismatches

TDR Sensitivities

We know that TDR basically measures only two parameters, impedance and time. They are changes in impedances at a given time in the line.

Ideal Line

See figure 16. Assume the ideal condition where Zs = Zo = ZL. Here, all the energy is absorbed by ZL and there are no reflections.

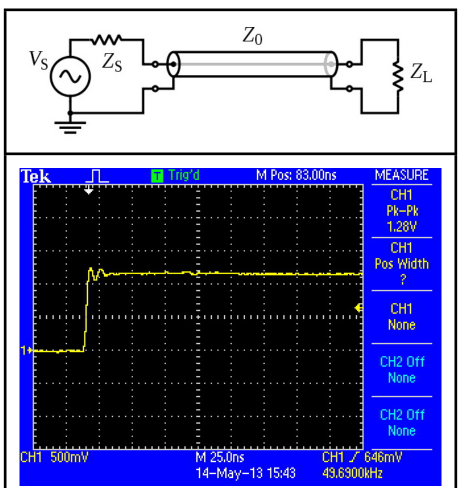


Figure 16. Ideal Transmission Line Zs=Zo =ZL

The ideal line does not exist in reality. There are always some faults; they may be small but they are there. In the following examples, I have purposely induced larger errors to better illustrate the concept.

Inductive Fault

See figure 17. In this example, there is an inductive component in part of the line. This may occur when the shield has been compromised or a connector is defective.

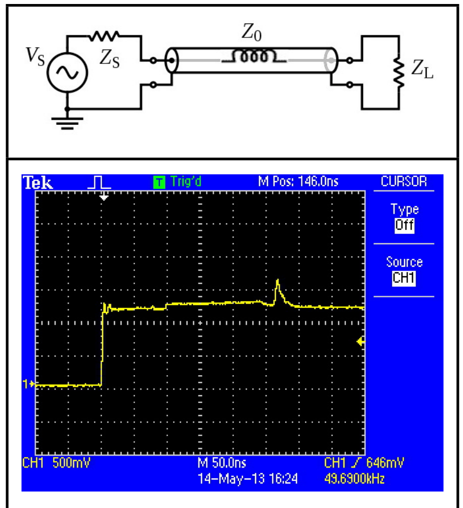


Figure 17. Faulty transmission line Zo contains an inductive component in series

Capacitive Fault

See figure 18. In this example, there is a capacitive component in part of the line. This may occur when the shield has been pinched close to the center conductor in a coaxial transmission line or the line is defective or the loss is due to the dielectric having a localized defect.

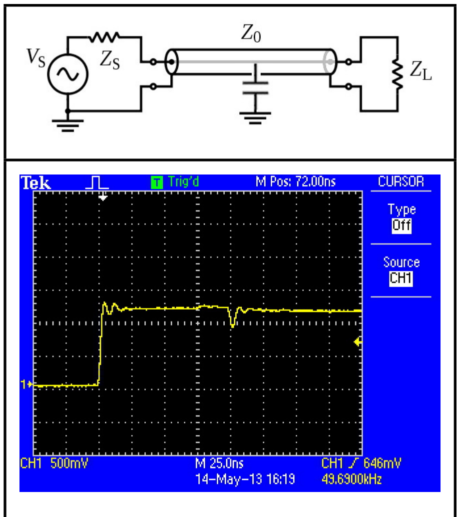


Figure 18. Faulty transmission line Zo contains a capacitive component to ground.

Impedance Mismatch ZL > Zo

See figure 19. In this example, there is an impedance mismatch in part of the line.

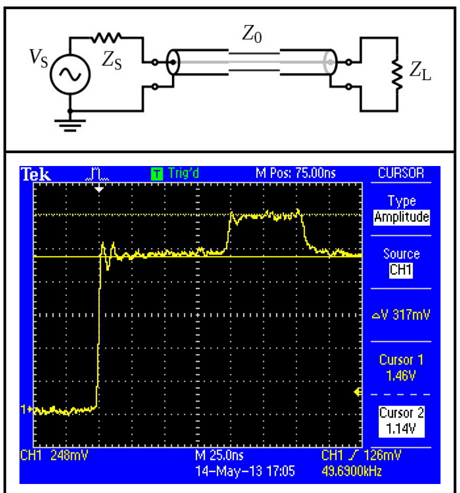


Figure 19. Mismatched transmission Line Zo>ZL=Zs

This may occur when line impedances with differing Zo are connected in series. In this case, a piece of RG 58 50 Ω coax was connected to a section of RG 59 75 Ω coax and then further connected to a section of RG 58. This problem is quite common and can result in unexpectedly high VSWR conditions.

Impedance Mismatch ZL < Zo

See figures 20 and 21. In this example, there is an impedance mismatch in part of the line.

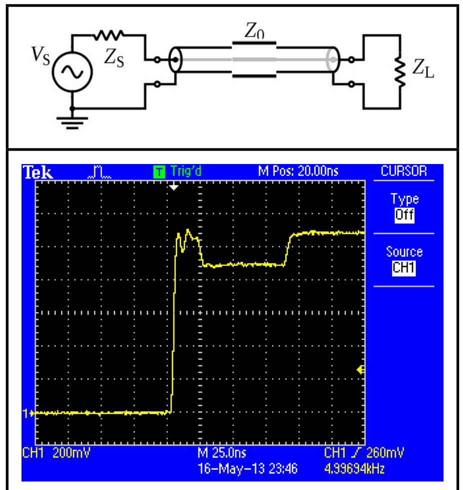


Figure 20. Mismatched transmission Line Zo<ZL=Zs

This may occur when line impedances with differing Zo are connected in series. I purposely set Zs to 75 Ω. In this case, a piece of RG 59 50 Ω coax was connected to a section of RG 58 75 Ω coax and then further connected to a section of RG 59. This problem is quite common and can result in unexpectedly high VSWR conditions.

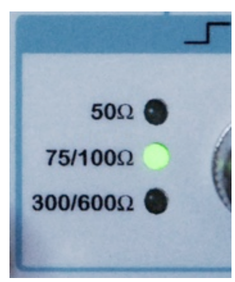


Figure 21. Zs set to 75 Ω

ECB Trace Impedance Variations

See figure 22. In the following example, a circuit board trace was examined for correct strip line design. The scope display clearly shows the impedance variations. The positive going Zo indicates trace width over a ground plane which is narrow (higher impedance) and the negative going variations indicate trace width which are wider (lower impedance).

As a starting point, some microwave engineers use .125” trace width over a ground plane to achieve a Zo of 50 Ω over Fiber Reinforced Plastic (FRP-4) PCB material.

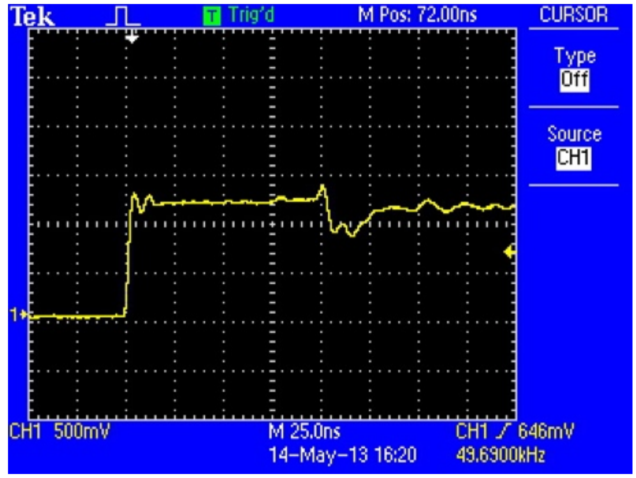


Figure 22. ECB strip line impedance variations

High Resolution Pulse TDR

See figure 23. The fast Tr ≤ 150 ps pulse allows for very high resolution measurements. The length of an SMA connector clearly reveals itself. A TDR measurement of an SMA cable with a Vf of .66 with one end open displays a major reflection at 9.88 ns.

This cable is 38.5 inches in length. The aberrations on the trailing edge are the reflections caused by the connector. Note a cable loss of 10 dB at the 2.2 GHz (the equivalent FFT frequency of the incident pulse). It has been my experience that when displayed on a high bandwidth scope, Zo changes in distance of just a few millimeters are clearly observable.

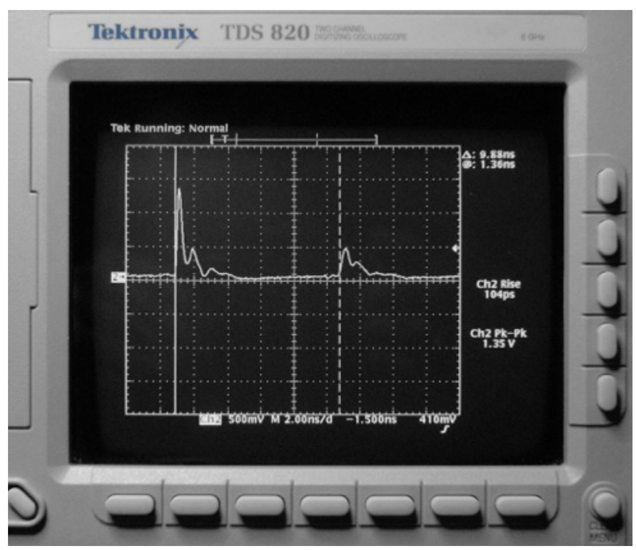


Figure 23. Detail of high resolution TDR measurement when viewed on a Tektronix TDS 820 6 GHz DSO

9. Zo Measurement by ZL Substitution

See figure 24. We know that if ZL = Zo there will be no reflections. So, if we could somehow measure ZL, we would know the line impedance Zo.

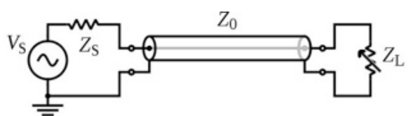


Figure 24. Zo terminated with variable ZL

The VZ500 Variable Terminator

See figure 25. An adjustable ZL VZ500 is nothing more than a 500 Ω variable resistor which can be adjusted to match the line Zo. The only requirement is that it have low series inductance and low shunt capacitance.

Figure 25. VZ500 variable terminator

Adjust for Minimum Reflections

See figure 26. We have connected the VZ500 variable resistor to a length of RG 59 75 Ω cable and adjusted VZ500 for minimum reflections as observed on the oscilloscope display.

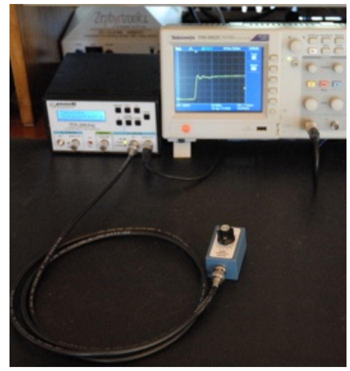


Figure 26. RG 59 cable connected to variable ZL

Reading the RL Resistance

See figure 27. After confirming that RL VZ500 resistor has been adjusted for minimum reflections, remove it from the cable end and measure the DC resistance with an ordinary ohm meter. In this example, we see that it reads 74 Ω. That is very close to the line's 75 Ω impedance.

Figure 27. Measurement results of RG 59 cable

10. CALIBRATION

The unit was calibrated at the factory for optimum performance. I may require recalibration from time to time. I you have the proper calibration equipment and skill, you can calibrated it yourself. Refer to this procedure and the schematics.

Preperation

a) Insure the unit is turned off.

b) Locate J8 and connect a temporary jumper (short).

c) Turn the on.

d) You will be prompted for the calibration steps:

e) Remove the temporary Jumper.

Calibrate the Keypad

a) Press the Select Key
b) Press the Zs Key
c) Press the Calc Key
d) Press the Length Key
e) Press the Up key
f) Press the Down key
g) Press the Enter Key (A brief message “Calibration Completer” appears)

Calibrate the avalanche high voltage

a) Complete steps 1-5 above.
b) HV Calibrate VSet = 53 (This may be any value between approx. 20 to 100).
c) Use the Up and Down keys to set the value to the default 53.
d) Press ENTER

Note: To check the actual voltage locate the HV test located next to C24. It should be set to 70VDC. This voltage sets the ideal avalanche performance and may vary depending on component characteristics. If you have a 6GHz bandwidth scope or better, you can check waveform for best pulse characteristics.

Calibrate the pulse and step shape

a) Adjust C24 and C10 for best Pulse shape.
b) Adjust C4 for least overshoot and best rise time.
c) Adjust R4 for 20nS pre-trigger delay.

Calibrate Zo Calibration (50 ohms).

a) Connect an RG58 cable and 50 ohm termination to the DUT port.
b) Adjust R24 to set the incident pulse to 50 ohms

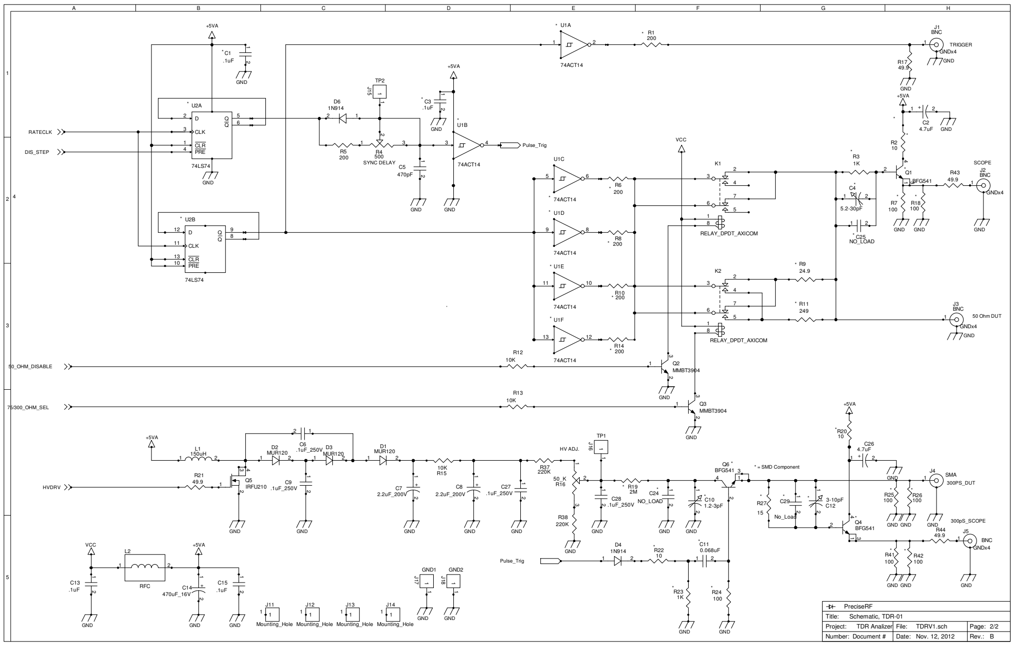
Calibrate LCD R36 for best display.

Set the Option “Enter ID” using the Up and Down keys

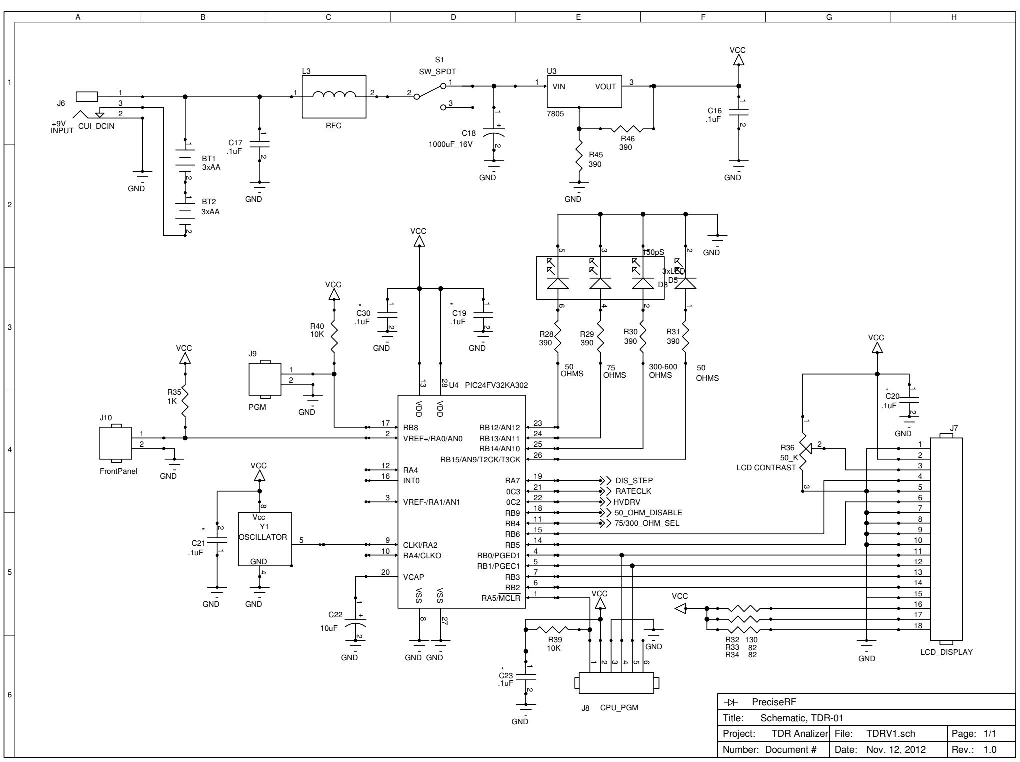
End

11. SCHEMATICS

Pulse Generator



CPU and Power supply



12. BILL OF MATERIALS

preciseRF **BOM - TDR PCB Rev C2**

QTY	Product/Value	Reference Designators	Digikey Part Number	Manufacture	Part Number	Order
1	PCB	TDR-1 REV C		preciseRF	TDR-1 REV C	
7	.1uF	C1 C3 C19 C20 C21 C23 C30	399-8140-6-ND	Kemit	C1206C104K3RACT	
5	.1uF_100V	C12 C13 C15 C16 C17	445-2634-ND	TDK	FK26XR72A104K	
4	.1uF_250V	C6 C9 C27 C28	445-2637-ND	TDK	FK26XR72G104K	
1	1.2-3pF	C10	SG9008TR-ND	Sprauge	SGC3S03	
2	2.2uF_250V	C7 C8	P5864-ND	Panasonic	ECA-2EG2R2	
1	4.7uF 50V	C2	P5177	Panasonic	ECA-1HM4R7	
2	5.2-30pF	C4 C24	490-1961-ND	Murata	TE03R300F169800	
1	10uF	C22	P5134-ND	Panasonic	ECA-1CM100	
1	22pF	C11	478-3779-1-ND	AVX	12061A220KPT2A	
1	330pF	C5	399-7719-ND	Kemet	PFR5331J100J11L4BULK	
1	470uF_6.3V	C14	P5114-ND	Panasonic	ECA-0JM471	
1	1000uF_16V	C18	P5142-ND	Panasonic	ECA-1CM102	
0	NO_LOAD	C25				
3	IN914	D4 D6 D8	1N914BCT-ND	FAIRCHILD	1N914BTR	
1	3xLED	D5	754-1289-ND	Kingbright	WP932SA/3GD	
1	1XLED	D7	754-1297-ND	Kingbright	WP934CB/GD	
3	MUR120	D1-D3	MUR120-TPMSCT-ND	Micor Commer	MUR120TP	
4	BNC	J1 J2 J3 J5	A97569-ND	TE	5-1634513-1	
1	CPU_PGM	J8	A31116-ND	TE	3-644456-6	
1	CUI_DCIN	J6	CP-047A-ND	CUI Inc.	PJ-047A	
1	FrontPanel	J10	WM4111-ND	Molex	22272021	
2	LCD_DISPLAYCBL	J7	WM09-04A-ND	Molex	25001-0904	
1	PGM	J9	A31112-ND	TE	3-644456-2	
1	SMA	J4	CONSMA002-L-ND	Linx	COMSMA002-L	
2	RELAY	K1-K2	PB1094-ND	AIXCOM	IM03TS	
1	150uH	L1	AIAP-01-151-K-TCT-ND	Abarcon	AIAP-01-151-K-T	
3	RFC	L2 L3 L4	240-2492-ND	Laird	28C0236-0EW-10	
2	MMBT3904	Q2-Q3	568-4510-1-ND	NXP	MMBT3904.215	
2	BFG541	Q1 Q6	568-1984-1-ND	NXP	BFG541.115	

preciseRF **BOM - TDR Front Panel Rev A**

QTY	Product/Value	Reference Designators	Digikey Part Number	Manufacture	Part Number
1	TDRFP PCB	Rev A		**preciseRD**	TDRFP PCB, Rev A
1	1.3K	R6	1.3KXTR-ND	Yageo	MFR-25FRF-52-1K30
1	150	R1	150XTR-ND	Yageo	MFR-25FRF-52-150R
1	200	R2	200XTR-ND	Yageo	MFR-25FRF-52-200R
1	270	R3	270XTR-ND	Yageo	MFR-25FRF-52-270R
1	390	R4	390XTR-ND	Yageo	MFR-25FRF-52-390R
1	680	R5	680XTR-ND	Yageo	MFR-25FRF-52-680R
7	Button	S1 - S7	401-1988-ND	C&K	D6C-90-F2-LFS
1	2 Pin Connector	J1	WM2000-ND	Molex	22013027
2	Female Pins	J1A, J1B	WM1114CT-ND	Molex	850113
5"	Wire	Green	A2015-G-100-ND	Alpha Wire	3050 GR005
5"	Wire	Yellow	A2015Y-100-ND	Alpha Wire	3050 YL005

preciseRF **BOM - TDR Front Panel Rev A**

QTY	Product/Value	Reference Designators	Digikey Part Number	Manufacture	Part Number
1	Enclosure	Enclosure	HM166-ND	Hammond	1598E
1	Power Supply	Power Supply 9V, 600mA	T980-P5P-ND	CUI Inc.	EPS090066
1	LCD Display	Display	NHD-0216K1Z-FS(RGB-FB\	Newhaven	NHD-0216K1Z-FS(RGB)FBW-REV1
9	Screw, #4-40 x 0.25"				
1	Nut, #4-40 KEP				
2	Cable	LCD Cable	WM09-04A-ND	Molex	SD-25001-001
1	Users Manual	Manual		preciseRF	
4	Screw, #6-32 x 1/2 PHPS Self Tapping, Steel/Zinc			Olander	
4	Spacer, #6 x 1/4" Steel Zinc, Clear			Olander	

preciseRF		BOM - TDR PCB Rev C2			
QTY	Product/Value	Reference Designators	Digikey Part Number	Manufacture	Part Number
1	IRFU210PBF	Q4	IRFU210PBF-ND	Vishay	IRFU210PBF
1	2.2 Ohm	R16	2.2QBK-ND	Yageo	CFR-25JB-52-2.2R
1	1K	R35	1.00KXTR-ND	Yageo	MRF25FRF-52-1k0
1	2M	R19	541-2.0MECT-ND	Vishay	CRCW12062M00JNEA
1	10	R22	541-10.0FCT-ND	Vishay	CRCW120610R0FKEA
1	33	R43	541-33.0FCT-ND	Vishay	CRCW120633R0FKEA
1	49.9 Ohm	R17	541-49.9FCT-ND	Vishay	CRCW120633R0FKEA
5	10K	R12 R13 R15 R39 R40	10KQBK-ND	Yageo	CFR-25JB-52-10K
2	2.2	R2	541-2.2ECT-ND	Vishay	CRCW12062R2JNE-A
2	22 Ohm	R21, R45	22QBK-ND	Yageo	CFR-25JB-52-22R
1	50_K Pot	R36	3362P-503LF-ND	Bourns	3362R-1-503LF
1	1K Pot	R4	3362P-102LF-ND	Bourns	3362R-1-102LF
1	50 Pot	R42	3362P-500LF-ND	Bourns	3362R-1-500LF
1	100K	R37	100KXBK-ND	Yageo	MFR-25FRF-52-100K
1	220K	R38	221KXBK-ND	Yageo	MFR-25FBF-52-221K
2	82	R33-R34	82QBK-ND	Yageo	CFR-25JB-52-82R
5	100	R7 R18 R24 R25 R26	541-100FCT-ND	Vishay	CRCW1206100RFKEA
1	130	R32	130QBK-ND	Yageo	CFR-25JB-52-130R
1	30	R9	541-30.0FCT-ND	Vishay	CRCW120630R0FKEA
5	150	R3 R6 R8 R10 R14	541-150FCT-ND	Vishay	CRCW1206150RFKEA
1	1.5k	R41	541-1.50KFCT-ND	Vishay	CRCW12061K50FKEA
5	200	R1 R23	541-200FCT-ND	Vishay	CRCW1206200RFKEA
1	430	R11	541-430FCT-ND	Vishay	CRCW1206249RFKEA
4	390	R28 R29 R30 R31	390QBK-ND	Yageo	CFR-25JB-52-390R
1	66.5	R27	541-66.5FCT-ND	Vishay	CRCW120666R5FKEA
2	16.5	R20 R44	541-16.5FCT-ND	Vishay	CRCW120616R5FKEA
1	SW_SPDT	S1	CKN1517-ND	C&K	E101SD1AV2BE
1	74ACT14	U1	296-14492-1-ND	TI	CD74ACT14M96
1	74LS74	U2	296-14484-1-ND	TI	CD74ACT74M96
1	LM7805CT-ND	U3	LM7805ACT-ND	FAIRCHILD	LM7805CT
1	PIC24FV32KA302	U4	PIC24FV32KA302-I/SP-ND	MicroChip	PIC24FV32KA302
1	OSCILLATOR	Y1	CTX749-ND	CTS	MX045HS-3C32M000
2	Battery Case	BT1 BT2	2479K-ND	Keystone	2479

13. Additional Information

James A. Strickland, Allen Zimmerman, Gordon Long and George Frye, all from Tektronix at the time, wrote a comprehensive Measurement Concepts paper, "TIME-DOMAIN REFLECTOMETER MEASUREMENTS" in the late 1960's. It is still considered the authoritative reference despite it being more than 40 years old. Of all the papers and information I researched in preparation of this application note, I found it to be most enlightening and fairly easy to read and understand. http://www.davmar.org/TE/TekConcepts/TekTDRMeas.pdf

If you are into home-brewing circuit board level projects, this application note entitled, "Time Domain Methods for Measuring Crosstalk on PCB Quality Verification" will help you layout your circuit board traces for best-high frequency performance.

http://www.coe.montana.edu/ee/lameres/courses/eele461_spring12/information/TDR_AppNote_Tektronix_Xtalk_11499_EN.pdf

A detailed discussion is also available at the ARRL website:

http://www.arrl.org/files/file/Technology/tis/info/pdf/q1106037.pdf

http://www.arrl.org/files/file/Technology/tis/info/pdf/9706057.pdf

CPU and firmware: Rob Kirkpatrick KI6HNA

Microwave & Analog design: Roger Stenbock W1RMS

preciseRF
www.preciserf.com ™

Precision Ham Radio Measurements

22781 Airport Rd NE Suite D-1
Aurora, Oregon 97002 Phone: (503) 915-2490
www.preciserf.com Email: sales@preciserf.com