Practical Time-Domain Reflectometer

History

Original article published in May 1989 issue of QST "Practical Time-Domain Reflectometer" by Tom King, KD5HM

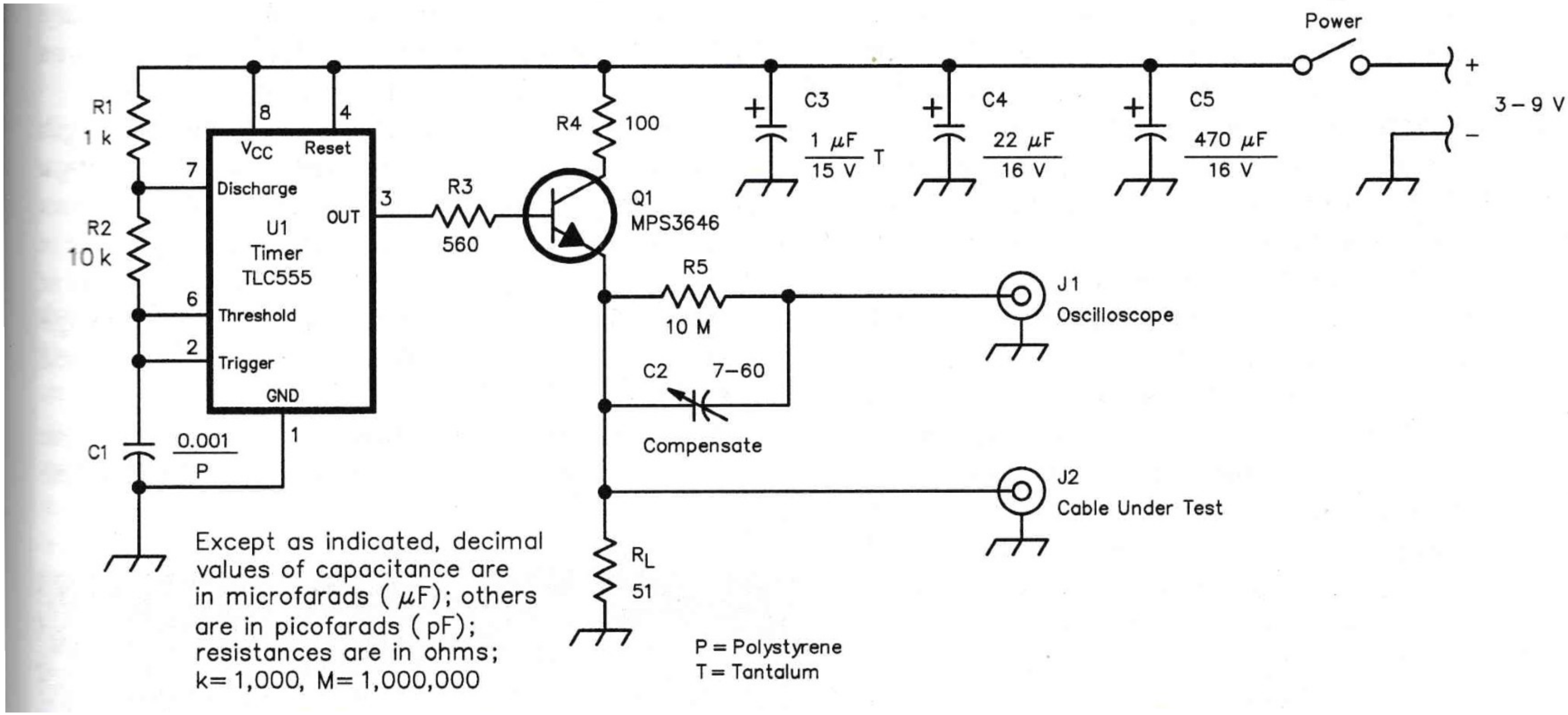
Reprinted in ARRL Antenna Book 19th Edition (2000)

A time-domain reflectometer (TDR) is an electronic instrument used to determine the characteristics of electrical lines by observing reflected pulses.

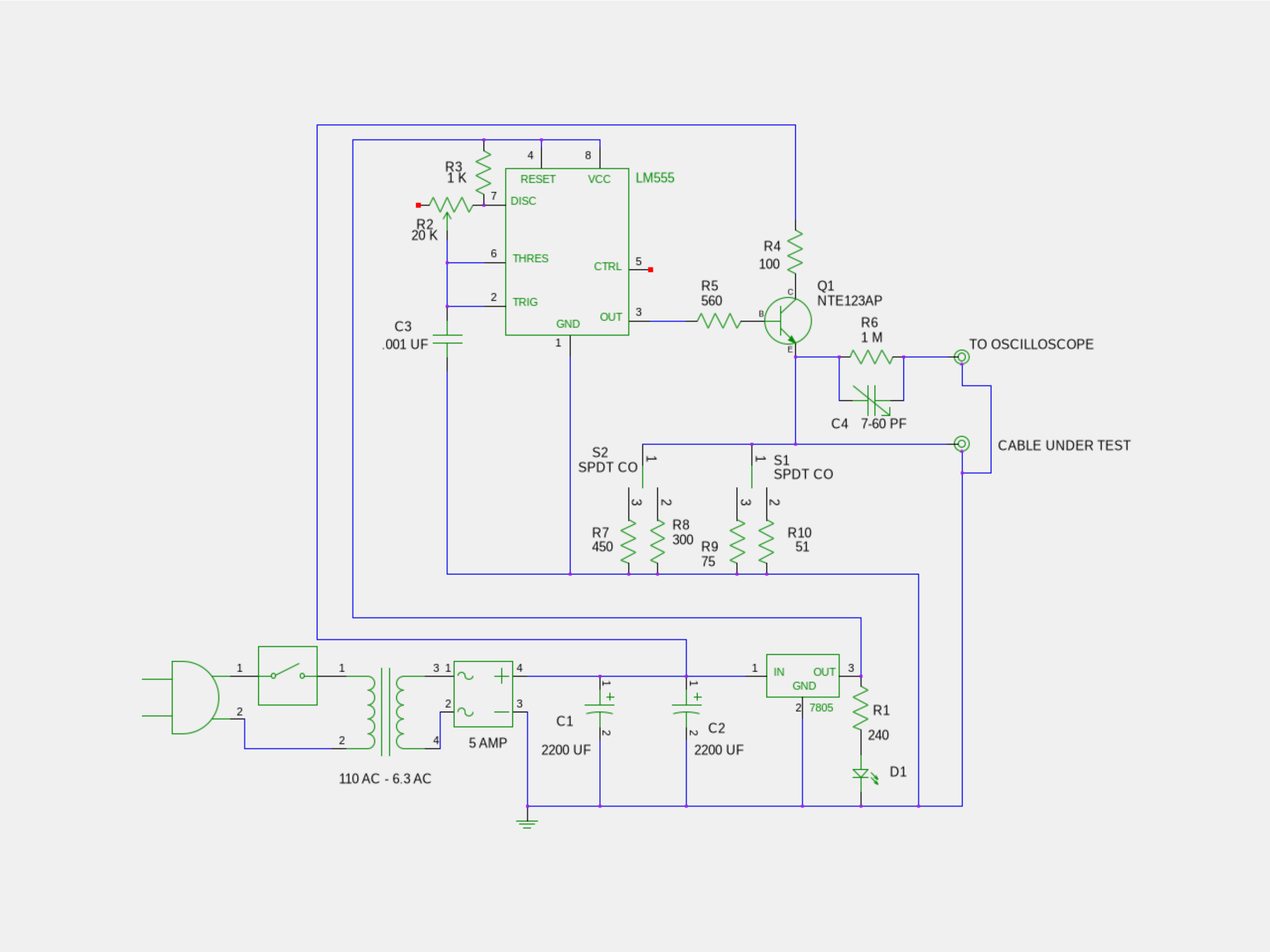
It can be used to characterize and locate faults in metallic cables for example, twisted pair wire or coaxial cable and to locate discontinuities in a connector, printed circuit board, or any other electrical path.

A TDR measures reflections along a conductor. In order to measure those reflections, the TDR will transmit an incident signal onto the conductor and listen for its reflections. If the conductor is of a uniform impedance and is properly terminated, then there will be no reflections and the remaining incident signal will be absorbed at the far-end by the termination. Instead, if there are impedance variations, then some of the incident signal will be reflected back to the source.

The impedance of the discontinuity can be determined from the amplitude of the reflected signal. The distance to the reflecting impedance can also be determined from the time that a pulse takes to return.



Original Circuit Diagram from the ARRL Antenna Book



Updated Circuit Diagram Modifications Made:

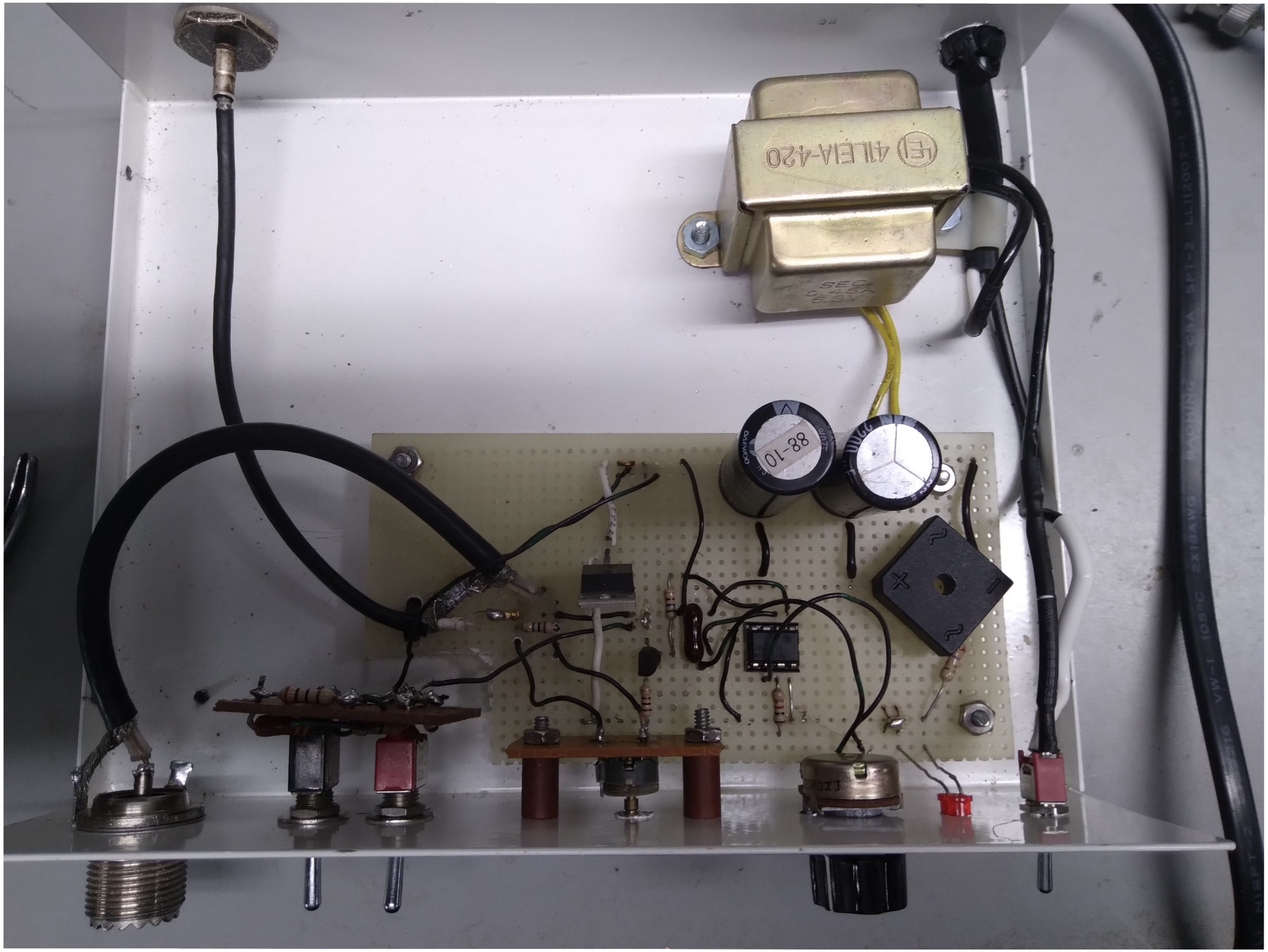
Added internal power supply
Added multiple switchable terminating resistors for different coax impedances
Modified Lm555 oscillator to have variable frequency
MPS3646 transistor no longer available – replaced with NTE123AP transistor
A better transistor replacement would be a 2N2369 with a faster rise time

Front Panel:

Power On/Off Switch
LED – Power on Indicator
FREQUENCY – Adjustable from ≈ 30 kHz to ≈ 600 kHz
PROBE CAL – Output to Oscilloscope is the same as a 10X Probe
CENTER OFF SPDT SWITCHES – Most Common Impedance Values for internal termination
CABLE IN – Input for Cable Under Test

Rear Panel (Not shown)

SCOPE OUT 10X – BNC connector to the Oscilloscope Input



Definitions and terms

Propagation of a signal in free space = 186282 Miles/Second

Velocity Factor - the ratio of the speed at which a signal passes through the medium to the speed of signal in free space (Always less than 1)

Rise Time – The amount of time from the start of a pulse until it reaches a stable value

Nanosecond – 10^{-9} seconds

Distance a signal travels in free space in 1 nanosecond = .984 feet or 11.8 Inches

$$\frac{Miles/Second \times Feet/Mile}{nanoseconds/second} = Feet/nanosecond$$

OR

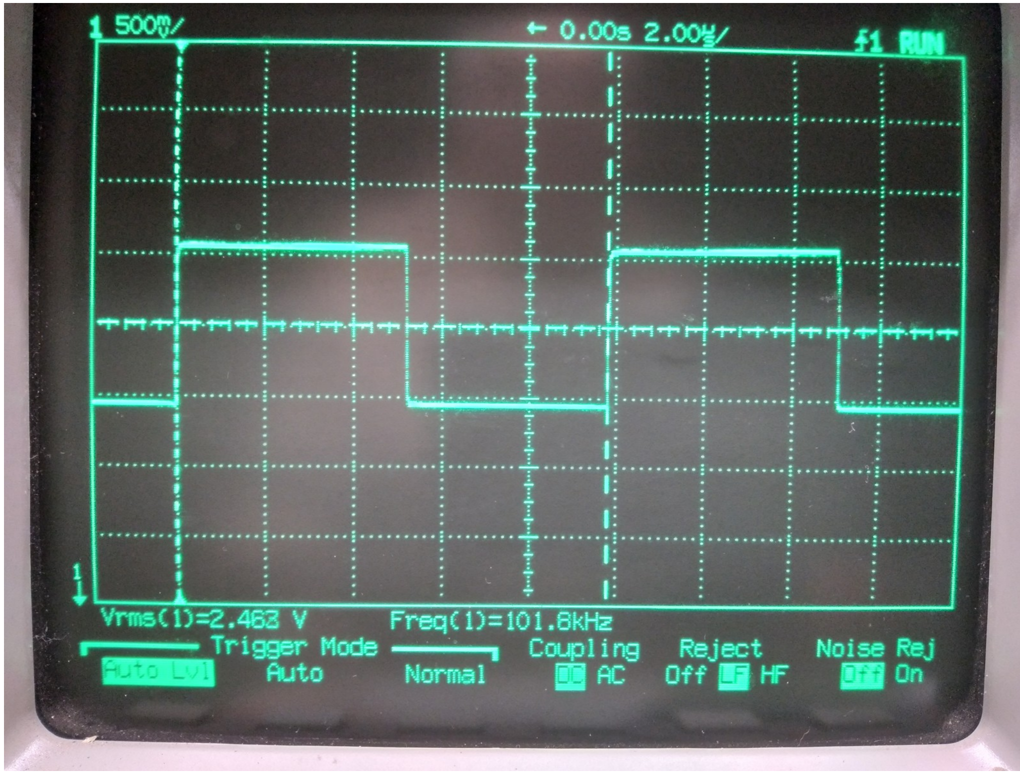
$$\frac{Miles/Second \times Feet/Mile \times Inches/Foot}{nanoseconds/second} = Inches/nanosecond$$

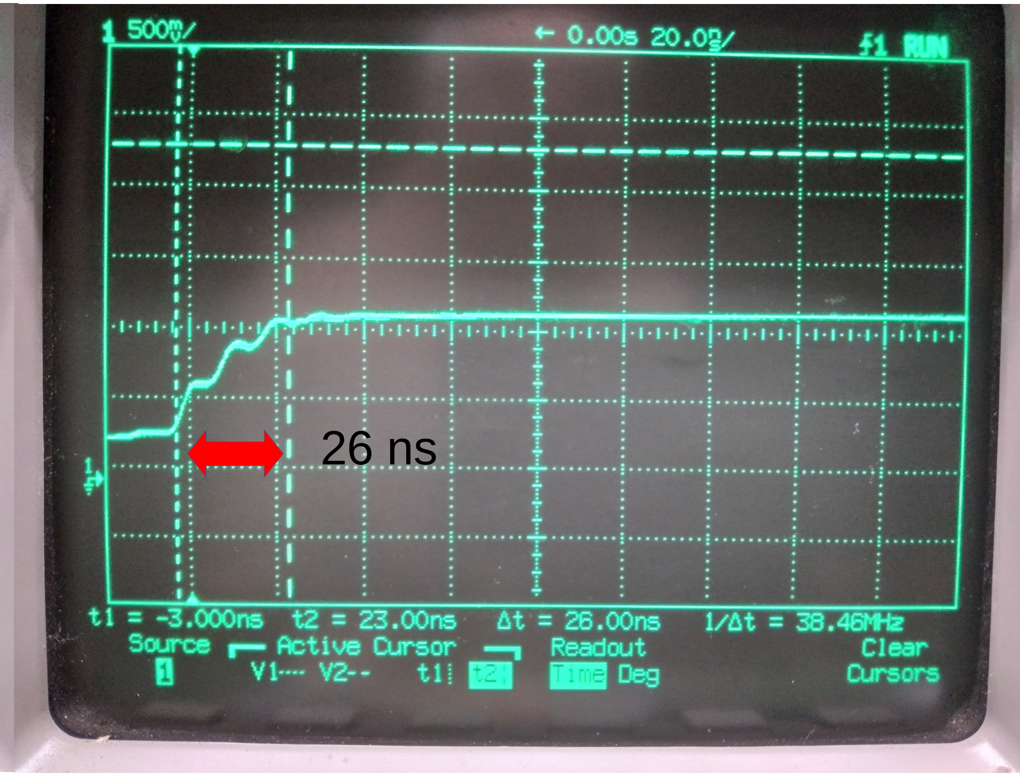
$$\frac{186282 \times 5280}{10^9} = .984 \quad Feet$$

OR

$$\frac{186282 \times 5280 \times 12}{10^9} = 11.8 \quad Inches$$

Initial Setup and Calibration





The PROBE CAL Capacitor must be adjusted for the best possible square wave

The Frequency should be set based on the coax cable length
- Shorter cables may need to use a Higher frequency

The Shortest cable that can be measured is based on the rise time of the square wave

- The return pulse can not be determined during the rise time
- The pulse must travel to the end for cable and back so the time displayed is double

$$\frac{26\,ns \times .984\,feet}{2} = minimum\ cable\ length\ 12.79\ feet$$

Cable Standards

Parameters for manufacturing cables are:

The material for the conductors
The impedance of the cable
The jacket material
The cable dimensions
The minimum bend radius
The attenuation measured in dB per unit length of cable
The rated temperature for the cable

Notice that velocity factor is not one of the required parameters for cable

Determining Velocity Factor

Use a published table to get cable values

Or

Use a TDR to compute the velocity factor

The two items are needed to compute the velocity factor are:

- The physical length of the cable – Measured in feet
- The electrical length of the cable – Computed using the TDR data

Table 1

Characteristics of Commonly Used Transmission Lines

RG or Type	*Part Number*	*Z_0 Ω*	*VF %*	*Cap. pF/ft*	*Cent. Cond. AWG*	*Diel.*	*Shield*	*Jacket*	*OD in.*	*Max V (RMS)*	*Matched Loss (dB/100) 1 MHz*	*10*	*100*	*1000*
RG-6	Belden 8215	75	66	20.5	#21 Solid	PE	FC	PE	0.275	2700	0.4	0.8	2.7	9.8
RG-8	TMS LMR400	50	85	23.9	#10 Solid	FPE	FC	PE	0.405	600	0.1	0.4	1.3	4.1
RG-8	Belden 9913	50	84	24.6	#10 Solid	ASPE	FC	P1	0.405	600	0.1	0.4	1.3	4.5
RG-8	WM CQ102	50	84	24.0	#9.5 Solid	ASPE	S	P2	0.405	600	0.1	0.4	1.3	4.5
RG-8	DRF-BF	50	84	24.5	#9.5 Solid	FPE	FC	PEBF	0.405	600	0.1	0.5	1.6	5.2
RG-8	WM CQ106	50	82	24.5	#9.5 Solid	FPE	FC	P2	0.405	600	0.2	0.6	1.8	5.3
RG-8	Belden 9914	50	82	24.8	#10 Solid	TFE	FC	P1	0.405	3700	0.1	0.5	1.6	6.0
RG-8	Belden 8237	52	66	29.5	#13 Flex	PE	S	P1	0.405	3700	0.2	0.6	1.9	7.4
RG-8X	TMS LMR240	50	84	24.2	#15 Solid	FPE	FC	PE	0.242	300	0.2	0.8	2.5	8.0
RG-8X	WM CQ118	50	82	25.0	#16 Flex	FPE	S	P2	0.242	300	0.3	0.9	2.8	8.4
RG-8X	Belden 9258	50	80	25.3	#16 Flex	TFE	S	P1	0.242	300	0.3	1.0	3.3	14.3
RG-9	Belden 8242	51	66	30.0	#13 Flex	PE	D	P2N	0.420	3700	0.2	0.6	2.1	8.2
RG-11	Belden 8213	75	78	17.3	#14 Solid	FPE	S	PE	0.405	600	0.2	0.4	1.5	5.4
RG-11	Belden 8238	75	66	20.5	#18 Flex	PE	S	P1	0.405	600	0.2	0.7	2.0	7.1
RG-58C	TMS LMR200	50	83	24.5	#17 Solid	FPE	FC	PE	0.195	300	0.3	1.0	3.2	10.5
RG-58	WM CQ124	53.5	66	28.5	#20 Solid	PE	S	P2N	0.195	1400	0.4	1.3	4.3	14.3
RG-58	Belden 8240	53.5	66	28.5	#20 Solid	PE	S	P1	0.193	1400	0.3	1.1	3.8	14.5
RG-58A	Belden 8219	50	78	26.5	#20 Flex	FPE	S	P1	0.198	300	0.4	1.3	4.5	18.1
RG-58C	Belden 8262	50	66	30.8	#20 Flex	PE	S	P2N	0.195	1400	0.4	1.4	4.9	21.5
RG-58A	Belden 8259	50	66	30.8	#20 Flex	PE	S	P1	0.193	1400	0.4	1.5	5.4	22.8
RG-59	Belden 8212	75	78	17.3	#20 Solid	TFE	S	PE	0.242	300	0.6	1.0	3.0	10.9
RG-59B	Belden 8263	75	66	20.5	#23 Solid	PE	S	P2N	0.242	1700	0.6	1.1	3.4	12.0
RG-62A	Belden 9269	93	84	13.5	#22 Solid	ASPE	S	P1	0.260	750	0.3	0.9	2.7	8.7
RG-62B	Belden 8255	93	84	13.5	#24 Solid	ASPE	S	P2N	0.260	750	0.3	0.9	2.9	11.0
RG-63B	Belden 9857	125	84	9.7	#22 Solid	ASPE	S	P2N	0.405	750	0.2	0.5	1.5	5.8
RG-142B	Belden 83242	50	69.5	29.2	#18 Solid	TFE	D	TFE	0.195	1400	0.3	1.1	3.9	13.5
RG-174	Belden 8216	50	66	30.8	#26 Solid	PE	S	P1	0.101	1100	1.9	3.3	8.4	34.0
RG-213	Belden 8267	50	66	30.8	#13 Flex	PE	S	P2N	0.405	3700	0.2	0.6	2.1	8.2
RG-214	Belden 8268	50	66	30.8	#13 Flex	PE	D	P2N	0.425	3700	0.2	0.6	1.9	8.0
RG-216	Belden 9850	75	66	20.5	#18 Flex	PE	D	P2N	0.425	3700	0.2	0.7	2.0	7.1
RG-217	M17/79-RG217	50	66	30.8	#9.5 Solid	PE	D	P2N	0.545	7000	0.1	0.4	1.4	5.2
RG-218	M17/78-RG218	50	66	29.5	#4.5 Solid	PE	S	P2N	0.870	11000	0.1	0.2	0.8	3.4
RG-223	Belden 9273	50	66	30.8	#19 Solid	PE	D	P2N	0.212	1700	0.4	1.2	4.1	14.5
RG-303	Belden 84303	50	69.5	29.2	#18 Solid	TFE	S	TFE	0.170	1400	0.3	1.1	3.9	13.5
RG-316	Belden 84316	50	69.5	29.0	#26 Solid	TFE	S	TFE	0.098	900	1.2	2.7	8.3	29.0
RG-393	M17/127-RG393	50	69.5	29.4	#12 Solid	TFE	D	TFE	0.390	5000	0.2	0.5	1.7	6.1
RG-400	M17/128-RG400	50	69.5	29.4	#20 Solid	TFE	D	TFE	0.195	1900	0.4	1.1	3.9	13.2
LMR500	TMS LMR500	50	85	23.9	#7 Solid	FPE	FC	PE	0.500	2500	0.1	0.3	0.9	3.3
LMR600	TMS LMR600	50	86	23.4	#5.5 Solid	FPE	FC	PE	0.590	4000	0.1	0.2	0.8	2.7
LMR1200	TMS LMR1200	50	88	23.1	#0 Tube	FPE	FC	PE	1.200	4500	0.04	0.1	0.4	1.3
Hardline														
½"	CATV Hardline	50	81	25.0	#5.5	FPE	SM	none	0.500	2500	0.05	0.2	0.8	3.2
½"	CATV Hardline	75	81	16.7	#11.5	FPE	SM	none	0.500	2500	0.1	0.2	0.8	3.2
7/8"	CATV Hardline	50	81	25.0	#1	FPE	SM	none	0.875	4000	0.03	0.1	0.6	2.9
7/8"	CATV Hardline	75	81	16.7	#5.5	FPE	SM	none	0.875	4000	0.03	0.1	0.6	2.9
LDF4-50A	Heliax – ½"	50	88	25.9	#5 Solid	FPE	CC	PE	0.630	1400	0.05	0.2	0.6	2.4
LDF5-50A	Heliax – 7/8"	50	88	25.9	0.355"	FPE	CC	PE	1.090	2100	0.03	0.10	0.4	1.3
LDF6-50A	Heliax – 1 5/8"	50	88	25.9	0.516"	FPE	CC	PE	1.550	3200	0.02	0.08	0.3	1.1
Parallel Lines														
TV Twinlead		300	80	5.8	#20	PE	none	P1	0.500					
Transmitting Tubular		300	80	5.8	#20	PE	none	P1	0.500	8000	0.09	0.3	1.1	3.9
Window Line		450	91	4.0	#18	PE	none	P1	1.000	10000	0.02	0.08	0.3	1.1
Open Wire Line		600	92	1.1	#12	none	none	none	varies	12000	0.02	0.06	0.2	0.7

Approximate Power Handling Capability (1:1 SWR, 40°C Ambient):

	1.8 MHz	*7*	*14*	*30*	*50*	*150*	*220*	*450*	*1 GHz*
RG-58 Style	1350	700	500	350	250	150	120	100	50
RG-59 Style	2300	1100	800	550	400	250	200	130	90
RG-8X Style	1830	840	560	360	270	145	115	80	50
RG-8/213 Style	5900	3000	2000	1500	1000	600	500	350	250
RG-217 Style	20000	9200	6100	3900	2900	1500	1200	800	500
LDF4-50A	38000	18000	13000	8200	6200	3400	2800	1900	1200
LDF5-50A	67000	32000	22000	14000	11000	5900	4800	3200	2100
LMR500	12000	6000	4200	2800	2200	1200	1000	700	450
LMR1200	39000	19000	13000	8800	6700	3800	3100	2100	1400

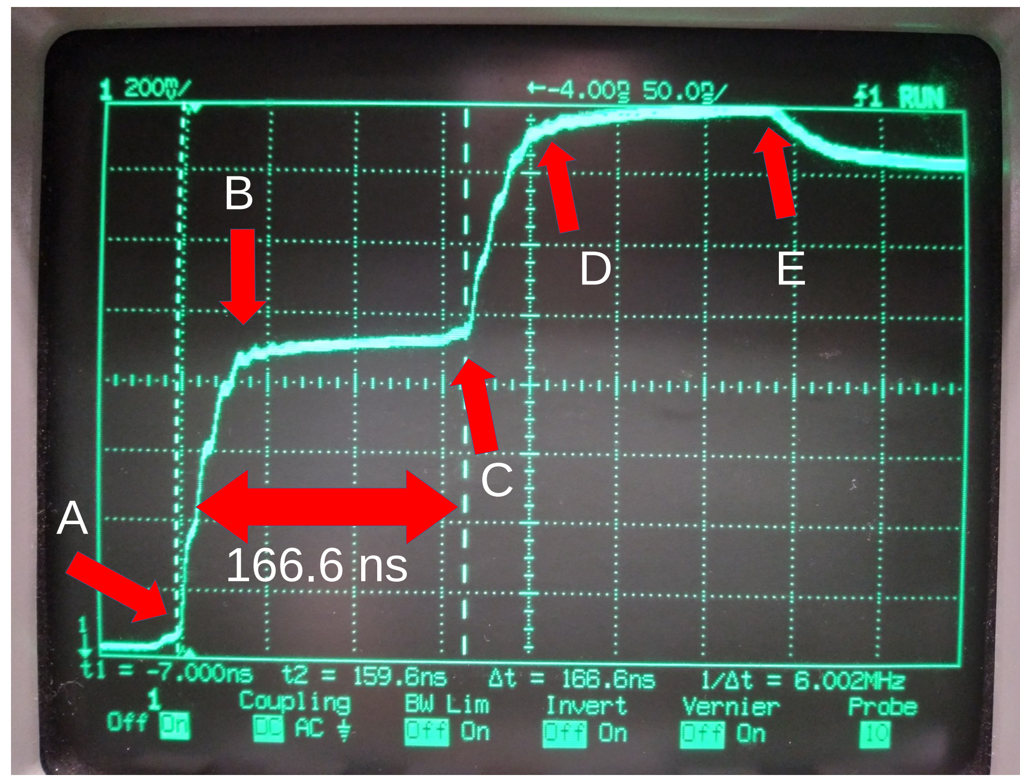
Legend:

ASPE Air Spaced Polyethylene
BF Flooded direct bury
CC Corrugated Copper
D Double Copper Shields
DRF Davis RF
FC Foil/Copper Shields
FPE Foamed Polyethylene
Heliax Andrew Corp Heliax
N Non-Contaminating
P1 PVC, Class 1
P2 PVC, Class 2
PE Polyethylene
S Single Shield
SM Smooth Aluminum
TFE Teflon
TMS Times Microwave Systems
WM Wireman
** Not Available or varies

Computation of Velocity factor

A length of RG-58 coaxial cable will be used for our first example

- The physical length of the cable is 53.75 feet attached to the TDR
- The cable is open at the other end
    - The current at the end of the cable is at a minimum and the voltage is at a maximum
    - The reflected signal is in phase with the outgoing signal
    - This will show an increase in signal over outgoing signal



The oscilloscope output shows the beginning of the output pulse

The point A is the start of the pulse

AB is the rise time of the pulse

AC is the portion of the cable that represents the characteristic impedance (50Ω)

CD indicates an impedance mismatch (open line)

CE is the return pulse

AC is time for the pulse reach the end of the cable and return (CE could also be used)

The time between the measured between the cursors is 166.6 nanoseconds

Computation of Velocity factor

Let's do some math…...

First we will use the published chart values to get the electrical length of the cable

- Physical length of the coax cable is 53.75 feet
- From the chart the velocity factor for RG-58 coax is .66
- The chart values of velocity factor for RG-58 cable varies from .66 to .83

$$L_e = \frac{L_p}{VF} = \frac{52.75}{.66} = 81.44\,feet$$

Now let's use the TDR values to get the electrical length of the cable

- Physical length of the coax cable is 53.75 feet
- Pulse time to the end of cable and back is 166.6 ns

$$L_e = \frac{P_{ns} \times C_{F/ns}}{2} = \frac{166.6 \times .984}{2} = 81.97\,feet$$

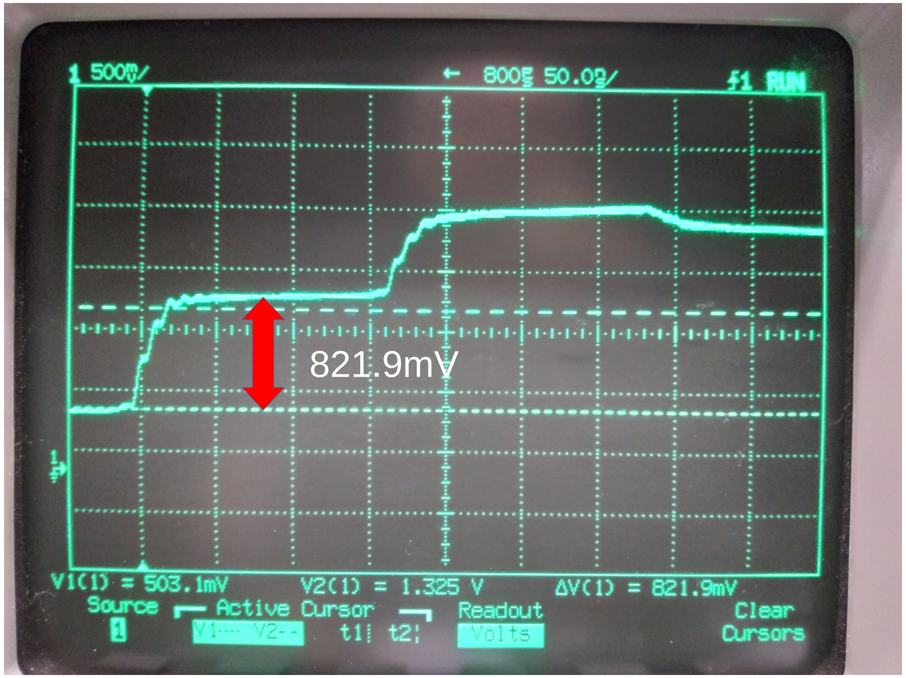
Using this TDR data the velocity factor is:

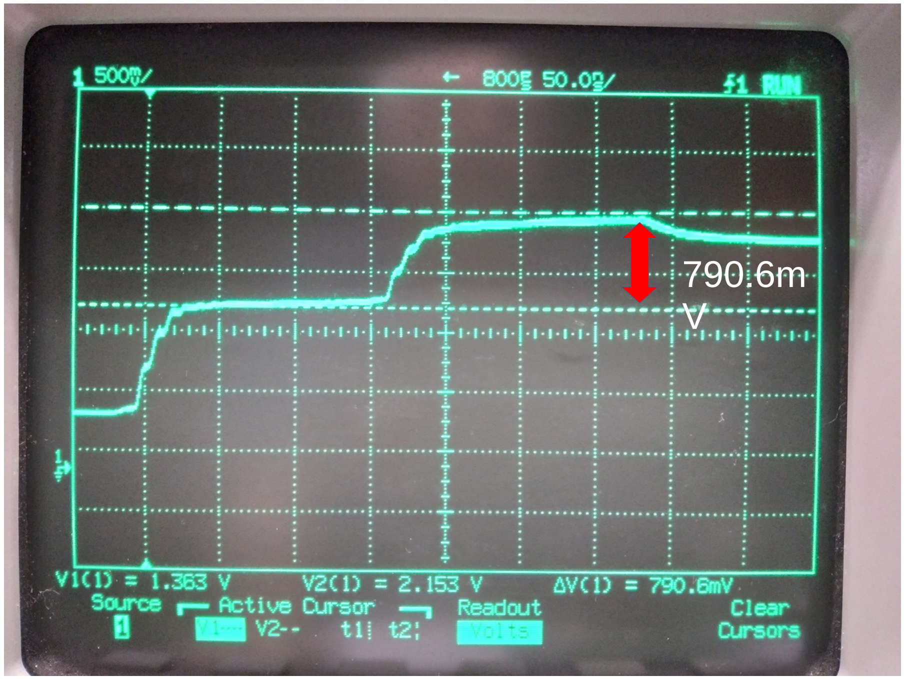
$$VF = \frac{L_p}{L_e} = \frac{53.75}{81.97} = .656$$

L_e = Electrical length
L_p=Physical length
P_{ns}=Pulse width in nanoseconds
$C_{F/ns}$=speed of light in free space in feet per nanosecond
VF=velocity factor

Cable Loss

We can use data from the TDR to determine cable loss





First off gain or loss is expressed as power ration expressed in Db
We can assume that the voltage reading can used for power if we multiply by 1 ampere

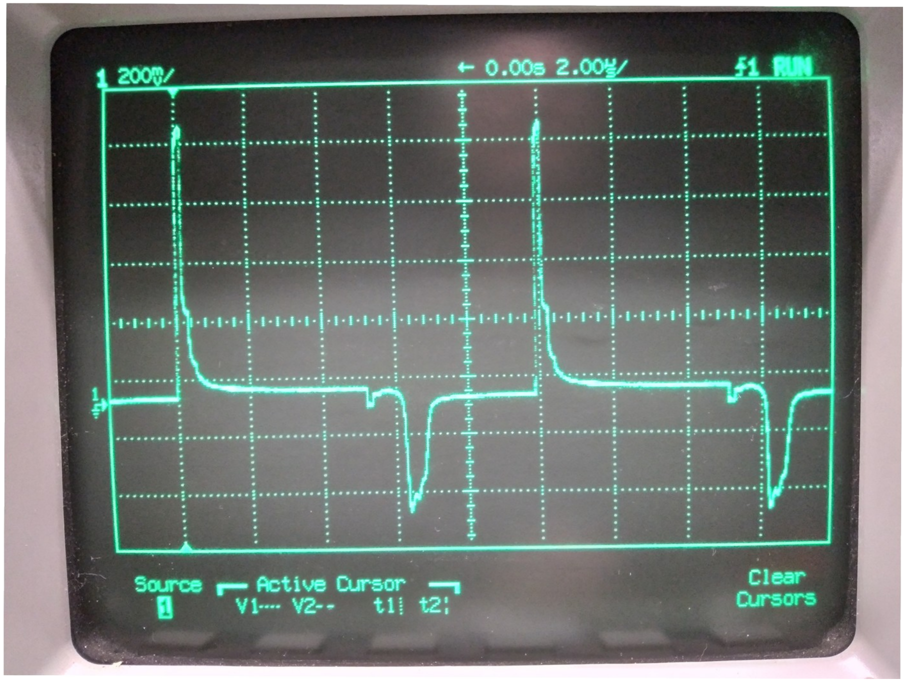
$$Db = 10 \times \log\left(\frac{P_1}{P_2}\right) = 10 \times \log\left(\frac{790.6}{821.9}\right) = 10 \times -.0169 = .169\ Db$$

Cable loss is usually expressed in Db per 100 feet but our cable is 53.75 feet long so

$$Db_{100} = \frac{Db_{measured} \times 100}{L_{cable}} = \frac{.169 \times 100}{53.75} = \frac{16.9}{53.75} = .314\ Db$$

The charts list the loss for RG-58 coax between .3 and .4 Db per 100 feet at 1 Mhz

What About A Shorted Cable?



With a shorted cable the current at the end of the cable is at maximum and voltage is at minimum

The reflected signal is 180° out of phase so the reflected voltage is subtracted from the pulse

The oscilloscope output shows the beginning of the output pulse

AB is time for the pulse reach the end of the cable and return

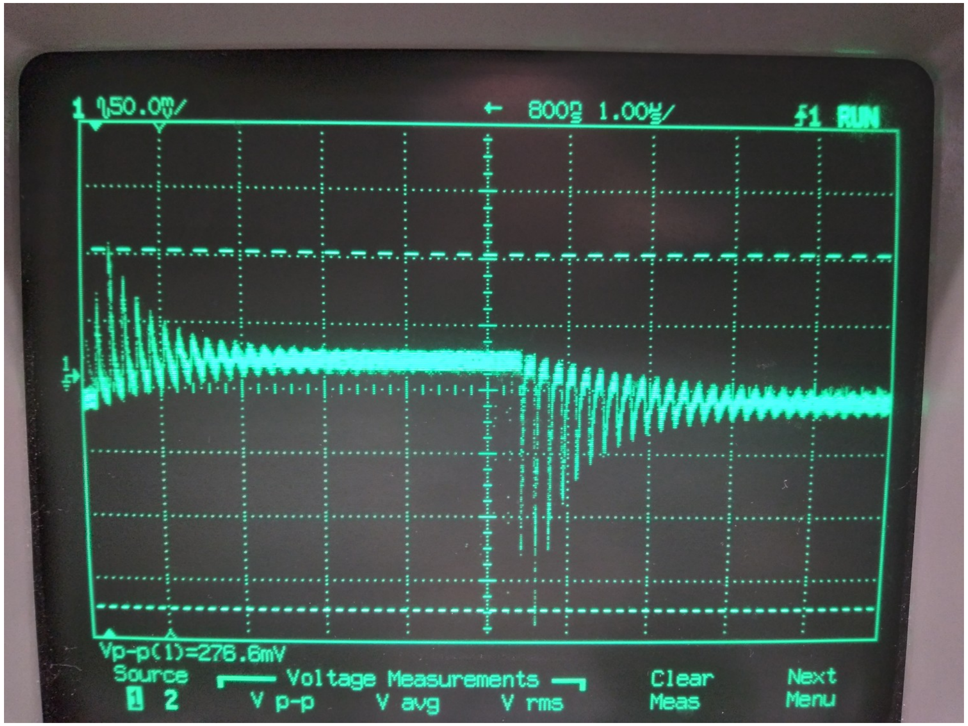
The distance between the two cursors is 166.6 ns

This is the same as open cable so this value can be used in the electrical length and velocity factor calculations

Determine the Impedance of a Cable

The switches set the internal impedance for the cable under test.
This impedance absorbs the energy of the returning pulse.

When the internal impedance is off and the cable is left open at the other end the oscilloscope trace looks like this



Of course we have a mismatch at the open end of the cable but we also have a mismatch at the TDR end with the impedance switches in the off position

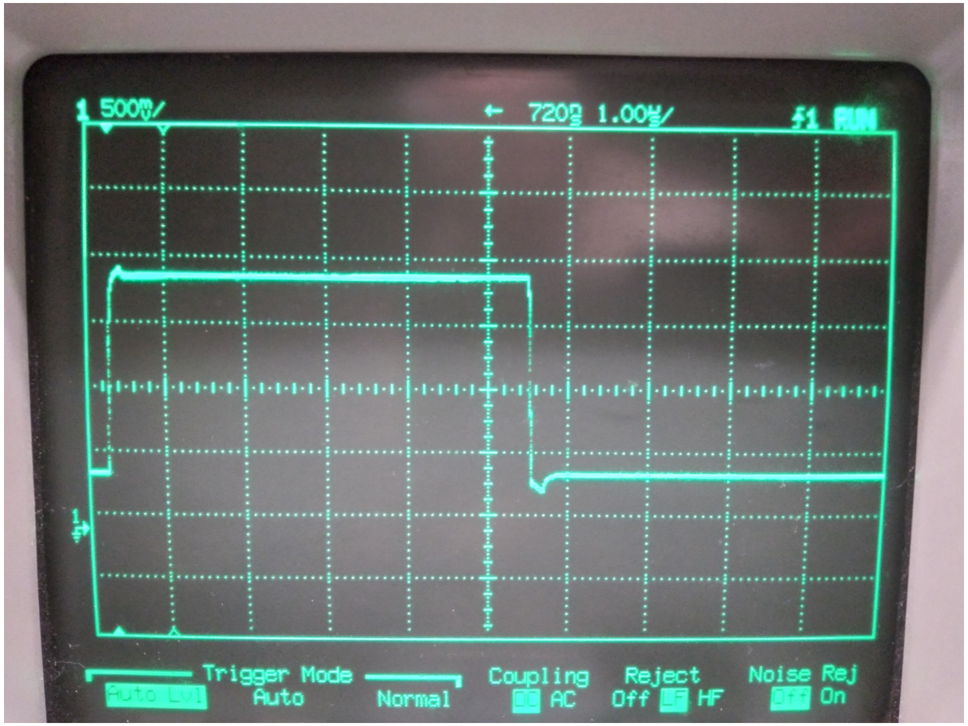
The pulse is rereflected at the TDR end of the cable so the pulse signal bounces back and forth

Notice the the signal decreases as time progresses

This is an indication of the cable loss

Determine the Impedance of a Cable

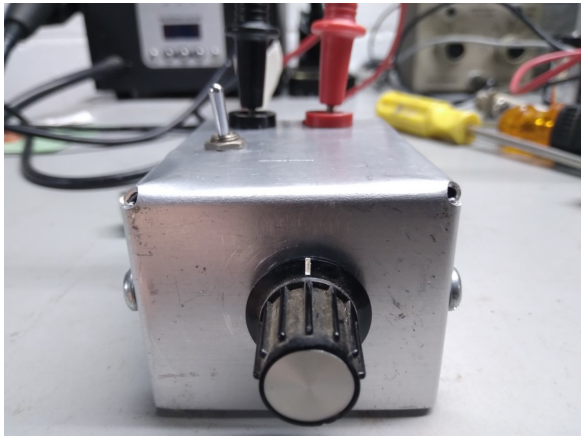
When the internal impedance is off and the cable is terminated with a 50 Ω impedance the oscilloscope trace looks like this



But what if we're not sure of the impedance of the cable?
For RG-58 cable the impedance is listed from 50 Ω to 53.5 Ω

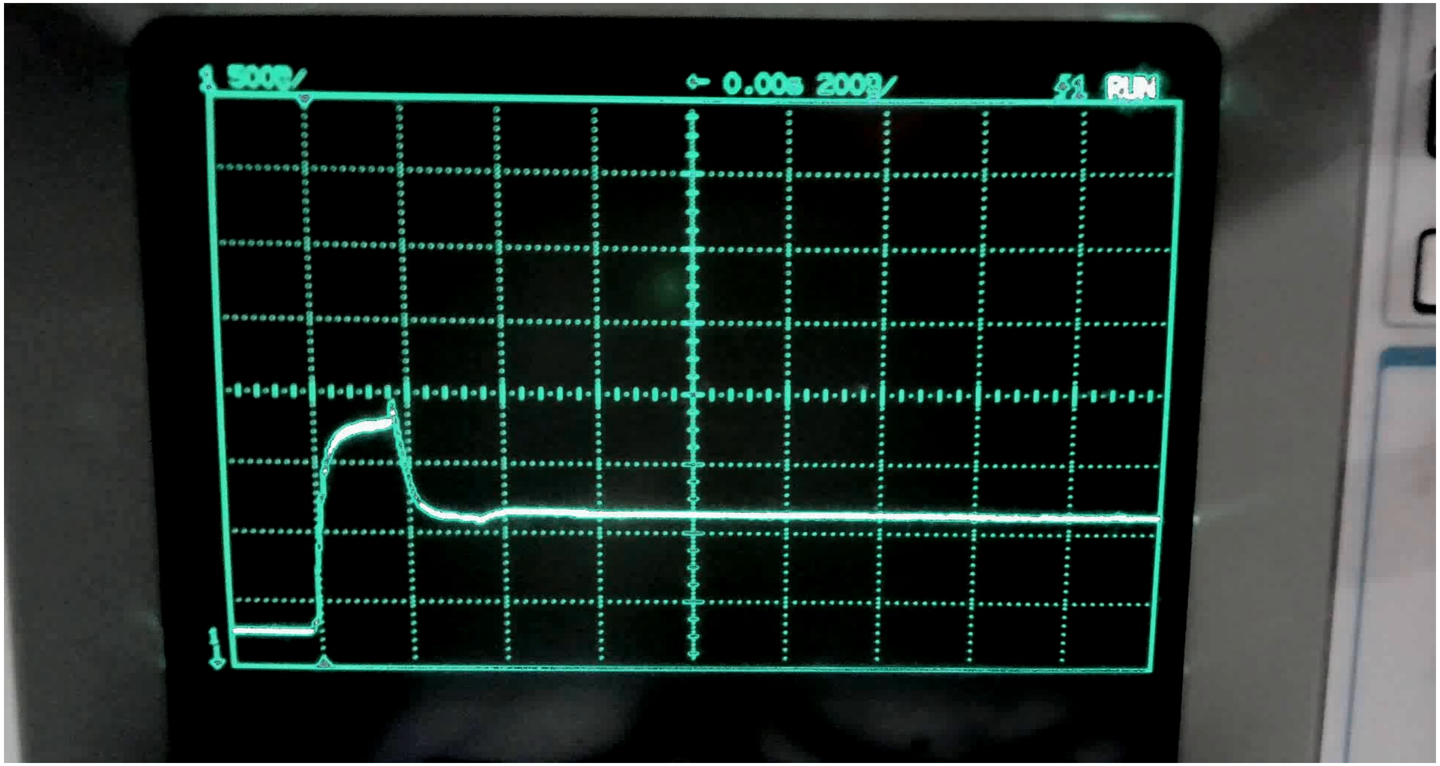
The way to use the TDR to determine the impedance is to use a variable resistor and attach it to the end of the cable

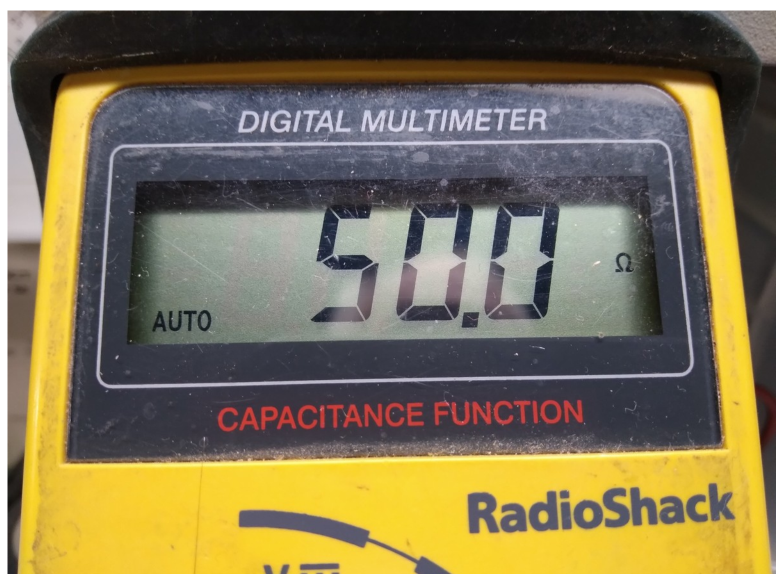
This multi-turn 500 Ω resistor that allows us to do that



By adjusting the resistor for the flattest possible line then reading the resistor's value this is the impedance of the cable

The next slide is an example of this


0.00s
RUN


DIGITAL MULTIMETER
50.0
Ω
AUTO
CAPACITANCE FUNCTION
RadioShack

Let’s Look at Another Cable

2 Pieces of RG-8X Coax Cable
First Piece 50.25 feet
Second Piece 19 feet
Joined Together with a Coaxial Tee Connector (will explain later)
Total Physical Length 69.25 feet

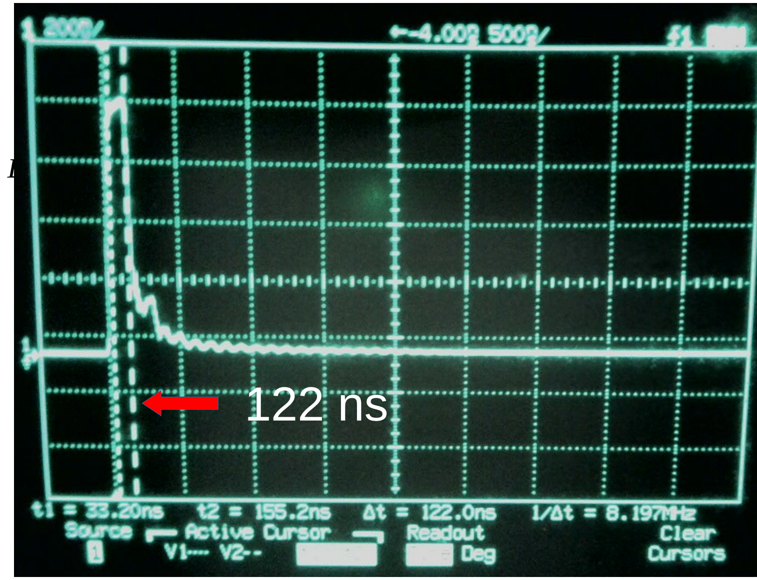
$$L_e = \frac{P_{ns} \times C_{F/ns}}{2} = \frac{167.8 \times .984}{2} = 82.56\ feet$$

$$VF = \frac{L_p}{L_e} = \frac{69.25}{82.56} = .84$$

L_e = Electrical length
L_p=Physical length
P_{ns}=Pulse width in nanoseconds
$C_{F/ns}$=speed of light in free space in feet per nanosecond
VF=velocity factor

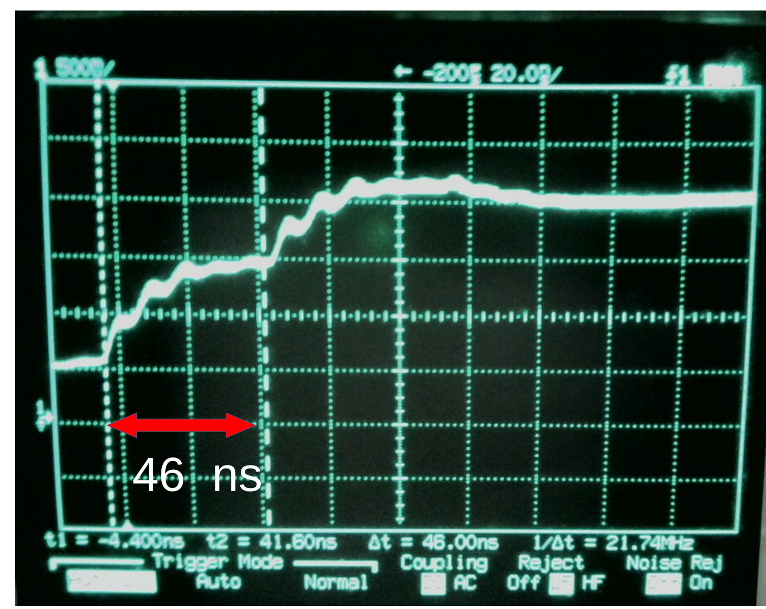
Now that we have the velocity factor for the cable we will introduce a short using the coax tee we used to connect the two cables together

$$D_{short} = \frac{P_{ns} \times C_{F/ns} \times VF}{2} = \frac{122 \times .984 \times .84}{2} = 50.42\, feet$$



Now we will introduce a open using the coax tee by unscrewing the coax connector

$$D_{open} = \frac{P_{ns} \times C_{F/ns} \times VF}{2} = \frac{46 \times .984 \times .84}{2} = 19\, feet$$

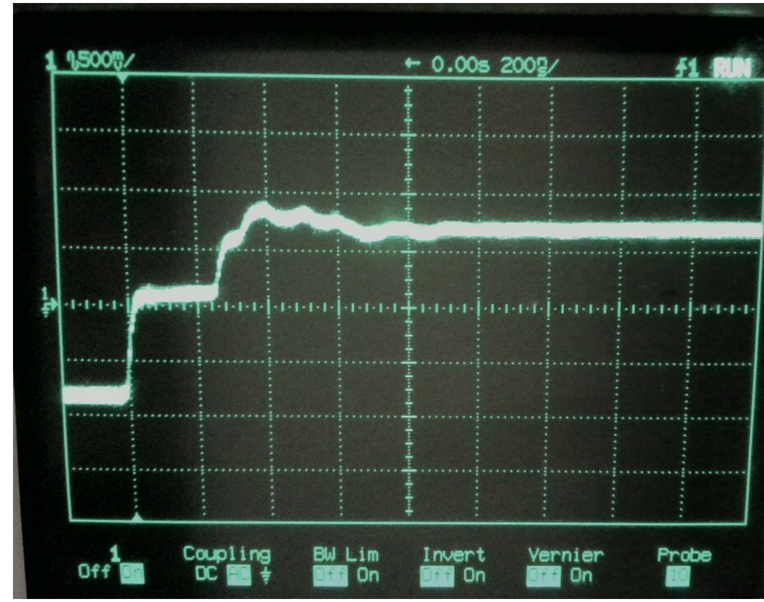


The Real World

Oscilloscope image of a dipole antenna

19 ft RG-8X to antenna switch
6 ft RG-58 to antenna tuner in bypass mode
100 ft RG-8 to ladder line
31 ft 450 Ω open wire ladder line
105 ft flat top dipole antenna

TDR internal termination 50 Ω



Oscilloscope image of a dipole antenna

19 ft RG-8X to antenna switch
6 ft RG-58 to antenna tuner in bypass mode
100 ft RG-8 to ladder line
31 ft 450 Ω open wire ladder line
105 ft flat top dipole antenna

TDR internal termination 450 Ω

The Real World

Using a TDR on a cable allows us to determine:

- The Electrical Length
- The Velocity Factor
- The Loss
- The impedance
- Find Open or Shorts

Knowing these factors can be used for:

- Finding bad cables
- Making quarter and half wave tuning stubs
- Making quarter wave matching sections

Where to Next?

Rework the 555 Oscillator

- The best duty cycle for the 555 timer is 50%
- Modify the timing circuit to allow for shorter duration pulses

Build a higher frequency unit

- Allow finding the cable losses at higher frequencies

Spend more time experimenting with stubs and matching section for filters

Questions????????????