More on Transmission Lines and SWR – Part V

By Don Steinbach, AE6PM

The first four articles in this series were designed to provide some background definitions and equations as they apply specifically to transmission lines and SWR. There aren't any scientific breakthroughs there – it's all based on information that's been around for years. The remainder of this series will focus on applying this information to real world situations.

Practical Considerations

The effort expended working on an antenna trying to drive the SWR down could often be better spent just making contacts instead. Bear in mind that a 1 dB change in signal level is, by definition, the minimum perceptible change – in other words, the smallest change that your ear can detect. Your receiver S-meter is designed so that a 6 dB change is one S-unit (more or less) or a 4x change in power, so a 3 dB increase or decrease (2x in signal power) is one-half of one S-unit. That's not to say that an extra dB or two wouldn't help to snag that rare station, but let reality and common sense be your guide.

The total loss in dB for a mismatched transmission line is:

$$\mathrm{TMLL} = 10 \log \left[(a^2 - |\rho^2|) / (a(1-|\rho^2|))\right]$$

Where:

$a = 10^{ML/10} = 10 \wedge (ML/10)$
$|\rho| = (SWR - 1)/(SWR + 1)$
TMLL = Total mismatched line loss
ML = Matched-line loss of the transmission line in dB
SWR = SWR at the load (antenna)
(Ref: ARRL Handbook for Radio Communications, 88th Edition, page 20.5)

The additional transmission line loss for various matched-line loss and SWR at the antenna is shown in Table 1. The format is the same as Table 1 in Part 4, so the two can be used together to relate matched-line loss, SWR at the antenna, SWR at the transmitter, and additional transmission line loss. Adding the matched-line loss to the additional transmission line loss in Table 1 below yields the total transmission line loss. For example, if the matched-line loss is 2 dB and the SWR at the antenna is 4, the additional line loss due to SWR is 1.27 dB and the total transmission line loss is 3.27 dB. Looking back at Table 1 in Part 4, the same 2 dB matched-line loss and SWR at the antenna of 4 shows a SWR of 2.22 at the transmitter. Finally we can see all of the effects of loss in the transmission line.

Table 1 – Additional transmission line loss for various matched-line loss and SWR at the antenna.

Matched -Line Loss							
	0.5 dB	1 dB	2 dB	3 dB	4 dB	5 dB	6 dB
SWR at Antenna	Additional Line Loss Due to SWR						
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.5	0.04	0.07	0.11	0.13	0.15	0.16	0.17
2	0.11	0.20	0.32	0.39	0.43	0.46	0.48
2.5	0.20	0.35	0.55	0.68	0.75	0.80	0.83
3	0.29	0.50	0.79	0.97	1.07	1.14	1.18
4	0.48	0.82	1.27	1.53	1.68	1.78	1.84
5	0.66	1.12	1.71	2.04	2.24	2.36	2.43
6	0.84	1.41	2.11	2.50	2.73	2.87	2.95
7	1.02	1.69	2.49	2.93	3.18	3.34	3.43
8	1.19	1.95	2.84	3.32	3.60	3.76	3.86
9	1.35	2.19	3.16	3.68	3.97	4.15	4.26
10	1.51	2.42	3.46	4.01	4.32	4.51	4.62

Sanity Check

SWR readings can be counterintuitive. Consider the case of a ground-mounted ¼-wave vertical antenna. Here a 50-ohm SWR of 1 isn’t necessarily a good thing. You start with the vertical radiator and add a few radials and the feed point impedance is about 50 ohms and the SWR is 1. All is well, or is it? You know that as you add more radials the effect of the lossy ground under the antenna is reduced, the antenna efficiency is improved and the take-off angle becomes lower – all good things. But, as you add more radials, the SWR increases until with 120 radials the SWR is about 1.4 because the feed-point impedance is now about 35 ohms instead of 50 ohms as the antenna configuration approaches its theoretical best (over an infinite ground plane). In this instance, the lowest SWR occurred with the worst-case ground system because the 15-ohm loss in the ground system when added to the 35-ohm radiation resistance of the antenna makes the total feed-point impedance 50 ohms, but 30% of the transmitter power was wasted on the earthworms.

Similarily, the feed point impedance of a half-wave dipole antenna varies with its height above ground and its proximity to other conductors. It ranges from a low of about 10 ohms (over a perfectly conducting ground) or 45 ohms (over average real earth) to a maximum of nearly 100 ohms (Ref: ARRL Handbook for Radio Communications, 88th Edition, page 21.3). So, a SWR of 2 referred to 50 ohms for a half-wave dipole is within normal bounds.

Extremely short antennas, compared to the wavelength, such as car antennas for HF mobile can have very low radiation resistance, on the order of a few ohms, so the SWR referenced to 50 ohms and measured at the antenna feed point will be very high (maybe 10 to 50 or more) and if it isn’t, there is reason to believe that there is a large loss somewhere in the system, probably in the ground path.

It’s always best to know what you’re trying to measure and what to expect in order to avoid reaching erroneous conclusions.

SWR Facts

There are misconceptions about the effects of standing waves on the transmission line. Here are some facts:

1. High SWR doesn’t cause interference to other electronic devices because SWR by itself doesn’t generate new signals.
2. High SWR doesn’t cause the transmission line to radiate.
3. High SWR doesn’t cause RF in the shack.
4. High SWR can result in component damage caused by large voltages or currents.
5. High SWR isn’t necessarily bad if loss in the transmission line isn’t eating up your power.
6. A SWR of 2:1 at the antenna can be cause for concern on VHF and UHF because of the typically high transmission line loss at these frequencies.
7. A SWR of over 3:1 at the antenna on HF is usually not a cause for concern if quality coax 100 feet or less in length is used, since the transmission line loss is usually low.
8. A SWR of 100:1 or more at the antenna on HF is usually not a cause for concern if open-wire transmission line is used because the loss in the transmission line is so low. There may be high voltages present, however.
9. SWR is a measure of reflected power, not lost power.
10. SWR can be measured with simple equipment easily built by the average person.
11. Most solid-state transceivers will begin reducing their output power when the SWR exceeds 2:1.
12. Most automatic antenna tuners can only accommodate a limited range of SWR due to practical voltage and current limitations.
13. Reflections, the very nature of standing waves, can adversely affect signal quality since the receiver will receive the same signal multiple times at ever decreasing amplitudes. This could be an issue with some digital modes, causing intersymbol interference.

The SWR Meter

Since you’ve read many words about SWR to this point, some insight into how to measure SWR is in order. SWR meters are often seen at swap meets priced at $10 to $25. Older manufacturers include Heath, Knight, Swan, EF Johnson, Calrad and RadioShack. See Fig. 1 for some examples. You can also build your own.

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Fig.1. Typical SWR Meters Found at Swap Meets. Clockwise from left, the Heathkit AM-2, Swan SWR-1A Yaesu YS-500, Heathkit HM2140A and the Micronta 21-520A.

The basic SWR meter consists of a sampling line (aka directional coupler) that provides a sample of the forward and reflected power from the main transmission line. That and a rf wattmeter to measure the sampled forward and reflected power is all that you need. The parts to build the directional coupler will only cost a couple of dollars. The only problem with this approach is that the rf wattmeter will set you back a few hundred dollars. The solution to the rf wattmeter issue is to convert the rf power measurement to a dc voltage that can be measured with an inexpensive panel meter or a multimeter that you probably already own. This takes two diodes, two resistors and two capacitors for a total cost of less than a dollar.

The sampling line (directional coupler) can be constructed several different ways: (1) two parallel lines in a 3-sided trough approximating a section of coax cable, (2) a section of coaxial cable with a small insulated wire threaded under the cable shield, (3) stripline constructed on a etched circuit board, and (4) a toroidal core – usually ferrite - with a few turns of wire wound on it with the transmission line center conductor passing through it. The latter is the simplest to build mechanically and is widely used. See Figures 2A through 2C for a view of some different construction methods.

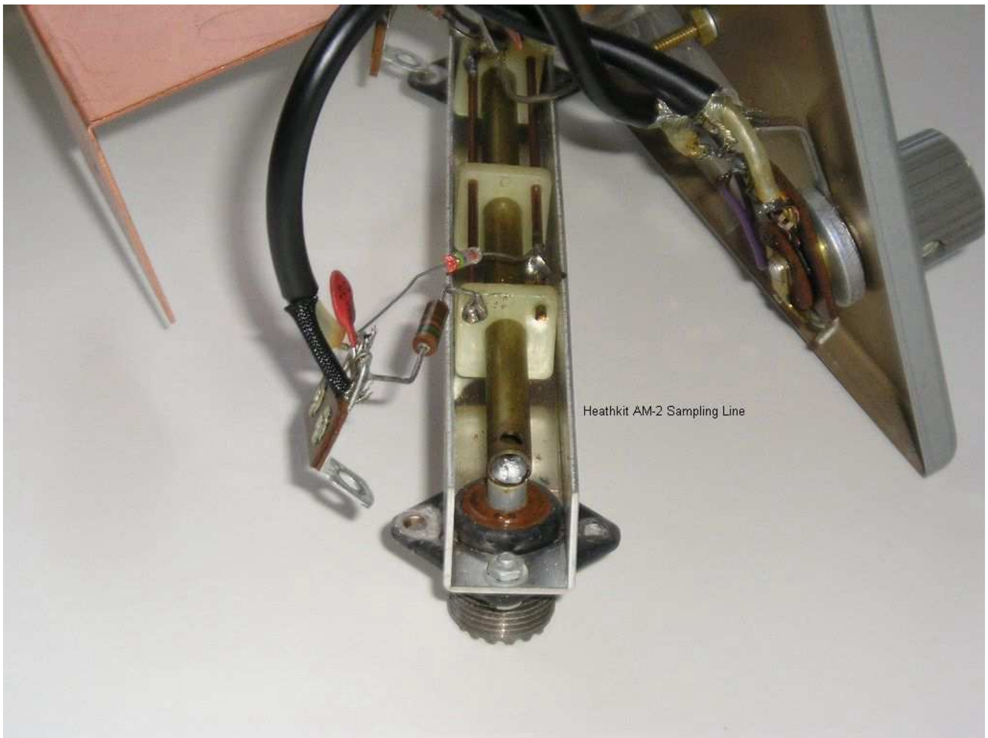
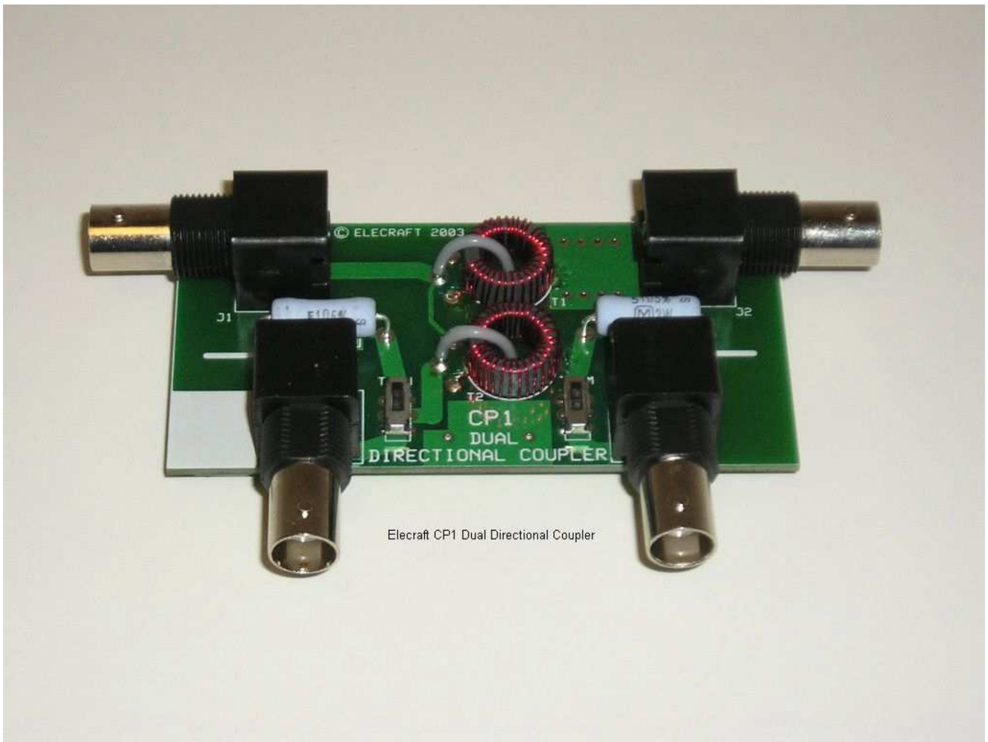


Fig. 2A. The Heathkit AM-2 uses a brass tube center conductor with two parallel sampling lines in a u-shaped trough. See Fig. 3 for the schematic diagram.

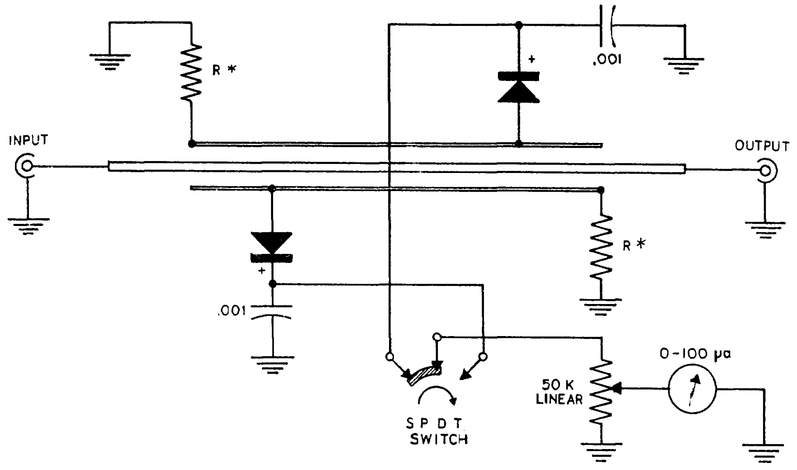
Fig. 2B. The Heathkit HM2140A uses a toroid winding with a single wire through the center as a sampling circuit. See L101 in the photo. The vertical white wire connects the input and output coax connectors and the toroid winding senses the forward and reflected power.



Elecraft CP1 Dual Directional Coupler

Fig. 2C. The Elecraft CP1 is a true directional coupler with sense windings for the forward and reverse directions. This is available in kit form. See the “Transmission Line Signal Sampling” article in the December 2009 SCCARA-GRAM for information on the design of the toroidal transformers.

A typical SWR meter circuit is shown in Figure 3. The SPDT switch selects the dc voltage to the meter from the diodes connected to the two sampling lines, one for the forward (incident) wave and the other for the reflected wave. Some units use two meters, eliminating the switch. The crossed-needle dual-movement single meter approach is also popular, although I find it difficult to read with any accuracy. Regardless of any enhancements or bells and whistles, all SWR meters are based on the concept in Fig. 3.



* NOTE

R = 100Ω or 150Ω

Two 100Ω resistors and two 150Ω resistors are included in the kit.

The 100Ω resistors are used for 75Ω input and output.

The 150Ω resistors are used for 50Ω input and output.

HEATHKIT REFLECTED POWER
AND STANDING WAVE RATIO BRIDGE
MODEL AM-2

Fig. 3. Schematic diagram of the Heathkit AM-2 SWR meter.

The Antenna Analyzer

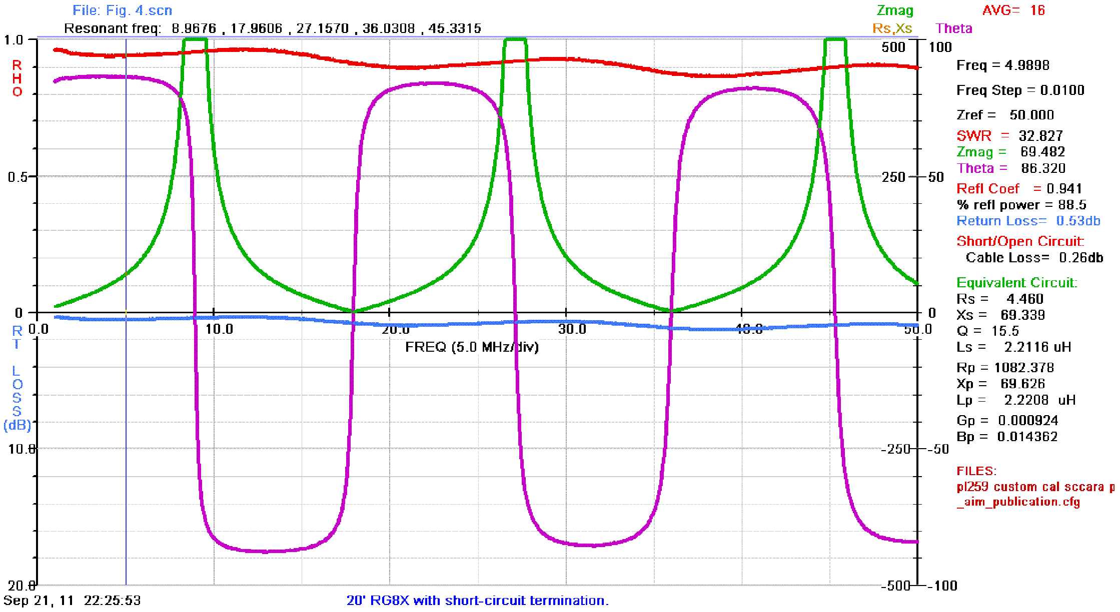
The antenna analyzer is a useful instrument for characterizing a transmission line. Many purchasers of an analyzer use it simply to measure the SWR (at the transmitter) of an antenna + transmission line system. This could just as well be accomplished with a $15 flea-market SWR meter (or building one) and using the existing transceiver as a signal source. Many transceivers have SWR meters already built in, so even the $15 could have been saved. Admittedly, the handheld analyzer is conveniently portable and that's certainly one of the reasons that we do what we do.

On the up-side, the analyzer is ideally suited for doing many other tasks, other than simply reporting SWR, if one elects to read the manual. One of those tasks is making measurements to characterize a transmission line by itself, which is the subject of the remainder of this article.

Basically, all analyzers generate a rf waveform to be sent down the transmission line (the incident wave). The returned signal (reflected wave) is analyzed for amplitude and phase as compared to the transmitted (incident) wave and all of the displayed parameters are derived from this information. Simple enough in principal.

The major discriminators between the presently available analyzers have to do with their immunity to strong extraneous signals in the presence of the desired (generated) signal and the accuracy of their computational algorithms and the limitations of their rf detectors. QST has published reviews and comparisons of most, if not all, of the analyzers available to the hobbyist, but that's not part of this article. The more sophisticated analyzers may also be able to 'back out' the effects of the transmission line. The importance of that was illustrated in Figures 1 and 2 of Part 3 of this series.

The AIM4170 analyzer designed by W5BIG and sold by Array Solutions is used for the examples in the remainder of this article. The AIM4170 is a small "black box" that connects to a PC. The test specimen is a 20-foot piece of RG8X coaxial cable with factory-installed PL259 connectors on each end, purchased at a DeAnza swap meet. The analyzer can compute and display a multitude of user specified parameters as shown in Fig. 4.



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File: Fig. 4.scn
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AVG=  16
Freq = 4.9898
Freq Step = 0.0100
Zref =   50.000
SWR  =  32.827
Zmag =   69.482
Theta =   86.320
Refl Coef   = 0.941
% refl power = 88.5
Return Loss=  0.53db
Short/Open Circuit:
  Cable Loss=  0.26db
Equivalent Circuit:
Rs =    4.460
Xs =   69.339
Q =  15.5
Ls =    2.2116 uH
Rp = 1082.378
Xp =   69.626
Lp =    2.2208  uH
Gp =  0.000924
Bp =  0.014362
FILES:
pl259 custom cal sccara p
_aim_publication.cfg
Sep 21, 11  22:25:53
20' RG8X with short-circuit termination.
```

Fig. 4. A graphical display of some measured parameters of a coaxial cable as a function of frequency. See the text.

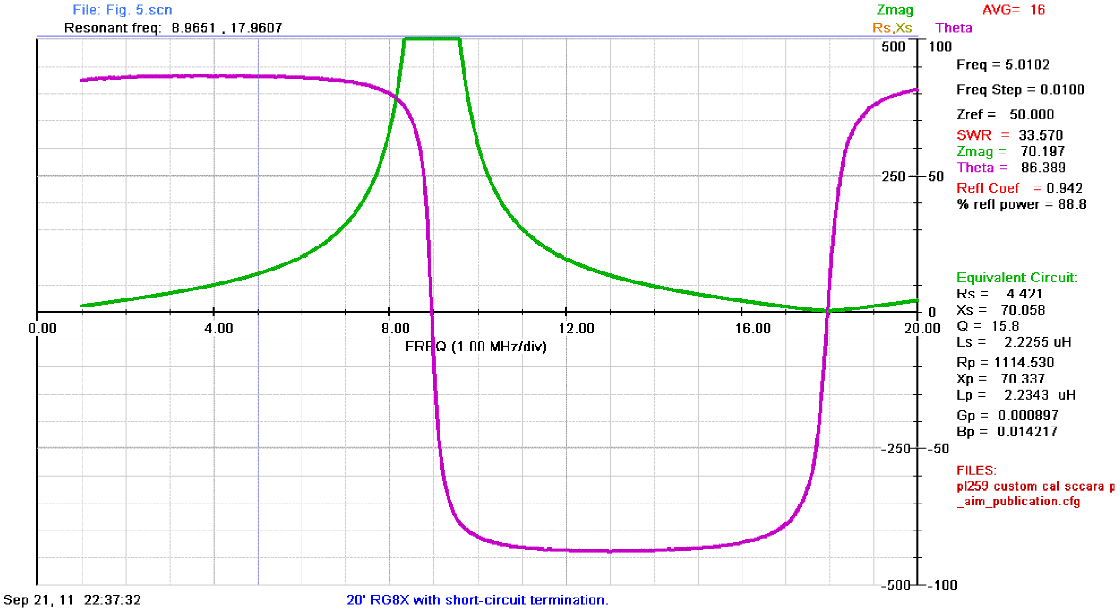
Figure 4 is a plot of four parameters looking into the open end of my 20' coax cable terminated in a short circuit. The parameters are:
1. Zmag, the magnitude of the impedance (the green trace).
2. Theta, the phase angle of the impedance (the magenta trace).
3. Rho or ρ , the reflection coefficient (the red trace).
4. RL, return loss (the blue trace).

Note that the reflection coefficient (rho, the red trace near the top of the graph) and the return loss (the blue trace just below the horizontal "0" axis) remain fairly constant since they are relatively independent of frequency, but increase slightly as the frequency increases. On the other hand, Zmag, the green trace, and Theta (the magenta trace) are very frequency-dependent. We'll look at those characteristics in more detail shortly. Note also how the plotted data repeats every half-wavelength (λ/2) as the frequency is varied from 1 to 50 MHz.

Turning off all of the traces except for Zmag and Theta and re-plotting for 1 to 20 MHz results in the impedance-only plots in Fig. 5 (with the far end of the cable short-circuited) and Fig. 6 (with the far end of the cable open-circuited). In both cases the lowest frequency where the phase angle (Theta) is zero is the frequency where the transmission line is ¼ wavelength long (λ/4) and the next higher frequency where the phase angle is zero is the frequency where the line is ½ wavelength long (λ/2). The impedance (Zmag) continually changes with frequency, repeating at every λ/2 frequency.
The input impedance of the cable repeats the terminating (load) impedance at every λ/2 frequency, and the inverse of the terminating impedance at every λ/4 frequency.

The cable appears inductive if the phase angle is positive, as it is below 8.97 MHz in Fig. 5, and capacitive if the phase angle is negative as it is from 8.97 MHz to 17.96 MHz in the Figure. At 8.97 MHz the phase angle is zero indicating a resonant condition (since inductive and capacitive reactances cancel) and the magnitude of the impedance (Zmag) is a maximum, which would be infinite if not limited by shunt impedances in the cable and the connectors. The high value of Zmag indicates that this a parallel-resonant circuit and that it is electrically λ/4 long since the measured impedance (very high) is the inverse of the load impedance (a short circuit).

At 17.96 MHz, the cable is an electrical half-wavelength long and repeats the impedance seen at its far end, which is a short circuit or zero ohms. At this frequency the cable is again a resonant circuit (since inductive and capacitive reactances cancel), but series-resonant this time as evidenced by its low (near zero) impedance in series with the load.



```
Freq = 5.0102
Freq Step = 0.0100
Zref =   50.000
SWR  =  33.570
Zmag =   70.197
Theta =   86.389
Refl Coef   = 0.942
% refl power = 88.8

Equivalent Circuit:
Rs =    4.421
Xs =   70.058
Q =  15.8
Ls =    2.2255 uH
Rp = 1114.530
Xp =   70.337
Lp =    2.2343  uH
Gp =  0.000897
Bp =  0.014217

FILES:
pl259 custom cal sccara p
_aim_publication.cfg
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Fig. 5. Expanded view (1 to 20 MHz) of coax cable parameters when terminated in a short circuit.

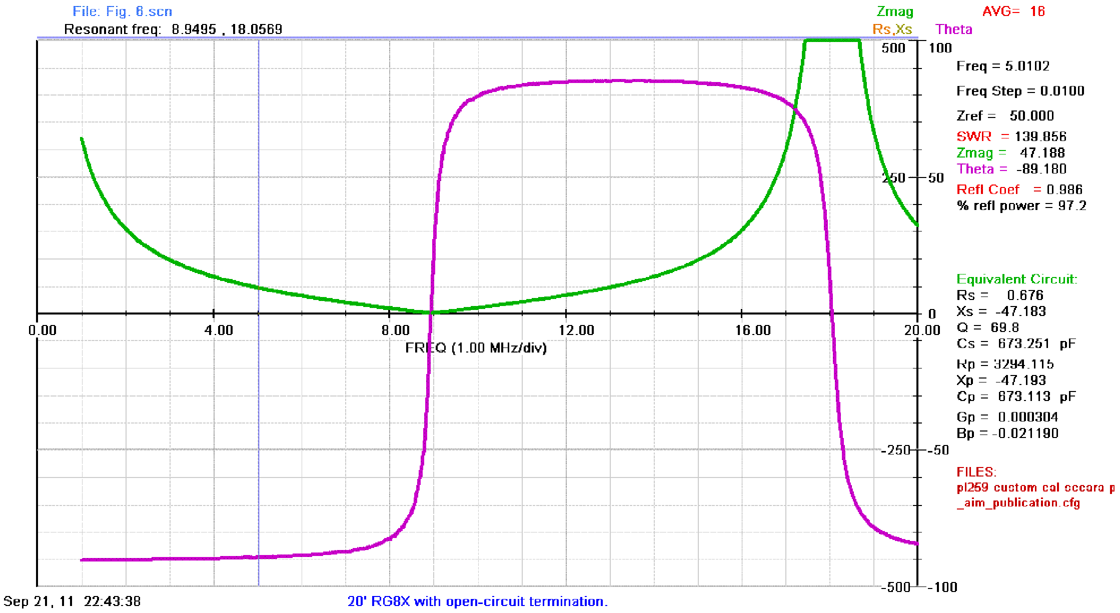

Fig. 6. Expanded view (1 to 20 MHz) of coax cable parameters when terminated in an open circuit.

In Fig. 5, where the line is terminated in a short circuit, we observed that the λ/4 frequency is 8.97 MHz. Likewise, in Fig. 6 where the line is terminated in an open circuit, the λ/4 frequency is 8.95 MHz. It's much easier to determine these frequencies by finding where the phase angle passes through zero than it is to find the minimum or maximum impedance value (Zmag). The difference between the short- and open-circuit readings is probably due to some reactance in the terminations – possibly slightly inductive in the short circuit and slightly capacitive in the open circuit – and the fact that the analyzer algorithm interpolates between data points (10 kHz in this case). Averaging the two readings yields 8.97 Mhz.

The analysis of Fig. 6 is the same as for Fig. 5 except that the far end is terminated in an open circuit instead of a short circuit. Table 2 summarizes the results of our analysis of the plots in Figs. 5 and 6.

Table 2 - Summary of open- and shorted-circuited transmission line characteristics.

Transmission Line Length	Short-Circuited Line (Fig. 5)	Open-Circuited Line (Fig. 6)
Less than λ/4	Inductive	Capacitive
λ/4	Parallel resonant	Series resonant
Between λ/4 and λ/2	Capacitive	Inductive
λ/2	Series resonant	Parallel resonant

Short sections (stubs) of transmission lines can be used as capacitors or inductors in impedance matching networks, and as traps at the series-resonant frequencies. Looking at Fig. 6, for example, that piece of coax “hanging” off of your main transmission line (as with a T connector) would act as a trap at 8.95 MHz (and odd multiples thereof) where it’s almost a short-circuit, but have no effect at twice those frequencies where it’s almost an open circuit. Obviously those frequencies don’t have any application in the ham bands, but changing the length of this “stub” raises the series-resonant frequency if shortened and lowers it if lengthened. Also, for a given series-resonant frequency, a short-circuited stub needs to be about half as long as an open-circuited stub. My experience based on this 20’ test specimen is that there is no difference whether the coax cable stub is coiled up or stretched out in a straight line.

Characterizing the Coax Cable

Given a length of coax cable of unknown ancestry, what can we learn about it? If the manufacturer and part number are still visible, we can probably find out enough by visiting the manufacturers’ web site. If the cable is unidentifiable we can still find out all we need to know: specifically (1) the characteristic impedance, (2) the velocity factor and (3) the loss.

We sometimes need to know the velocity factor with greater accuracy even if the cable is identifiable, especially if the coax will be used as a stub for impedance matching or filtering. The velocity factor can vary considerably from the published value, and also within the same roll of coax. We also might want to know the cable loss around some particular frequency. The published characteristics of some typical transmission lines are shown in Tables 3 and 4.

Table 3 – Nominal Velocity Factors for Common Transmission Lines (ref: ARRL Handbook for Radio Communications, 88th Edition, page 22.48)

Transmission Line Type	Velocity Factor	Description
None (vacuum)	1.00	No dielectric loss, no copper loss
600 ohm open wire	0.95-0.99	#12 bare copper, VF varies with spacer material
450 ohm twinlead	0.91	WM CQ 553 (#18 flex)
300 ohm twinlead	0.80	Belden 8225 (#20 flex)
Coax, foam dielectric	0.83	RG-8 Belden 9913F
Coax, foam dielectric	0.82	RG-8X Belden 9258
Coax, solid dielectric	0.66	RG-58A Belden 8259
Coax, solid dielectric	0.66	RG-213 Belden 8267

Table 4 – Nominal Matched Loss for Common Transmission Lines at 10 MHz, 100 MHz and 1000 MHz (ref: ARRL Handbook for Radio Communications, 88th Edition, page 22.48)

Transmission Line Type	Matched Loss (dB/100’)			Description
	10M	100M	1000M	
None (vacuum)	N/A	N/A	N/A	No dielectric loss, no copper loss

600 ohm open wire	0.06	0.2	Not used	#12 bare copper, VF varies with spacer material
450 ohm twinlead	0.2	0.7	2.9	WM CQ 553 (#18 flex)
300 ohm twinlead	0.2	1.1	4.8	Belden 8225 (#20 flex)
Coax, foam dielectric	0.6	1.5	4.8	RG-8 Belden 9913F
Coax, foam dielectric	0.9	3.2	11.2	RG-8X Belden 9258
Coax, solid dielectric	1.5	5.4	22.8	RG-58A Belden 8259
Coax, solid dielectric	0.6	2.1	8.0	RG-213 Belden 8267

Characterizing the Coax Cable: Characteristic Impedance

The simplest method is to terminate the transmission line with a known resistance and measure the SWR over a wide range of frequencies (e.g., 3 to 30 MHz).

SWR = Zo/R or R/Zo
Note: The smaller quantity is always used in the denominator so the SWR will be greater than or equal to 1.

Zo = R x SWR or R/SWR

Where:
R = the resistance of the termination
Zo = the characteristic impedance of the transmission line

Characterizing the Coax Cable: Velocity Factor

The physical length of a transmission line is less than the electrical length because the electromagnetic wave travels slower through the cable than in free space. With the far end of the line open-circuited, vary the frequency of the analyzer until the lowest frequency at which the phase angle is zero is found. This will be the frequency at which the line is 1/4-wavelength long. Repeat the measurement with the line short-circuited and average the two. For the 20’ piece of RG8X in this article, we measured 8.95 MHz and 8.97 MHz respectively for an average of 8.96 MHz. An electrical wave in free space travels at 983,569,082 ft/sec.

The wavelength in a physical transmission line becomes:

$\lambda = (983.6/f)VF$

where:
λ = wavelength in feet
f = frequency in MHz
VF = velocity factor

For our 20’ cable with a λ/4 frequency of 8.96 MHz

VF = 20 x (8.97 x 4)/983.6 = 0.73

Characterizing the Coax Cable: Loss

The simplest method is to use an analyzer to measure the return loss (RL) with the far end of the line open-circuited and again with the far end short-circuited at the frequency of interest. Add the two values obtained and divide by 2 to obtain the average value of the RL

The transmission line loss in dB = RL/2 (assuming the analyzer reports the RL as the total measured loss in dB from the analyzer to the termination and back).

A second method is to measure the SWR at the frequency of interest.
The transmission line loss in dB = 10 log [(SWR + 1)/(SWR – 1)].

A third method, described on page 6 of the Autek Research Instructions for the Vector RX Antenna Analyst Model VA1, is to either open-circuit or short-circuit the transmission line and find the minimum Zmag nearest the frequency of interest.
The transmission line loss (matched line loss) at that frequency is:

ML (dB) = 8.69 x minimum Zmag / Transmission line characteristic impedance.

The End

This concludes this series of articles. If you have any comments, corrections or questions, feel free to contact me at ae6pm@arrl.net or send them to the Editor (Gary, WB6YRU) for publication. The original Word version of these articles can be downloaded from http://ae6pm.com/SCCARA-GRAM_Articles/. There is an underscore between SCCARA-GRAM and Articles.

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