An SWR-Feedline-Reactance Primer
Dipole Samples

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Introduction: The Dipole, SWR, and Reactance

Let's take a look at a very common antenna: a 67' AWG #12 copper wire dipole for 7.15 MHz, that is, the center of the 40-meter band. We shall place the antenna at a height of 50' above average ground, which is ground with a conductivity of 0.005 S/m and a dielectric constant of 13. **Fig. 1** shows the general outline of the small antenna system.

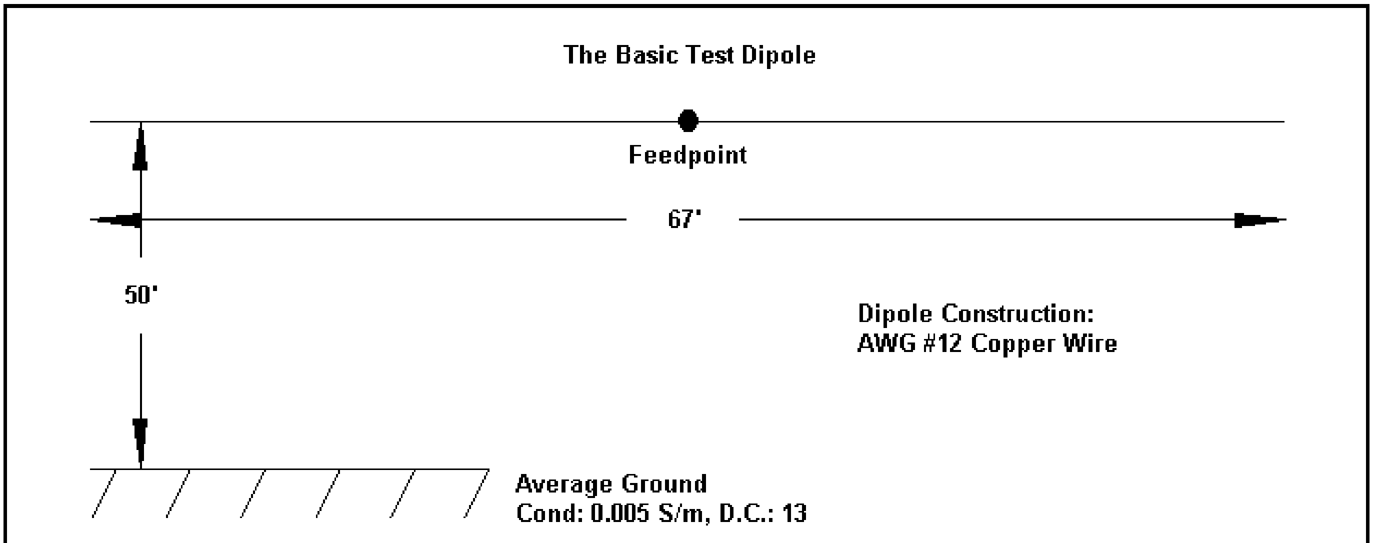
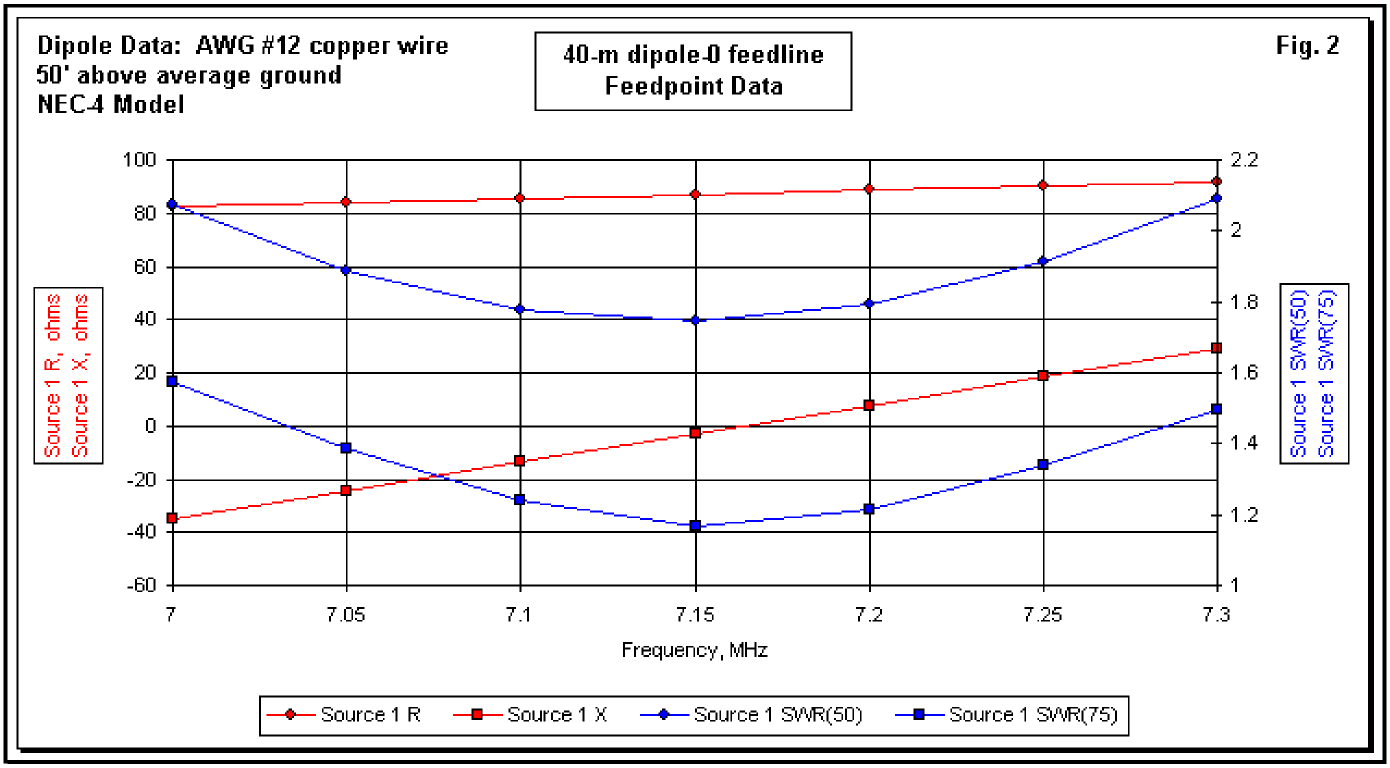


Fig. 1

If I model this antenna, I obtain a feedpoint impedance of 87.12 - j2.98 Ohms. There is nothing wrong with either the model or the antenna. The near-resonant impedance is not very close to 70 Ohms because it is not supposed to be. The resonant impedance (and the resonant length) of a dipole varies with the height of the antenna above ground. At some heights, the impedance will be greater than 70 Ohms, while at other heights, the impedance will be under 70 Ohms. The value undulates up and down between a height of 1/4-wavelength and 1.25 wavelengths, but gradually smooths out as the antenna height increases above 1.25 wavelengths.

Normally we would expect the antenna to perform over the entire 40-meter band from 7.0 to 7.3 MHz. So let's perform a frequency scan and graph the results. **Fig. 2** shows what we get for our effort.



Examine the blue lines first. The antenna provides us with a better SWR curve using a 75-Ohm reference than with a 50-Ohm reference. Given the near-resonant impedance of about 87 Ohms, the curves are exactly what we should expect.

The red lines show us why the SWR curves increase their value away from the near-resonant frequency of 7.15 MHz. The resistive component (upper red line) does not change much across the 40-meter band. However, the reactance describes a nearly linear curve between 7.0 and 7.3 MHz. At the low end of the band, the reactance is mostly capacitive, indicating that the antenna is short for resonance at 7.0 MHz. At 7.3 MHz, we find the highest value of inductive reactance, indicating that the antenna is too long to be resonant at that frequency.

Everything that we have examined is such commonplace knowledge that some instructions sets that accompany SWR meters and antenna analyzers cite some rules of thumb.

1. If you lower the frequency and the SWR goes down, then the antenna is long and the reactance at the feedpoint is inductive. If you raise the frequency and the SWR goes down, then the antenna is short and the reactance at the feedpoint is capacitive.

2. If your meter gives you a value for reactance but does not tell you whether the value is inductive (+) or capacitive (-), you can use Rule 1 to tell the difference. If a lower frequency yields a lower value of reactance, then the reactance is inductive. If a higher frequency gives a lower reactance value, then the reactance is capacitive.

Unfortunately, such rules of thumb usually fail to mention two important facts that give the rules some validity. First, the rules apply to near-resonant antennas based on a half-wavelength center-fed element. Second, the rules apply to the antenna feedpoint and to certain other situations, but not to all measurement situations. Like most rules of thumb, these ignore the fact that we also have fingers.

In this case, the "fingers" represent that fact that we ordinarily make our SWR and resistance/reactance measurements some distance from the actual antenna feedpoint. Between the feedpoint and the measuring instrument, we normally have a length of feedline. In my experience, a large number of newer antenna builders have no idea what happens to the impedance value between the antenna feedpoint terminals and the other end of the feedline connected to the measuring instrument.

Most builders know that if there is a good match between the antenna feedpoint and the feedline, the impedance will be almost the same everywhere along the line. From **Fig. 2**, we can see that we almost have a perfect match at 7.15 MHz between the antenna and the 75-Ohm cable. However, that match becomes worse each side of the near-resonant mid-band frequency. If we try to use a 50-Ohm cable, then we do not have even a 2:1 SWR at the band edges. The increasing reactance, inductive or capacitive, increases the SWR value and presents the line with a complex impedance at the antenna terminals.

At this point, most texts would introduce a set of equations to use for calculating what happens along the feedline. Of course, few readers actually perform the calculations. So we shall try a different tack. The following notes will present a series of graphs--all resembling in format **Fig. 2**. However, each one will use a different feed line characteristic impedance and a different line length. We shall look at 50-Ohm cable, the most commonly used feedline for dipoles, and then at 75-Ohm coax, the better match for the 40-meter dipole at a 50' height. Finally, we shall examine a special hybrid case.

For all of our exercises, we shall presume that the cable has a velocity factor of 1, which we can easily do in modeling. In real situations, the electrical lengths of the cables would be multiplied by the velocity factor of the cable we actually use. However, should you replicate these exercises using actual coaxial cables, be certain to measure the velocity factor rather than relying upon published figures. I have found reputable cables as much as 5% off the published figures.

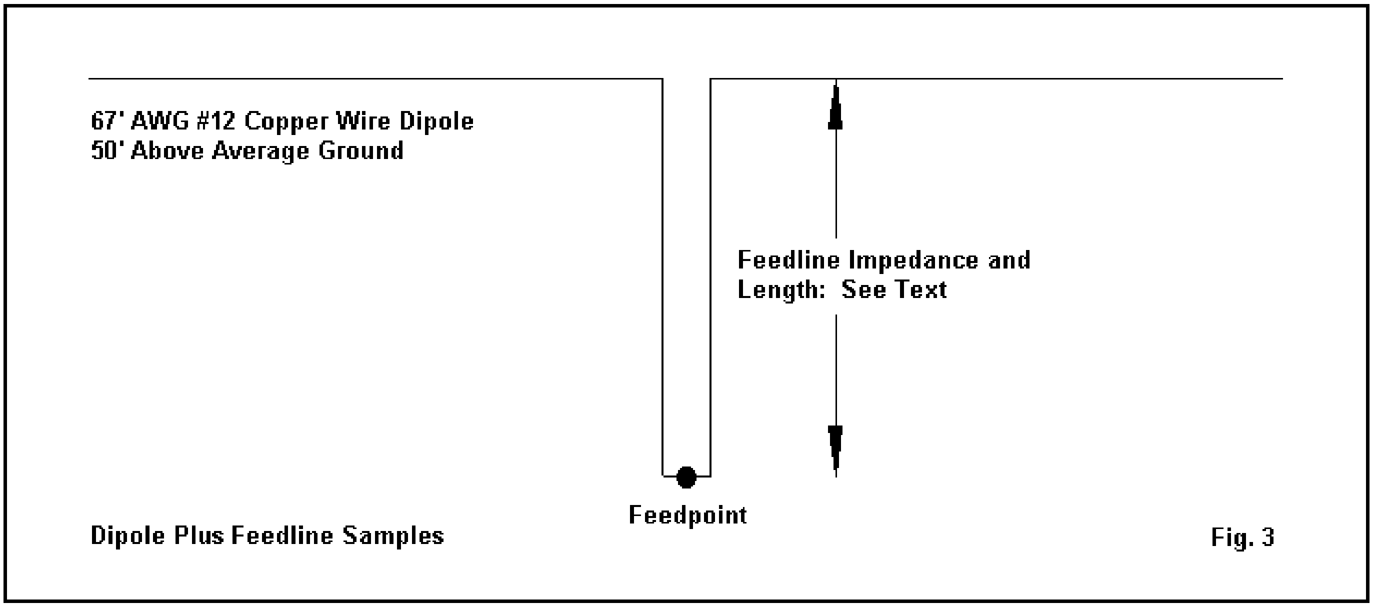
We shall look at cables from 1/4-wavelength to 3/4-wavelength long. The electrical lengths of these cables are as follows, assuming that they are calculated based on a wavelength at 7.15 MHz (137.562').

Length in Wavelengths	**Length in Feet**
1/4	**34.39**
3/8	**51.59**
1/2	**68.78**
5/8	**85.98**
3/4	**103.17**

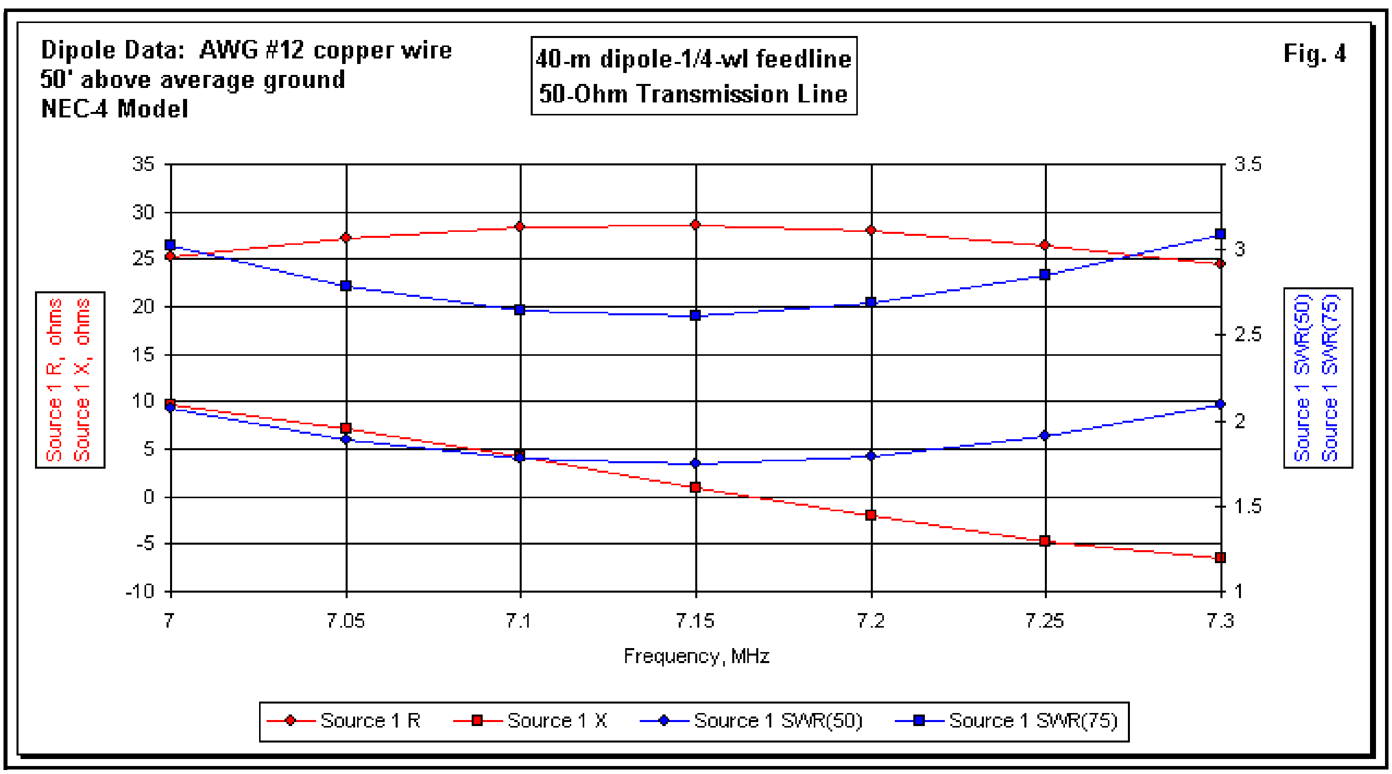
The values that we shall derive will be for lossless cable. As the cable becomes longer, losses will reduce the SWR value at the source end, with commensurate changes in the resistance and reactance values that result in the reduced SWR value. The losses will vary with the cable ratings. At one end of the scale, there are very lossy cables, although not especially at 7 MHz. At the opposite extreme are hardlines with losses that rival the best open-wire parallel feedlines. For our purposes, which focus around understanding the feedpoint reactance at the source end of the lines, the losses in real lines will not be significant.

The 40-Meter Dipole with a 50-Ohm Cable

Our first two major sample situations involve the use of the dipole with a single feedline, as shown in outline form in **Fig. 3**.



The first of the two situations described by the sketch makes use of 50-Ohm feedline. We shall examine the resistance, reactance, and the 50-Ohm and 75-Ohm SWR values for each of the sampled feedline lengths in the table.

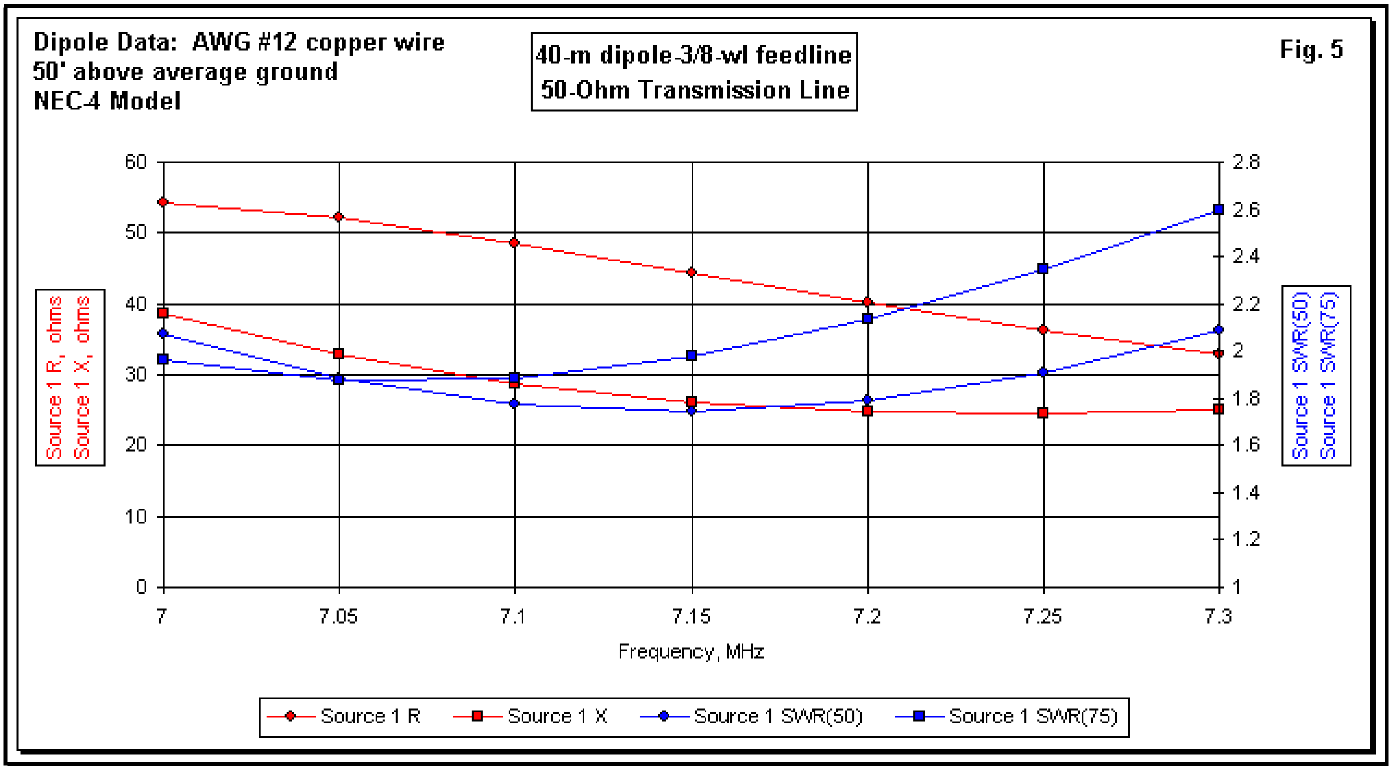


The 1/4-wavelength feedline shows an impedance at 7.15 MHz of 28.66 + j0.98 Ohms. We know that a 1/4-wavelength transmission line forms a transformer so that the source impedance is the square of the line impedance divided by the load or antenna impedance, assuming we have nothing except resistive impedance. The presence of reactance complicates the calculation considerably, but at the near-resonant frequency of 7.15 MHz, the reactance is too low to make a difference in the outcome. 2500 divided by 87.12 equals 28.69.

However, off the resonant frequency, we have a rapidly rising reactive component to the antenna terminal impedance. Therefore, even though the antenna terminal impedance shows a slowly rising curve in **Fig. 2**, the impedance curve for the resistive component describes an arc, with band edge values both lower than the band-center value.

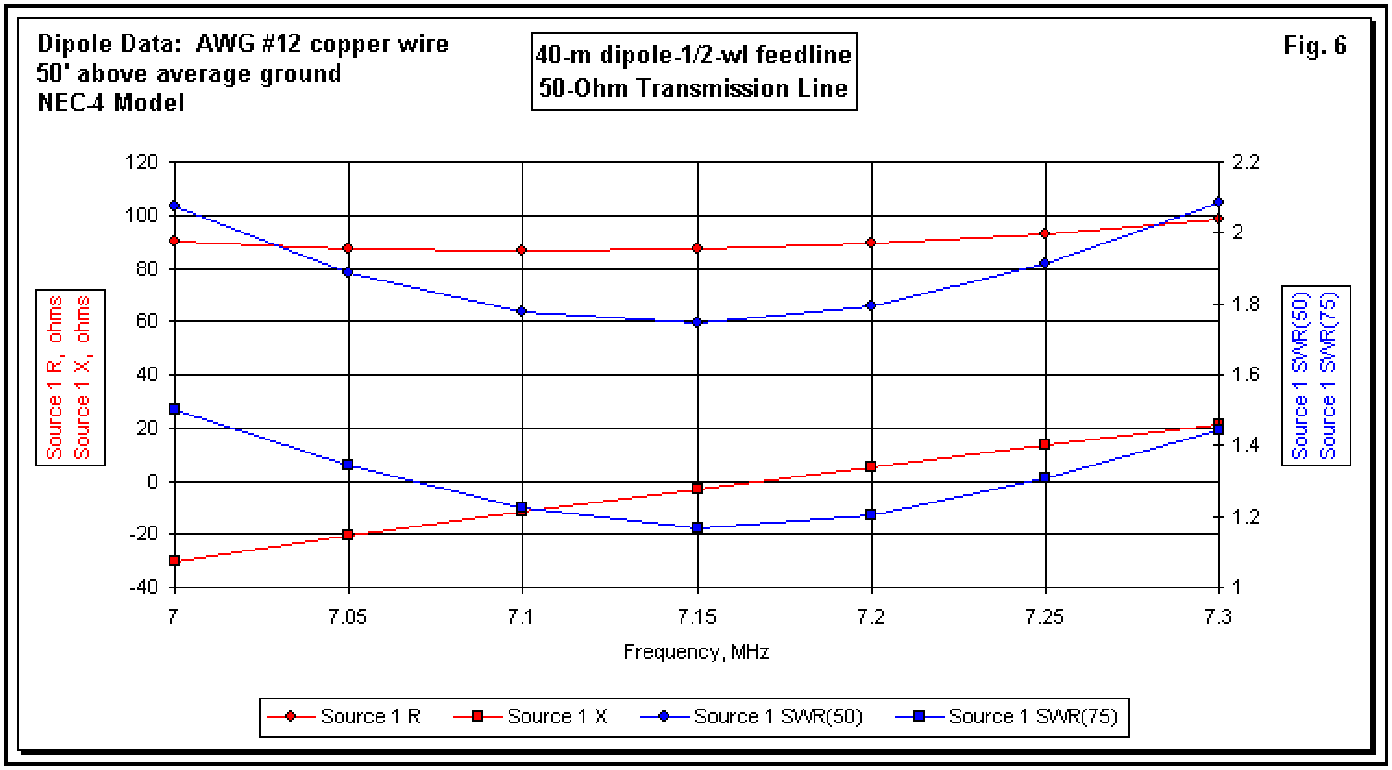
With a 1/4-wavelength feedline, we can also notice a radical change in the reactance curve. Instead of showing a "rising" curve from capacitive to inductive reactance, the 1/4-wavelength line curve descends from an inductive value at the low end of the band to a capacitive value at the high end. The rules of thumb that apply to the antenna terminals reverse themselves with the line in place.

Because the 50-Ohm coax performs a downward transformation on impedance across the band, neither the 50-Ohm nor the 75-Ohm SWR curves are very heartening for operating the antenna.



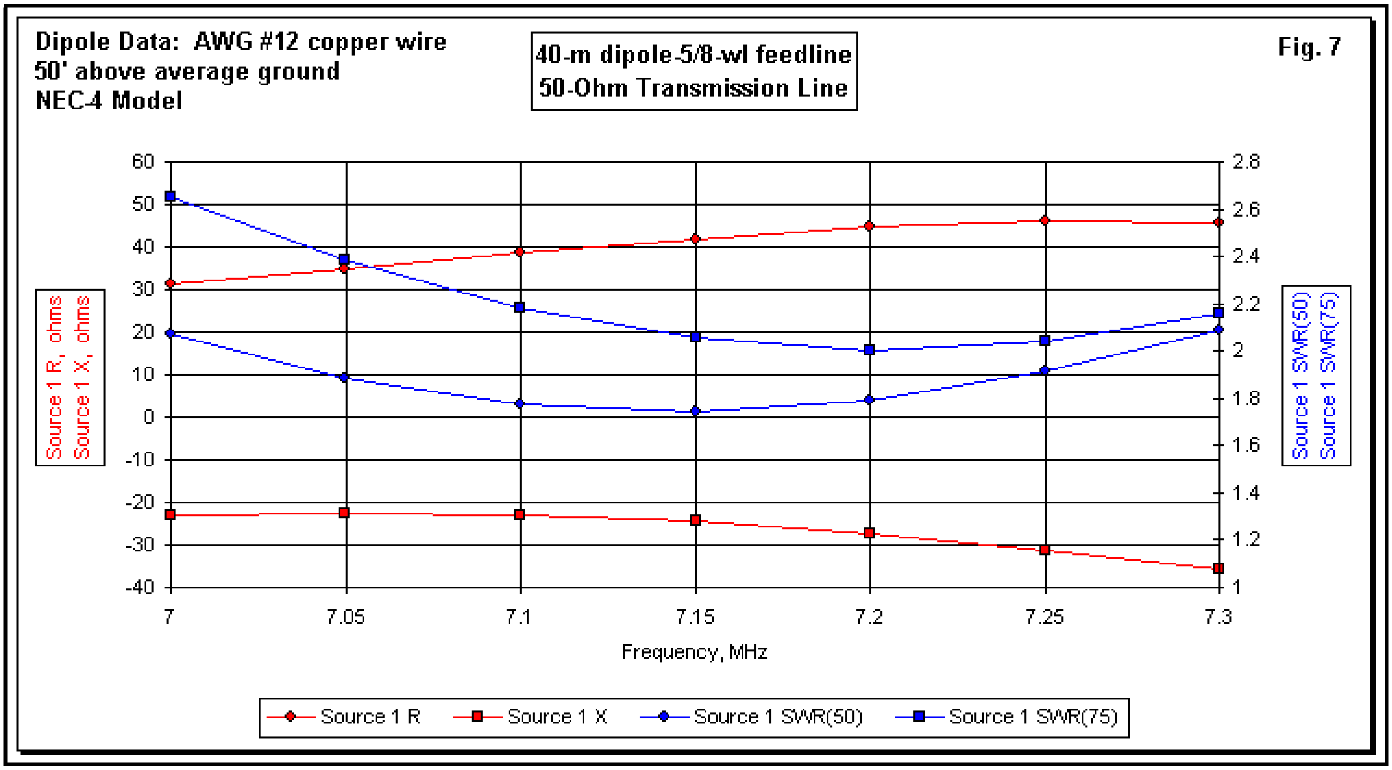
The values for the 3/8-wavelength 50-Ohm feedline in **Fig. 5** are no better when it comes to the SWR cures. The impedance at the source end at 7.15 MHz is 44.46 + j26.01 Ohms. (Incidentally, I am giving the impedance values to two decimal places, as reported by the modeling software, so that anyone who wished to replicate the modeling exercise can compare results without ambiguity. The values are about 2 decimal places too precise for measuring instruments generally available to amateurs.) Although the resistive component of the impedance seems to favor 50-Ohm cable, the reactive component sets the impedance at a value quite distant from 50 Ohms.

Interestingly, the reactive component of the impedance remains entirely inductive across the band. The curve generally descends except for the last graphed increment, where it shows a very slight rise. Given the very slight change in reactance across the band, not to mention the reverse direction of the curve relative to the curve for the antenna terminals, the rules of thumb become entirely useless in determining the type of reactance in a real measurement situation.



The curves for the 1/2-wavelength 50-Ohm line in **Fig. 6** should seem familiar. With a 1/2-wavelength line, the impedance at the design frequency should reproduce the impedance at the antenna terminals. The reported value of 87.12 - j3.04 comes within 0.05 Ohm of reactance of being perfect. As well, the reactance and resistance curves show the same general tendencies as those for the antenna feedpoint.

However, as we move away from the design frequency toward the band edges, the line length will no longer be 1/2-wavelength. At 7 MHz, the line will be short and at 7.3 MHz, the line will be long. If you closely compare the resistance and reactance curves in **Fig. 2** with those in **Fig. 6**, you discover an interesting phenomenon. The resistance curve for the 1/2-wavelength line case shows a wider span than the spread at the antenna terminals--about a 6.5 Ohm differential. In contrast, at the end of the 1/2-wavelength line, the reactance shows a narrower span than at the antenna terminals, nearly 21 Ohms (or about 32%) narrower. As a result, the SWR curves are somewhat flatter with the 1/2-wavleength line, although perhaps not enough to make an operational difference.



As we increase the line length to 5/8 wavelength, as shown in **Fig. 7**, we lose the reactance curve that tracks the one for the antenna terminals. In fact, the new reactance curve is almost a mirror image of the curve for 3/8 wavelength. As well, the reactance values are all capacitive, in contrast to the all-inductive values for the 3/8-wavelength line. The 7.15-MHz impedance of 41.89 - j24.53 Ohms reflects the mirror imaging. And once more, the curve descends in value with rising frequency, although the very small change in reactance itself would suffice to make the rules of thumb quite useless.

Once more, neither the 50-Ohm nor the 75-Ohm SWR curves are very promising for full-band operation of the antenna. In contrast to their 3/8-wavelength line mirror images, the 5/8-wavelength lines yield peak 75-Ohm SWR values at the high end of the band, rather than at the low end.

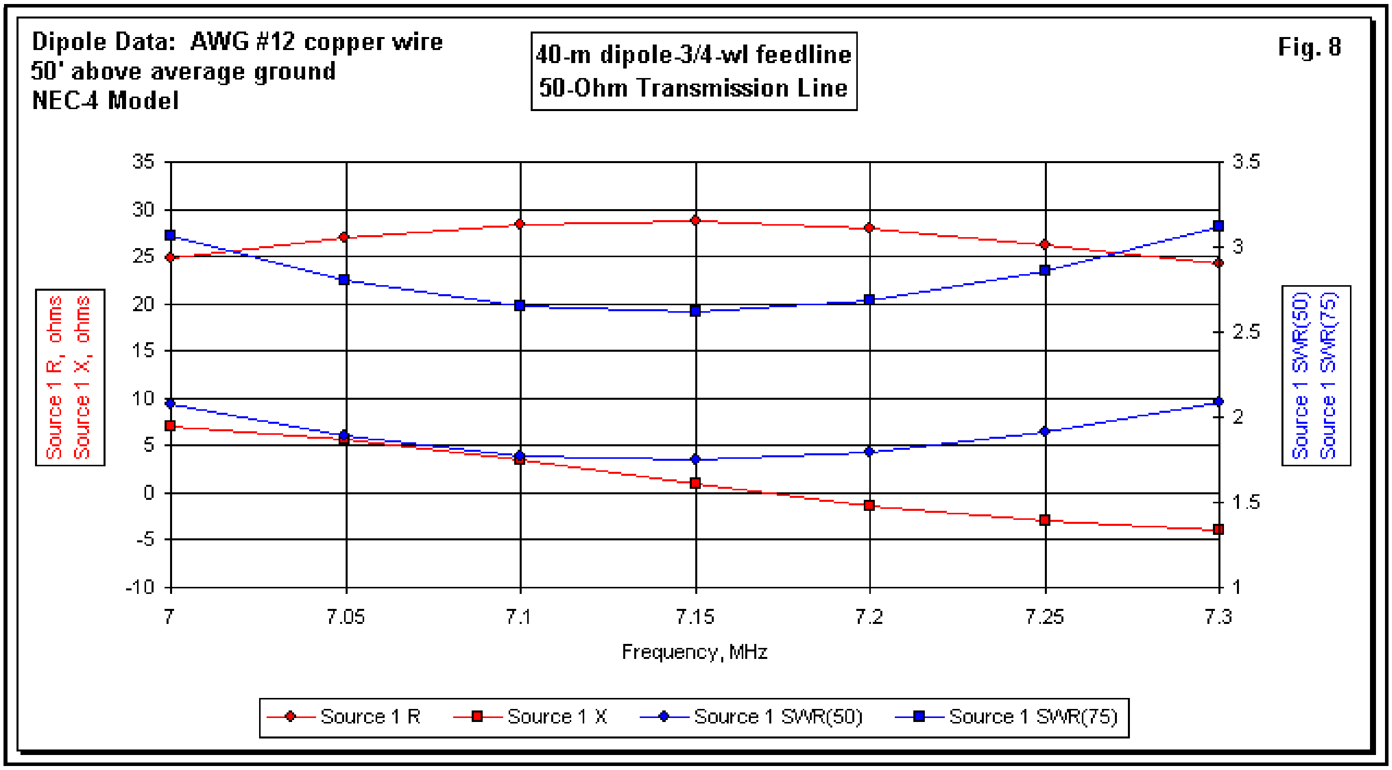


Fig. 8 shows the curves for a 3/4-wavelength 50-Ohm transmission line. We are taught quite correctly that at the design frequency for which the line is exactly 3/4-wavelength, the impedance will be the same as for a 1/4-wavelength line. The reported value is 28.66 + j0.97, only j0.01 Ohm reactance different from the report for the 1/4-wavelength line.

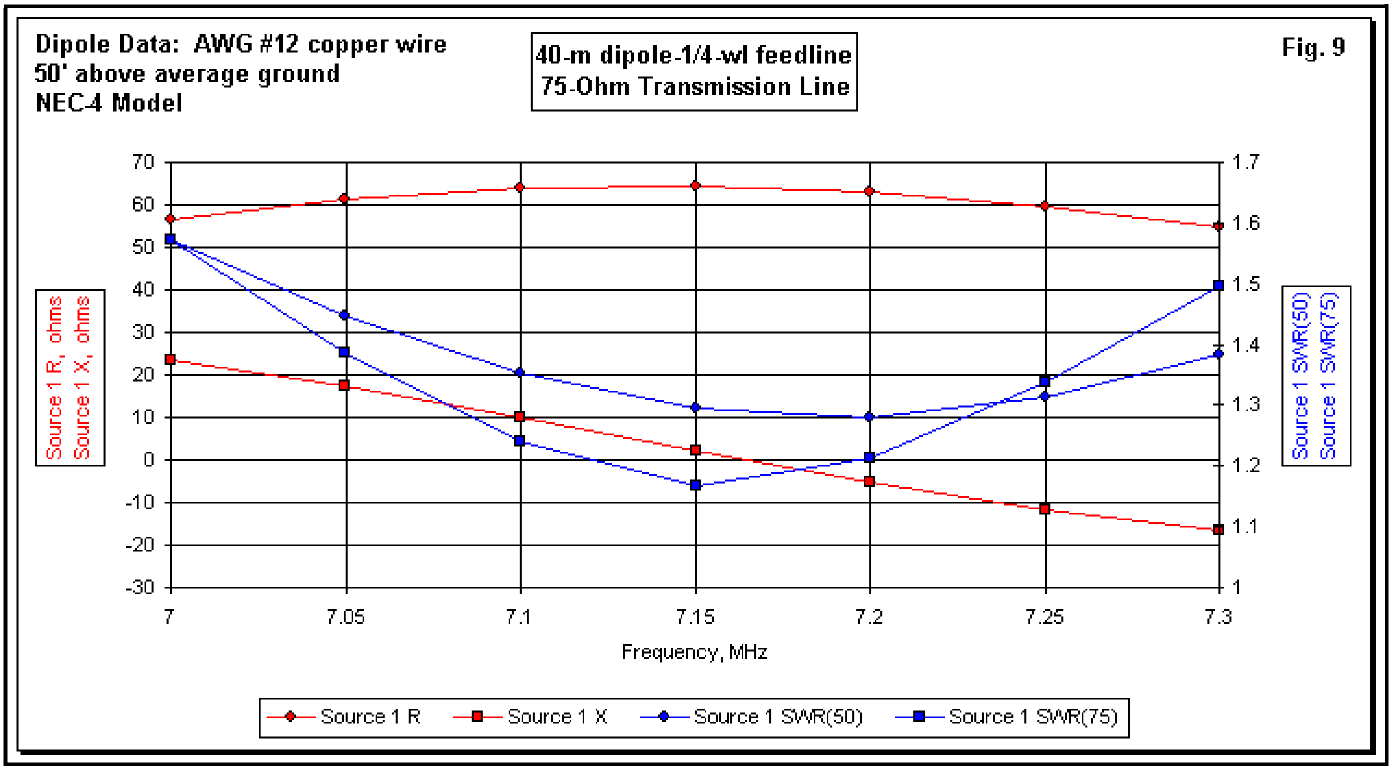
However, away from the design frequency in either direction, the line is no longer 3/4 wavelength. Still, the amount (as a percentage) by which it departs from 3/4 wavelength is less than the same frequency departure for the 1/4-wavelength line. Therefore, the reactance spreads for the two lines differ, with the longer line showing a little over 30% less of a reactance spread across the band. Nonetheless, the SWR curves for the 3/4-wavelength line are no more promising for full-band operation than the ones for the 1/4-wavelength line.

We have seen two cases in which we have separate graphs for line lengths that are separated by 1/2 wavelength: the case of no transmission line and a 1/2-wavelength line, and the case for 1/4-wavelength and 3/4-wavelength lines. In both instances, we noted identical trends in the curves. The major difference between the curves within each case is that the longer line produced a narrower spread of the reactance over the full width of the 40-meter band.

As a result, we would expect the the curves for a 7/8-wavelength line would show the same trends as those for a 3/8-wavelength line and the curves for a 1-1/8-wavelength line would show the same trends as for the 5/8-wavelength line. The reactance spreads would simply be somewhat narrower in each case. Of course, the longer we make the line physically, the more that actual line losses will modify these values, with the actual amount of modification depending on the loss per unit length of the chosen line. Nonetheless, the span of values that we have examined should be sufficient to provide a fairly clear picture of the impedance transformations that occur along a 50-Ohm transmission line with the starting terminal impedance values for the 40-meter dipole at a 50' height. As well, they show fairly clearly the limitations of the rules of thumb that gave rise to the exercise.

The 40-Meter Dipole with a 75-Ohm Cable

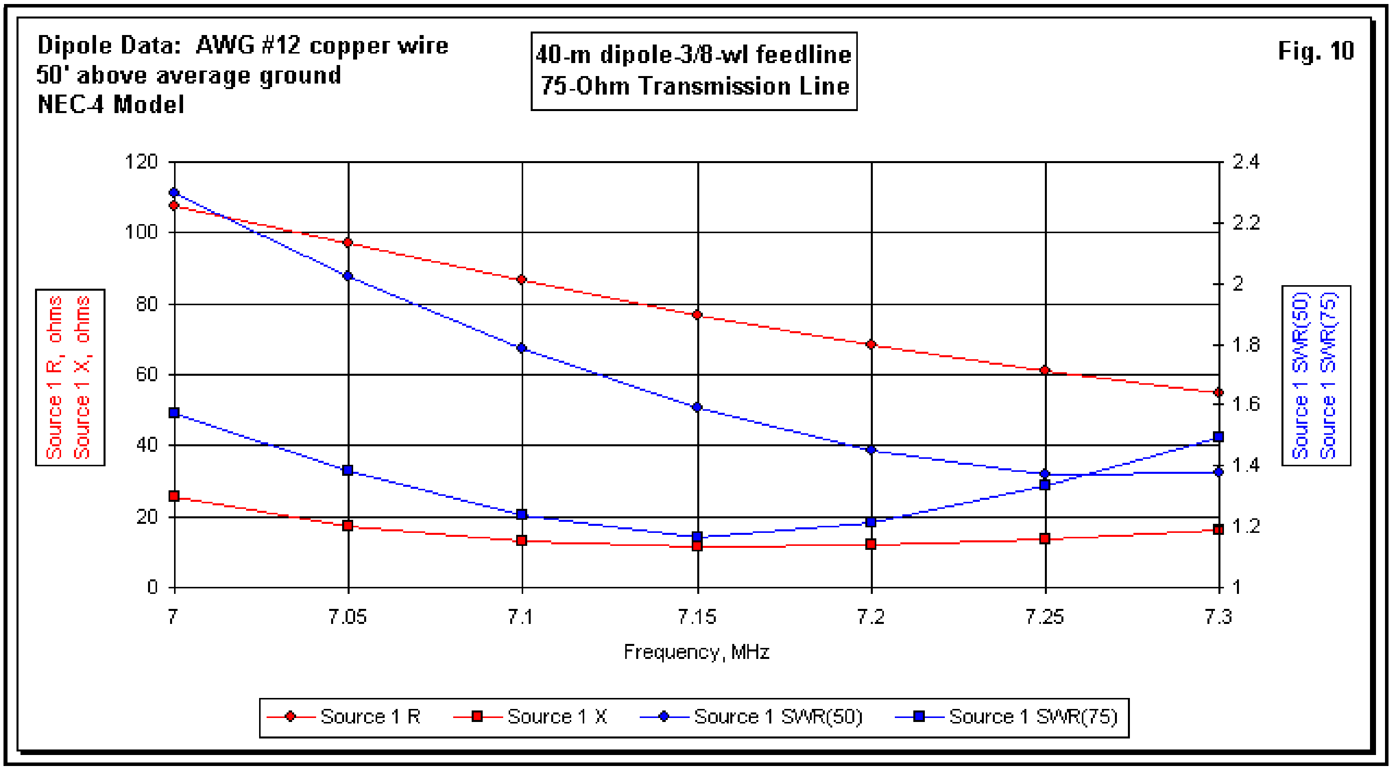
We should never accept a set of data without having a means to confirm its general validity. So far, you have only my word that transmission lines perform in the manner described. In order to provide some confirmation that the general ideas are correct, let's re-run the same set of exercises. Instead of a 50-Ohm cable, this time we shall use a 75-Ohm transmission line. As in the first case, we shall use a velocity factor of 1, since the velocity factors of existing 75-Ohm cables vary as much as do those for 50-Ohm cables. Conveniently, the same table of fractional wavelengths at 7.15 MHz will serve us well for the re-run.



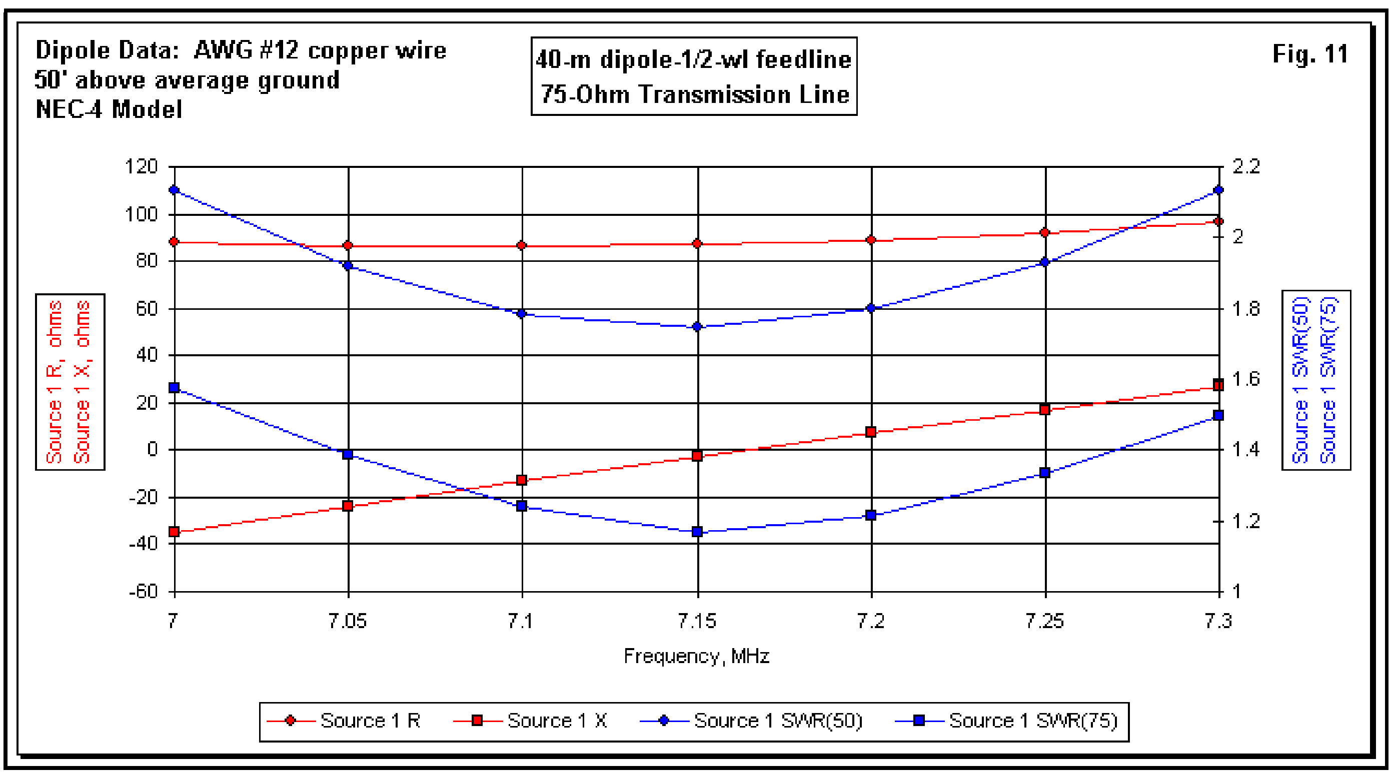
If we replace the 50-Ohm cable with a 1/4-wavelength section of 75-Ohm feedline, as shown in **Fig. 9**, we obtain a mid-band impedance of 64.49 + j2.19 Ohms. This value is a product of the same simplified calculation that we used with the 50-Ohm line. However, this time, we divide the square of 75 (5625) by the antenna terminal resistance (87.12) to arrive at a calculated impedance of 64.6, just a little off from the value we get when we factor in the very small reactive component at the antenna terminals.

The band-edge resistance values are in the 50s while the reactance varies from j23 to -j12 Ohms. The result is a set of SWR curves that are usable across the 40-meter band. We shall have occasion just a bit further down the road to use this system within a larger antenna-feedline system.

For the moment, we may note that the direction of the reactance curve is the same as with the 1/4-wavelength 50-Ohm line. This provides part of the confirmation that we needed, namely, that the 50-Ohm results were--with respect to trends--perfectly general.



The 3/8-wavelength 75-Ohm transmission line also reflects the trends shown by its 50-Ohm counterpart. Compare **Fig. 10** with **Fig. 5** for the 50-Ohm cable of the same length. The reactance is wholly inductive. As well, reactance curve shows a slight downward trend, except for the highest end of the operating passband. The 7.15-MHz impedance is 76.72 + j11.56 Ohms. Hence, the 75-Ohm SWR curve remains exceptionally good, but the 50-Ohm curve has taken a tilt for the worse.



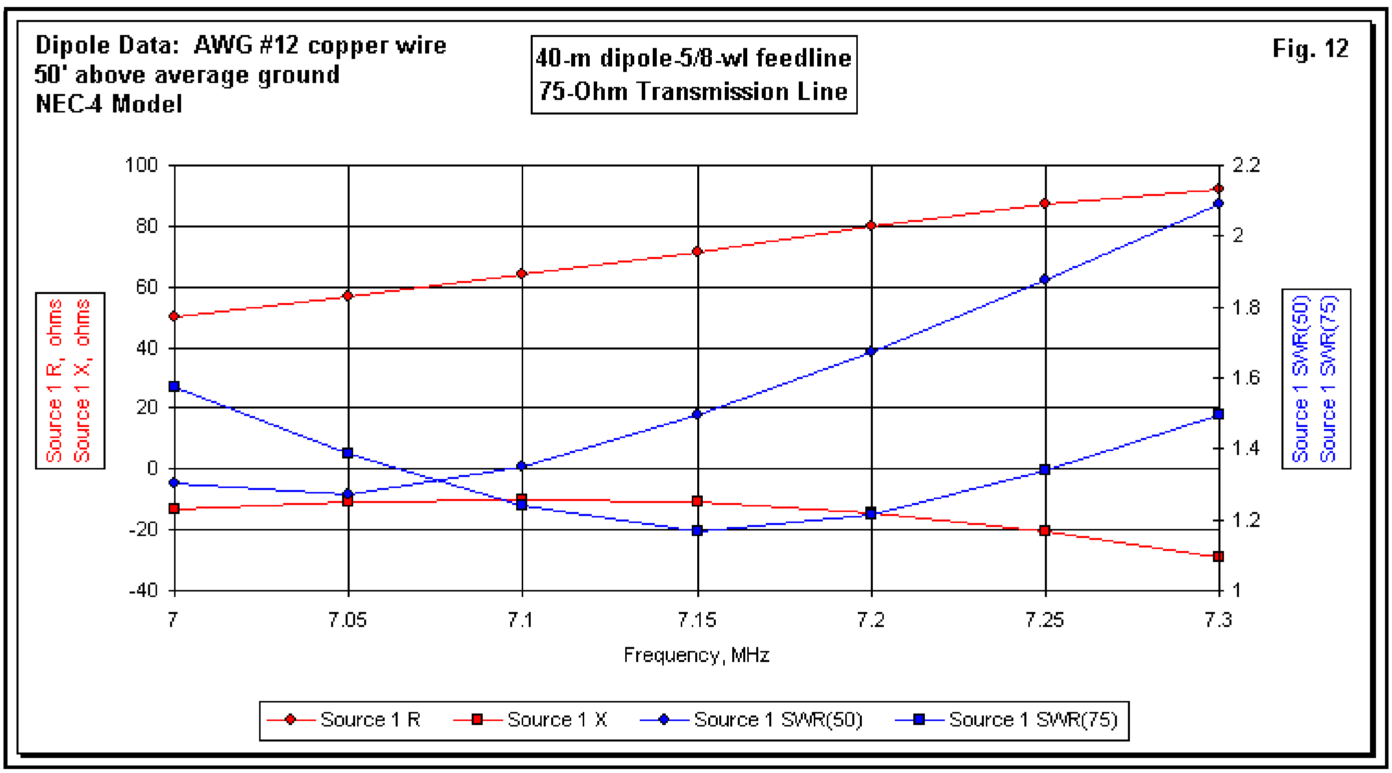
The 1/2-wavelength 75-Ohm line yields curves in **Fig. 11** that closely resemble those in **Fig. 2** and in **Fig. 6**, the graphs of the antenna with no transmission line and the graph for a 1/2-wavelength 50-Ohm line. The 7.15-MHz impedance is 87.12 - j3.08 Ohms--within an eyelash of the impedance reported for the antenna with no transmission line at all. However, let's look at the band-edge impedances for the 3 cases:

TL Situation	7.0 MHz	7.3 MHz
No Line	82.48 - j35.20	91.86 + j29.15
1/2-WL 75-Ohm Line	87.71 - j34.89	96.54 + j26.96
1/2-WL 50-Ohm Line	89.92 - j30.12	98.24 + j21.34

Although the differences are small, the trends are clear. As we reduce the characteristic impedance of the 1/2-wavelength line, the band-edge resistance increases, but the band-edge reactance decreases. Does this trend hold for transmission lines with impedances above 87 Ohms? There are 93-Ohm and 125-Ohm coaxial cables, so let's replicate the chart using those lines.

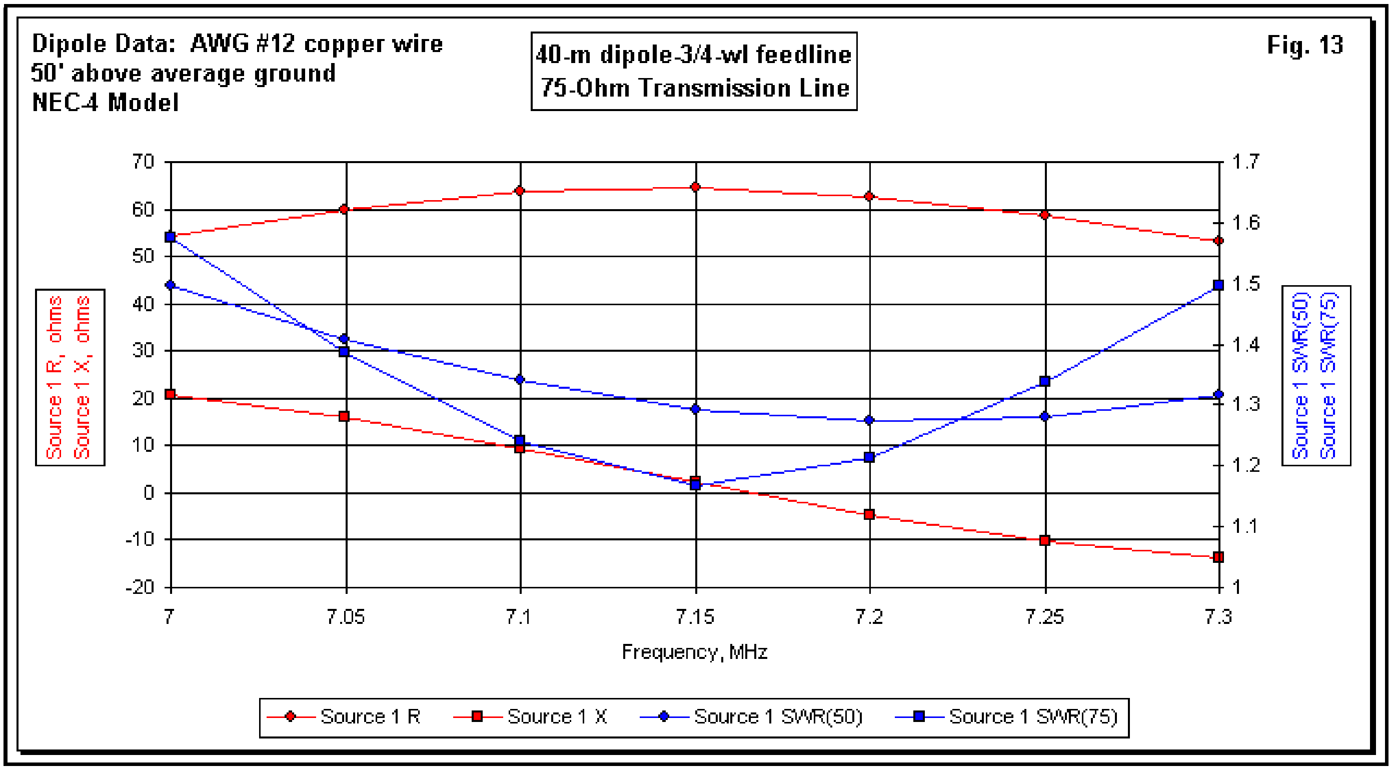
TL Situation	7.0 MHz	7.3 MHz
No Line	82.48 - j35.20	91.86 + j29.15
1/2-WL 93-Ohm Line	86.80 - j37.21	95.80 + j29.62
1/2-WL 125-Ohm Line	85.81 - j40.50	94.96 + j33.27
1/2-WL 87.12-Ohm Line	87.06 - j36.51	96.01 + j28.82

As we increase the transmission line characteristic impedance, using a 1/2-wavelength line, the resistance decreases and the reactance increases. However, the resistive portion of the band-edge impedance does not decrease relative to the antenna terminal impedance, but rather to the band-edge values of a hypothetical 87.12-Ohm line, shown in the last line of the new table. The reason for this reference line is that even the perfectly matched line loses its perfection of match as we move away from the frequency at which it is exactly 1/2-wavelength. The lesson here is that we must--when setting trends with any precision--compare truly comparable items. The no-line case is satisfactory for some comparisons, but for seeing the resistance-reactance trend in 1/2-wavelength lines, we need to make our reference also a 1/2-wavelength line, in this case perfectly matched at the design frequency.



The 5/8-wavelength 75-Ohm line in **Fig. 12** reflects the trends shown for the 50-Ohm line in **Fig. 7** and is the virtual mirror image of the graph for the 3/8-wavelength line in **Fig. 10**. The mid-band impedance is 71.69 - j10.85 Ohms. The reactance is wholly capacitive and has such a shallow curve as to negate any possible application of the rules of thumb that gave rise to this exercise. The 75-Ohm SWR curve remains very good, but the 50-Ohm SWR curves reaches excessive values at the high end of the 40-meter band.

Once more, our 75-Ohm work confirms the general trends, but not the specific values, revealed by the earlier 50-Ohm work.

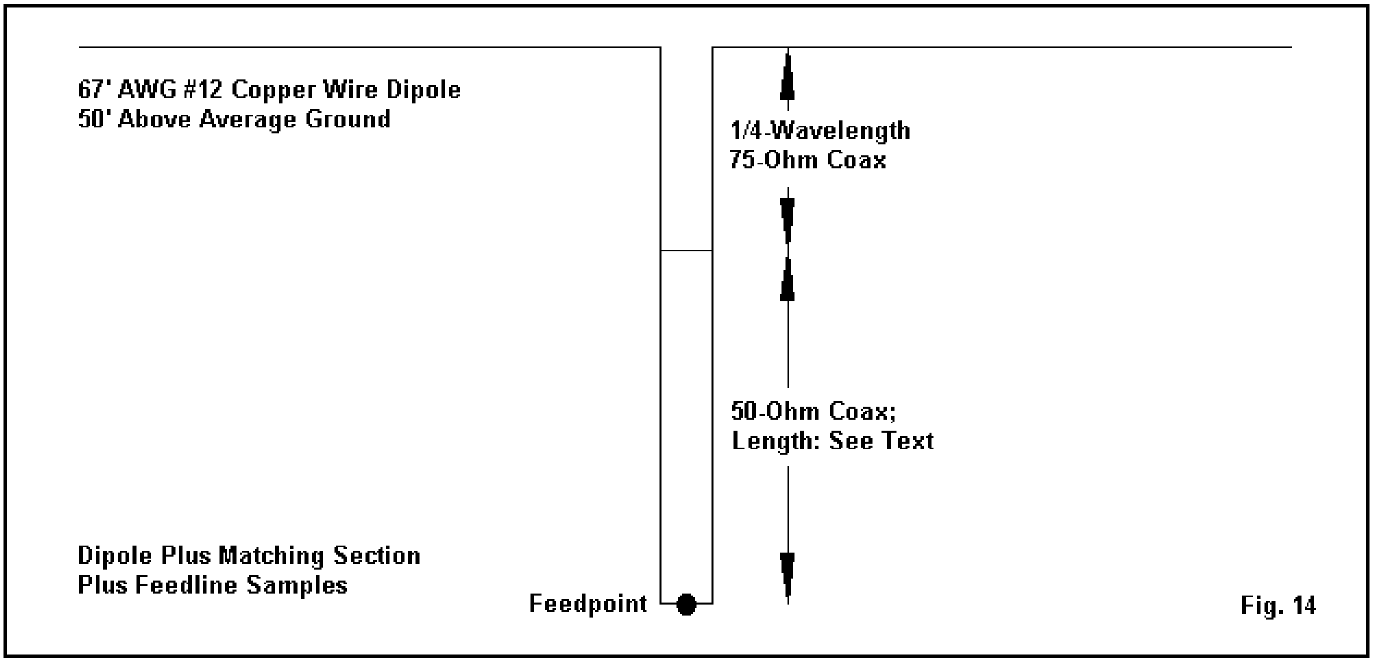


The 3/4-wavelength line, graphed in **Fig. 13**, shows once more that the values and trends tend within limits to replicate themselves every 1/2-wavelength down a lengthening transmission line. The 7.15-MHz impedance is 64.49 + j2.19 Ohms, the same value that we obtained for a 1/4-wavelength line. However, as we noted for the 50-Ohm line case, the band edge values will vary somewhat between 1/4-wavelength and 3/4-wavelength lines, due to differences in how much each line differs from its length at band center.

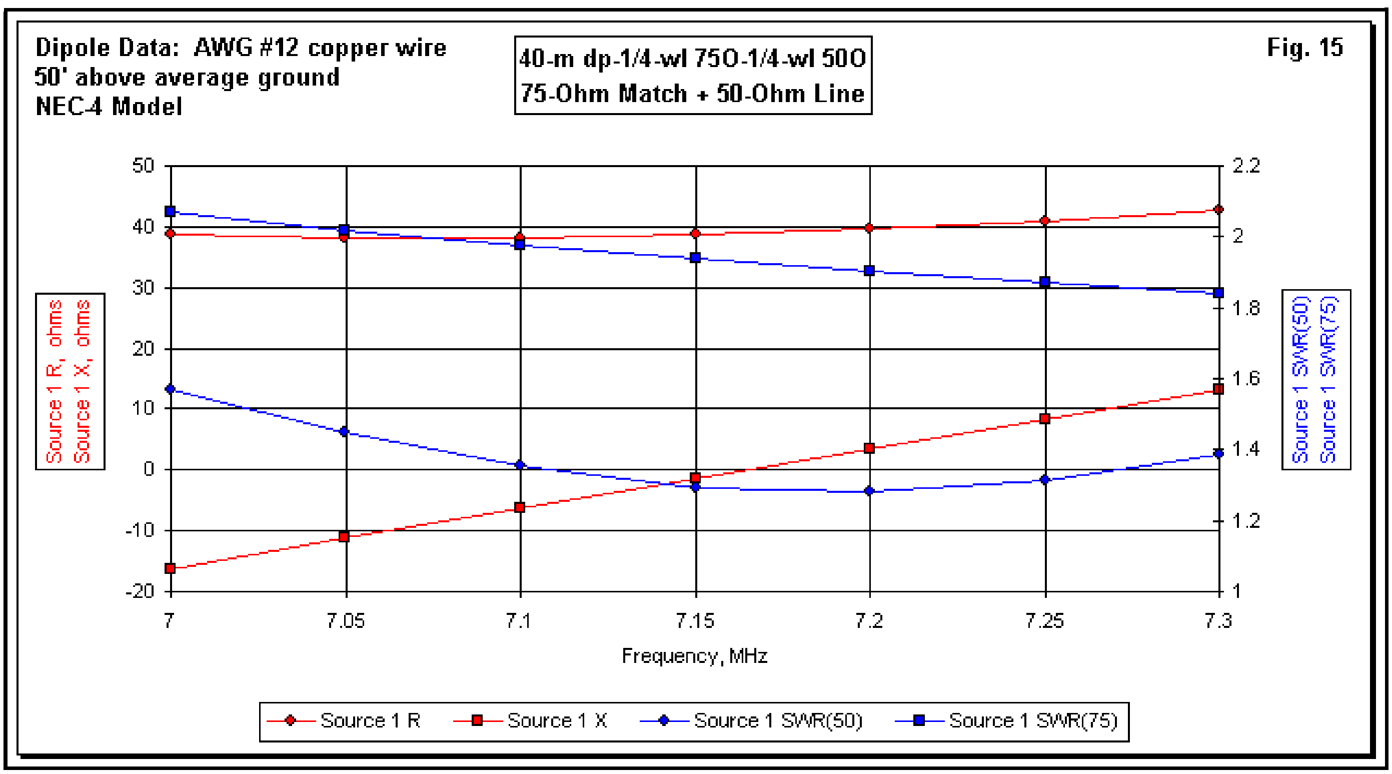
Although the data for resistance and SWR in our sequence of graphs is interesting, our main goal has been to explore what happens to reactance as we increase the length of a transmission line away from the antenna feedpoint. Sometimes graphing phenomena can give us a better set of long-term intuitively correct expectations than a series of simple calculations in numerical form. If we remember the general trends shown by the graphs, then we shall be in a better position to apply or to withhold application of the rules of thumb with which we started.

The 40-Meter Dipole with a 75-Ohm Matching Section and a 50-Ohm Cable

The case in which we placed a 1/4-wavelength 75-Ohm transmission line from the antenna terminals to the source presented us with the best overall 50-Ohm SWR curve. Before we leave our dipole altogether, let's explore a possibility: let's use the 75-Ohm line as a matching section and then let the remainder of the line be 50 Ohms. **Fig. 14** outlines the system.

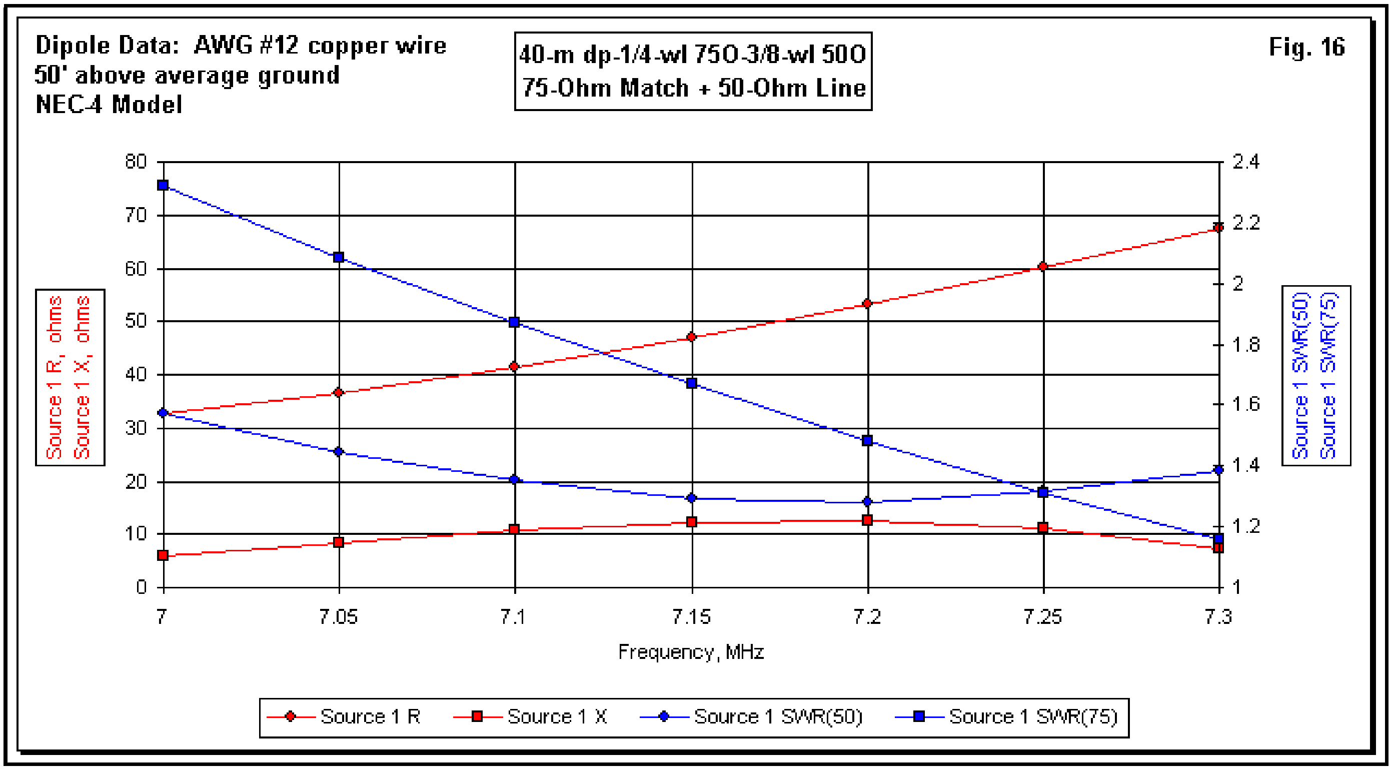


As our work so far has shown us, we might as easily have used a 3/4-wavelength section of 75-Ohm cable as the matching section. In either case, we would expect that 50-Ohm SWR curves would be superior to any that we experienced when we connected the 50-Ohm cable directly to the antenna terminals. Let's do a complete survey, so that we can detect oddities, if they should occur.



Remember that the 7.15-MHz impedance at the end of the 75-Ohm matching section is 64.49 + j2.19 Ohms. Hence, with a 1/4-wavelength length of 50-Ohm cable added to the system, we shall obtain an impedance that is roughly 2500 divided by 64.5, or about 38.8 Ohms. As shown in the graph in **Fig. 15**, the impedance at 7.15 MHz is 38.72 - j1.32 Ohms.

Despite the impedance conversion, the 50-Ohm SWR never rises to 1.6:1. As well, we find a rising reactance curve, the same trend--with different values--that we found at the antenna terminals. The reason is straightforward: the first 1/4-wavelength section reversed the direction of the curve, and the second 1/4-wavelength section reversed it once more.



The 3/8-wavelength 50-Ohm cable addition, graphed in **Fig. 16**, shows what should be by now very familiar characteristics. The 50-Ohm SWR curve once more does not rise to 1.6:1. The reactance curve is wholly inductive, but is so flat as to make the rules of thumb irrelevant to any practical application to this situation. The 7.15-MHz impedance is 46.86 + j12.08 Ohms. The resistive component is closer to 50 Ohms than was the 1/4-wavelength line value, but the reactance is higher. The result is the same--a mid-band SWR of 1.29:1.

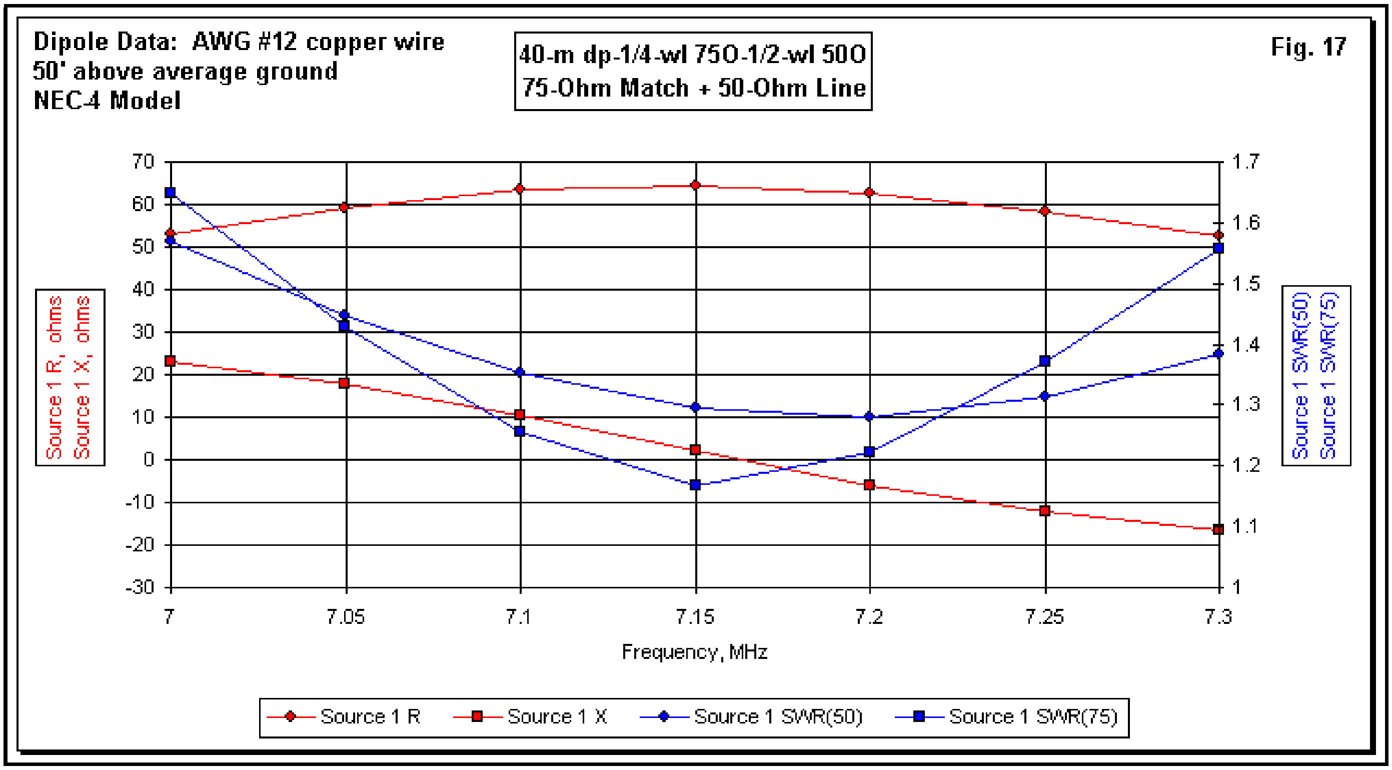
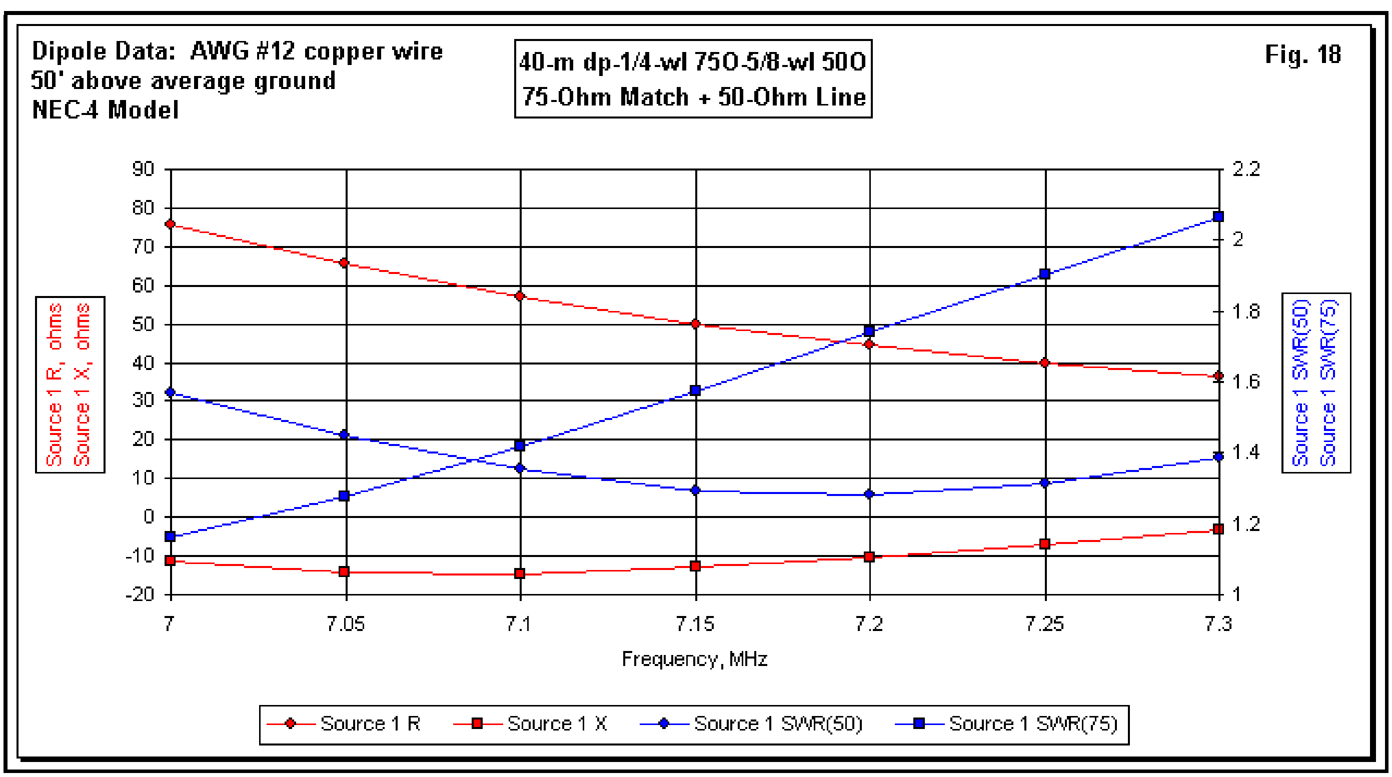
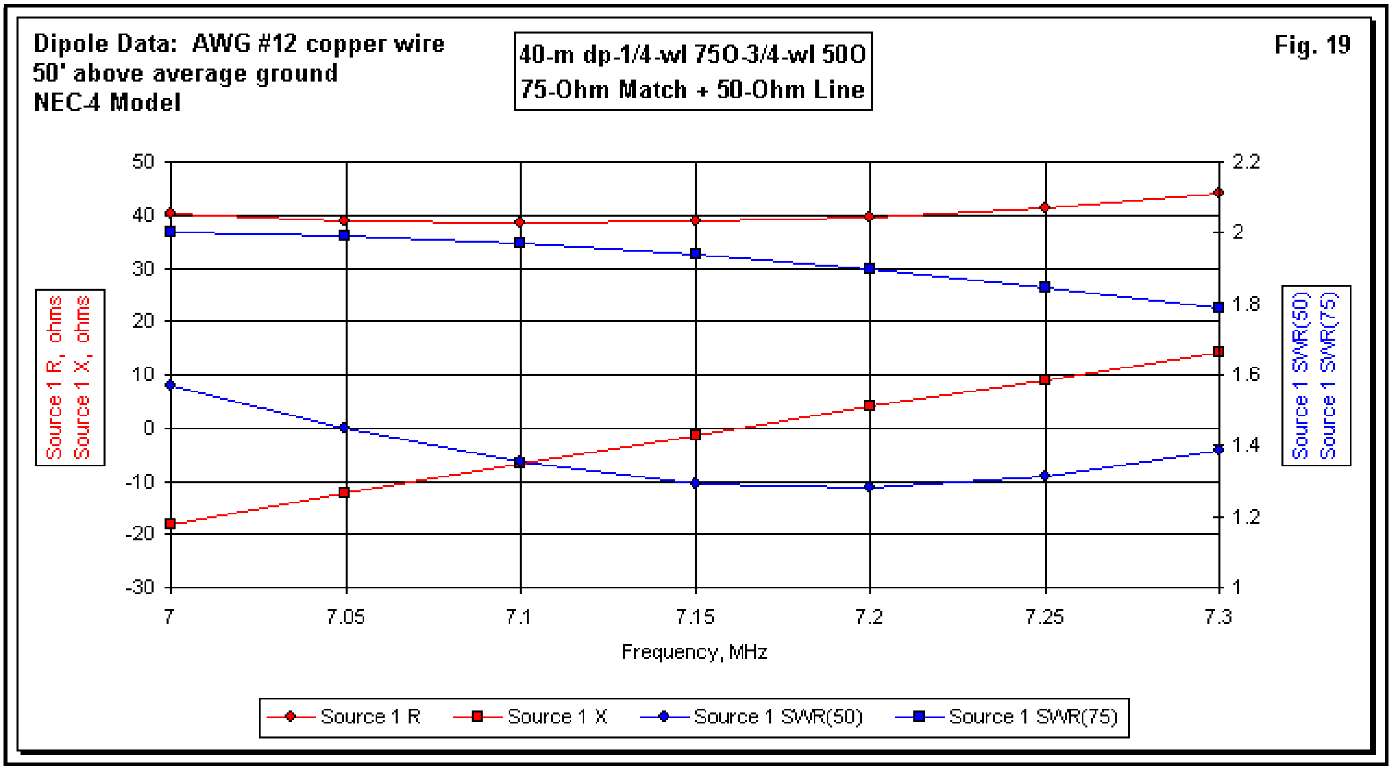


Fig. 17 shows the curves when we add a 1/2-wavelength 50-Ohm line to our matching section of 75-Ohm cable. The 75-Ohm SWR curve shows a very low mid-band value, but rises rapidly toward the band edges, although the peak values is well under 2:1. However, the 50-Ohm SWR curve has not changed, with a 1.29:1 mid-band value and a peak value of 1.57:1.

The reactance curve has its typical downward slope, replicating the curve that we would obtain at the end of the 75-Ohm matching section. Also as expected, the mid-band impedance is 64.49 + j2.23 Ohms, the value that we found at the end of the matching section.



At the end of a 5/8-wavelength 50-Ohm line added to the matching section, we obtain the values shown in **Fig. 17**. The resistance and reactance graph lines are virtual mirror images of those we saw in **Fig. 16** for the 3/8-wavelength line. The mid-band impedance is 50.03 - j12.92 Ohms, which yields a 50-Ohm SWR value of 1.29:1. The peak band-edge value at 7 MHz is 1.57:1.



The graph for a 3/4-wavelength 50-Ohm addition to the matching section in **Fig. 19** replicates--within limits that we have previously noted--the results for the 1/4-wavelength line in **Fig. 15**. The reactance shows a rising line, while the mid-band impedance is 38.72 - j1.32 Ohms. The 50-Ohm SWR at 7.15 MHz is 1.29:1, while the peak value (at 7 MHz) is 1.57:1.

Perhaps the most notable feature in this sequence of graphs is the fact that the 50-Ohm SWR curve did not change at all as we increased the length of 50-Ohm cable that followed the 1/4-wavelength 75-Ohm matching section. Our previous comparison of 1/4-wavelength and 3/4-wavelength line sections showed a smaller spread for the reactance across the band. Perhaps we can lower the band-edge peak 50-Ohm SWR values if we replace the shorter matching section with a longer one.

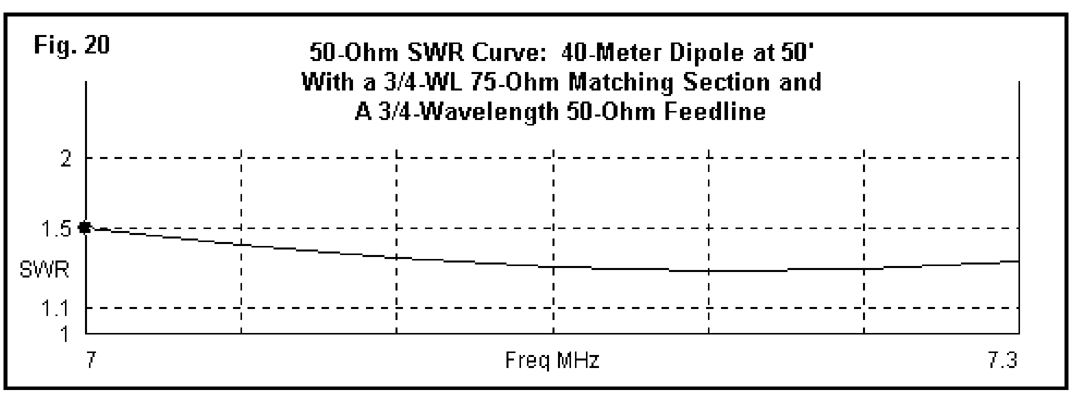


Fig. 20 shows the results of the replacement. The minimum 50-Ohm SWR value does not change; it is still 1.29:1. However, the maximum value is now 1.49:1, perhaps a small decrease, but one that may bring the maximum value under the amplifier power reduction or shut-down value.

Remember that the matching technique that we used in this example applies to a specific "situated-antenna." That is, the feedpoint impedance at the antenna terminals had to be close to the 87-Ohm mid-band value. This condition exists for a 40-meter dipole at 50' or about 0.36-wavelength up. Since the impedance of a resonant dipole will vary with its height above ground at least to about 1.25 wavelengths, changing the antenna height will require a different matching technique.

Nevertheless, the example does illustrate at least two different properties of focal interest in this introduction to transmission line transformations. First, it illustrates a simple application of series matching using only transmission lines. For a more detailed account of series matching techniques, see "Series Matching: A Review".

Second, the sample matching situation further illustrates what happens to the SWR curves, the resistance curve, and especially the reactance curve at the source point when we place various types and combinations of feedlines between the antenna terminals and the measuring point, that is, the source. The matching-section example shows that having a good working familiarity with these transformations has multiple benefits. Familiarity with the curves tells us when to apply the overworked rules of thumb and when to ignore them because they are irrelevant to a situation. The same familiarity also tends to give us intuitively correct expectations and understandings of the measured results we obtain. Final, the familiarity also opens avenues of opportunity for effecting the level of matching required by a given antenna situation.

For these reasons, we should let familiarity grow into downright intimacy with the phenomena that we are exploring. Therefore, we need a second part to this primer to explore other situations than that of a simple dipole. Even then, we shall not be complete in our knowledge, but, then, intimacy never is.