Insulated Wire and Antennas

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Introduction

Insulated copper wire intended for home wiring is often used for antennas and ground systems, both elevated and buried. This wire is readily available at hardware and home improvement emporiums and often significantly less expensive than the equivalent wire without insulation (bare). Among amateurs there has been a recurring discussion whether it's necessary or even useful to strip the insulation. Stripping a few hundred feet isn't a serious chore but if you're laying out a 160m radial field with thousands of feet of wire then stripping would be a chore. Although this question has popped frequently for as long as ham radio has been around I've never seen careful discussion of the subject using both theory and experimental tests. Some years ago I wrote I wrote a pair of QEX articles[1,2] discussing antenna wire but I didn't explore the dielectric loading effect of insulation.

We can address the question "to strip or not to strip?" in an organized way. What follows are some modeling and experimental results. I make no claim this is a complete or final answer but it should at least provide food for thought.

Concerns

Concerns fall into three categories:

1) Does the insulation introduce additional loss? Even if the loss for new wire is small, what happens to the loss after years of exposure to UV and weather?

2) Even if there is no loss, insulation will introduce some dielectric loading, i.e. the tuning of the antenna will be affected. Does this matter and can it introduce any pathologies, i.e. serious problems?

3) Mechanical issues. What happens to the conductor as the insulation deteriorates, oxidation, corrosion, etc? Because of it's larger diameter does an insulated wire build up a greater ice load in winter storms? Etc.

Plan of attack

There are some tools we can use to address these questions. In the case of insulation induced loss we can wind samples of wire into an air-core inductor and measure its Q. The Q of inductors with Q>100 are very sensitive to conductor loss. Even a small change in RF resistance is magnified as a change in Q. My Nov/Dec 2000 QEX article explained this in detail so I'll not repeat that information here but a PDF of the article can be found at: www.antennasbyn6lf.com. I used this approach test additional samples of new and old insulated wire.

To explore the effect of dielectric loading I used EZNEC Pro with the NEC4.2 engine[3] combined with Dan Maguire's AutoEZ EXCEL based program[4]. This raises the question of "how much can we rely on NEC modeling"? That's a fundamental question so last year I took a careful experimental look at this issue and reported my results in the Jul/Aug 2016 issue of QEX[5], which makes a pretty good case for NEC, at least for low or buried wires with or without insulation. For the present discussion I'm going to assume the NEC modeling answers are good enough we can make some judgments. The NEC QEX article is also available at: www.antennasbyn6lf.com.

The wire

Figure 1 - Sample of degraded #12 radial wire.

This discussion will assume either solid #12 or #14 copper wire with THHN insulation because this is by far the most common and is representative of this class of wire. The insulation is PVC with a thin nylon coating. When exposed to UV and weather extended periods the nylon coating usually flakes off and the color of the underlying PVC fades. Besides a roll of new wire I had on hand thousands of feet of well exposed #12 wire used for my 160m vertical array and other antenna projects going back 20 years. In addition Guy Olinger, K2AV, sent me ten samples including insulated and bare, new and very weathered #14 THHN. This allowed me to test both new and very weathered wires.

Test inductor results

Figure 1 shows a typical sample of used wire. Notice that the outer nylon cover is flaking off and the insulation is bleached (the original color was red). the Insulation is a bit brittle and the copper oxidized. I also happened to have the coil form used for the QEX wire HF resistance article so I used that as the coil form using the same number of turns. This allowed me to compare the earlier work with the present. Each wire sample was wound on the coil form as shown in figure 2.

Figure 2 - Old radial wire wound into an inductor.

Q was measured with an HP4342A Q-meter as shown in figure 3. An HP5334A frequency counter was used to determine the test frequency. Here are the results:

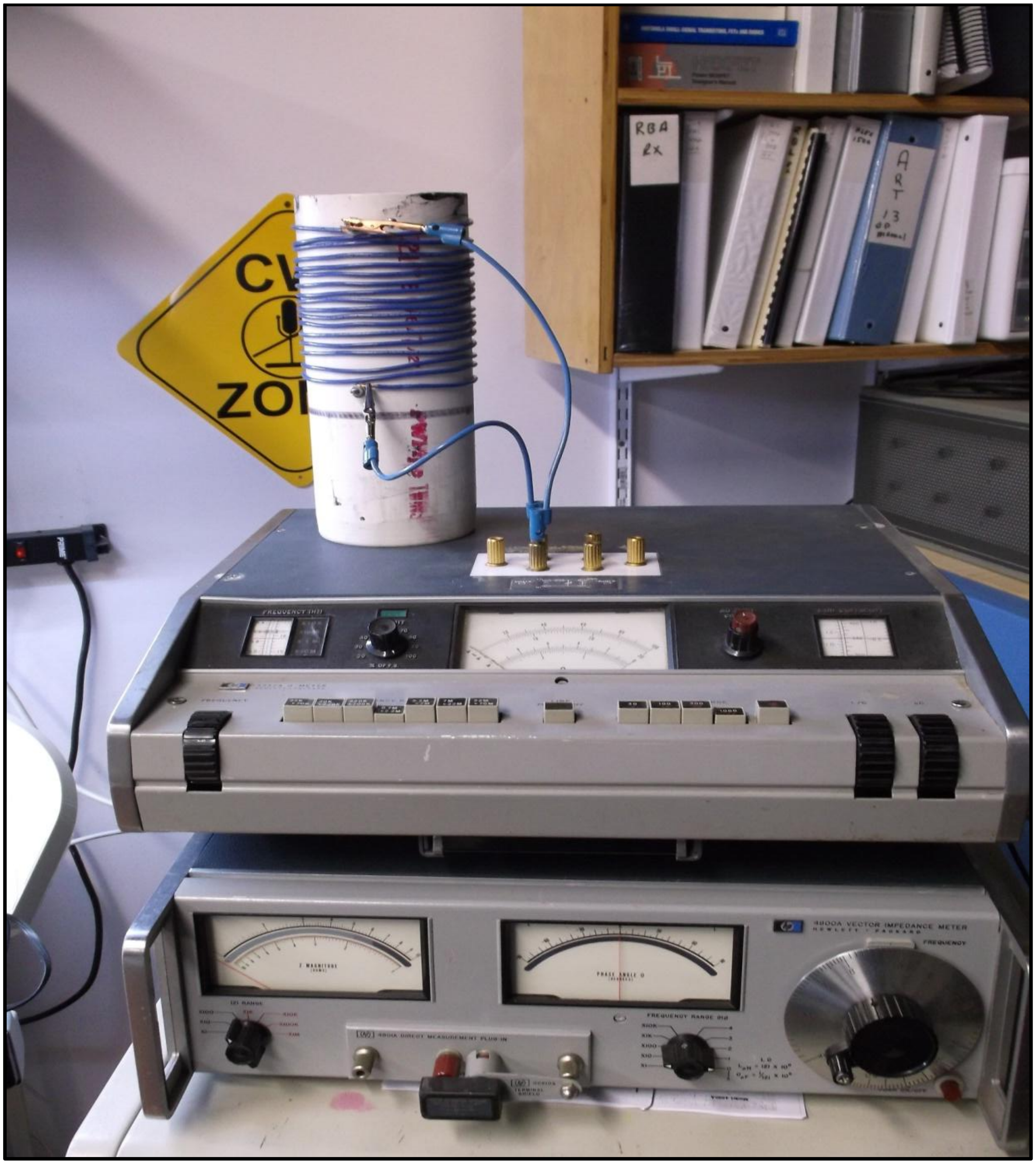

Figure 3 - Q-meter.

Table 1 - Q comparison for N6LF #12 wire.

wire	**1.8 MHz Q**	**3.9 MHz Q**
old #12	**405**	**470**
new #12	**400**	**460**

Table 2 - Q comparison for K2AV #14 wire at 3.6 MHz.

Wire	Q
Bare	395
New ins	390
R1	394
R2	396
R3	398
R4	400
R5	382
R6	390
R7	405
R8	395

Samples R1-R8 were weathered radials supplied by K2AV. The small variations in Q are to be expected with the informal winding.

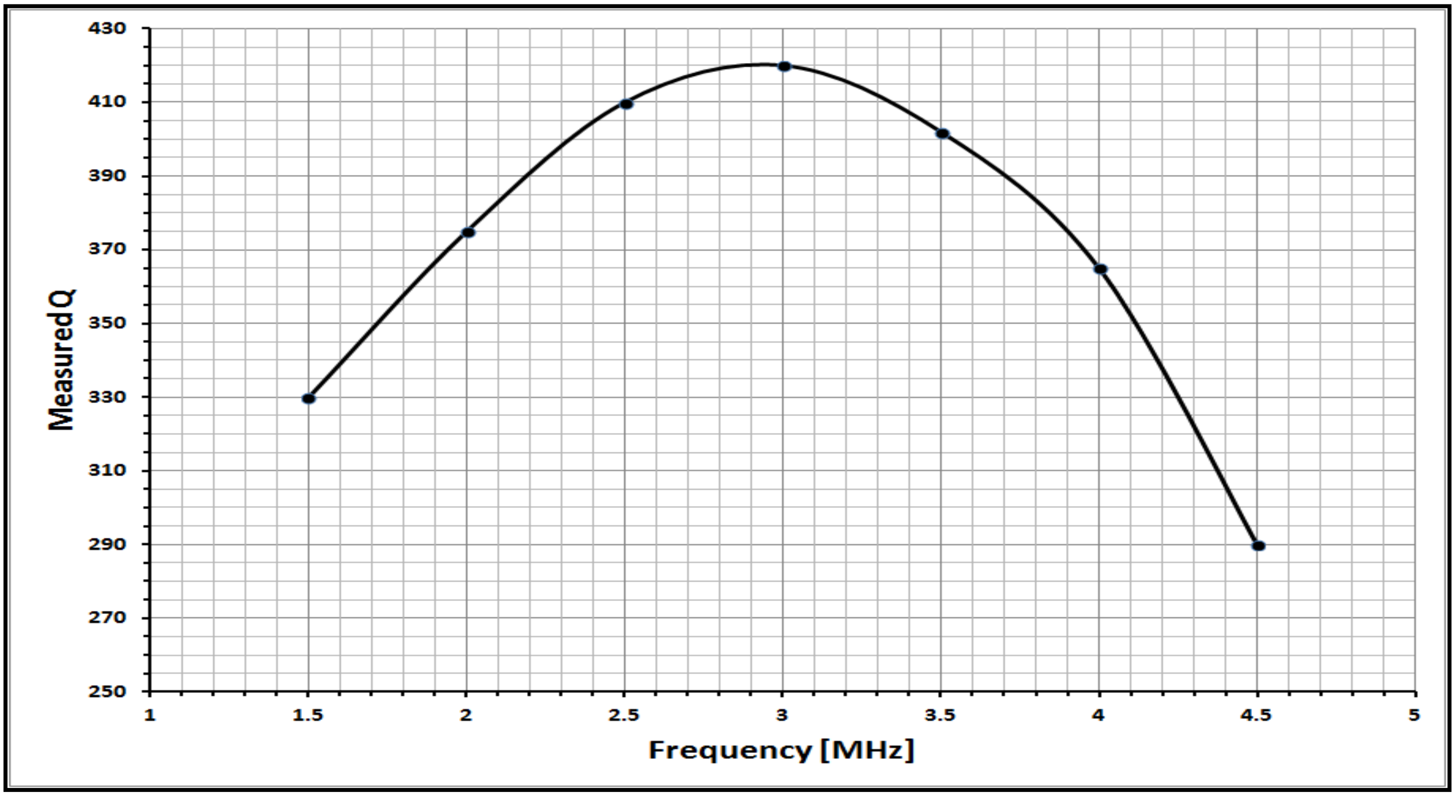

Figure 4 - Q versus frequency for sample R6.

I also performed a Q measurement varying the frequency from 1.5 to 4.5 MHz on some new #14 and sample R6 from K2AV as shown in figure 4. Measurements for the two samples were almost identical so the graph is for R6.

These experiments didn't show any loss introduced by the insulation, either new or very weathered.

Insulated dipoles

To see the dielectric loading effect of insulation we can use a dipole in free space and examine the feedpoint impedance as we change from bare to insulated wire. Er is the relative dielectric constant, Er=3.2 for PVC and Er=4 for nylon. The nylon coating is very thin so it probably doesn't effect the total Er very much. I used Er=3.3 as a compromise. The dipole model was adjusted to be resonant at fr=1.83 MHz using bare wire. Insulation was then added with the results shown in table 3.

Table 3 - 160m dipole in free space, Er=3.3.

wire	frequency	dipole length	Ri	Xi
Bare #12	**1.830 MHz**	**262.4'**	**72.2Ω**	**0**
insulated #12	**1.830 MHz**	**262.4'**	**71.7Ω**	**+27.9Ω**
insulated #12	**1.803 MHz**	**262.4'**	**70.3Ω**	**0**
insulated #12	**1.830 MHz**	**259.6'**	**70.3Ω**	**0**

Adding insulation reduces fr from 1.830 MHz to 1.803 MHz due to dielectric loading. Since there are no losses in the model the shifts in Ri represent a change in radiation resistance (Rr). Insulation changes both the feedpoint impedance and fr, reducing Ri (72.2→71.7Ω) as well as fr (1.830→1.802 MHz). When the antenna is shortened from 262.4" to 259.6' to restore the original fr, Ri is further reduced to 70.3Ω. Adding insulation does effect the feedpoint impedance. The insulation makes the wire electrically a little longer (≈1.5%).

Now let's suppose we have a buried dipole or a radial system. Burial in soil reduces the resonant frequency drastically so for this example we'll use a dipole length of 30', a burial depth of 1' and average soil, σ=0.005 S/m and Er=13. Figure 5 shows the behavior of the of the feedpoint impedance (|Zi|) versus frequency as a function of insulation thickness ("A" in inches) varying from zero (bare wire) to 0.020". Clearly the presence of insulation and it's thickness have a profound impact on |Zi| and fr!

The current distribution along the buried dipole is shown in figure 6. The upper curve is with insulation and the lower is for bare wire. We'll see this difference in current distribution again when we look at a vertical with a buried radial system.

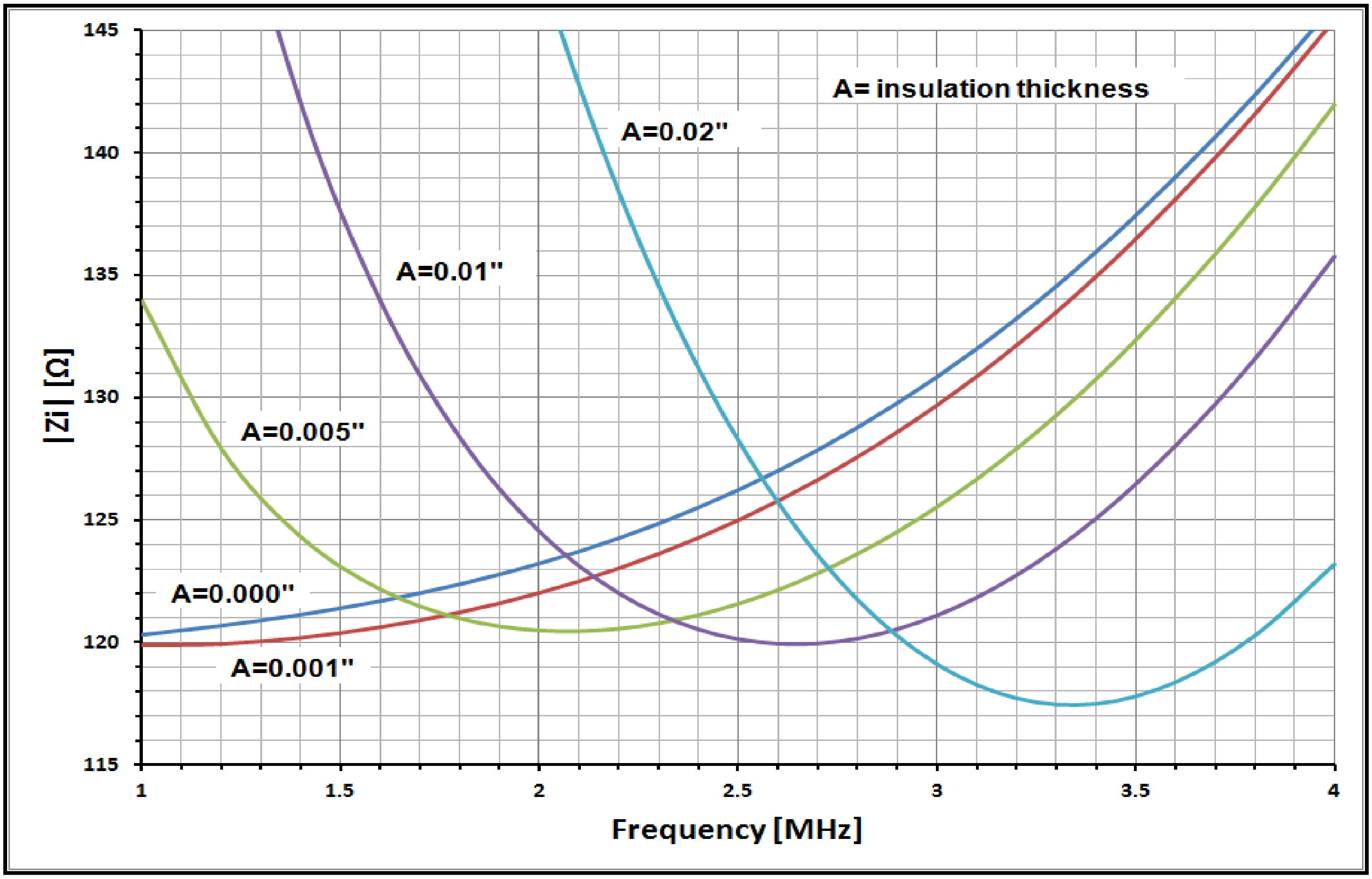

Figure 5 - Magnitude of the feedpoint impedance.

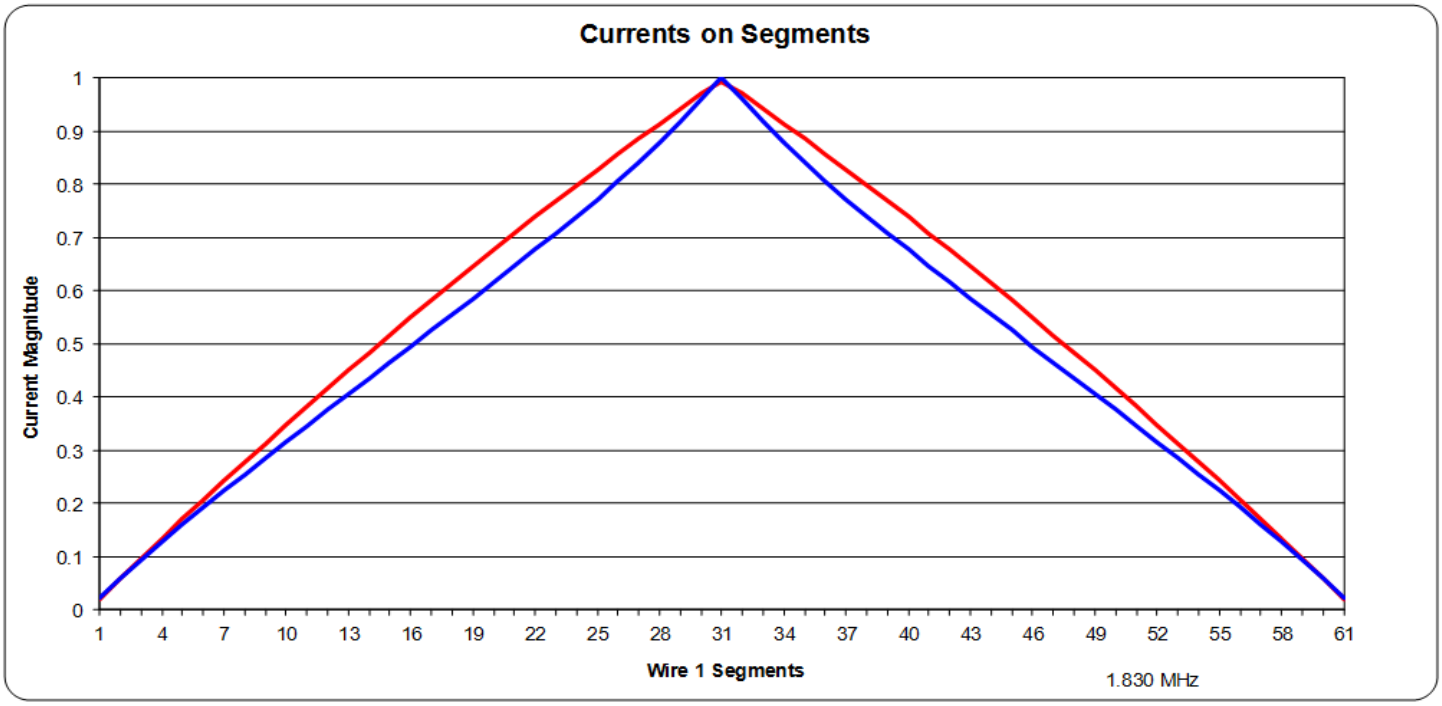

Figure 6 - current distribution along the dipole with and w/o insulation.

Verticals with elevated ground systems

Now let's look at the effect of changing from bare to insulated radials in a ground-plane vertical (GPV) like that shown in figure 6. The vertical and all the radials are #12 wire.

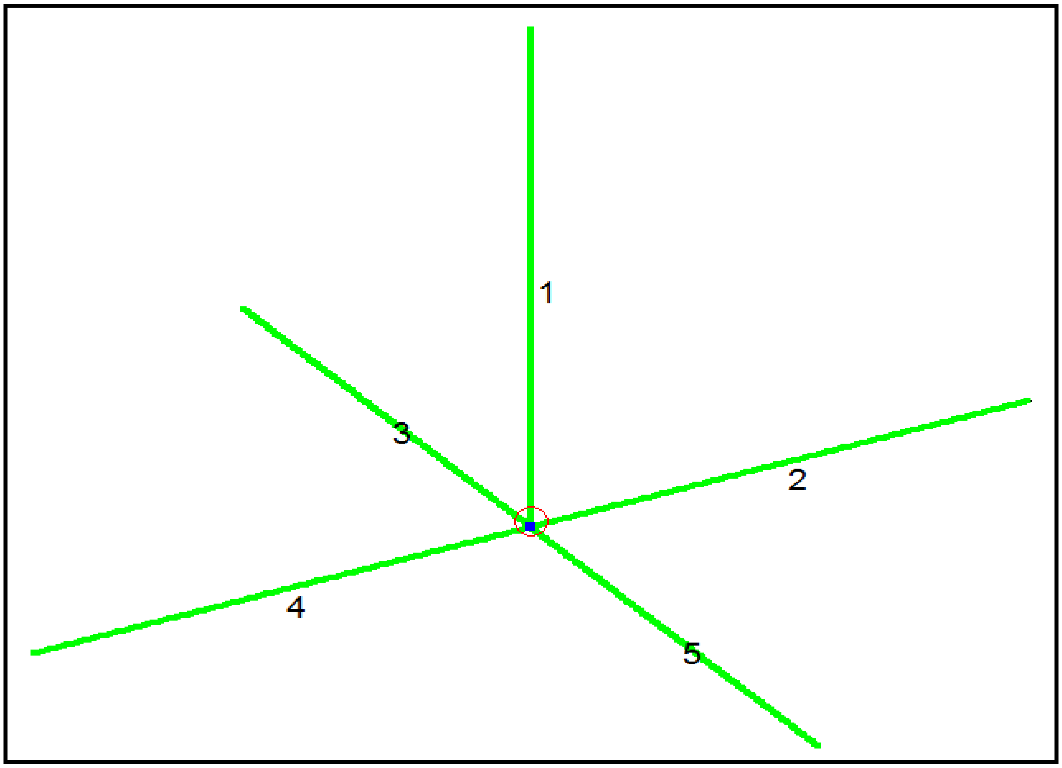

Figure 7 - GPV with 4 radials.

Typically the radials will be wire but the vertical may be either wire or tubing. Tubing is typically not insulated so in this example I looked at three cases: all bare wire, all insulated wire and insulated radials only. In table 4 the length of the vertical (wire 1) was constant at 134'. Er=3.3 for the insulation and perfect ground was assumed.

Table 4 -Dimensions and impedances with and w/o insulation.

vertical	radials	f [MHz]	radial length	Ri [Ω]	Xi [Ω]
bare	bare	1.830	127.6'	37.1	0
insulated	insulated	1.830	127.6'	37.9	+17.2
insulated	insulated	1.802	127.6'	36.1	0
insulated	insulated	1.830	115.7'	37.8	0
bare	insulated	1.830	127.6'	37.2	+3.2
bare	insulated	1.825	127.6'	36.9	0
bare	insulated	1.830	125.4'	37.2	0

When the vertical and the radials are bare fr=1.83 MHz. Adding insulation to the vertical and the radials decreases fr=1.802, essentially the same as for the free space dipole. When the radials are shortened to re-resonate the antenna, Ri increases with insulated wire. However, fr drops much less (to 1.825 MHz) when only the radials are insulated. The same modeling was repeated placing the antenna over real ground. Ri increased to reflect ground losses but the shift in Ri with and without insulation was nearly the same.

When the radial number was increased to 8, the frequency shift between bare and insulated radials (vertical un-insulated) was only -3 kHz and increasing the radial number reduced the effect of radial insulation even more. At least for a symmetric radial system with the antenna resonant, insulation appears to have little impact.

Radial length effects

When the antenna is not ideal, i.e. the radials are too long or the radials are not all the same length, there can asymmetric currents on the radials, then the insulation may not be so benign. My Mar/Apr and May/Jun 2012 QEX article[6] on elevated ground systems showed that in some cases the there can be a large increase in loss when the radials are asymmetric or too long. I will not repeat all those details here but a PDF of the article can be found at: www.antennasbyn6lf.com.

Figure 8 shows the average gain (Ga) of the figure 7 antenna as the radial length is varied. The height was held constant while the radial length was varied. The height of the antenna above ground (J) was varied from 8' down to 1.2" over average soil (0.005 S/m, Er=13). The vertical conductor was not insulated. The dashed lines represent bare wire radials and the solid lines insulated wire radials. The effect of overly long radials can be dramatic (-8dB!) when the radials are well elevated but that's a very unrealistic condition and not likely to be encountered in practice. However, when the radials are lying on the ground even quite normal radial lengths (65-75') can introduce unexpected loss which is worse with insulation! Figure 9 is a graph of Ri versus radial length.

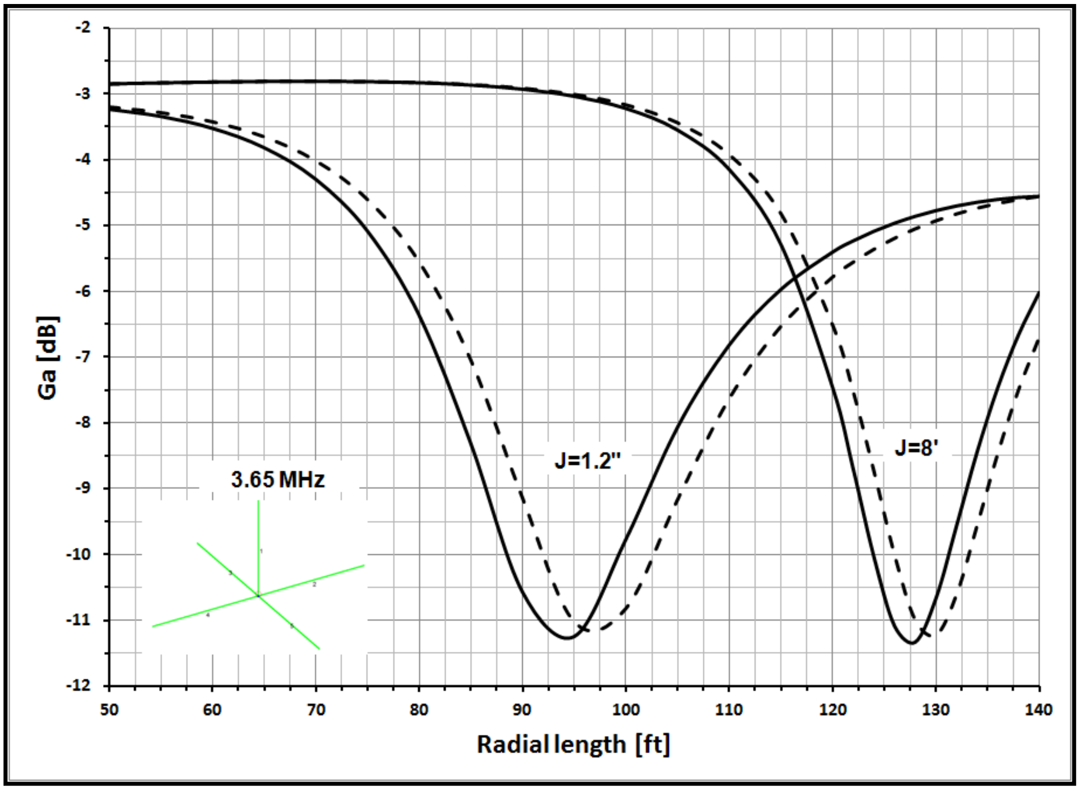

Figure 8 - Average Gain (Ga) for a GP with the base at 1.2" and 8'.

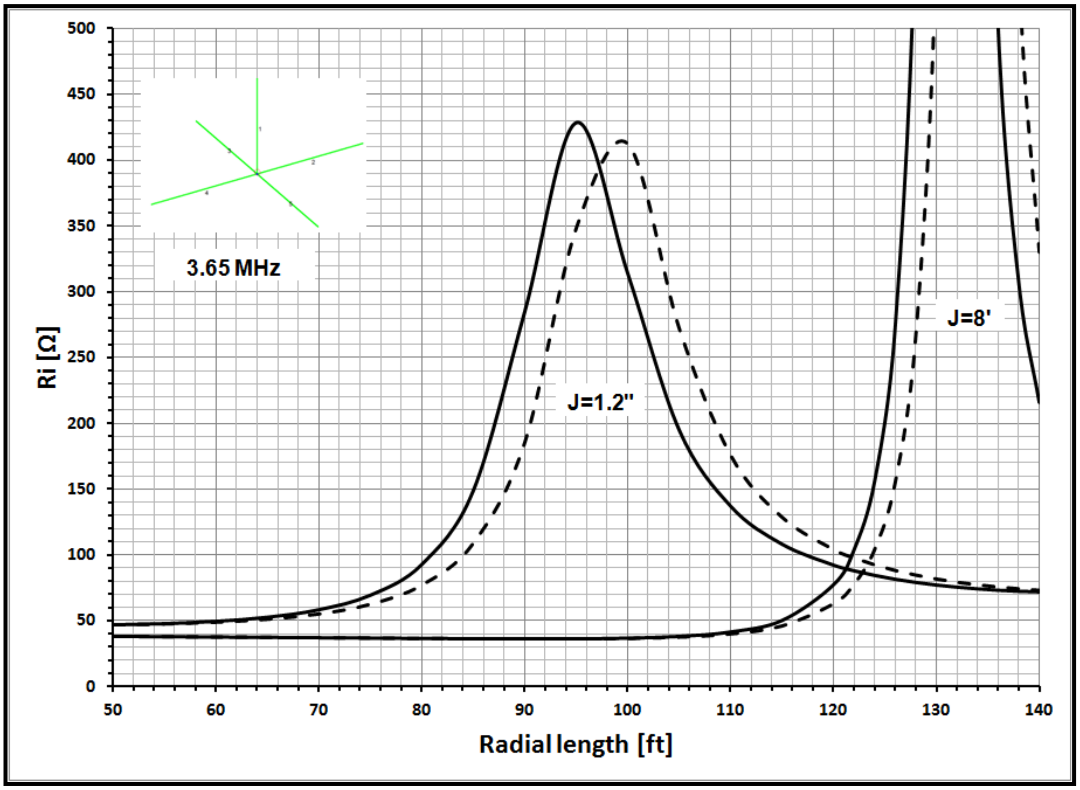

Figure 9 - Ri for a GP with the base at 1.2" and 8'.

Figure 9 shows the effect on Ri as the radials are made longer but the scale makes it difficult to really see what's going on with radial lengths of practical interest. Figure 10 has a expanded scale version of the 1.2" base height data in figure 9.

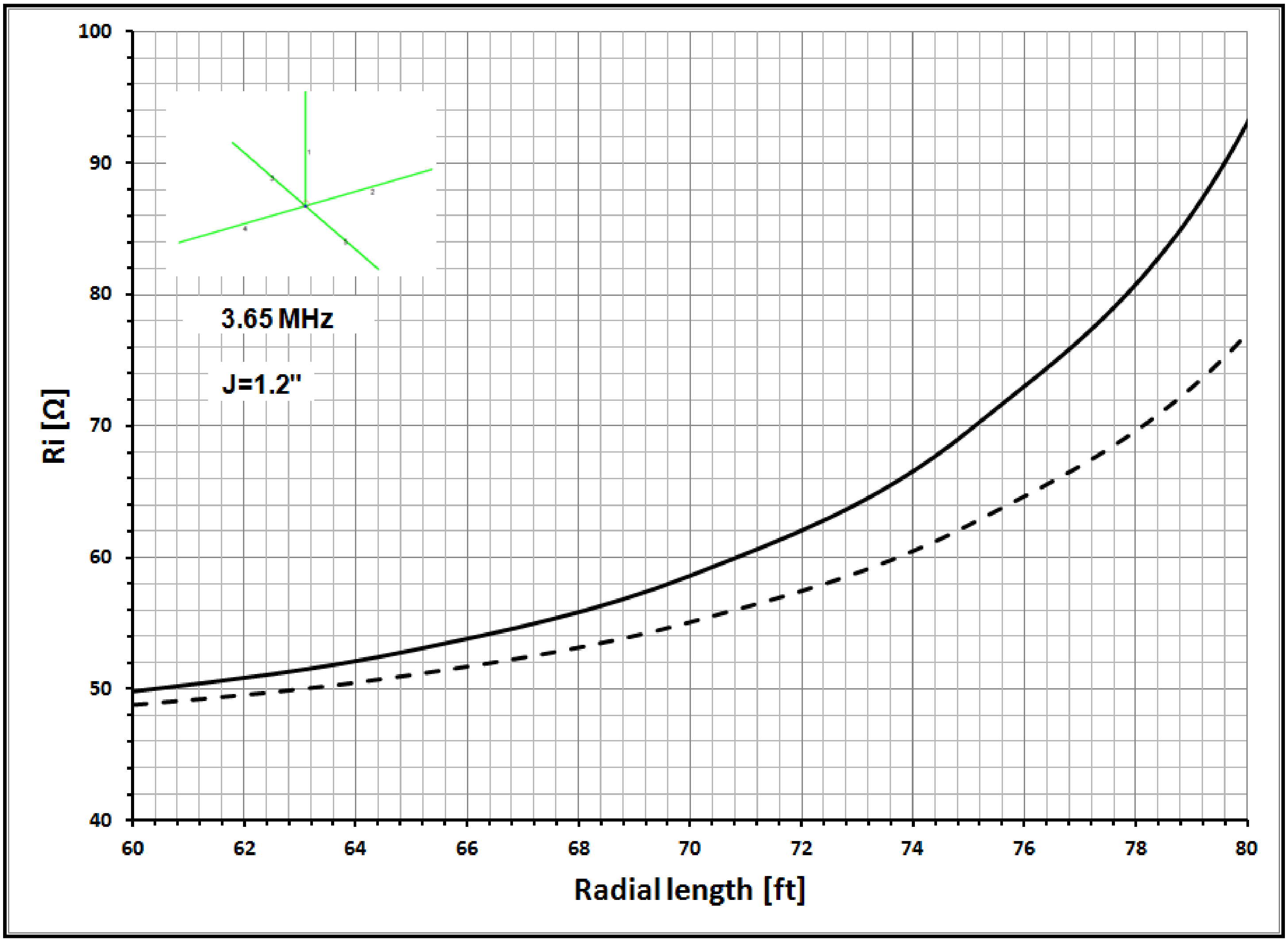

Figure 10 - Ri versus radial length for a GP with the base at 1.2".

Now we can see that for radials lying on the ground surface it is possible to have a significant increase in Ri with insulation which should show up with a measurement of feedpoint impedance. It should be pointed out however, that this effect is reduced when more radials are added. Experimental verification of this was shown in my QST[7] (figure 2) and QEX[8] (figures 3 and 4) articles.

Radial asymmetry

Besides the effect of radial length, GP antennas with sparse radial systems are very susceptible to asymmetries in radial length which can lead to significant increases in Ri and signal loss. As Dick Weber, K5IU, has shown[9], these effects do occur in actual antennas. In an elevated system, radial current asymmetry can be introduced by, differences in radial length, nearby conductors or even lateral variations in ground electrical characteristics under the radial system. For this discussion we'll look at the case with a difference in length between radials. The following graphs assume the radial system is elevated 8' over average ground (0.005/13). The vertical is not insulated and has a constant length of 34'. The antenna is designed for the 40m band, 7.0-7.3 MHz and #12 copper wire is assumed. The insulation is assumed to be THHN (Er=3.3). Copper losses are included in the model. In the symmetric case the radial lengths are all 34.1'. For the asymmetric case, two radials are 33.1' and the other two are 35.1' long. Figure 10 is a graph of the feedpoint impedance, Xi versus Ri. For the symmetric case adding insulation has very little effect but for the asymmetric case the addition of insulation makes a significant difference.

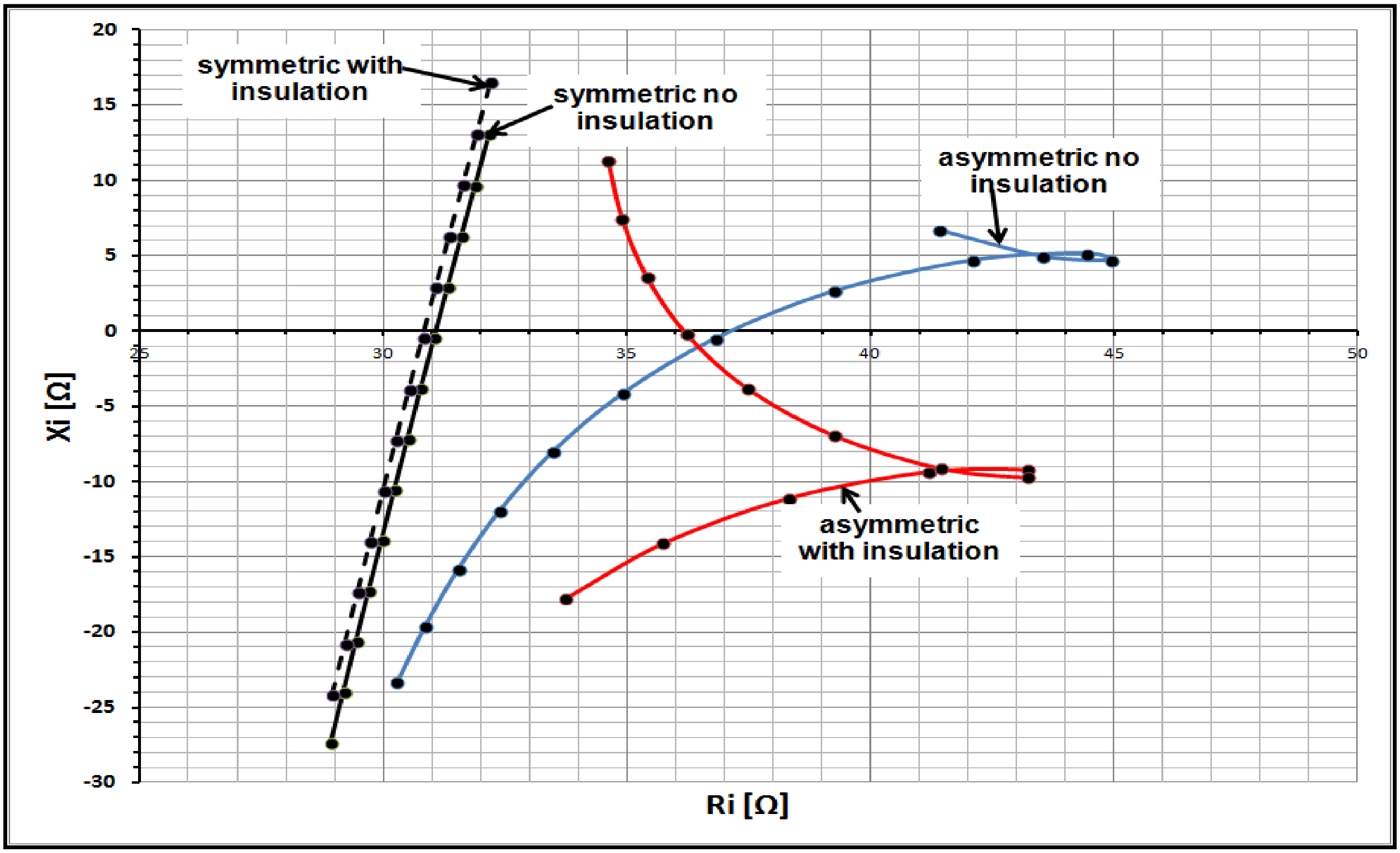

Figure 11 - Feedpoint Xi versus Ri.

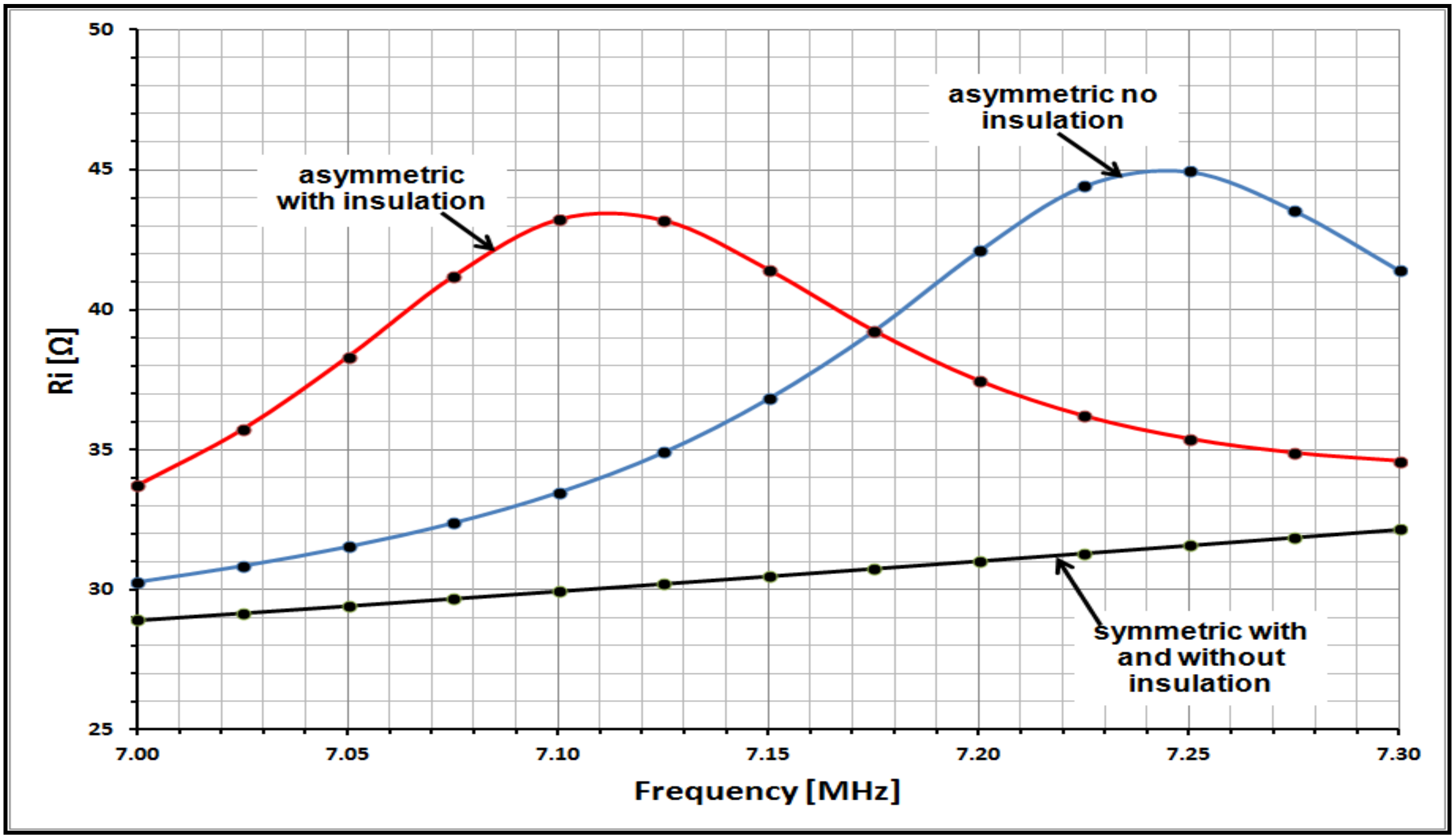

Figure 12 - Feedpoint Ri versus frequency.

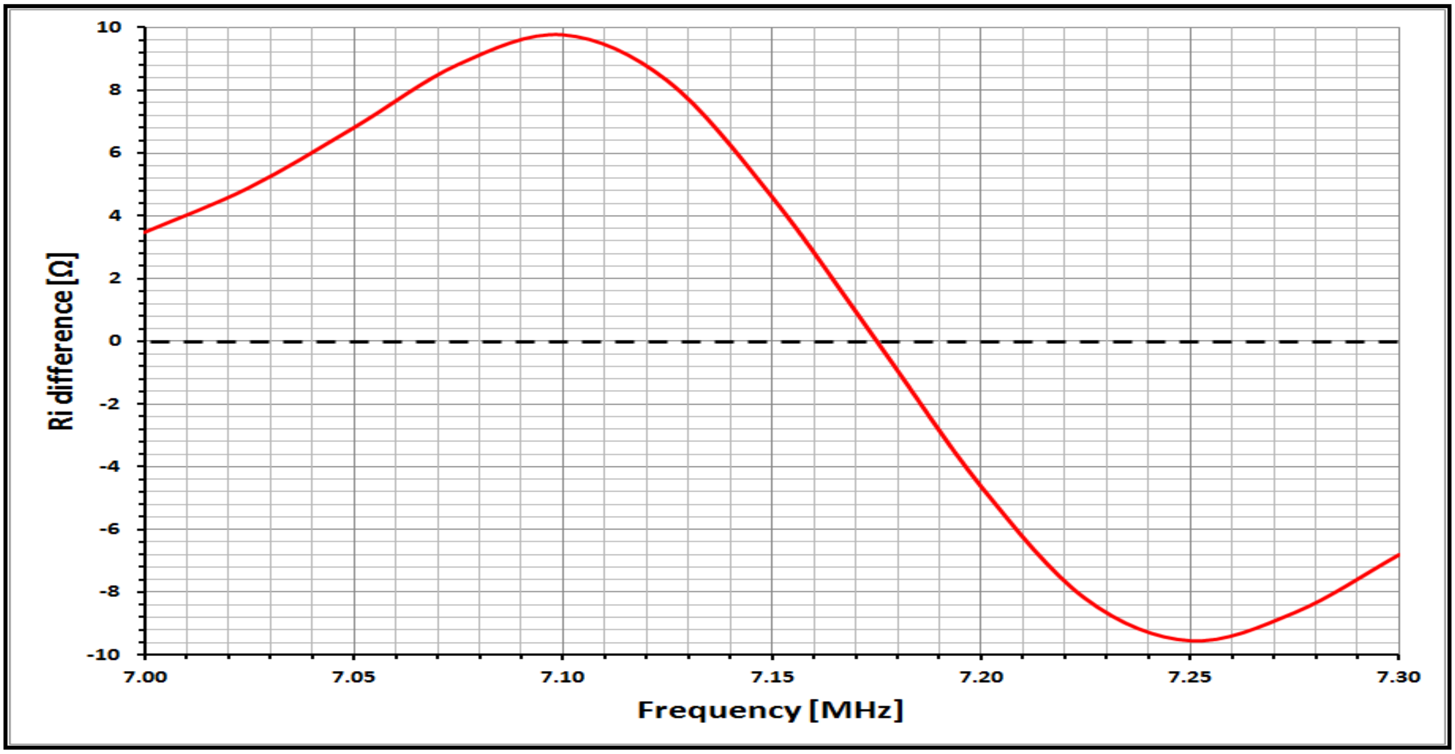

Figure 13 - Ri difference with and without insulation.

We can look closer at the variation of Ri by graphing Ri versus frequency as shown in figures 12 and 13. Both with and without insulation Ri can be substantially larger than the symmetric case. The effect of insulation is to shift the plot lower in frequency but the effect is still much the same. In this example there can be up to ±10Ω difference! If you choose a single frequency to measure Ri the change between no insulation and insulated would depend on what frequency you chose. At 7.10 MHz adding insulation significantly increases Ri but at 7.25 MHz, adding insulation significantly reduces Ri. Confusing!

The raises the question of "how much of the Ri increase is due to higher losses?" We can explore that with graphs for average gain (Ga) which show the total loss including ground losses and far-field losses. However, the far-field losses are constant so the differences in Ga will reflect changes in copper and soil loss near the antenna. Ga versus frequency is graphed in figures 14 and 15.

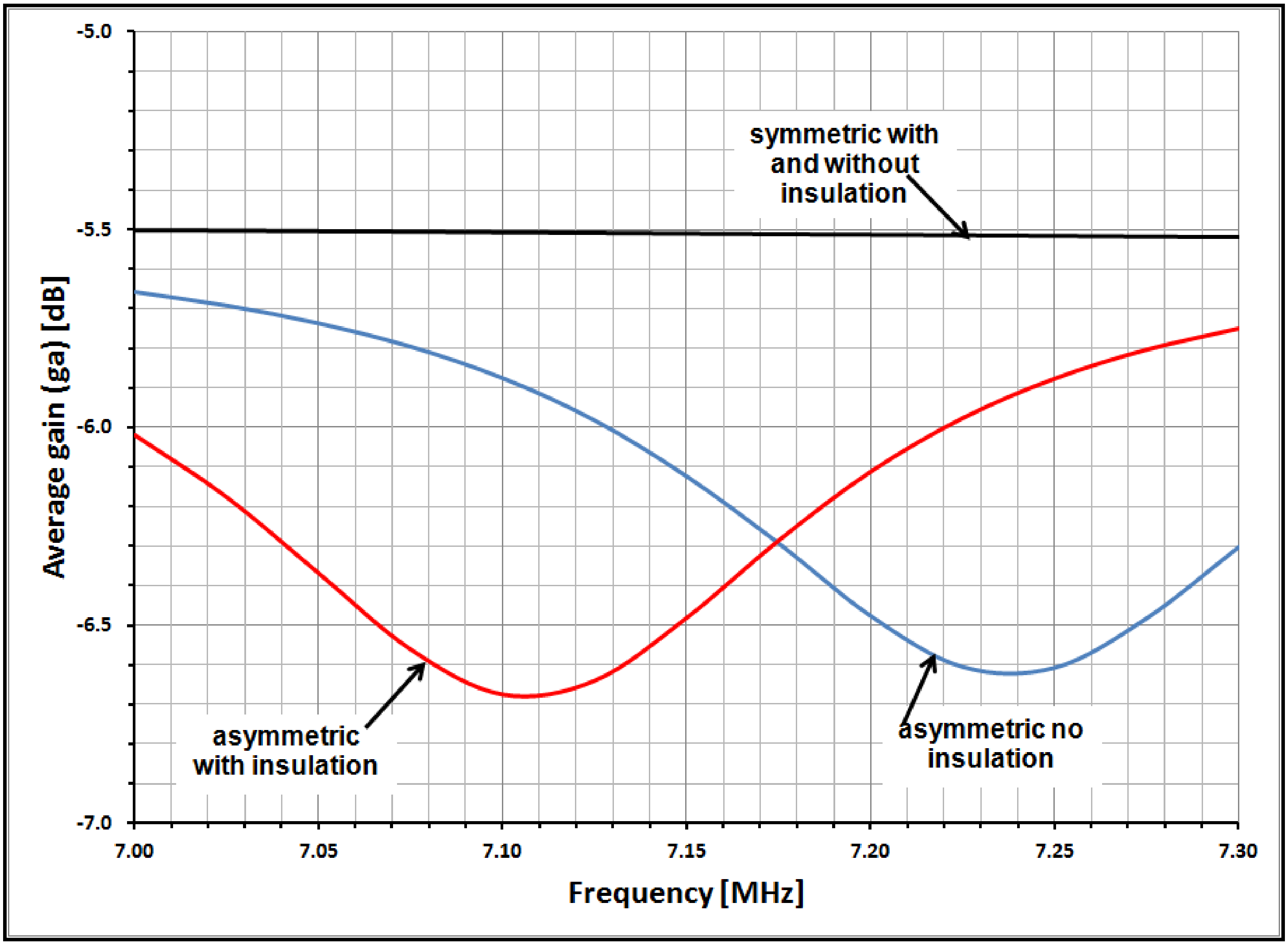

Figure 14 - Average gain (Ga).

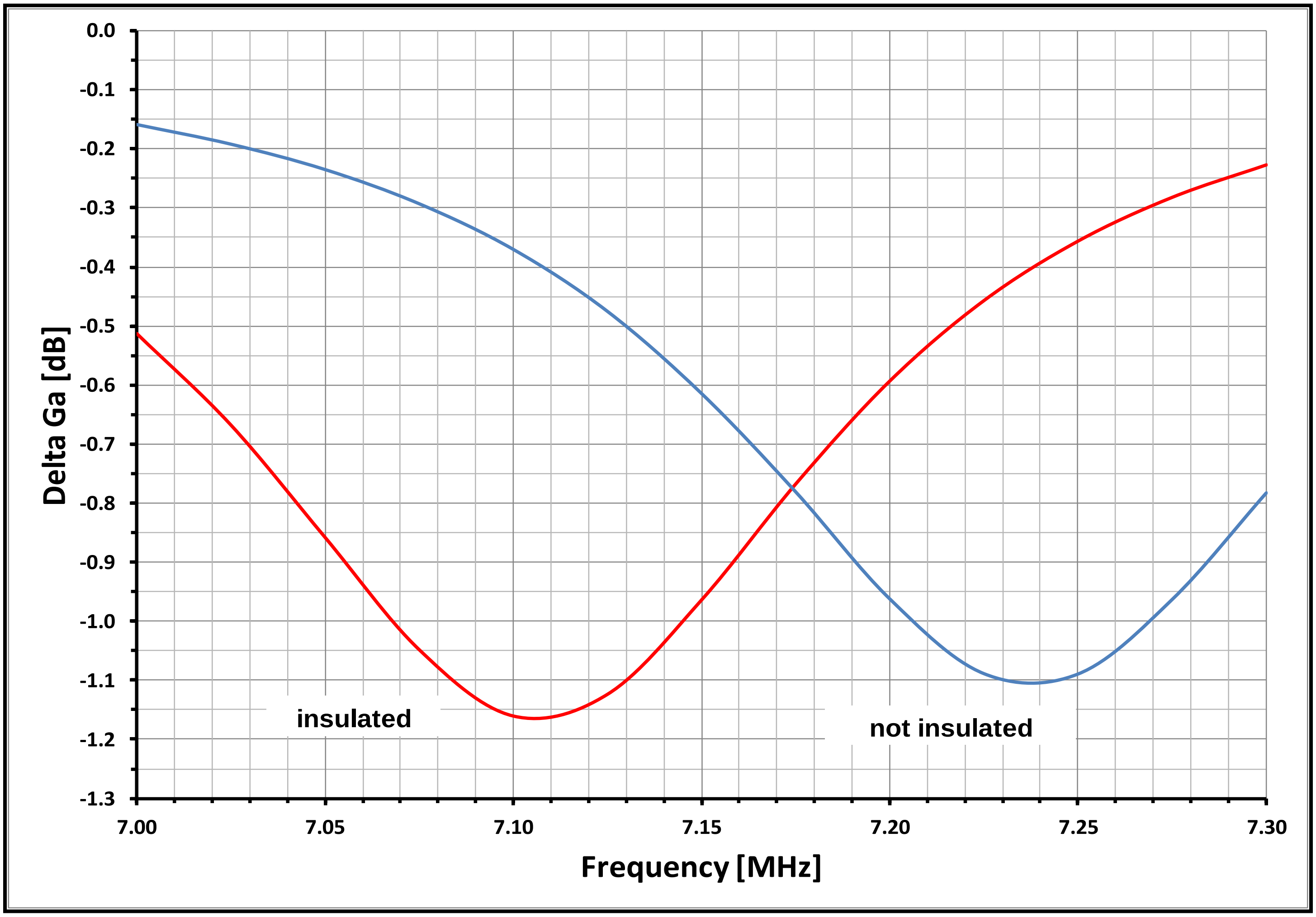

Figure 15 - Ga differences between symmetric and asymmetric radial systems.

These figures show that the increase in Ri is associated directly with a loss in radiated signal. This is mostly due to increased ground loss under the radials and also increased copper loss.

The reason for the increase in loss can be seen in the radial currents which are shown in figures 16, 17 and 18. In the case of symmetric radials, for Io= 1A, each radial has 0.25A of current at the inner end tapering off approximately as the cosine of radius. The radial currents are all in phase with the base current (Io). However, in figures 17 and 18 we see that the current distribution is asymmetric. More importantly the radial currents are be well above 0.25A. Given that Io=1A this looks like a violation of Kirchhoff's law which requires the sum of the currents at a node to be zero. What's happening in this case is that the currents are <u>not</u> in phase but <u>the vector sum of the currents is zero</u>! These much higher radial currents are the source of the additional losses.

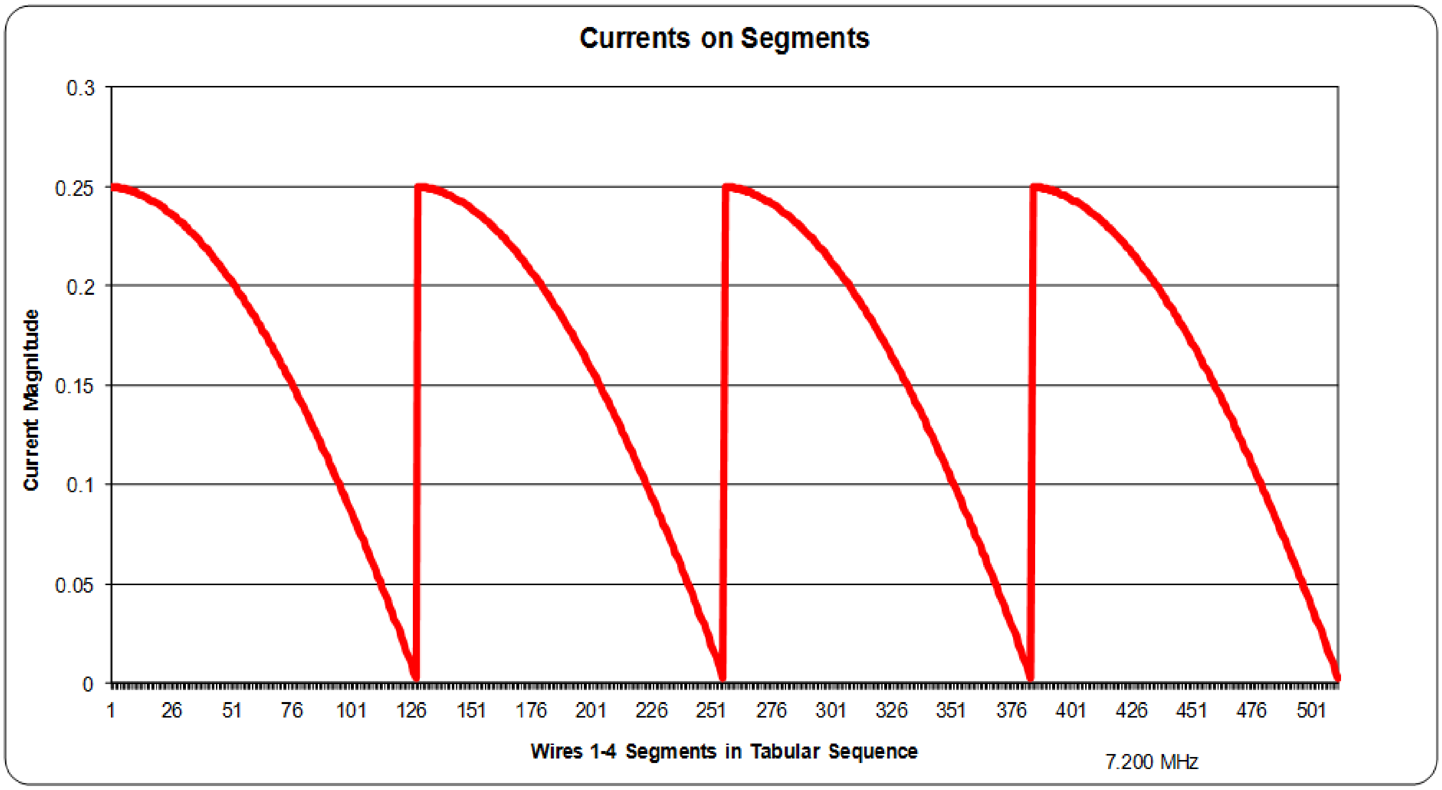

Figure 16 -Radial currents with symmetric radials. No insulation.

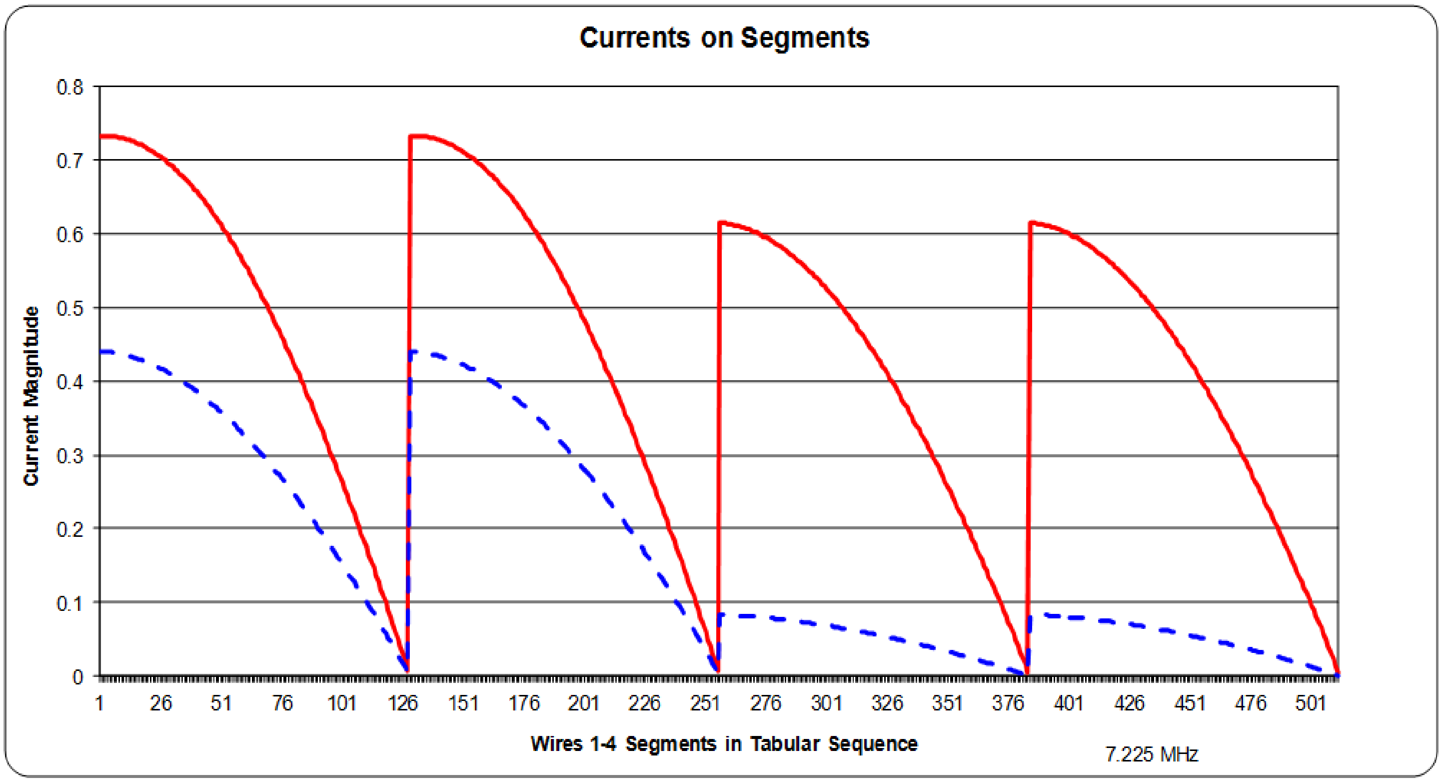

figure 17 - Radial currents with asymmetric radials. No insulation.

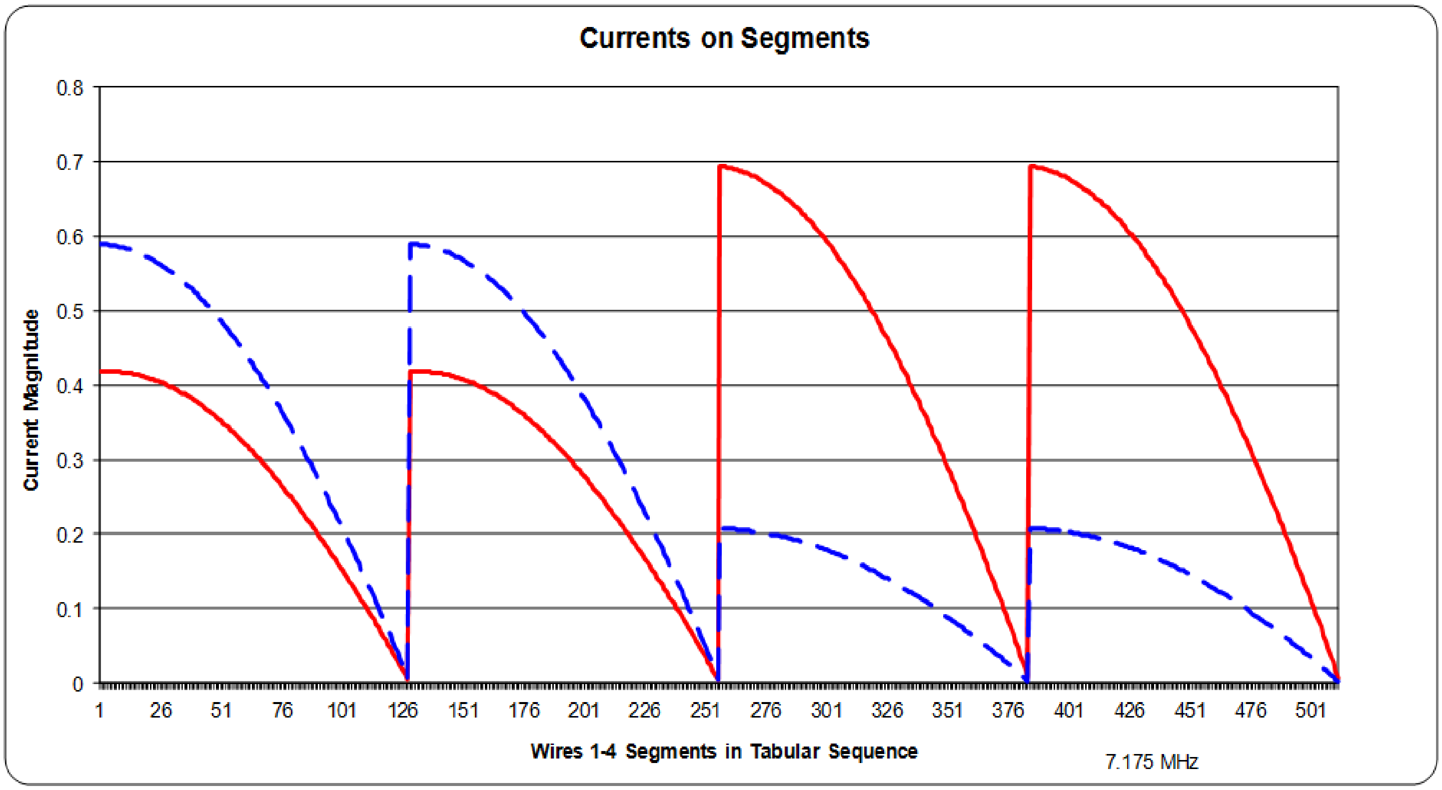

figure 18 - Radial currents with asymmetric radials. With insulation.

The dashed lines in figure 17 and 18 are for f=7.0 MHz. The frequencies for the solid lines are given in the lower right corners. The asymmetry in the radial currents varies as we move across the band.

Verticals with buried radials

Eight buried radials is about the smallest number of practical use. Figure 19 gives an example. The radials are #12 wire 135' long, buried 1'. The height of the vertical was adjusted to resonate the antenna. Table 5 summarizes the modeling results.

Table 5 - Vertical with buried radials.

radials	f [MHz]	vertical height	Ri [Ω]	Xi [Ω]	Ga [dB]
bare	1.830	129.0162	49.57	0.00	-5.16
insulated	1.830	129.0162	48.74	-2.44	-5.09
insulated	1.835	129.0162	49.07	0.00	-5.09
insulated	1.830	129.363	49.06	0.00	-5.08

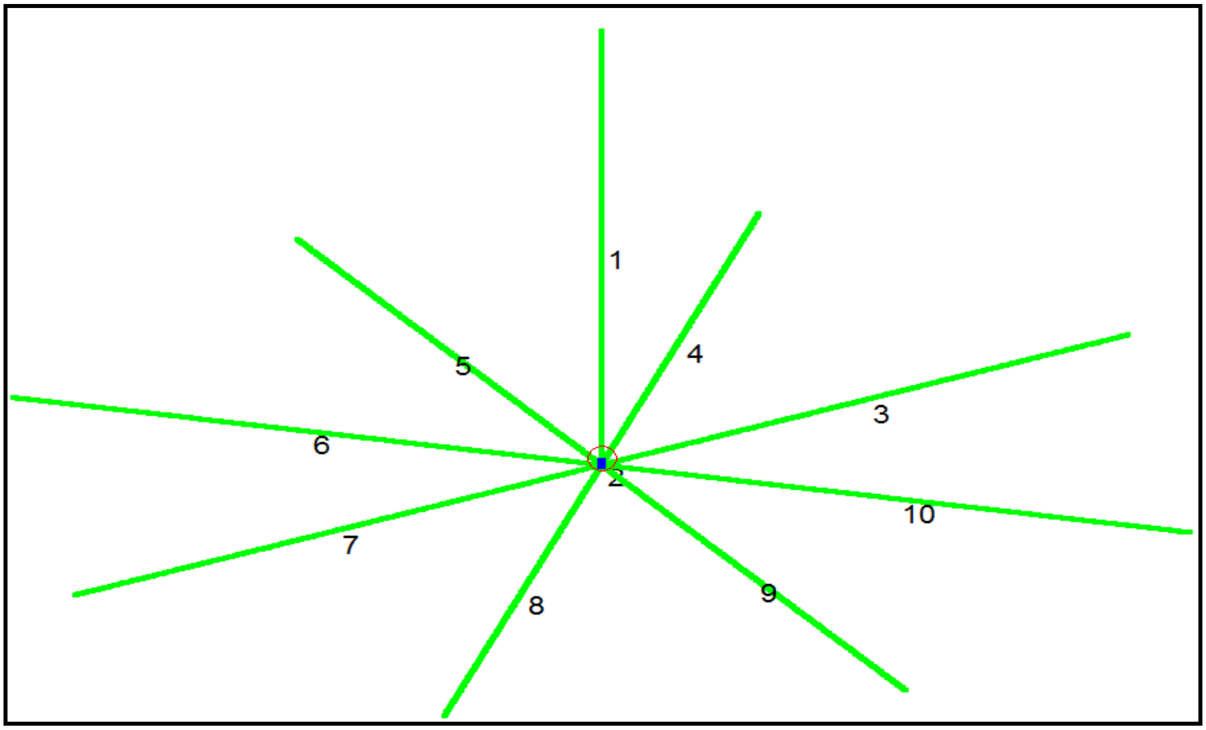

Figure 19 - 160m vertical with buried radial system.

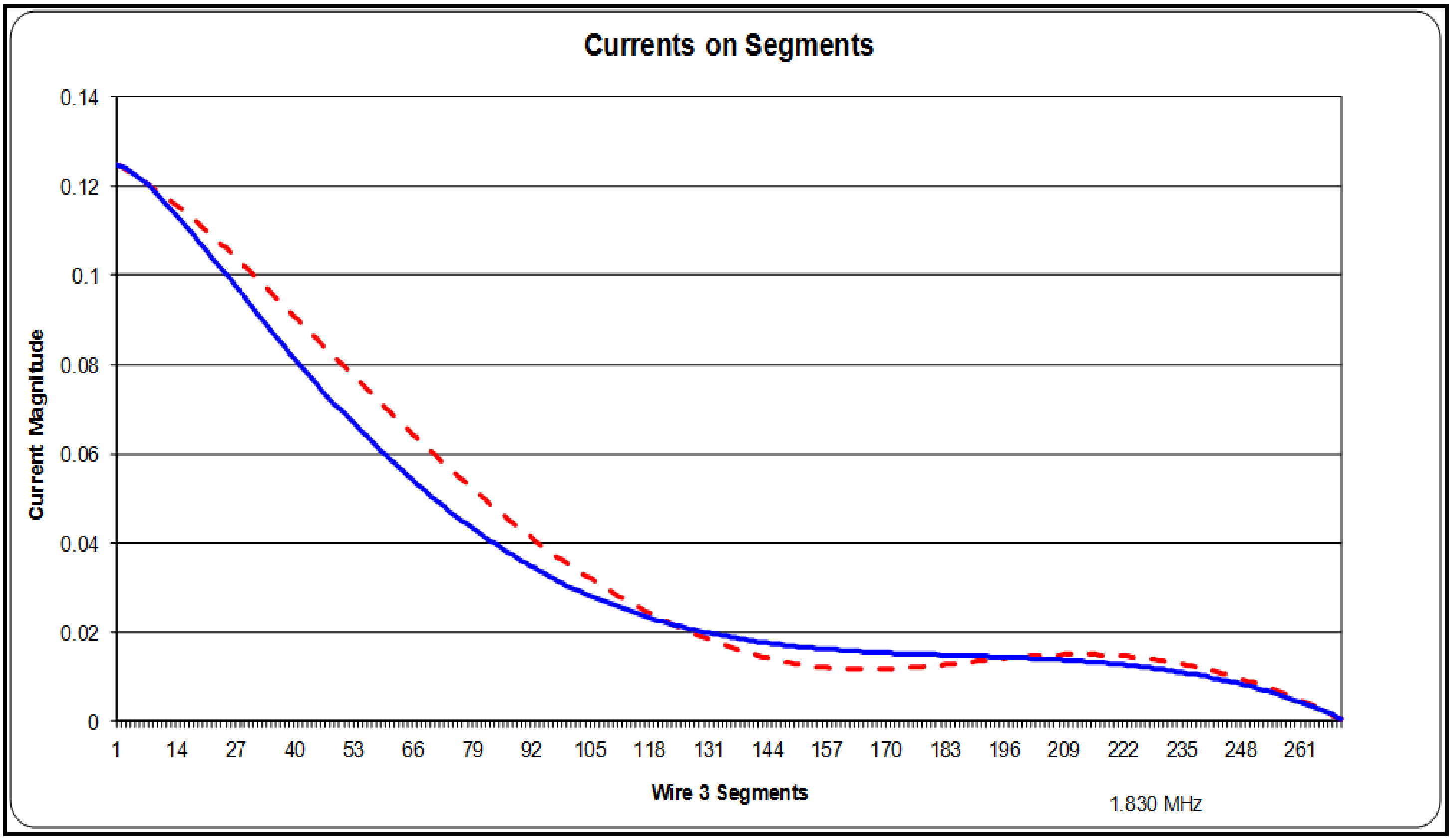

Figure 20 - Radial current distribution.

The current distribution along a radial is shown in figure 20. The solid line is for the bare wire and the dashed line represents insulated wire.

In this example the resonant frequency increases by 5 kHz as opposed to the decrease we have seen for the dipole and GPV. The effect of insulation on Ri and Ga is very small. There appears to be no reason not to use insulated radials in a buried system.

Mechanical issues

Leaving the insulation on the wire increases the weight of the wire and, if there is icing, the increased diameter could lead to even more weight. From a corrosion point of view insulated radials are very likely to last longer than bare radials, especially for ground surface or buried radials.

Conclusions

Looking at all these considerations it's clear that in general leaving the insulation on the wire is pretty benign and loss due to the insulation, either new or old, does not seem to be significant. However, it was shown that in certain cases, mostly related to GP-verticals with sparse radial systems there can be a substantial impact. However, that really occurs only when very few radials are used. These problems tend to go away as the radial count is increased to twelve or more for elevated radials and 16-20 for ground surface or buried radials.

References

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[7] Severns, Rudy, N6LF, “An Experimental Look at Ground Systems for HF Verticals”, QST, Mar 2010, pg. 30

[8] R. Severns, N6LF, Experimental Determination of Ground System Performance - Part 2, QEX magazine, January/February 2009, pp. 48-52

[9] Dick Weber, K5IU, Optimum Elevated Radial Vertical Antennas, Communication Quarterly, Spring 1997, pp 9 - 27