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Rudy Severns, N6LF

PO Box 589, Cottage Grove, OR 97424; **n6lf@arrl.net**

Insulated Wire and Antennas

N6LF studies the use of insulated versus bare copper wire, and concludes that leaving the insulation on the wire is generally benign, however, in certain cases with sparse radial systems there can be a substantial impact.

Insulated copper wire intended for home wiring is often used for antennas and ground systems. This wire is readily available at hardware and home improvement emporiums and often significantly less expensive than the equivalent wire without insulation. 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 160 m 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 a pair of *QEX* articles[1, 2] discussing antenna wire but I didn't explore the dielectric loading effect of insulation, so I thought it might help to extend that discussion to include the effect of insulation. To answer some of the questions I used a combination of modeling and experimental results. I make no claim that this is a complete or final answer but it should at least provide food for thought.

Concerns

Our 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 serious problems?

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

Plan of Attack

To evaluate 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 again to test samples of new and old insulated wire.

To explore the effect of dielectric loading I used EZNEC Pro[3] with the NEC4.2 engine combined with Dan Maguire's AutoEZ EXCEL based program[4]. This raises the question "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[5] of *QEX*, 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 for us to make some judgments. The NEC *QEX* article is also available at **www.antennasbyn6lf.com**.

The Wire

This discussion will assume either solid #12 AWG or #14 AWG 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 over 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 AWG wire used for my 160 m 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 AWG THHN. This allowed me to test both new and very weathered wires.

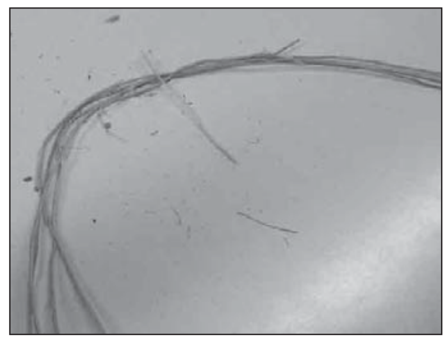

Figure 1 — Sample of degraded #12 AWG radial wire.

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 brittle and the copper oxidized. I also happened to have the coil form used for the *QEX* wire article so I used that for the coil form using the same number of turns as before. This allowed me to compare the earlier work with the current. Each wire sample was wound on the coil form as shown in Figure 2. Q was measured with an HP4342A Q-meter as shown in Figure 3. An HP5334A frequency counter was used to determine the test frequency.

Tables 1 and 2 show the results. Samples R1 through R8 were weathered radials supplied by K2AV. The small variations in Q are to be expected with the informal winding.

I also measured the Q varying the frequency from 1.5 to 4.5 MHz on some new #14 AWG 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 appear to 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. The relative dielectric constant ε_r is 3.2 for PVC and 4 for nylon. The nylon coating is very thin so it probably doesn't effect the totalt ε_r very much so I used ε_r of 3.3 as a compromise. The 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.

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 from 72.2 to71.7 Ω as well as fr from 1.830 to 1.803 MHz. When the

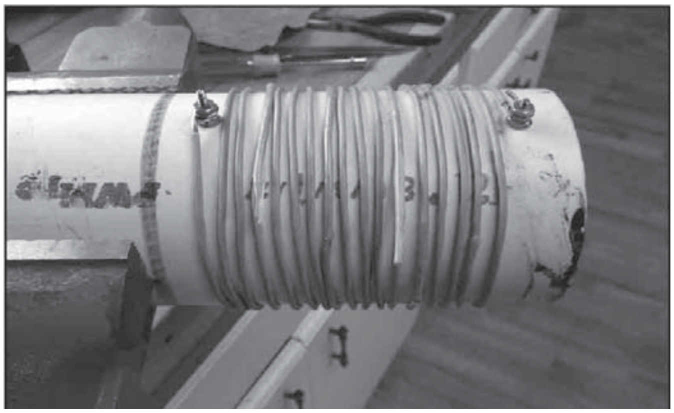

Figure 2 — Old radial wire wound into an inductor.

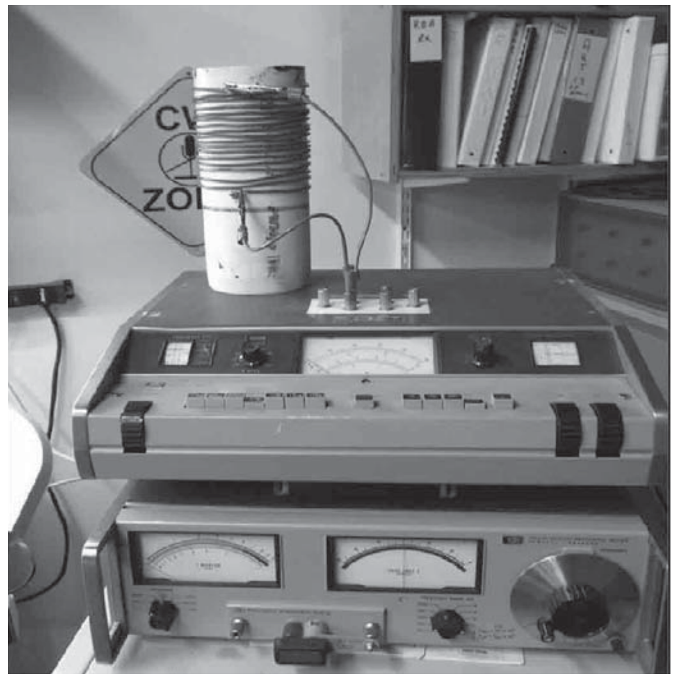

Figure 3 — HP4342A Q-meter shown on top of a vector impedance meter.

Table 1
Comparison of Q for N6LF #12 AWG wire.

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

Table 2
Comparison of Q for K2AV #14 AWG wire at 3.6 MHz.

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

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

wire, #12 AWG	*frequency, MHz*	*dipole length. ft*	*Ri, Ω*	*Xi, Ω*
bare	1.830	262.4	72.2	0
insulated	1.830	262.4	71.7	+27.9
insulated	1.803	262.4	70.3Ω	0
insulated	1.830	259.6	70.3Ω	0

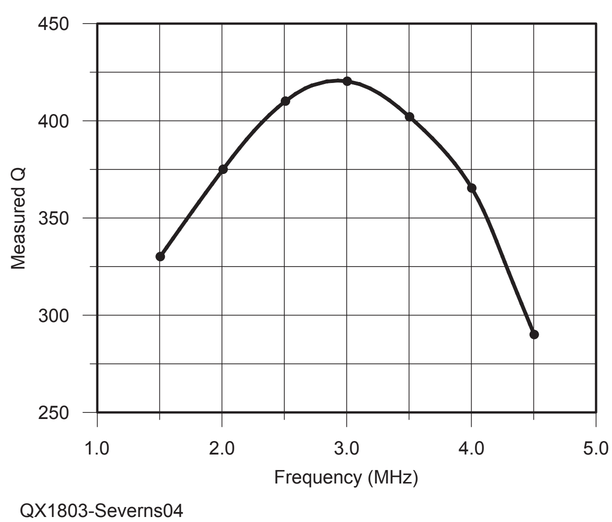

Figure 4 — Q versus frequency for sample R6.

antenna is shortened from 262.4 to 259.6 ft to restore the original fr, Ri is further reduced to 70.3 Ω. 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 ft, a burial depth of 1 ft and average soil, $\sigma = 0.005$ S/m and $\varepsilon_r = 13$. 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 inches. 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.

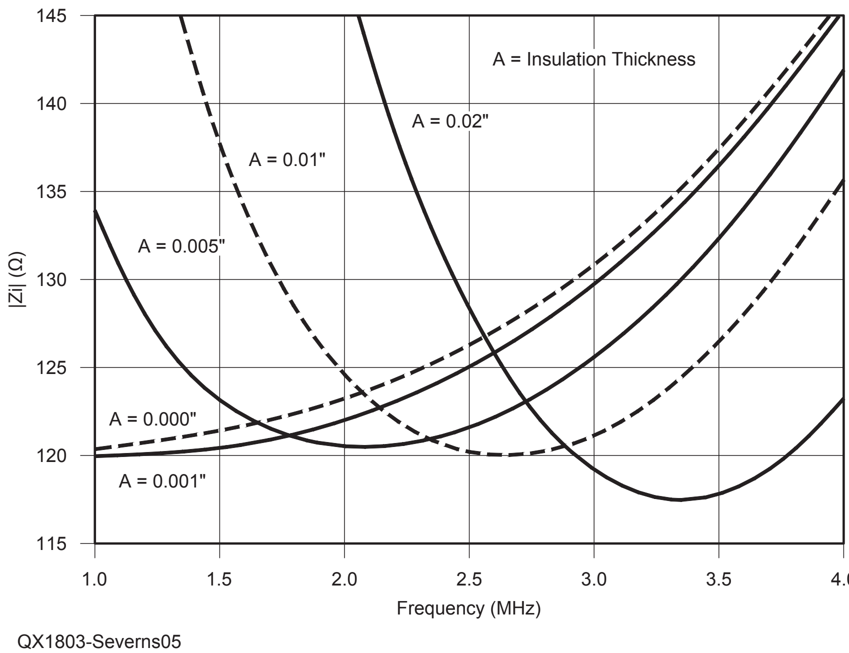

Figure 5 — Magnitude of the feedpoint impedance.

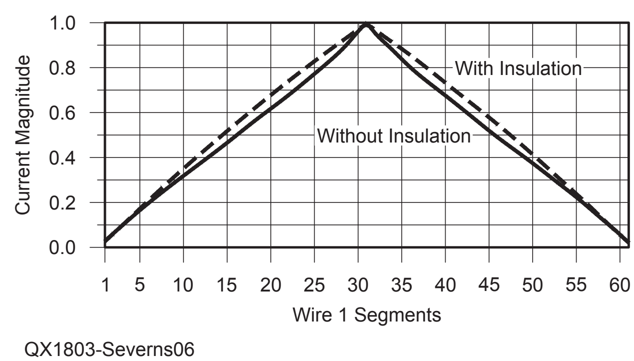

Figure 6 — Current distribution along the dipole with and without insulation.

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 7. The vertical and all the radials are #12 AWG wire.

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 feet; $\varepsilon_r = 3.3$ for the insulation and perfect ground was assumed.

When the vertical and the radials are bare fr = 1.83 MHz. Adding insulation to the vertical and the radials decreases fr = 1.802 MHz, essentially the same as for the free space dipole. With insulated wire, when the radials are shortened to re-resonate the antenna, Ri increases. 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 number of radials was increased to 8, the frequency shift between bare and insulated radials (vertical un-insulated) was only -3 kHz and increasing the number of radials 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.

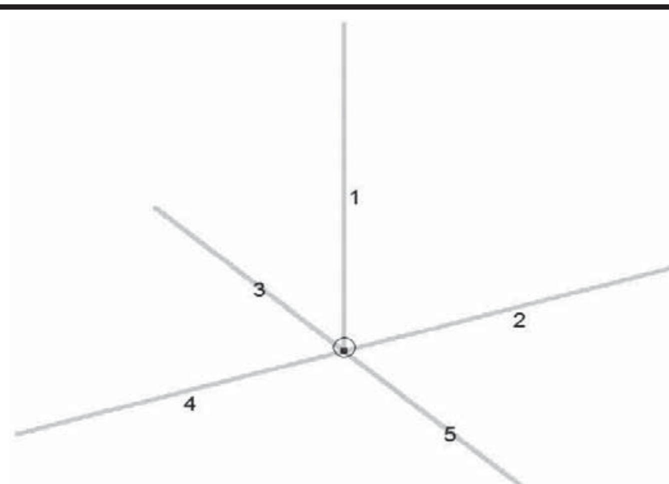

Figure 7 — NEC rendition of GPV with 4 radials.

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 be asymmetric

Table 4
Dimensions and impedances with and without insulation.

vertical	*radials*	*f, MHz*	*radial length, ft*	*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

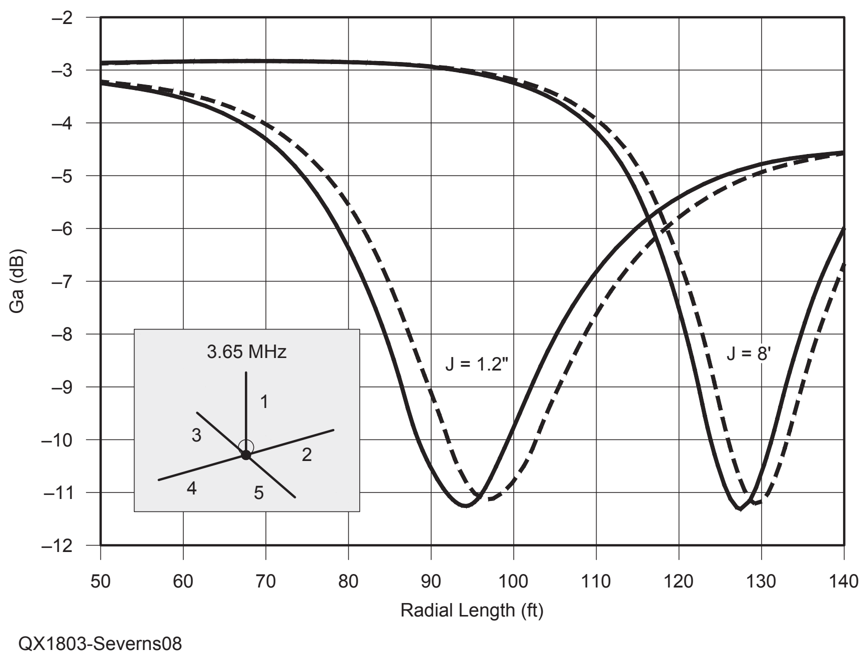

Figure 8 — Average Gain (Ga) for a GP with the base at 1.2 inches, and at 8 feet.

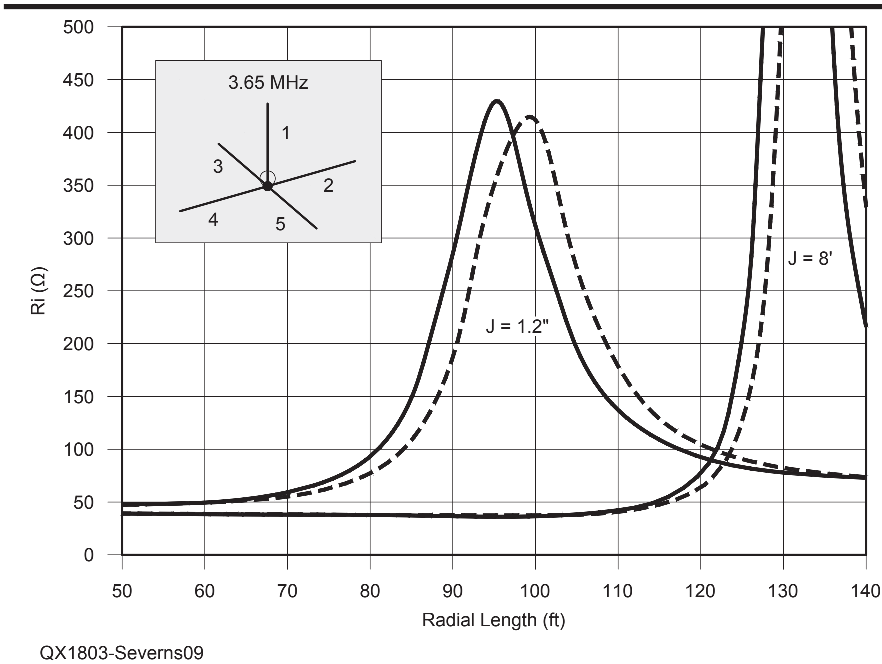

Figure 9 — Ri for a GP with the base at 1.2 inches and 8 feet.

currents on the radials and 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 there can be a large increase in loss when the radials are asymmetric or too long.

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 feet down to 1.2 inches over average soil (ε_r = 13, σ = 0.005 S/m). 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 (-8 dB) 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 ft) can introduce unexpected loss, which is worse with insulation. 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 an expanded scale version of the 1.2 inch base height data in Figure 9. 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 Figure 2 of my *QST* [7] and Figures 3 and 4 of my *QEX* [8] 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 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 ft over average ground (13, 0.005). The vertical is not insulated and has a constant length of 34 ft. The insulation is assumed to be THHN (ε_r = 3.3) and copper losses are included in the model. In the symmetric case the radial lengths are all 34.1 ft. For the asymmetric case, two radials are 33.1 ft and the other two are 35.1 ft long. Figure 11 is a graph of the feedpoint impedance, Xi versus Ri. For the

Table 5
Vertical with buried radials.

radials	*f, MHz*	*vertical height, ft*	*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

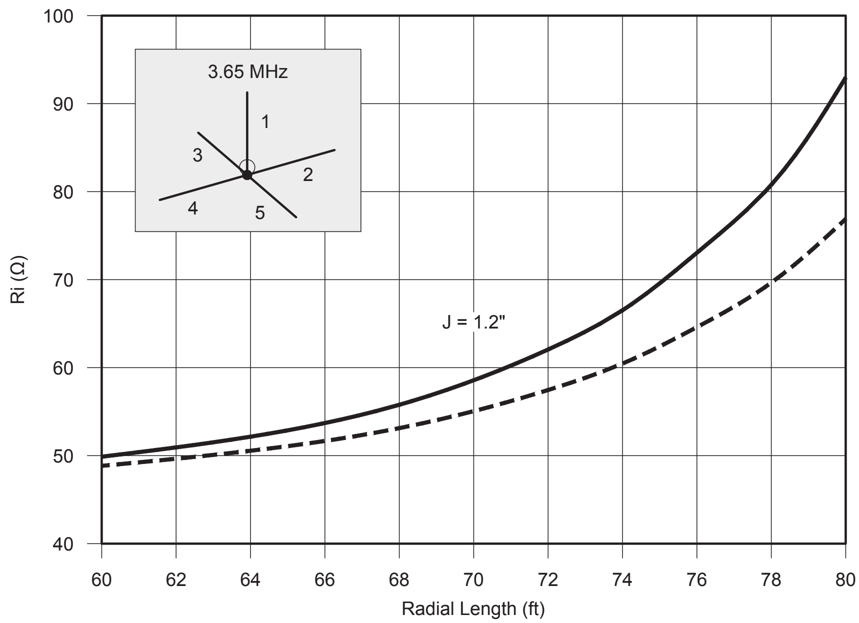

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Figure 10 — Ri versus radial length for a GP with the base, and at 1.2 inches.

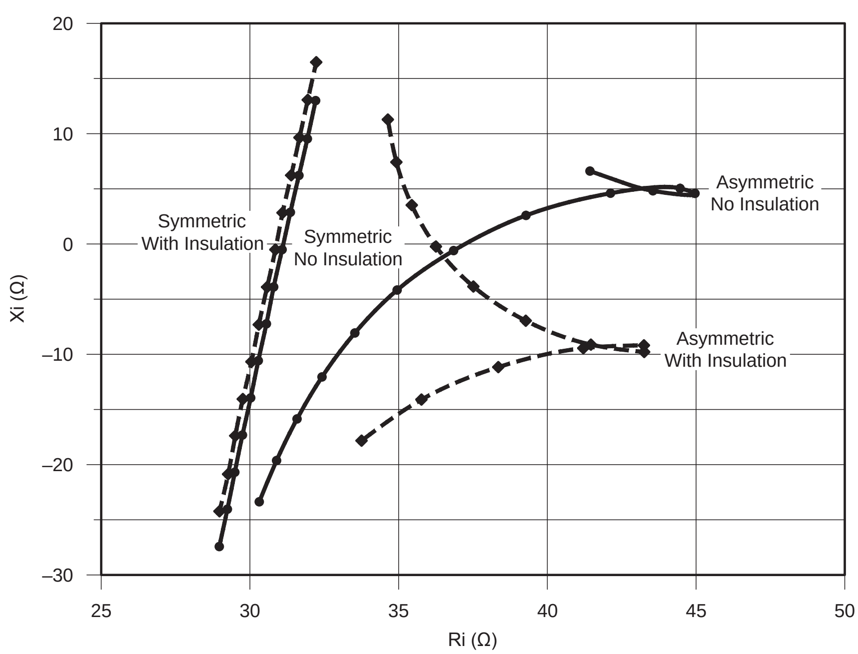

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Figure 11 — Feedpoint Xi versus Ri.

symmetric case adding insulation has very little effect but for the asymmetric case the addition of insulation makes a significant difference.

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 ±10 Ω difference. If you choose a single frequency to measure Ri the change between not insulated 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! That 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. These figures show that the increase in Ri is associated directly with a loss in radiated signal.

The reason for the increase in loss can be seen in the radial currents shown in Figures 16, 17 and 18. In the case of symmetric radials, for I_0 = 1 A, each radial has 0.25 A 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 I_0. However, in Fgures 17 and 18 we see that the current distribution is asymmetric. More importantly the radial currents are well above 0.25 A. Given that I_0 = 1 A, this looks like a violation of Kirchhoff's law which requires the sum of the currents at a node to add up to zero. What's happening in this case is that the currents are not in-phase, however, the vector sum of the currents is zero. These much higher radial currents are the source of the additional losses.

The dashed lines in Figure 17 and 18 are for 7.0 MHz. The frequencies for the solid lines are labelled in the figures. 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 AWG wire 135 ft long, buried 1 ft. The height of the vertical was adjusted to resonate the antenna. Table 5 summarizes the modeling results.

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

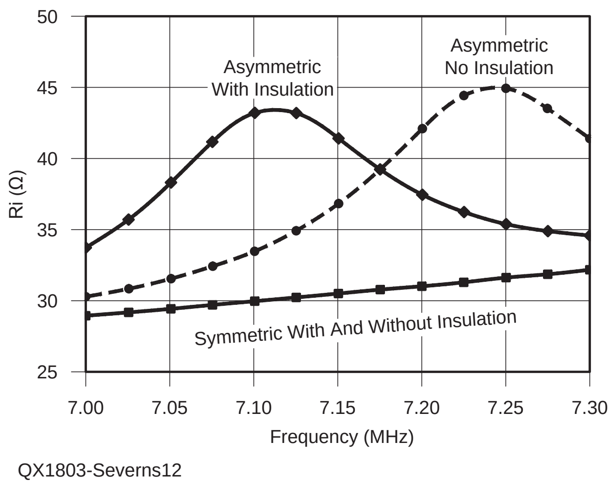

Figure 12 — Feedpoint Ri versus frequency.

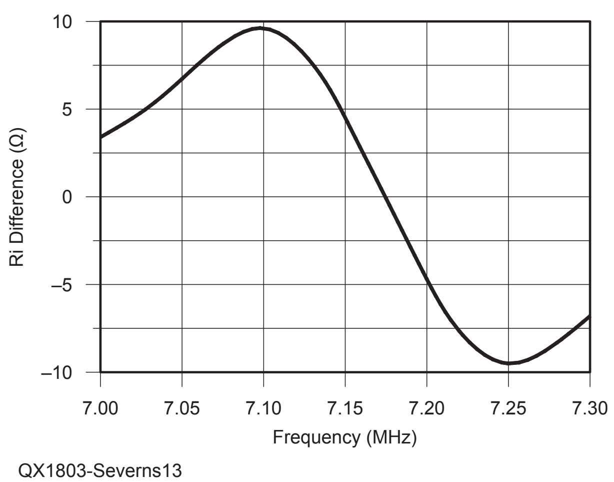

Figure 13 — Ri difference with insulated radials. There is no variation for radials without insulation.

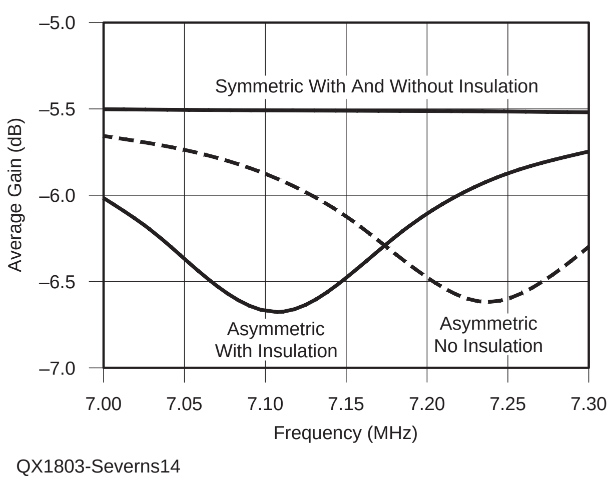

Figure 14 — Average gain (Ga).

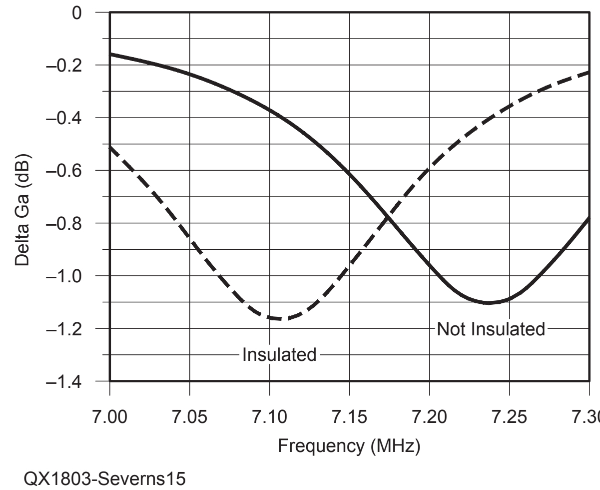

Figure 15 — Ga differences between symmetric and asymmetric radial systems.

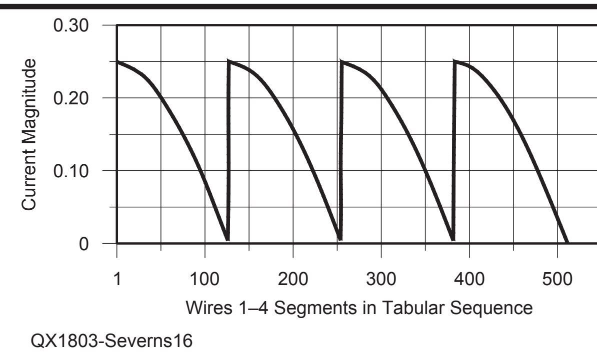

Figure 16 — Radial currents with symmetric radials, no insulation.

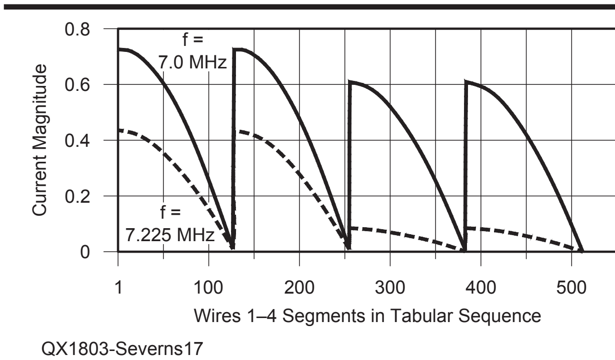

Figure 17 — Radial currents with asymmetric radials, no insulation.

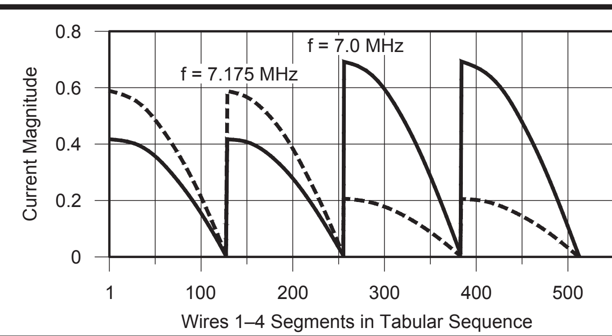

Figure 18 — Radial currents with asymmetric radials, with insulation.

insulated wire. In this example the resonant frequency increases by 5 kHz as opposed to the decrease we had 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.

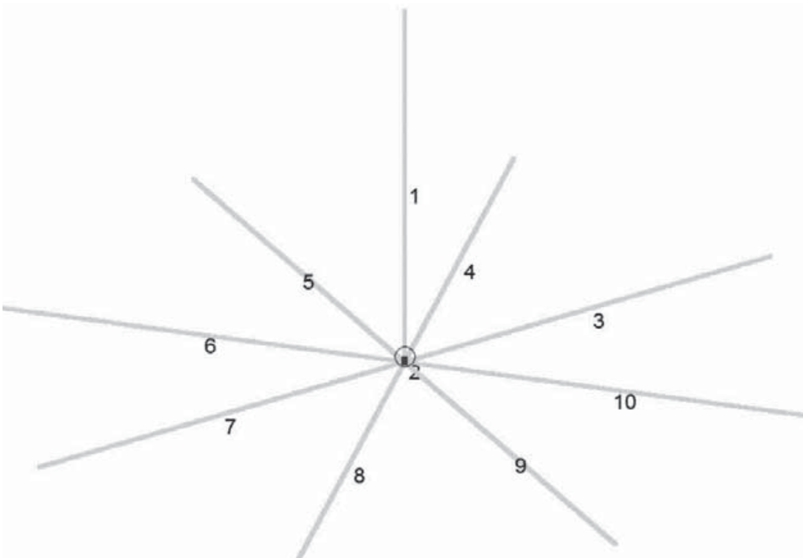

Figure 19 — 160 m vertical with buried radial system.

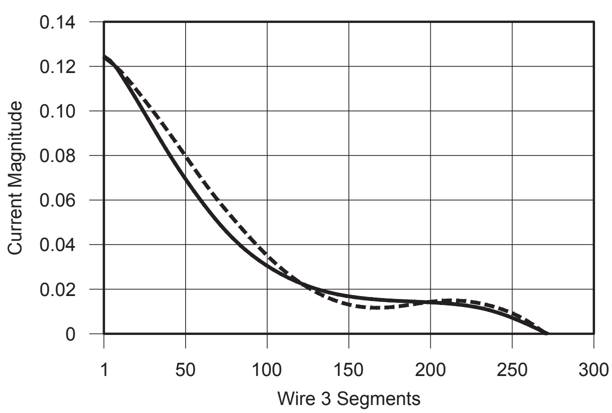

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Figure 20 — Radial current distribution.

Mechanical Issues

Leaving the insulation on the wire increases the weight of the wire. 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

From this work it seems that leaving the insulation on the wire is generally 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.

Rudy Severns, N6LF, was first licensed as WN7WAG in 1954. He is a retired electrical engineer, an IEEE Fellow and ARRL Life Member.

Notes

[1]R. Severns, N6LF, "Conductors for HF Antennas", *QEX*, Nov./Dec., 2000, pp. 20-29.
[2]R. Severns, N6LF, "Tech Notes", *QEX*, May/June 2002, pp. 55-56.
[3]R. Lewallen, Roy, W7EL, EZNEC Pro/4 v6, **www.w7el.com**.
[4]D. Maguire, AC6LA, AutoEZ, **ac6la.com/autoez.html**.
[5]Rudy Severns, N6LF, "The Case of the Declining Beverage-on-Ground Performance", *QEX*, Jul./Aug., 2016, pp. 7-18.
[6]Rudy Severns, N6LF, "A Closer Look at Vertical Antennas With Elevated Ground Systems", *QEX*, Mar./Apr., and May./Jun., 2012.
[7]R. Severns, 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*, Jan./Feb., 2009, pp. 48-52.
[9]D. Weber, K5IU, "Optimum Elevated Radial Vertical Antennas", *Communications Quarterly*, Spring 1997, pp. 9 – 27.