Conductors for HF Antennas

Putting up an antenna for the low bands? What kind of wire will you use? This analysis may change your plans.

By Rudy Severns, N6LF

Most of us give little thought to the wire from which we fabricate antennas. Most of the time that's okay, but some antennas are quite sensitive to conductor loss. Then we need to think carefully about our choice of wire or other conductor. Recently, I have been building 160-meter wire arrays using hundreds of feet of wire in each. Some of the spans are over 600 feet, and they are attached to poles and trees that move in the wind. For this reason, I initially used #12 stranded Copperweld with PVC insulation. One of the antennas is a two-element, end-fire array—essentially a vertically polarized W8JK. It is a problem with any end-fire array that to obtain gain, the radiation resistance must be lowered by closely spacing the elements. In the case of a W8JK array, the impedance is in the range of 8 to 20Ω. As Krause pointed out in Reference 1, this makes the obtainable gain very sensitive to conductor resistance. The problem is particularly severe on 160 meters because the wire used is very long (over 700 feet in my array) and tubing is impractical.

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The performance of the W8JK array was good, but I had a feeling that I could get much more from the antenna. This led me on a hunt to identify possible losses: to measure wire resistance, to analyze expected conductor losses, to finite-element model solid-copper and Copperweld (copper-clad steel) wire and to model the effects of wire losses on antenna performance. The results are interesting and give insight into appropriate conductor selection. It turns out my intuition was right, the conductor loss was high. The wire resistance was double the expected value, but the reason for that was a surprise.

Conductors

Many types of wire, conductive strips and tubes can be and are used for antennas. The reference against which other wires are judged is solid #12 AWG, soft-drawn, bare copper. Other common choices are:

- seven-strand, hard-drawn copper
- solid #12 AWG Copperweld
- 19-strand Copperweld (#12 AWG)
- aluminum electric-fence wire, in various sizes

- Alumoweld (aluminum-clad steel, see Reference 2)
- #8 AWG aluminum clothesline
- aluminum tubing
- thin copper or aluminum strips
- stainless steel tubing
- towers and galvanized steel guy wires

Occasionally galvanized steel fence wire, stainless steel or copper plated steel electric fence wire is suggested for antennas. These are *very poor* choices, as I will show shortly. Table 1 lists the resistivity and conductivity for some common conductors. The values for steel are only approximate because they vary greatly with the exact composition and processing history.

Sometimes silver plating is suggested for conductors. The conductivity of silver is only 6% better than copper, but when the surface oxidizes, silver oxide is a much better conductor than copper oxide. We will not be considering silver conductors for the rest of this article, however.

Skin Effect

The resistance of wire at a given frequency depends on three things: size, electrical properties of the material (including surface corrosion!) and the

Table 1—Conductivity and Resistivity of Conductors

Material	*Conductivity* (σ) siemens/meter	*Resistivity* (ρ) ohm-cm
Silver	6.2×10^{7}	1.62×10^{-7}
Copper (annealed)	5.8×10^{7}	1.7241×10^{-6}
Aluminum (99.9%)	3.81×10^{7}	2.62×10^{-6}
Iron	1.03×10^{7}	9.71×10^{-6}
Low-carbon steel (AISI 1040)	0.5×10^{7}	20×10^{-6}
Stainless steel (AISI 304)	0.11×10^{7}	90×10^{-6}

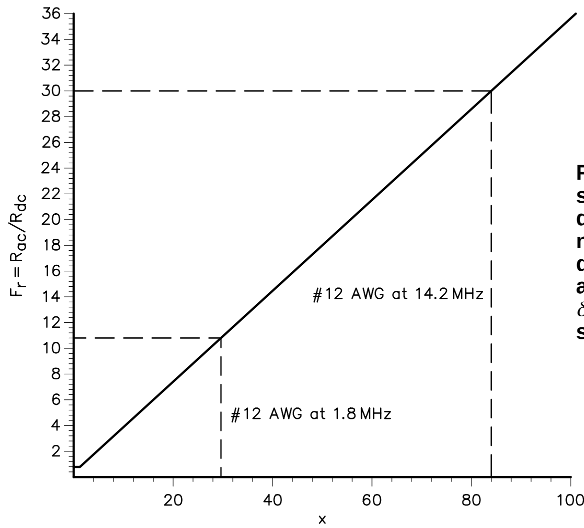

Fig 1—R_{ac}/R_{dc} ratio for solid round wire. Wire diameter (*X*) is normalized to the skin depth, , where *d* is the actual wire diameter and δ is the skin depth in the same units.

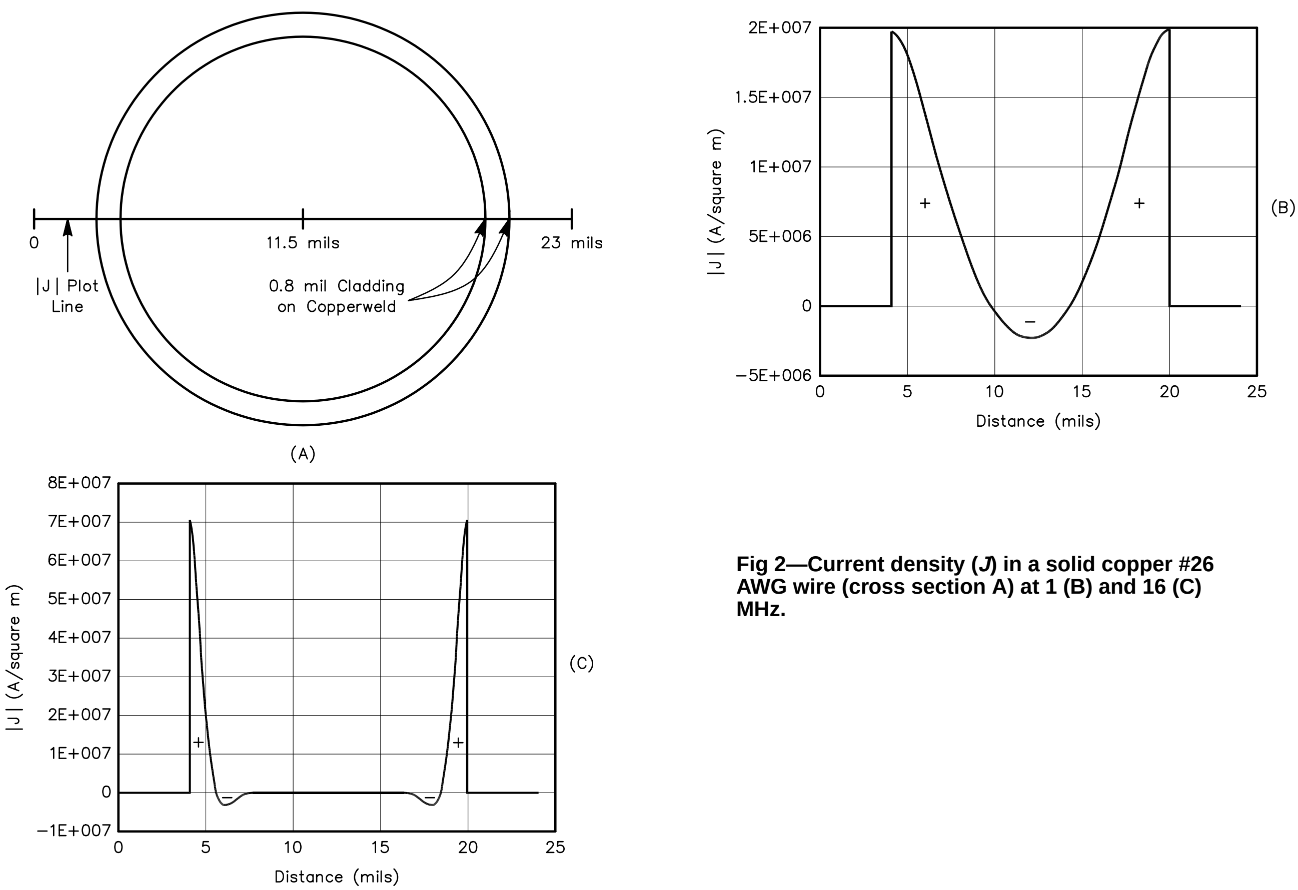

Fig 2—Current density (*J*) in a solid copper #26 AWG wire (cross section A) at 1 (B) and 16 (C) MHz.

resistance increase due to skin effect. Skin effect is the tendency for current to crowd to the outer perimeter of a conductor as frequency is increased. It is characterized by the depth at which the current density (J) has fallen to about 0.37 ($1/e$, where e=2.718). For good conductors, the skin depth (d) is expressed by:

$$\delta = \sqrt{\frac{1}{\pi \sigma \mu f}} \text{ meter} \qquad \text{(Eq 1)}$$

where:

δ = skin depth (meters)

μ = permeability = μ_r μ_o; μ_o= 4×10^{-7} H/m; μ_r = relative permeability

σ = conductivity in siemens/m (mho/m)

f = frequency (hertz)

For copper at room temperature:

$$\delta = \frac{2.602}{\sqrt{f_{MHz}}} \text{ mils} \qquad \text{(Eq 2)}$$

For f = 1.8 MHz, δ =1.94 mils. For f = 14.2 MHz, δ = 0.69 mils. The Appendix contains a graph of the relation between skin depth and frequency for copper at 20° and 100°C.

For round wire, the variation of R_{ac}/R_{dc} (F_r, or resistance factor) with normalized wire diameter $X = d/\delta\sqrt{2}$ is shown in Fig 1. The variable d is the wire diameter, in the same units as δ. The equation from which the graph is derived is given in the Appendix. For #12 AWG copper wire at 1.8 MHz, X = 29.5 and F_r = 10.8. For the same wire at 14.2 MHz, X = 83 and F_r = 30. This thirty-fold resistance increase at 20 meters is due to skin effect! It cannot be ignored on any amateur band.

I am fortunate to have access to finite-element modeling (FEM) CAD software that can directly calculate and graph current distribution and power loss in conductors such as solid copper wire or Copperweld, which is made of two different materials. The graphs in Figs 2 through 5 were generated using FEM software (see Reference 2).

Figs 2B and 2C give plots of the current density (J in A/m^2) along the line shown in Fig 2A, for solid #26 AWG copper wire (δ = 15.9 mils) at 1 and 16 MHz. The crowding of current to the outside perimeter of the wire and how crowding worsens as frequency increases is clearly shown. This is why the apparent resistance of the wire increases so much. At some points within the wire, the instantaneous current is actually flowing backwards (minus signs) due to the self-induced eddy currents that are the underlying phenomena responsible for skin effect. These currents must be balanced by more forward current (+) to keep the average current unchanged. That is, the same number of carriers must come out one end of the wire that you put in the other end. The net result is increased power dissipation for a given RMS current.

In Copperweld wire, the copper cladding on the outside of the wire is typically about 10% of the wire radius. For #26 AWG wire, the cladding thickness would be about 0.8 mils (0.0008 inches). Fig 3 graphs J for #26 AWG Copperweld. It is clear that the current is flowing only in the copper cladding; there is almost no current in the steel core. This is predicable from the skin-depth equation; δ is inversely proportional to the square root of the permeability. For steel, μ_r is highly variable, affected by the composition of the steel, the processing and even

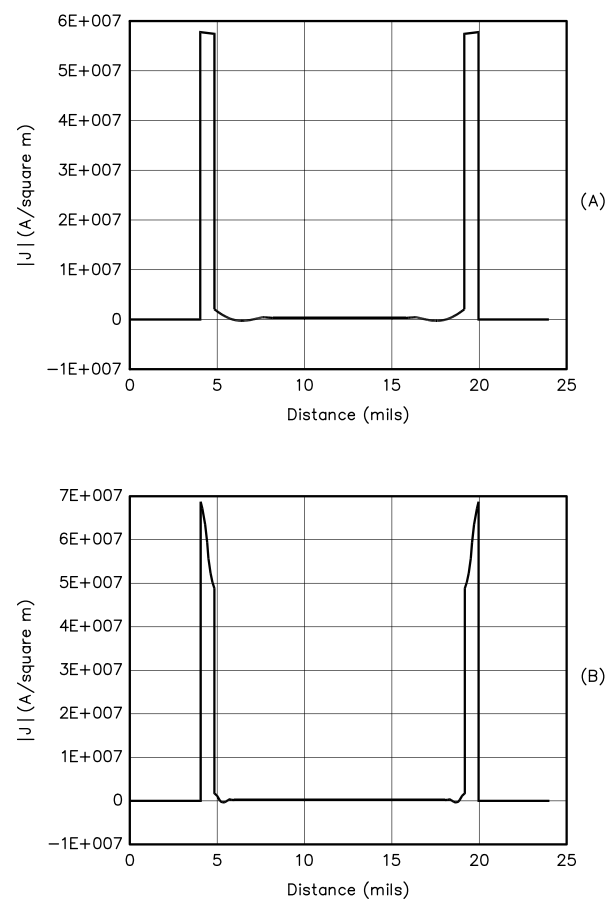

Fig 3—Current density in a #26 AWG Copperweld wire with 0.8-mil cladding at 1 (A) and 16 (B) MHz.

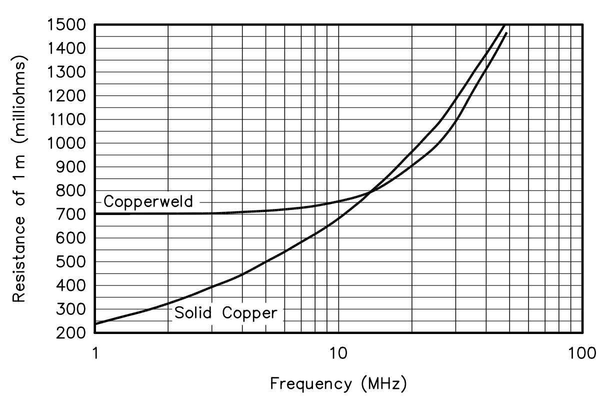

Fig 4—Resistance comparison of 1-meter lengths of #26 AWG solid copper and #26 AWG Copperweld with 0.8-mil cladding from 1 to 30 MHz. Derived from FEM modeling.

the current level. Losses can actually increase as the current increases because μ_r increases with flux density (B), reducing the skin depth and increasing R_{ac}. Thus, μ_r can be from 1000 to 10,000 or more, which means that the skin depth at 1 MHz and above is very small. Copperweld behaves very much like a tubular conductor. This can allow the conductor loss to actually be less or greater than a solid conductor of the same outside diameter, depending on the wall thickness and frequency.

A graph of R_{ac} for 1-meter lengths of #26 AWG solid copper and Copperweld (0.8-mil cladding) wires is given in Fig 4. Below about 14 MHz, the solid copper wire has less resistance. In fact at 2 MHz (160 meters), the Copperweld has more than twice the resistance of solid copper wire. This is simply because current in the Copperweld is crowded into a thin layer. The tube is too thin! Above 14 MHz, however, the tube has less resistance and the Copperweld is superior. Notice also that at low frequencies, the resistance of the Copperweld is nearly constant.

This can be explained from Fig 3, which shows that at low frequencies the current density is basically uniform and changing frequency doesn't change J much. As you reach the middle range of frequencies, current distribution in the tube is better than that in the solid wire and the loss is less. At some high frequency, current distribution in the tube will equal that in the solid wire (the core no longer matters) and its resistance will be the same. In Fig 4, the resistances begin to converge above 50 MHz. The resistances shown in Fig 5 for #12 AWG wires clearly illustrate the convergence at high frequencies. Thus, there is a region, depending on the cladding thickness, where Copperweld is superior to solid wire, but below this region, it is inferior!

Fig 5 is a graph of R_{ac} for 1-meter lengths of four different #12 AWG wires: solid copper, Copperweld with 4-mil and 2-mil cladding and an approximation for 19 strands of #26 Copperweld with 0.8-mil cladding. Again, we see the excess resistance for the 0.8-mil Copperweld at 160 meters, but now the crossover frequency with solid copper is just above 7 MHz. For 30 through 10 m, the stranded Copperweld is somewhat better (5-10%) than solid copper. Copperweld with 4-mil cladding (which is standard for solid #12 AWG Copperweld) is slightly better (≈5%) than solid wire on 160 meters and equal at higher frequencies. While the electrical properties are good and the wire is very strong and durable, the stiffness of Copperweld and its strong desire to remain coiled make it the devil's own invention to work with. Wear gloves and eye protection when working with it!

For 40 meters and up, stranded Copperweld is a good choice: It has low resistance, good strength and is reasonable to work with. For 80 and 160 meters however, the resistance is quite a bit higher and may be a problem for some antennas. Solid copper or Copperweld would be a better choice. In the case of iron fence wire, stainless steel wire or copper-plated steel electric-fence wire, the skin depth will be very small and the ac resistance very large. The copper plating on electric-fence wire is simply too thin to be of any help at HF.

We must also consider that the current distribution on all but the shortest antennas is not constant but nearly sinusoidal or a portion of a sinusoid. Because the losses are proportional to I^2R_{ac}, the loss will be different in different parts of the antenna. This can be accounted for by placing an equivalent resistance (R_{eq}) at the current loop, such that R_{eq} dissipates the same total power as the wire. The efficiency (η) of an antenna, taking into account only the radiation resistance (r_r) and the equivalent wire resistance, will be $\eta = r_r/(r_r+R_{eq})$. For $\lambda/2$ or $\lambda/4$ conductors with sinusoidal current distributions, $R_{eq} = R_{ac}/2$, where R_{ac} is the ac resistance for the entire wire length. A derivation of this result is given in the Appendix. For constant current distribution along the conductor, $R_{eq} = R_{ac}$.

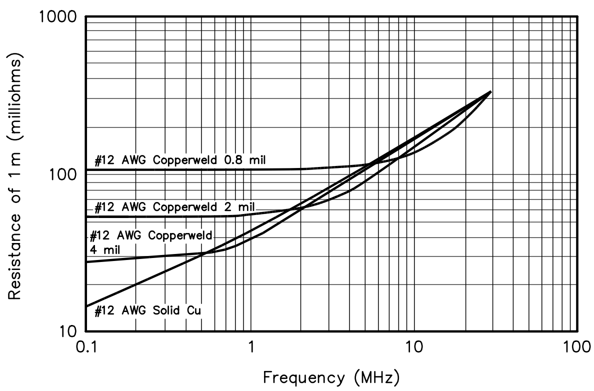

Fig 5—Resistance comparison of 1-meter lengths of #12 AWG solid copper, #12 AWG Copperweld with 4-mil cladding and an equivalent wire for 19-strand #26 AWG Copperweld with 0.8-mil cladding from 1 to 30 MHz. Derived from FEM modeling.

Table 2—Wire loss comparison for #12 wires.

	14.2 MHz Dipole		*1.85 MHz Dipole*		*1.85 MHz Ground-Plane*		*1.85 MHz W8JK*	
Conductor	*Gain (dBi)*	*Loss (dB)*	*Gain (dBi)*	*Loss (dB)*	*Gain (dBi)*	*Loss (dB)*	*Gain (dBi)*	*Loss (dB)*
Perfect	2.14	0	2.14	0	5.27	0	5.93	0
Copper	2.09	–0.05	2.01	–0.13	5.10	–0.17	4.92	–1.01
19–strand Copperweld	2.09	–0.05	1.88	–0.26	4.81	–0.35	3.93	–2.0
Aluminum	2.07	–0.07	1.94	–0.20	5.01	–0.26	4.47	–1.46
Iron	–1.88	–4.02	–4.99	–7.13	–2.58	–7.85	–9.58	–15.5

Table 3—Wire loss comparison for #18 wires

	14.2 MHz Dipole		*1.85 MHz Dipole*		*1.85 MHz Ground–Plane*		*1.85 MHz W8JK*	
Conductor	*Gain (dBi)*	*Loss (dB)*	*Gain (dBi)*	*Loss (dB)*	*Gain (dBi)*	*Loss (dB)*	*Gain (dBi)*	*Loss (dB)*
Perfect	2.13	0	2.13	0	5.27	0	5.94	0
Copper	2.08	–0.05	1.99	–0.14	4.93	–0.34	4.06	–1.88
Aluminum	2.06	–0.07	1.92	–0.21	4.75	–0.52	3.29	–2.65

Effects of Wire Loss on Gain

Okay, so as frequency increases, the resistance of the wire increases and different conductors have more or less loss. *So what! Does it really matter?*

One way to get a handle on this question is to model some typical antennas and determine the effect of different wire sizes and materials on gain. You can also calculate R_{eq} and then calculate the efficiency of the antenna. This is done in the Appendix. Tables 2 and 3 show the results of modeling three different antennas using perfect, copper (Cu), aluminum (Al) and iron (Fe) conductors of two different sizes. I assumed a resistivity of 10^{-7} Ω-m and a relative permeability of 1000 for the iron wire. Steel wire could actually be worse (lower conductivity and higher permeability). The dipoles and the W8JK array are modeled in free space. The W8JK array has two λ/2 dipoles, spaced λ/8 apart and fed 180° out of phase. The ground-plane antenna has four radials, 10 feet above perfect ground.

The tables show several things of interest. First, for the same wire size, as frequency decreases the wire loss increases. This is because even though the wire resistance per-unit-length is decreasing ($1/\sqrt{f}$) the wire length is increasing (1/f). The net wire resistance increases as frequency decreases if the antenna length is scaled. This increase in wire loss can become important in low-band antennas. Second, except for the iron wire, the effect of wire loss and wire size is very small in dipole antennas. You can use copper or aluminum wire in fairly small sizes without compromising performance much. It is also clear that using iron fence wire is bad news.

The ground-plane antenna is more sensitive to wire characteristics than are the dipoles because of its lower impedance, but again the changes are small as long as copper or aluminum wire is used. The use of more radials will reduce wire loss.

The W8JK array, however, is very sensitive to wire size and material. With perfect conductors, the gain over a dipole is 3.8 dB. Using #18 AWG aluminum wire gives away most of that gain (–2.65 dB). Even with #12 AWG copper wire, there is still a loss of over 1 dB. In the W8JK, changing to a #6 AWG wire or two parallel, spaced #12 AWG wires reduces the wire loss to –0.53 dB.

Any low-impedance antennas, such as Yagis, end-fire arrays or short loaded verticals will be sensitive to wire size and conductivity. On 80 and 160 meters, many verticals are short and heavily loaded!

Flat-Strip Conductors

Up to this point, we have been considering round conductors. An alternative would be to use thin, flat conductors of either copper or aluminum. Fig 6A is a graph of R_{ac}/R_{dc} for thin, flat-strip conductors (see the Appendix for generating equation). For #12 AWG round copper wire at 1.8 MHz, $F_r \approx 11$. If we take the same wire and roll it out into a strip approximately 0.010×0.625 inches, the thickness of the strip in skin depths will be about 5. Looking at Fig 6 we see that for $X = 5$, $F_r = 2.4$, which is a factor of 4.6 lower than for the equivalent round wire. By dividing F_r by the corresponding values of X, we can create Fig 6B, which is a graph of resistance normalized to 1 Ω for a thickness of 1 skin depth. Notice that for $X < 1.5$, the $R_{ac} = R_{dc}$, but as foil thickness increases the resistance goes through a minimum at $X = \pi$ and then back up about 9% to level out at a constant R_{ac} regardless of the thickness. For $X < 1.5$, the current distribution in the conductor is almost uniform, so $R_{ac} = R_{dc}$. Above this point, the distribution in increasingly on the outer surfaces of the strip.

At high frequencies, all the current is on the outer perimeter of the strip so the thickness of the inside doesn't matter. Only the length of the perimeter counts. This is the same as for a round wire. The important difference between round and strip conductors is that for a round wire, you have to increase the diameter to reduce R_{ac}. This means you have a lot of unused copper (inside the wire) to buy. Strip or foil conductors can be kept thin and simply made wider to reduce R_{ac}. You put the extra copper to good use and in the end buy less.

Of course, there is the issue of increased wind area with a foil conductor. Foil also tends to "sail" and/or flutter in the wind, distorting the antenna shape and stressing the array. That is a downside! Putting a spiral twist in a foil conductor helps to keep it from flying around in the wind. I have found that 0.010×0.5- to 1-inch strip works pretty well and doesn't fly around or flutter too much. Unfortunately, copper and alu-

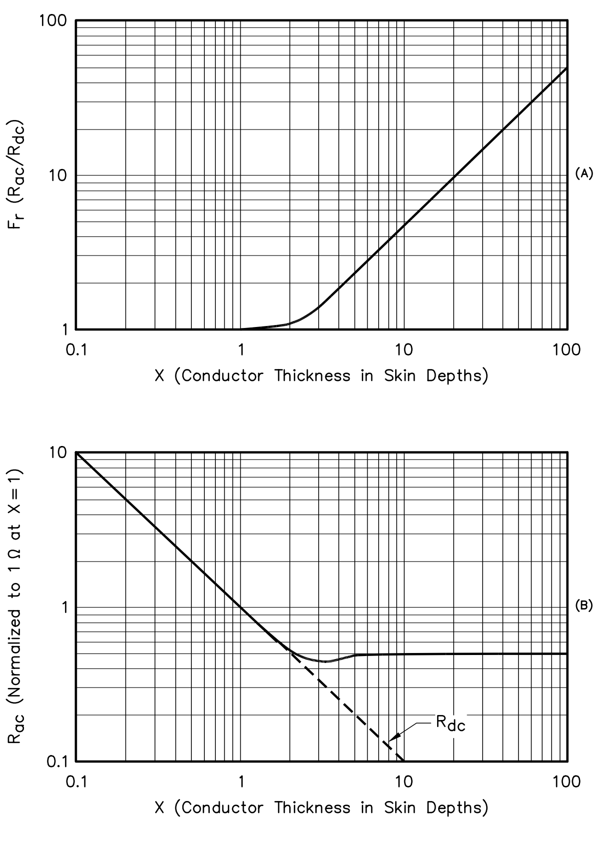

Fig 6—Resistance factor ($F = R_{ac}/R_{dc}$) for flat-strip conductors as a function of thickness in skin depths.

minum foils of appropriate sizes are not so readily available as round wire.

Composite Antenna Assemblies

In some cases, straight copper wire simply does not have the strength required, but the alternatives may have too much resistance. It is possible to compromise by using different conductors at different places in the antenna. Keep in mind that the losses are I^2R in nature. This means that the bulk of the losses occur in the high-current regions of the antenna. Fig 7 shows a 160-meter, two-element end-fire array mentioned earlier. The vertical portions have high current levels; they are made from 0.010×0.625-inch copper strip. The horizontal portions have much less current. The antenna is supported from the top between two poles 300 feet apart, so the upper wires have considerable stress. These are stranded Copperweld. The lower horizontal wires have very little stress; they are copper. The result is an antenna with minimum loss but strength where it is needed.

The 50-pF capacitors tune out the inductive reactance at the feedpoint. These must be high-voltage, high-current capacitors, which usually come in only a few standard sizes. The position of the capacitors and the lengths of the upper horizontal wires can be adjusted to give 450 Ω resistive at the feedpoint. That allows the use of 450-Ω ladder line as the feedline to ground level, where a 9:1 balun transforms to 50 Ω for the run back to the shack. Stub matching could be used instead.

Measurement of Wire Resistance

Theory and modeling are nice, but I wanted to make some actual measurements of wire resistance to confirm the modeling and calculations. Unless you have access to an impedance analyzer such as an HP4192 ($50,000 please!), this is not an easy measurement to make directly. After several false starts, I found it best to wind the wire into a large coil of well spaced turns and measure the Q on a Boonton 260A Q-meter. This gave reasonable results that are shown in Tables 4, 5 and 6. The values for resistance are probably not very precise, but the relative differences between different wires are clearly shown.

The coil is 17 turns (except for the #8 AWG aluminum wire which used 16 turns) spaced 1.5 wire diameters (with ¹/₈-inch Dacron rope) on a 4.2-inch ID PVC-pipe form. 4.5 inches long. The coil requires 19.5 feet of wire. The copper wire was #12 AWG, the antenna wire was 19 strands of #26 AWG Copperweld. (The Copperweld is nominally #13, but when I put a micrometer on the two wires, the sizes were not very different: 0.077 inches for the antenna wire, versus 0.082 inches for the solid copper wire. This results in only a 6% resistance difference.)

I took great care to make the two coils identical. They were both wound on the same form. Measurements were done with the same lead lengths and coil position relative to the Q-meter. A frequency counter was used to set the Q-meter frequency. The Q-meter zeros were carefully adjusted, and so on. The close values for the resonating capacitance show that the coils were very nearly identical.

Three things jump out at you from Tables 4 and 5:

- The Q for the coil made with stranded Copperweld is substantially lower than that of the solid copper wire coil.
- The variation in Q over frequency is different for each coil.
- The coil Qs begin to converge as the frequency is increased.

Remember that $Q = X_L/R_S$, where $X_L = 2\pi fL$ is the impedance, and R_s is the total series loss resistance.

In an antenna, we are interested in the resistance due to skin effect (R_{ac}), so we must separate the components of coil loss to get an estimate of the skin-effect loss. R_s has several components:

- skin effect in the conductor
- turn-to-turn and geometric proximity effects
- losses in the coil form
- loss in wire insulation
- radiation from the coil
- losses due to eddy currents in nearby conductors

Skin effect can be calculated quite accurately using the equation of Fig 1

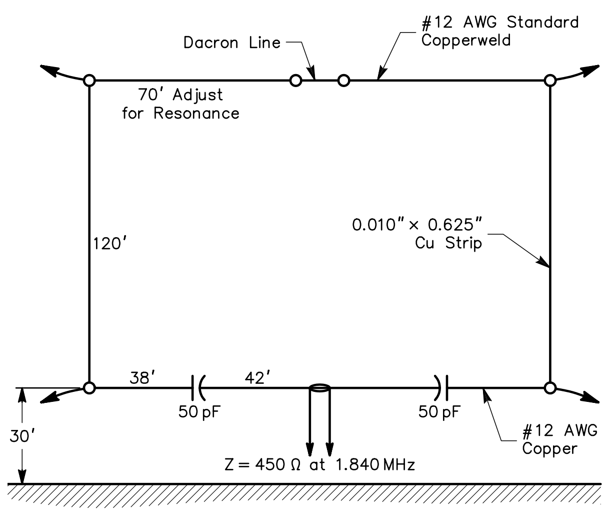

Fig 7—N6LF W8JK two-element vertical array using composite-wire construction.

Table 4 —#12 AWG bare solid copper wire test results using new wire

Frequency	*Resonating Capacitance*	*Measured Q*	X_L	R_S
1.8 MHz	359 pF	410	246.3 Ω	0.601 Ω
3.9 MHz	69 pF	360	591 Ω	1.64 Ω

Table 5—19-strand #26 AWG Copperweld test results using new wire

Frequency	*Resonating Capacitance*	*Measured Q*	X_L	R_S
1.587 MHz	460 pF	250	218 Ω	0.87 Ω
1.8 MHz	358 pF	270	247 Ω	0.92 Ω
3.9 MHz	68 pF	323	600 Ω	1.85 Ω

for a solid, round conductor. For 19.5 feet of #12 AWG copper wire at room temperature and 1.8 MHz:

R_{dc} = 0.031 Ω, from wire table (I measured the coil as 0.030 Ω on a bridge),

$R_{ac}/R_{dc} = F_r = 10.79$, from Fig 1,

$R_{ac} = R_{dc} \times F_r = 0.334$ Ω

At 1.8 MHz, the total R_s in Table 4 is 0.601 Ω, which indicates an additional loss resistance of 0.267 Ω beyond the skin effect.

Given the close similarity between the two coils, we can estimate the stranded Copperweld coil resistance component due to skin effect to be:

$R_{skin} \approx R_s - 0.267 = 0.915 - 0.267 = 0.648$ Ω

This is 1.9 times the resistance of solid copper wire! This agrees rather well with the comparison in Fig 5 between 0.8-mil clad Copperweld and solid copper wires. In a dipole, I don't think this would matter but in a W8JK array, it's bad news.

Looking again at Fig 5, we would expect the skin-effect loss for the two types of wire to converge as we go higher in frequency, reflected in more similar Qs. This is what we see in Tables 4 and 5. We would also expect the Q of the Copperweld coil to decrease with frequency because X_L is decreasing, but R_s is not. For the solid wire coil, both X_L and R_s are decreasing, so Q is more stable.

Emboldened by these results, I wound coils using several other wires I had on hand or was able to scrounge from friends. The test results are given in Table 6. I threw in the iron fence wire just for kicks!

The differences in the 14 different wires tested are quite easy to see:

- The #12 AWG wire is better than #14 AWG
- New insulation has very little effect (but weathered insulation may not be so benign!)
- Oxidation of bare wire definitely reduces the Q. Both samples were only mildly oxidized. Longer exposure would have further reduced the Q.
- Stranded wire is inferior to solid
- Very fine stranding (168-strand sample) reduces the Q significantly
- For the same size wire, solid Copperweld is just as good as solid copper
- At least at low frequencies, stranded Copperweld is inferior to solid Copperweld and other copper wires, solid or stranded
- Iron fence wire is bad news!

I also wanted to verify the advantage of Copperweld wire implied by Fig 4. Using #14 AWG solid copper and solid Copperweld, I wound free-standing three-turn coils and then two coils on a ceramic coil form. The results are shown in Table 7.

In both cases, the Copperweld produced a coil with somewhat higher Q, as predicted by Figs 4 and 5. Remember that only part of R_s results from skin effect, so the difference between the two wires is diluted by other losses. The tests were run a number of times to be sure the differences were real and repeatable.

Aluminum Wire Connections

Aluminum wire has the advantages of very low cost and a better strength-to-weight ratio (≈3×) than copper. The reduced conductivity (σ) of aluminum can be accommodated by using a larger wire size. For an equal resistance, it will still weigh less than copper. Keep in mind we are talking about equal R_{ac} not R_{dc}! The difference arises because of skin effect, which is proportional to $1/\sqrt{\sigma}$. The skin depth will be greater in aluminum than in copper (at the same frequency) because of the lower conductivity. The lower weight and higher strength is helpful in long spans and may put off the need to use Copperweld conductors.

However, aluminum has one major disadvantage. Making a low resistance connection that will remain low during extended exposure to the elements is not a trivial exercise. It is very possible for a poor connection to introduce significant loss, especially if it is at a high-current point. There are also corrosion problems with connecting copper conductors to aluminum conductors.

Alumoweld Wire

In addition to Copperweld, aluminum-clad steel wire is available under the name Alumoweld. It is available in a variety of sizes, although the smallest size available is #12 AWG. It is also available as stranded wire and stranded guy wire equivalent to the galvanized wire used for guys. While it is very stiff—handling very much the same as Copperweld or steel wire—it has some advantages. In most atmospheres, it is much more resistant to corrosion than galvanized steel. It is electrolytically compatible with the aluminum tubing frequently used in antennas, so it can be used for support wires in aluminum antenna structures to avoid dissimilar-metal corrosion.

Towers and Supports

It is quite clear that iron fence wire is a very poor choice for antennas, but what about steel towers and the use of galvanized or stainless steel guy wires as antenna elements? In towers, the surface area is much larger than that

Table 6—Comparison of Q for coils made with various wires at 1.8 MHz

Wire description	*Q*
New #12 bare soft-drawn solid copper	410
New insulated solid #12	410
New insulated stranded #12 THWN	350
New insulated 19 strand #26 Copperweld	270
New #14 bare soft-drawn solid copper	353
New #14 bare solid Copperweld	360
New #14 bare stranded Copperweld	194
Oxidized #14 bare stranded Copperweld	162
New #14 bare 7/22 stranded hard-drawn copper	338
Oxidized #14 bare 7/22 stranded hard-drawn copper	300
New #14 168 strand superflex	225
#14 aluminum electric fence wire	260
#8 aluminum clothesline	360
#13 iron fence wire	25

Table 7—Coil Qs measured at 25 MHz

Coil form	*Wire*	*Measured Q*	X_L	R_S
Air	Copper	285	145 Ω	0.51 Ω
Air	Copperweld	310	138 Ω	0.45 Ω
Ceramic	Copper	266	186 Ω	0.70 Ω
Ceramic	Copperweld	282	193 Ω	0.68 Ω

Appendix

A. Skin depth in copper

Fig A is a graph of skin depth in copper as a function of frequency for two temperatures.

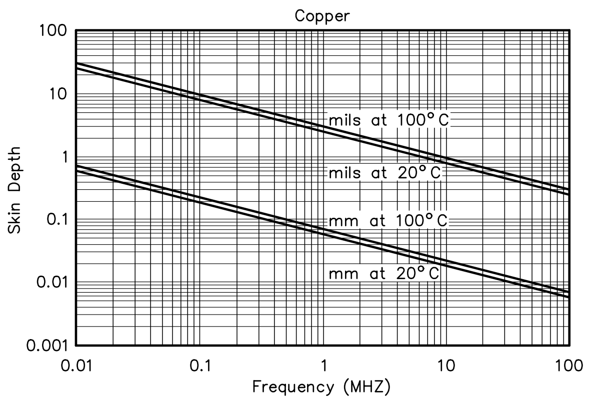

Fig A—Skin depth in copper at 20°C and 100°C; dimensions are in mils and millimeters.

B. R_{eq} Derivation

The current distribution in an antenna is usually a sinusoid or a portion thereof as indicated in Fig B. With the center as the origin:

$$I = I_{o(RMS)} \cos\left(\frac{\pi}{2}\right)\left(\frac{x}{l}\right) \quad \text{(Eq A)}$$

Note that I_o, the current at $x = 0$, is RMS! The wire loss is:

$$\Delta P = \Delta R I^2 dx \quad \text{(Eq B)}$$

Where ΔR is the resistance per unit length. The total power loss is then:

$$P = \int_a^b \Delta R I^2 dx = \Delta R I_o^2 \int_a^b \cos^2\left(\frac{\pi x}{2l}\right) dx$$

$$P = \left(\Delta R I_o^2\right)\left[\frac{l}{\pi}\sin\left(\frac{\pi x}{2l}\right)\cos\left(\frac{\pi x}{2l}\right) + \left(\frac{x}{2}\right)\right]_a^b \quad \text{(Eq C)}$$

$$R_{eq} = \frac{P}{I_o^2} = \Delta R\left[\frac{l}{\pi}\sin\left(\frac{\pi x}{2l}\right)\cos\left(\frac{\pi x}{2l}\right) + \left(\frac{x}{2}\right)\right]_a^b$$

For $a = 0$ and $b = l$:

$$P = I_o^2\left(\frac{\Delta R l}{2}\right)$$

$$R_{eq} = \left(\frac{\Delta R l}{2}\right) \quad \text{(Eq D)}$$

Where $\Delta R l$ is the total R_{ac} for the length of wire.

R_{eq} can be used directly to calculate the gain decrease due to conductor loss. The loss is simply the log of the efficiency:

$$loss = 10\log\left(\frac{r_r}{r_r + R_{eq}}\right) \text{ dB} \quad \text{(Eq E)}$$

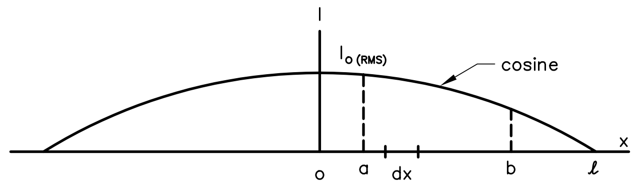

Fig B—Current distribution on an antenna wire and definition of equation quantities.

where r_r = radiation resistance. For a dipole in free space where r_r = 73 Ω, see Table 8.

The loss in gain by this calculation agrees with the gain loss in Table 2 that was derived using MOM (method of moments) in an antenna-modeling program.

C: Resistance Factor for Round Wire

$$F_r = \frac{R_{ac}}{R_{dc}} = \frac{\gamma}{2}\left[\frac{ber\gamma\, bei'\gamma - bei\gamma\, ber'\gamma}{ber'^2\gamma + bei'^2\gamma}\right]$$

$$\gamma = \frac{d}{\delta\sqrt{2}} \quad \text{(Eq F)}$$

δ = skin depth, d = wire diameter

where *ber* and *bei* are the real and complex parts of Bessel functions with complex arguments. They are often called Kelvin or Thompson functions. Most spreadsheet programs do not have these functions. Math programs like *Maple* or *Mathmatica* do have them. Fig 1 was done with Maple. It is possible to use series summation approximations that can be found in advanced math tables (see Reference 6).

D. Resistance Factor for Thin, Flat Foil where X = Thickness in Skin Depths

$$F_r = \frac{R_{ac}}{R_{dc}} = \frac{X}{2}\left[\frac{\sinh X + \sin X}{\cosh X - \cos X}\right] \quad \text{(Eq G)}$$

This equation may readily be evaluated with a spreadsheet. Most spreadsheets have both circular and hyperbolic functions.

Table 8—Loss due to conductor resistance for dipoles using #12 AWG solid copper wire

Frequency (MHz)	δ (mils)	*X*	F_r	*L* (feet)	R_{eq} (Ω)	*Loss* (dB)
1.84	1.92	29.8	10.8	267	2.29	–0.13
3.75	1.35	42.5	15.3	131	1.59	–0.09
7.15	0.98	58.7	21.0	68.8	1.15	–0.07
14.2	0.69	82.7	29.5	34.6	0.81	–0.05

of a wire. Although the skin depth will be very small, the large surface area should help greatly. I would be more concerned with the joints between tower sections, particularly in high-current regions. This problem has been addressed by attaching copper wire jumpers across tower joints. The problem will be much worse in crank-up towers, where the sections have sliding joints between them.

I would be more concerned about loss in a steel tower if it were being used as part of an array with low impedances, especially if the tower is electrically short and heavily loaded. In that case, I would consider installing a collar at the top of the antenna and attaching several parallel copper wires in a cage around the tower from top to bottom. This way the copper is the conductor not the tower. This allows the tower to be grounded directly but still have the feed point open. If the collar were made significantly larger than the tower, then it would not only reduce loss but also increase bandwidth and reduce the loading necessary because of the larger effective diameter of the antenna.

Sometimes the guy wires on a tower or the rigging on a sailboat are used as antennas. Depending on the antenna, these can be very lossy and should be

Why is there Skin Effect?

When a time-varying current flows in a conductor, a time-varying magnetic field will be created around the conductor. A simple example is shown in Fig C. A current flowing in the wire creates a magnetic field around the wire as indicated. The direction of the magnetic field in relation to the current obeys the "right-hand rule"—that is, if the thumb of your right hand extends in the direction of positive current flow as shown, the magnetic field will curl around the wire in the same direction as your fingers.

Just as a current creates a magnetic field, a time-varying field, from some external or internal source, will induce a time-varying current in a conductor. This is called an "eddy" current and higher frequencies yield greater-amplitude eddy currents in a given conductor. The direction of the eddy current is such that its magnetic field opposes the inducing field.

We can see how these currents and fields create skin effect by examining Fig D. This is a section of a round wire carrying a current from one end to the other. This current is labeled "A." It is simply the net current flowing through the wire. This current creates a magnetic field both inside and outside the wire as indicated by the dashed lines "B." This field, in turn, creates an eddy current ("C") as shown.

Notice that near the center of the wire, the eddy current opposes the desired current, but on the outer part of the wire, the eddy current aids the desired current. If we look at a cross-section of the wire, we see that the current density near the center is reduced, but near the outside, the current density is increased. As frequency increases, less current flows on the inside of the wire and more flows near the outside surface. Of course, the *net* current stays the same, but it is crowded into a smaller and smaller portion of the wire's cross-sectional area.

The result is that the apparent resistance of the wire increases because we are using only a small portion the available copper area to carry current. This means that the loss for a given current will be higher. In copper at HF, the current is crowded into a layer of 2 mils, or less, in thickness. The rest of wire only provides mechanical support for the thin outer layer that conducts!

There is another way to look at skin effect. If you have a large sheet of conductor and you irradiate it with a electromagnetic wave perpendicular to the surface, the wave will penetrate the surface for some small distance. The amplitude of the wave decreases exponentially and the depth at which the amplitude has decreased to $1/e \approx 37\%$ ($e \approx 2.718$, the base of natural logarithms) is referred to as the penetration or skin depth (δ). Increasing frequency decreases δ.—*N6LF*.

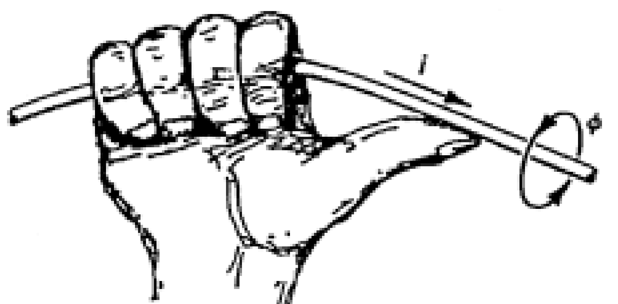

Fig C—The "right-hand rule" relates the direction of current flow to the magnetic field it produces.

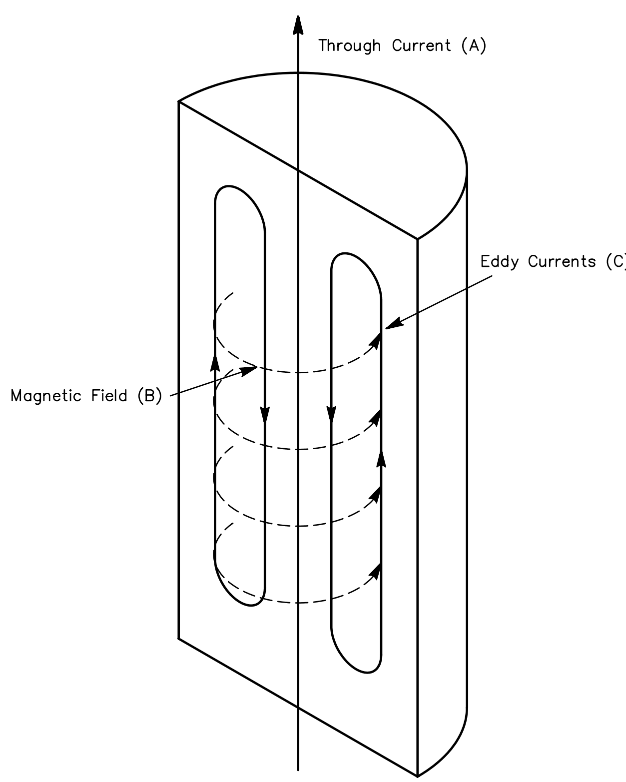

Fig D—Eddy currents in wire produce the skin effect. The through current (A) produces a magnetic field (B) that induces eddy currents (C). The eddy currents offset through current near the wire center and add to through current near the wire surface.

used with some caution. Note from Table 1 that the standard marine stainless steel (304) has a resistivity greater than 50 times that of copper. A number of years ago, I used an insulated backstay on my sailboat as a half-sloper, fed at the top and driven against the aluminum mast. To minimize the loss in the stainless steel backstay, I used a strip of copper (encased it in plastic tape to control corrosion) bent over the backstay in the form of a **U** for the distance between the two insulators. This proved very satisfactory during several years of cruising in temperate and tropical waters.

Stainless Steel and Mobile Antennas

Most mobile antennas are electrically short and heavily loaded, especially at and below 7 MHz. The result is very low radiation resistances. Because of its very high resistivity, stainless steel may not be a very good choice for these antennas despite the obvious mechanical and corrosion-resistance advantages. For example, consider an 8-foot center-loaded whip with a 0.5-inch diameter base section and a 0.125-inch diameter top section. The loss due to conductor resistance using stainless steel is 0.6 dB at 7.150 MHz, 1.3 dB at 3.8 MHz and 3.1 dB at 1.84 MHz. The use of stainless steel wire would result in losses very similar to steel fence wire.

Conclusions

For antennas with current-loop impedances above 35 Ω or so, any copper, Copperweld or aluminum wire in a variety of sizes will work just fine; however, for lower-impedance antennas, copper or Copperweld wire size #12 AWG or larger should be used. Copper or aluminum tubing is very effective for low-impedance antennas. For 80- and 160-meter antennas, the resistance of stranded Copperweld may be unacceptably high.

New insulation does not seem to affect loss, at least at 1.8 MHz, but surface oxidation does. Thin insulation should have only a very small effect on tuning but will suppress oxidation. This is a consideration for low-impedance antennas only.

By careful choice of conductor or combinations of conductors, considering both electrical and mechanical properties, it should be possible to keep the conductor loss low in almost any kind of antenna, with the possible exception of very small antennas.

Loose Ends

Despite the extensive discussion in this article, several subjects need more attention. I think the losses in steel towers need to be analyzed more closely. I also have not addressed losses from currents induced in guy and support wires. Usually these currents are small if the wire is short compared to $\lambda/2$, but steel wire can be quite lossy even with small currents. This subject needs some scrutiny. In searching through the literature, I found very little in the way of measurements or even discussion of antenna conductors. Books in the reference list contain some very useful tables, but if you know of any important articles I have missed please tell me.

Acknowledgment

I would like to express my thanks for the review and helpful comments provided by George Cutsgeorge, W2VJN. Mark Perrin, N7MQ, and Joe Brown, N7EZG, were very helpful in digging out great examples of "cruddy" wire for me to test. Tom Schiller, N6BT, told me about Alumoweld wire and related a number of hilarious anecdotes concerning antenna conductors.

Notes

1. J. Kraus, "Antenna Arrays with Closely Spaced Elements," *Proceedings of the IRE*, February 1940, pp-76-84, see Fig 5.
2. "Maxwell" by Ansoft Corporation, Four Station Square Ste 200, Pittsburgh, PA 15219-1119; tel 412-261-3200, fax 412-471-9427; e-mail **info@ansoft.com**; **http://www.ansoft.com**.
3. United States Alumoweld Company, Inc, 115 USAC Dr, Duncan, SC 29334; tel 800-342-8722, 864-848-1901, fax 864-848-1909; e-mail **sales@alumoweld.com**; **www.alumoweld.com**.
4. F. Terman, *Radio Engineers Handbook* (McGraw-Hill, 1943), pp 32-33.
5. D. Fink and W. Beaty, *Standard Handbook for Electrical Engineers*, 11th Ed., ISBN: 0070220050 (McGraw-Hill, 1999) Chapter 4.
6. *Radiotron Designer's Handbook*, 4th Ed. (RCA, 1952), pp 1408-1417.
7. M. Abramowitz and I. Stegun, *Handbook of Mathematical Functions*, National Bureau of Standards republished by Dover Publications (New York, 1965), pp 379-385.
8. R. Straw, N6BV, Ed., *The ARRL Antenna Book*, 18th Ed. (Newington: ARRL, 1997), Chapter 20.
9. J. Devoldere, ON4UN, *Low-Band DXing*, 3rd Ed. (ARRL, 1999), pp 8-5 through 8-7.