High-Efficiency Antennas for Hand-Held Radios

End-fed half-wave antennas provide better efficiency for hand-held radios than quarter-wave radiators or "rubber ducks."

By Richard Kiefer, K0DK

I started evaluating and building antennas for hand-held radios because I needed an efficient, lightweight antenna for backpack and mountaineering activities in remote locations of the western US. My typical backcountry outing involves carrying a variety of equipment, including a hand-held radio and antenna 10-20 miles into mountainous terrain. The campsite destinations and operating locations are typically 30-100 miles from the nearest VHF or UHF repeater. Under these conditions, reliable communications over long distances at low power with the most lightweight equipment is the goal. In developing the optimum hand-held radio antenna for such excursions I have considered, modeled and constructed many types such as rubber ducks, Yagis, vertical coaxial collinear arrays, dipoles and end-fed half-waves. After all the experimentation, I have concluded that the best solution, when you consider portability, ease of use and efficiency, is an end-fed half-wave antenna mounted in the normal manner on top of the radio. This style of antenna is lightweight, easily stored in a pack and self-supporting, which is important above the timberline, where there are no trees or bushes. The total weight of my Icom IC-Q7A with two AA lithium batteries and the $1/2$ wave antenna is 6.6 oz.

A half-wave antenna, whether end or center fed, can provide high transmission and reception efficiency and is much better than a shortened rubber duck. For convenience, the half-wave antenna is best fed from the end with a matching network, rather than in the center. The radiating element can be either a fixed length of stainless steel wire or a telescoping element. The homebrew antennas described here all use SMA connectors, which are common on most contemporary hand-held radios. As far as I know, no commercially available half-wave antennas have SMA connectors. Because of the high-Q coil used in the matching network, the efficiency of these homebrew antennas approximates that of a center-fed vertically polarized dipole. In this article, I describe the construction and performance of two homebrew end-fed half-wave antennas for 2 meters and 70 cm. I also compare the performance of these antennas with some commercial half-wave, quarter-wave and "rubber duck" antennas.

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Fig 1—Author with hand-held and homebrew 2-m half-wave antenna.

Fig 2—A hand-held with a K0DK 2-meter half-wave telescoping antenna.

Fig 3—A hand-held with a K0DK 70 cm half-wave whip antenna.

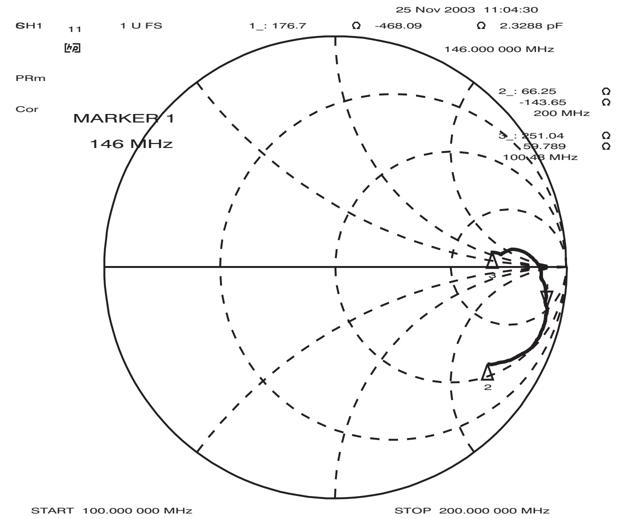
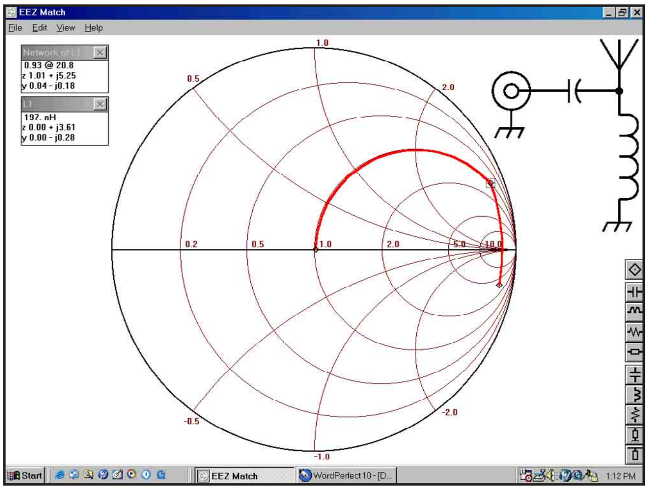


Fig 4—Impedance at the end of an unmatched 2-meter half-wave antenna element over the frequency range from 100 to 200 MHz.



Network of L1
0.93 @ 20.8
z 1.01 + j5.25
y 0.04 - j0.18

L1
197. nH
z 0.00 + j3.61
y 0.00 - j0.28

Fig 5—A Smith Chart plot of the impedance match necessary for the 2-meter half-wave antenna element. The 177–j468 Ω of the unmatched element is matched to 50+j0 with a parallel inductor of 197 nH and a series capacitor of 4.2 pF. The match is shown from the antenna end of the circuit.

Homebrew Half-Wave Antennas for Hand-Held Radios

The half-wave antennas described here use SMA connectors and a matching network as shown in Figs 2 and 3. One version of the antenna is designed for the 2-m band and the other for the 70-cm band. They both use the same construction technique, materials and matching network circuit topology. One particular advantage to a half-wave antenna with the matching network at its base is that the current maximum is high above your head in the middle of the radiating element. By keeping the current away from your head, the absorptive radiation losses and detuning are reduced. Both are important factors for hand-held operation. In addition, the body does not act as part of the antenna system (with current flowing through the capacity to your hand) as with a quarter-wave antenna or rubber duck. With a high-powered hand-held radio, it may also be safer to have the current maximum high above your head rather than near your eyes and brain.

Impedance Match for the end-fed half-wave antennas

If you measure the drive-point impedance at the end of a half-wave radiator mounted on a hand-held (see Fig 4), it is high, but finite, requiring a step-up network to match 50 Ω. Both antennas described here are fed at the end with a matching network consisting of a series capacitor and a parallel inductor. This topology, shown in Fig 5, works for any end-fed half-wave antenna independent of frequency. This is true because the impedance seen at the end of the half-wave radiator is always somewhere on the righthand side of the Smith Chart

For example, the measured drive-point impedance of a 36-inch-long stainless-steel wire at 146 MHz is 177-*j*468 Ω as shown by the Smith Chart. The impedances at 100 and 200 MHz are also given. This impedance is about the same whether the radiator is a stainless-steel wire or a telescoping element of approximately the same length.

The impedance-matching network transforms the 177–*j*468 Ω at the end of the radiating element to match the output of the hand-held radio's power amplifier. Thus, the hand-held is able to efficiently drive the antenna, to produce the same radiation pattern and efficiency as a center-fed dipole. A little power is lost in the matching network itself, heating the coil. This is because the Q of the coil is much lower than the Q of the Teflon-insulated capacitor.

The impedance match is accomplished as shown in Fig 5 by first rotating counterclockwise around the Smith Chart.[1] With a parallel inductor to ground of 197 nH to land on the constant-R circle that passes through the center.[2] This is the 50 Ω constant-R circle. Then the remaining inductive reactance is canceled with a series capacitor of 4.2 pF to "zero in" on the center of the Smith Chart at 50+*j*0. It also happens to be very convenient that the shunt component nearest the antenna element is a parallel inductor because it acts as a dc short to ground for ESD protection of the hand-held antenna connection. This same matching-circuit topology is used for both the 2-meter and 70-cm versions of the half-wave antennas.

Accurate Hand-Held Radio Impedance Measurements

To achieve proper impedance matching of hand-held antennas you must be able to accurately measure the drive point Z under a realistic condition. This condition must include the electrical effects of a person holding the radio and its antenna at a normal height above ground of about 5 feet. The drive-point Z is made up of the radiation and loss impedances. They are determined, in part, by the dimensions of the hand-held radio itself, its proximity to the

[1] Notes appear on page 45.

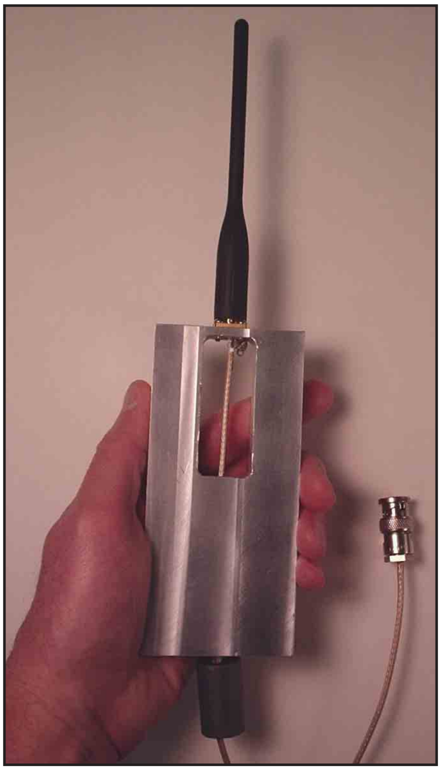


Fig 6—A dual-band rubber duck mounted to the hand-held simulator for measurements.

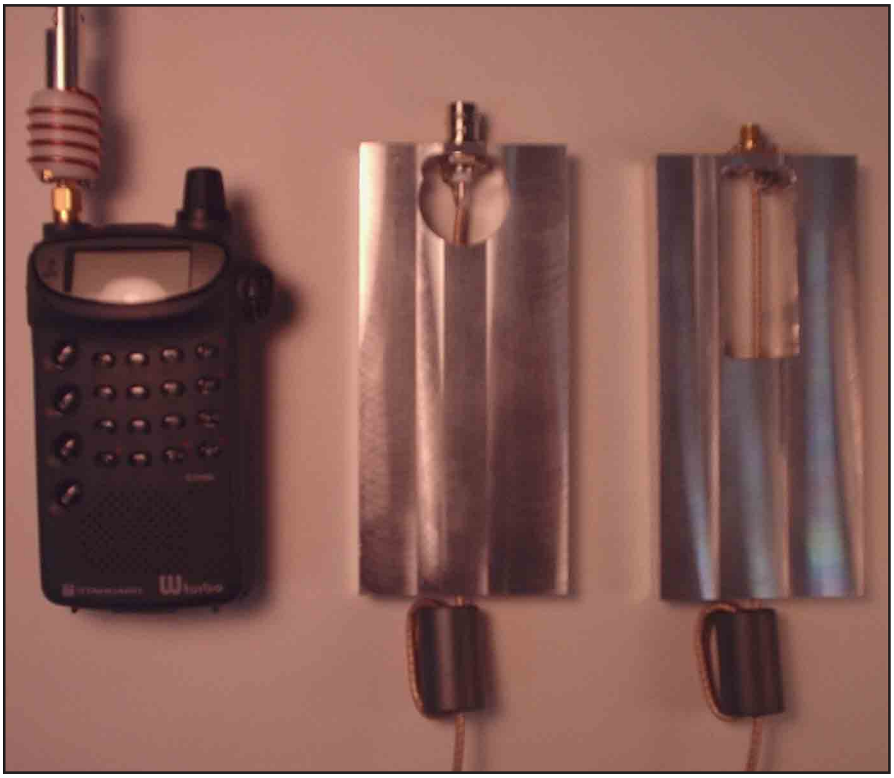


Fig 7—hand-held simulators used to measure the impedances and SWRs of hand-held antennas with either a BNC or SMA connectors.

human body and the electrical connection produced by the capacitance and conductance of the hand that holds the radio. All of these factors, along with the length of the antenna element, determine the impedance measured at the base of the antenna. This drive-point impedance must be as close to the radio-manufacturer's specification as possible. The best drive-point impedance is usually, but not always, $50+j0$ Ω. For example, I know of at least one power amplifier chip, the RF2172 from RF Micro Devices, that requires a load of $20-j1.6$ to achieve its maximum power output. In such cases, the optimum load impedance can only be determined by power-amplifier load-pull measurements, a subject beyond this discussion.

So to make accurate and representative hand-held antenna-impedance measurements, I use two hand-held simulators made from 0.5×5×2.5-inch aluminum blocks shown in Figs 6 and 7. These blocks approximate the size of a modern hand-held radio and provide the proper coupling to the human body when held in the hand. Each block has a coax connector mounted on one end with a 3 foot length of RG-318 Teflon coax attached. The coax is decoupled from the hand-held simulator by a large #43 material ferrite bead. This makes the impedance measurements and radiation pattern largely independent of the position of the coax. One hand-held simulator has a SMA connector mounted and the other a BNC. With one simulator or the other, I can measure a wide variety of commercial and homebrew antennas over a wide frequency range.

The instrument used to measure antenna impedance is a Hewlett-Packard HP-8753D network analyzer, which can determine the complex impedance of any antenna right at the connector on the simulator. The measurement reference plane is moved to the base of the antenna by calibrating the analyzer for S11 at the connector by the standard method using a 50-Ω reference load, an open and a short. Then all impedance measurements are made while the antenna and simulator are held in the hand as shown in the Fig 6.

For example, the impedance measurement for the homebrew 2-meter telescoping end-fed half-wave antenna is shown in Fig 8. The impedance is $59.5+j0.6$ Ω for a SWR of 1.2:1 at 146 MHz. That's not too bad for having started at $177-j468$ Ω. At the band edges, the antenna impedance is $54.6-j18$ at 144 MHz and $64.3+j9.7$ at 148 MHz. The SWR rises to 1.4 at 144 MHz and 1.35 at 148 MHz. The SWR does not rise to 2:1 until ±5 MHz of the center frequency.

Antenna Construction Details

The mechanical construction of the 2-meter and 70-cm versions of the half-wave antennas is essentially the same. The electrical circuit topology is also the same. Only a few of the dimensions, the number of coil turns and the radiating element-lengths, are different. In addition, the 2-meter version may use a radiating element that is made of either a length of stainless steel spring wire or a telescoping whip. The mounting details are slightly different for each radiator. Each antenna then consists of the main parts in Table 1, with dimensions given for the 2-meter version

The radiating element is approximately $^1/_2$-wave in length, on either 2 meters or 70 cm but the length need not be exact. The impedance at the end of the element will be somewhere to the far right of the Smith Chart if you are fairly close to a half-wave length. Also, the upper end of the telescoping element or the spring wire element should be capped with a bumper so it doesn't cause an injury. The telescoping antenna element is bolted into a hole in the mounting stud as shown in Figs 9 and 10. Then this entire antenna element assembly screws into the top of the coil form to clamp down the upper end of the coil wire. The upper end of the coil wire is set into a groove machined into the upper surface of the coil form. The depth of the cut is 0.010 inches less than the diameter of the wire, and the clamping force flattens the wire a little. This makes a solid electrical contact to between the coil and the radiating section of the antenna.

Fig 9—Matching network for 2-meter end-fed half-wave, telescoping element version.

In a similar manner, the SMA connector assembly fits into a machined groove on the bottom surface of

Table 1
Main Parts List for the 2-meter Antenna

Radiating element —RadioShack 35 inch telescoping replacement antenna or a 36 inch length of stainless steel spring wire 0.062 inches in diameter.
Coil form—0.70-inch diameter Delrin rod, cut with a shallow exterior left hand thread at 6 turns/inch. The interior thread is 24 turns/inch (full length).
Coil—$4^1/_2$ turns of #12 AWG bare copper wire.
Antenna-element mounting post—0.40-inch-diameter aluminum rod, threaded on one end with 24 turns/inch for $^3/_4$-inch.
Capacitor—made from a piece of Teflon insulated wire about 2 inches long.
SMA male connector—mounted to one end of the coil form with two #3-48 machine screws.

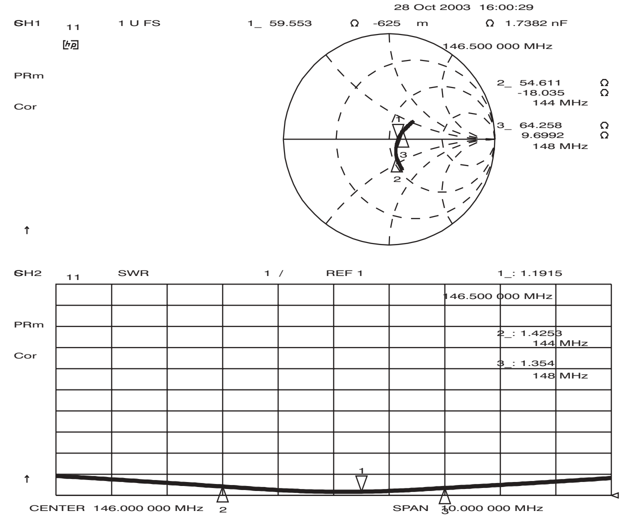


Fig 8—Drive-point impedance of the 2-meter version of the K0DK end-fed half-wave telescoping hand-held antenna.

the coil form to mechanically clamp the lower end of the coil. The depth of this cut is also 0.010 inches less than the diameter of the wire, for a tight press contact. See Figs 9 through 14. The SMA connector is held in place with two screws that thread into two holes in the coil form. The force produced on the upper and lower ends of the coil is sufficient to create a solid gas-tight, corrosion-resistant connection.

The series capacitor of the matching network is formed by a Teflon-insulated wire inserted into a hole drilled in the center of the threaded antenna element mounting post. The gimmick wire fits into a hole inside the threaded form, then the mounting post screws into the form. The capacitance is formed between the wire and the inside surface of the hole in the element mounting piece. The capacitor dielectric is the Teflon insulation of the short piece of wire as shown in the figures. The capacitor value is trimmed by cutting off the end in small increments, while observing the drive-point impedance of the antenna on the network analyzer using the hand-held simulator described above.

If the stainless-steel wire element is used instead of the telescoping element, the mounting stud is slightly different, as shown in Figs 12 and 13. The stainless steel wire is held in place with a setscrew as shown in the figures. The mounting stud then screws into the top of the coil form in the same manner. The capacitor is formed as before.

Notice that the coil provides a dc-ground connection between the antenna element and the case of the radio. This provides ESD protection for the radio front-end circuits in case you create a static discharge to the antenna. It also makes the antenna a lightning rod if you are operating outdoors. I have felt an electric-current tingling sensation while holding a hand-held on a mountaintop using this type of antenna. The air was highly charged with thunderstorm activity in the area, and I quickly descended to a lower, more protected location.

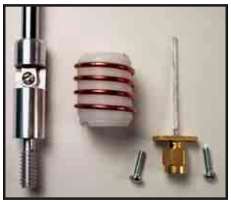


Fig 10—Disassembled matching network parts; radiator mount, coil, wire capacitor attached to SMA connector.

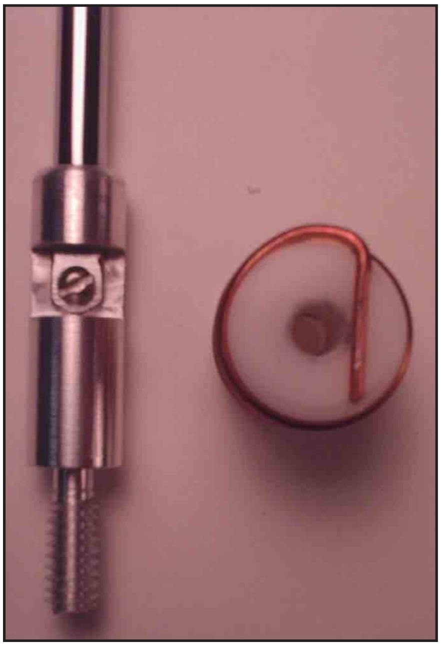


Fig 12—Top view of the 2 meter matching coil with the telescoping element.

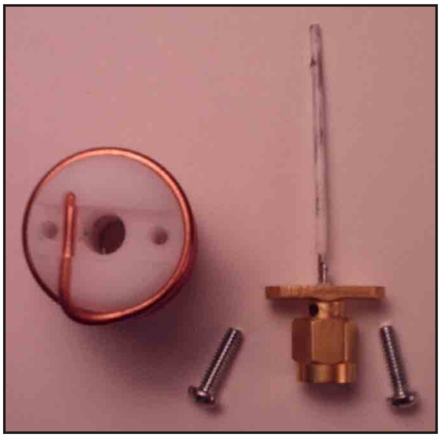


Fig 11—Bottom view of the 2 meter coil with the SMA connector and capacitor wire.

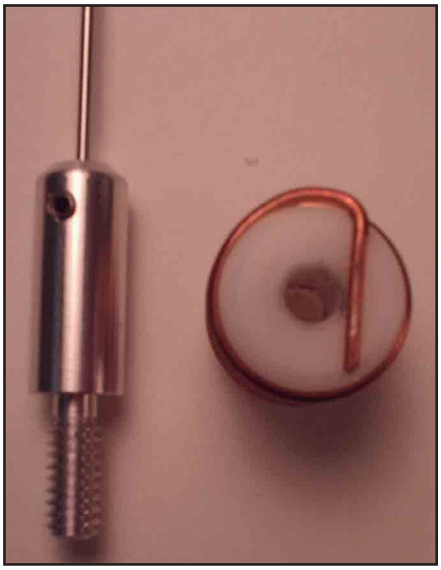


Fig 13—Top view of the 2 meter matching coil with the wire element.

Antenna Performance Comparisons

The performance proof of the homebrew end-fed half-wave antennas is in the measurement of gain and SWR. The relative gains are determined by a comparison with several different commercial antennas in outdoor measurements at an open-air test site (OATS) that is free of obstructions. The method of gain measurement for both the 2-meter and 70-cm antennas is as follows.

A battery-powered radio held in the hand, first at arm's length and then near the head, is used as a transmitting device for all antennas of the comparative tests. The power output of the Standard model C510A radio is 300 mW, which produces enough received signal strength in a nearby receiving antenna to be well above the noise floor of the receiving device. The hand-held is also equipped with with a 6 dB attenuator at its output. The attenuator is used to help present a consistent drive-point impedance, or high return loss, for the hand-held power amplifier. This insures that the power amplifier generates constant power for all antennas. The receiving antenna is a simple vertically polarized center-fed dipole. For the 2-meter measurements, the dipole is located 14 feet above the ground at a distance of 55 feet. For the 70-cm measurements, the dipole is located 5.5 feet above the ground at a distance of 40 feet.

A signal is transmitted by the hand-held first while held at arm's length and then held just a few inches from the head, in the normal talking position. These two received signal-strength measurements indicate how proximity to the user's head effects the radiation efficiency of the antenna. The receive signal strength was measured on a Hewlett Packard HP-8560A spectrum

Fig 14—2 meter matching network with the wire element.

analyzer set to 5-dB per division. This scale factor provides about 0.1-dB measurement resolution, which is far better than the measurement accuracy or repeatability for these tests.

For consistent readings, it is important to make the RF-level measurements insensitive to small variations in the position of the transmitting hand-held. This is best achieved when the ground reflection sums with the direct wave. So, the receiving antenna is positioned in the far field at a height and distance for a field strength maximum as calculated by

$$h1 = \left(\frac{\lambda}{4}\right)\left(\frac{s}{h2}\right) \qquad \text{(Eq 1)}$$

Where

$h1$ = height of the first maximum of the receiving antenna

$h2$ = height of the hand-held's transmitting antenna at its center

λ = wavelength transmitted, 2 m or 70 cm

s = the horizontal distance between the two antennas

For example, the 2-meter measurements are made at $h1$=14 feet, $h2$= 6.5 feet and s=55 feet. The 70-cm measurements are made at $h1$ = 5.5 feet, $h2$ = 4 feet and s = 40 feet. See the reference by John Kraus[3] for more details about choosing the best height for the antennas.

Results of the 2-Meter Gain Measurements

Here is how the performance of the homebrew end-fed half-wave antennas compares with a variety of commercial antennas. All measurements are made with the antennas vertically polarized. The gain of the homebrew antennas is as good or better than all of the commercial half-wave antennas and much better than any of the tested rubber ducks (Fig 15).

Notice in Table 2 that the greatest received signal strengths are created by the five end-fed half-wave antennas. The measured signals from all of the half-wave antennas are within 0.7 dB of each other. As a group, the end-fed half-wave antennas are an average of 1.4 dB stronger than the EMCO center-fed reference dipole. The EMCO reference dipole is less efficient possibly due to losses in its coaxial feedline and internal broadband balun. Notice also that the transmit signal strength of the end-fed half-wave antennas is not reduced more than a decibel or so when the hand-held is positioned in the normal talking position, near the head, rather than at arms length. The half-wave antennas are more efficient when near the body because the current maximum is at the center of the antenna and high above the head. There is also high current in the matching network coil at the base of the antenna, but its magnetic field seems to be confined enough so as not to interact much with the head and hand of the user.

In contrast, all of the rubber-duck antennas are much less efficient than any of the half-wave antennas. For example, the average of the transmit signal strengths of the rubber duck antennas is 5.9 dB weaker than the average of the half-wave antennas. The worst rubber duck is 7.9 dB weaker than the best half-wave antenna. This is very significant when you consider that a 6 dB increase in signal strength is the equivalent of multiplying your transmit power by a factor of four. (This loss applies on both transmit and receive.) Generally, the on-air tests of all of the antennas described in this article behave as the measurements would lead you to expect. In other words, the lower-gain antennas with high SWR usually are weaker into distant repeaters.

Fig 15—The hand-held antennas used for measurement comparisons to the homebrew half-wave antennas for 2 meters and 70 cm. In order from the left—Larson telescoping half-wave, AEA telescoping half-wave, Pryme quarter wave whip, Standard dual band for C510A, Larsen 2M, Larsen 70cm, Icom dual band for IC-Q7A, Standard dual band for C528A.

Table 2
2-Meter Antennas: Gain and SWR
(Note: See text "Accurate Hand-Held Radio Impedance Measurements".)

Antenna	*At arm's length*		*Near head*	
F$_0$=146.5 MHz (Vertical polarization)	*RF Level (Δ) in dBm*	*Impedance (SWR)*	*RF Level (Δ) in dBm*	*Impedance*
EMCO center-fed reference dipole tuned for 146.5 MHz [–19.5 (+0.0)]				
K0DK end–fed half–wave, whip	–18.7 (+0.8)	60–*j*0.6 (1.2)	–19.8 (–0.3)	73–*j*6
K0DK end–fed half–wave, stiff whip	–18.2 (+1.3)	55–*j*3.5 (1.1)	–19.3 (+0.2)	62–*j*10
K0DK end–fed half–wave, telescope	–17.7 (+1.8)	55–*j*8.9 (1.2)	–19.0 (+0.5)	58–*j*18
K0DK quarter wave, tape	–20.5 (–1.0)	93–*j*21 (2.0)	–22.5 (–3.0)	91–*j*17
Larsen end–fed half–wave, telescope	–17.3 (+2.2)	32–*j*28 (2.2)	–18.3 (+1.2)	43–*j*37
AEA end–fed half–wave, telescope	–18.3 (+1.2)	67–*j*0.6 (1.4)	–19.2 (+0.3)	78–*j*10
Pryme quarter wave, whip	–22.8 (–3.3)	100–*j*62 (2.9)	–25.0 (–5.5)	94–*j*57
Larsen 2 m rubber duck	–23.2 (–3.7)	56–*j*69 (3.4)	–25.6 (–6.1)	64–*j*68
ICOM 2 m/70-cm rubber duck for IC–Q7A	–24.2 (–4.7)	60–*j*26 (1.7)	–26.8 (–7.3)	64–*j*27
Standard 2 m/70-cm rubber duck for the C510A	–25.2 (–5.7)	63–*j*28 (1.7)	–28.0 (–8.5)	73–*j*26
Standard 2 m/70-cm rubber duck for the C528A	–23.3 (–3.8)	51–*j*53 (2.7)	–26.0 (–6.5)	55–*j*52

The results of the 2 Meter Impedance Measurements

All of the following antenna impedance measurements are made using the hand-held simulators shown above held at arms length. The drive-point impedances of all the antennas is measured using the HP8753D network analyzer in the manner described above. Read the network analyzer displays as follows - The upper part of the figure is a Smith Chart showing the impedance measured at the connector of the antenna plotted over a span of 10 MHz centered at 146 MHz. Three markers show the Z measured at 146.5, 144 and 148 MHz. Both the real and complex part of Z are shown as calculated from the S-Parameter S11. The lower part of the figure is a plot of SWR over the same frequency range as calculated from the measured impedance in relation to reference impedance of 50 W. The SWR markers are located at the same three frequencies. The bottom line of the graph indicates a SWR of 1:1 and the top line a SWR of 11:1.

From the Smith Chart in Fig 16 you can see that the SWR of the homebrew telescoping half-wave is pretty low across the band. This allows the hand-held power amplifier to drive the maximum power into the antenna for all frequencies. For some of the other measured antennas where the SWR is high the power amplifier of a given hand-held is often not able to develop enough voltage to drive the maximum power into the antenna. For example, the Pryme whip and the Larsen rubber duck exhibit a particularly high SWR making it unlikely that a hand-held will deliver its rated output power into the antenna. This factor contributes to the overall "inefficiency" of the antenna even though the power not transmitted into the ether is not lost as heat.

A low SWR for a hand-held antenna is also important when receiving a signal too because of the mismatch loss. For example, the received signal strength mismatch loss is about 1.25 dB for a SWR of 3:1. This is not a very great loss but can be important when signals are weak in a remote location or when you are inside a building or vehicle where the path loss to the repeater is very high.

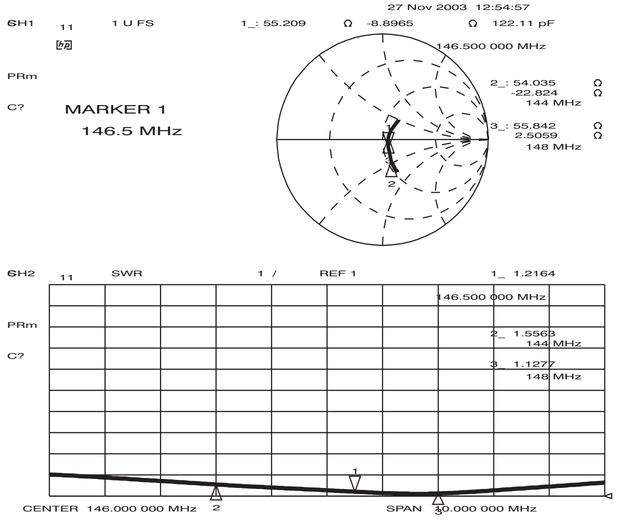


Fig 16—Impedance and SWR of the K0DK end-fed half-wave, telescope version.

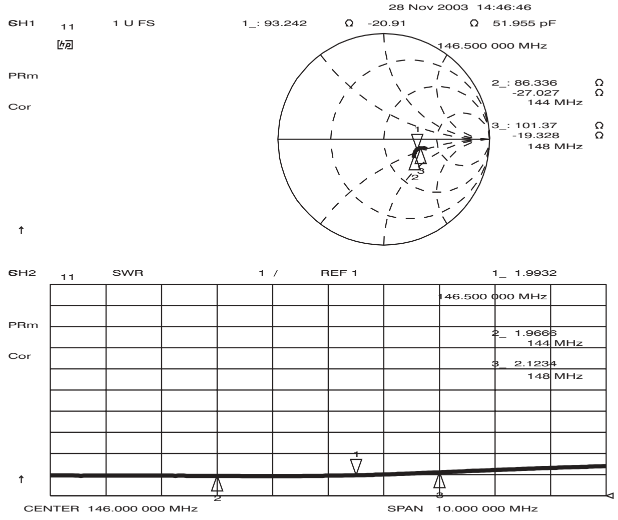


Fig 17—Impedance and SWR of the K0DK quarter wave, tape measure material.

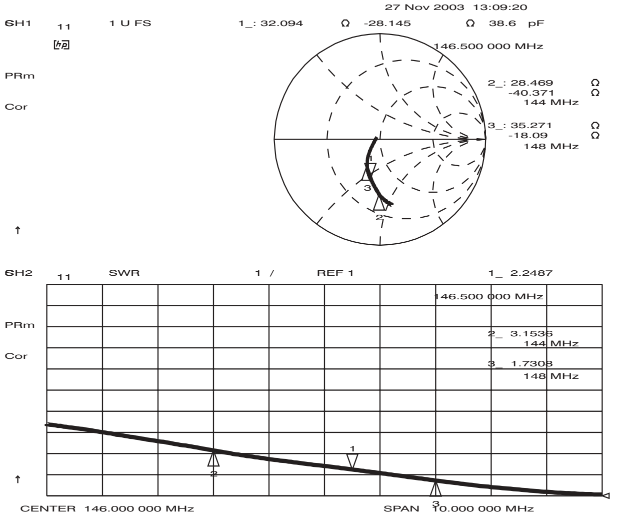


Fig 18—Impedance and SWR of the Larsen end-fed half-wave, telescope.

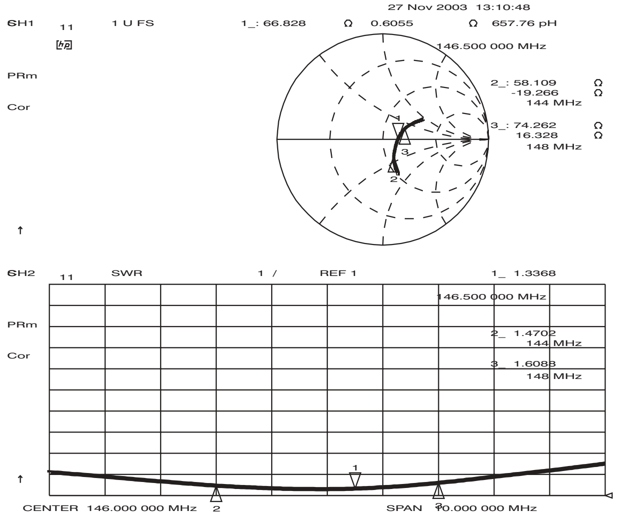


Fig 19—Impedance and SWR of the AEA end-fed half-wave, telescope.

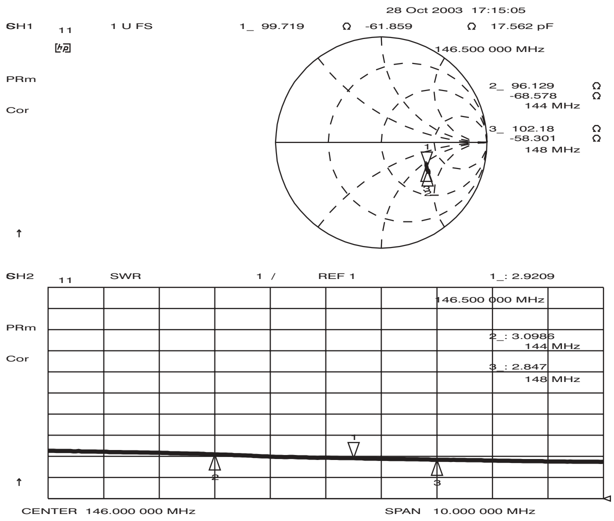


Fig 20—Impedance and SWR of the Pryme 2M/70cm quarter wave whip.

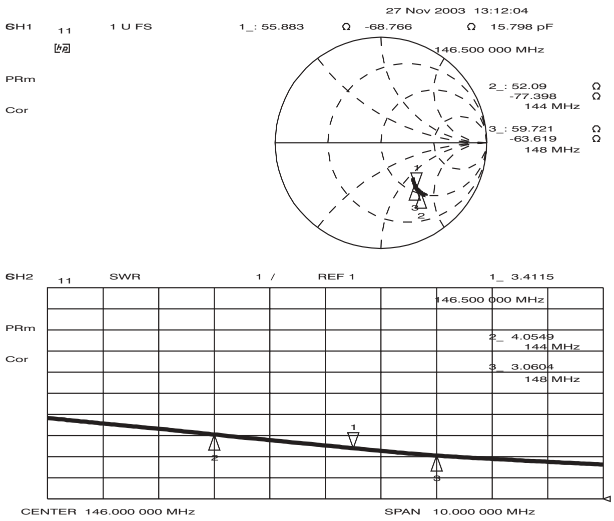


Fig 21—Impedance and SWR of the Larsen 2M rubber duck.

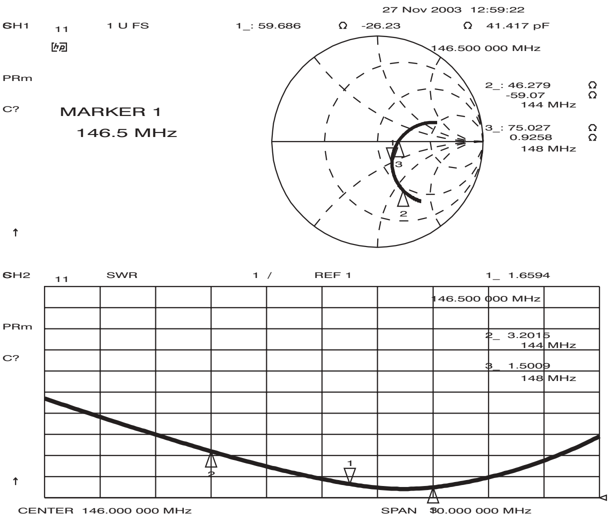


Fig 22—Impedance and SWR of the Icom 2M/70cm rubber duck for IC-Q7A hand-held.

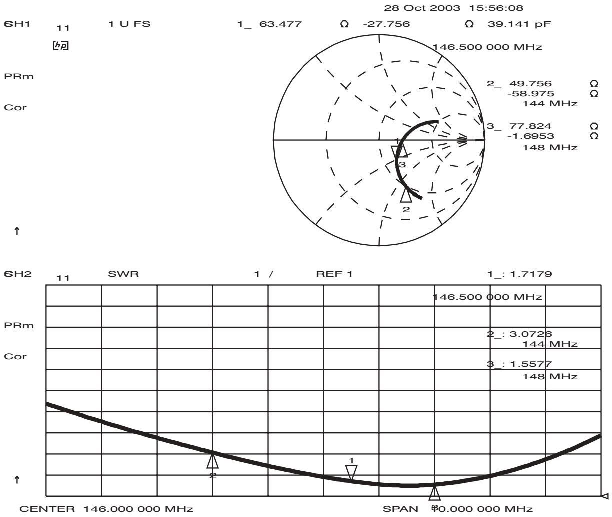


Fig 23—Impedance and SWR of the Standard 2M/70cm rubber duck for the C510A hand-held.

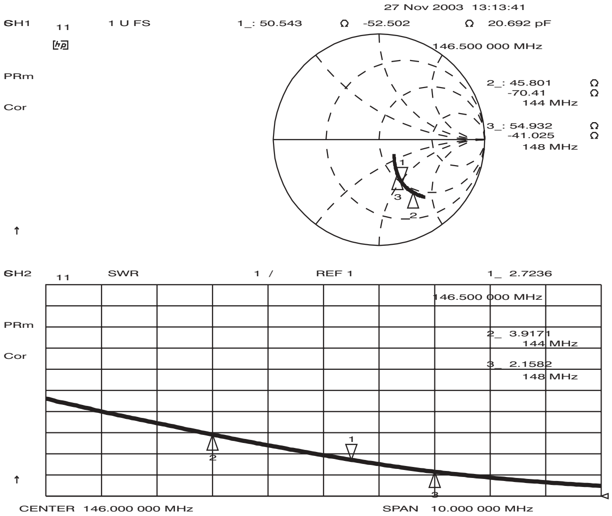


Fig 24—Impedance and SWR of the Standard 2M/70 cm rubber duck for C528A hand-held.

Results of the 70-cm Gain Measurements

Again, the homebrew half-wave antenna shows more gain than the rubber ducks. Refer to Table 3. In some cases, the advantage is slight, probably because the rubber ducks are much closer to a half-wave length on 70 cm than they are on 2 meters. For example, one half wavelength at 448 MHz is 33.5 cm and most of the rubber ducks used for this experiment are about 15-20 cm long. The transmit signal strengths of the rubber ducks are only an average of 4 dB worse than the

Table 3
70-cm antennas: Gain and SWR
(Note: See text "Accurate Hand-Held Radio Impedance Measurements".)

Antenna	*At arm's length*		*Near head*	
F_0=146.5 MHz (Vertical polarization)	*RF Level (Δ) In dBm*	*Impedance (SWR)*	*RF Level (Δ) in dBm*	*Impedance*
EMCO center-fed reference dipole tuned for 448 MHz [–32.5 (+0.0)]				
KØDK end-fed half-wave, whip	–34.3 (–1.8)	42+*j*10 (1.3)	–32.3 (+0.2)	46+*j*9.5
Pryme quarter-wave, whip	–40.0 (–7.5)	122+*j*19 (2.4)	–35.5 (–3.0)	137+*j*18
Larsen 70-cm rubber duck	–36.5 (–4.0)	56–*j*67 (3.4)	–39.8 (–7.3)	68–*j*58
ICOM 2 m/70cm rubber duck for IC–Q7A	–35.3 (–2.8)	38–*j*50 (3.0)	–36.0 (–3.5)	39–*j*41
Standard 2 m/70-cm rubber duck for the C510A	–34.8 (–2.3)	59–*j*48 (2.4)	–36.7 (–4.2)	56–*j*32
Standard 2 m/70-cm rubber duck for the C528A	–36.2 (–3.7)	66–*j*91 (4.4)	–38.6 (–6.1)	76–*j*75

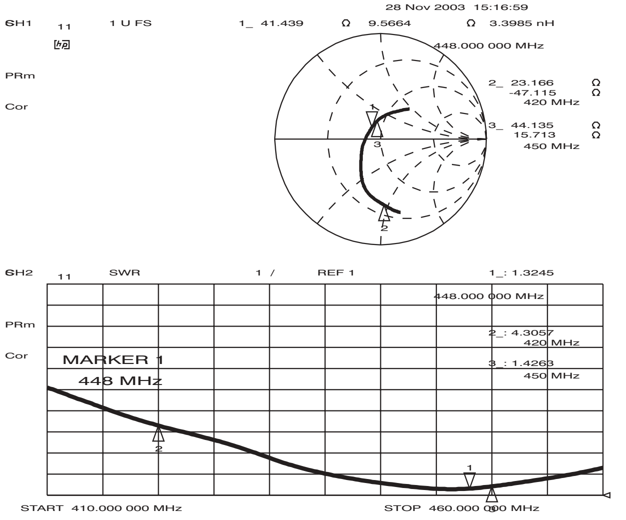


Fig 25—Impedance and SWR of the KØDK 70-cm end-fed half-wave, wire version.

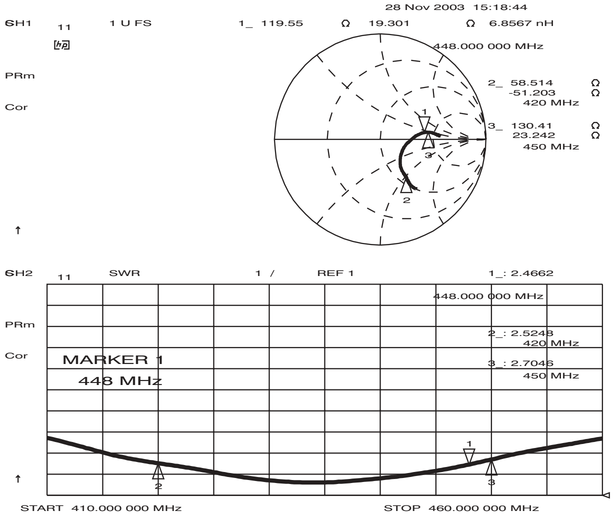


Fig 26—Impedance and SWR of the Pryme dual band whip at 70-cm.

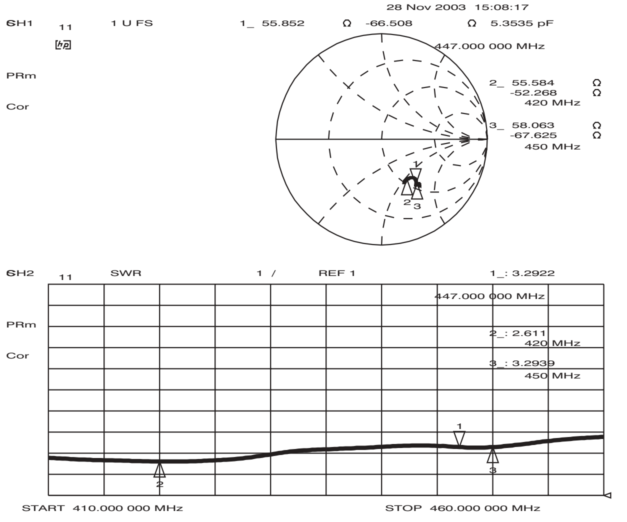


Fig 27—Impedance and SWR of the Larsen 70-cm rubber duck.

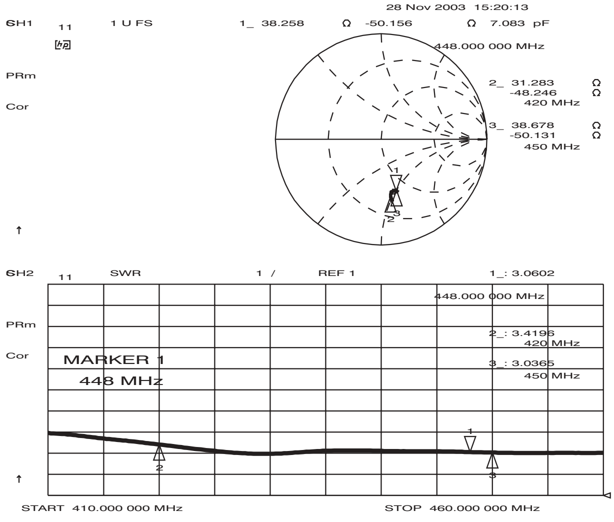


Fig 28—Impedance and SWR of the ICOM dual-band for IC-Q7A at 70-cm.

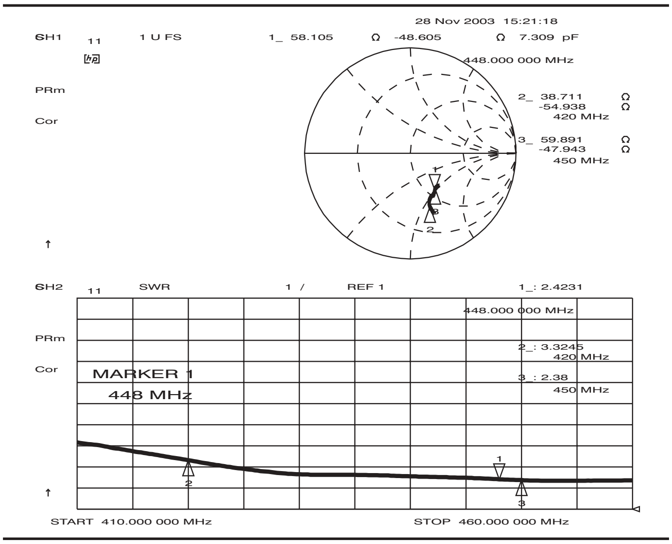


Fig 29—Impedance and SWR of the Standard C510A dual band duck at 70 cm.

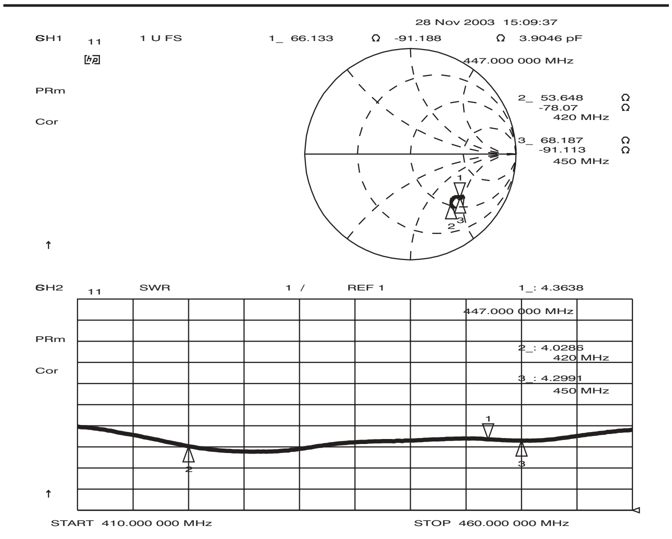


Fig 30—Impedance and SWR of the Standard C528A dual-band at 70 cm.

homebrew half-wave. This is not as large a difference as with the 2-meter antennas. Moving the rubber ducks closer to the head also reduces their gain as on 2 meters. The two whip antennas increased in gain when brought closer to the head of the user for unknown reasons. It is possible that the body acts as a reflector? It is also likely that the margin of measurement error for all of the data below is somewhat greater at 448 MHz than at 146.5 MHz because of the much shorter wavelength. Much smaller dimensional and positional differences also make a larger change in the readings.

*Richard Kiefer has been a licensed ham since 1959. His early interest in Amateur Radio led to Bachelor's and Master's degrees in Electrical Engineering with an academic emphasis in the subjects of radio-frequency and analog circuit design. He has worked as an electronics engineer since 1970, designing a variety of analog and RF circuits, antennas and microprocessor systems. He has also written software and firmware in several languages to control various circuits and hardware. Richard has worked for several electronic product-development companies, including IBM, Hewlett-Packard, Martin-Marietta and Armco Autometrics. For the past 24 years he has been the principal of Kiefer Electronic Development (***www.KED-Wireless.com***), an electronic product-development consultancy specializing in radio-frequency product design. He also holds five US patents. He currently enjoys working SSB DX on the 10-40 meter HF bands with a Yagi stack on a 100 foot rotating tower. He also works DX mobile through his EchoLink connected VHF repeater located at Boulder, Colorado. Richard's most recent interest is the study of efficient radio-spectrum management, including the Amateur Radio allocations, in relation to the recommendations of the FCC Spectrum Policy Task Force.*

Notes

[1] P. Smith, *Electronic Applications of the Smith Chart* (McGraw-Hill Book Company)

[2] C. Bowick, *RF Circuit Design*, (Howard W. Sams and Company) chapter 4, p 66.

[3] J. D. Kraus, *Antennas* (2nd edition, McGraw-Hill Book Company) section 18-3b, pp 811-813 and appendix E pp 870-871. □□