An Omnidirectional Gain Antenna for UHF without Radials

Challenged by a client to design a unique antenna for UHF, WB6IQN came up with a product that surprised him by the increase in gain over the typical collinear antenna. Here is his design adapted for the Amateur Radio Service.

By Ed Fong,* WB6IQN

It has been five years since I published my last article on antennas in *QST*. Since then, with the help of my graduate students, we have delivered over 5000 of both the base station (DBJ-1) and portable (DBJ-2) dual-band J-pole antennas[1, 2]. These antennas have seen use in both amateur and commercial deployment. I usually get my new ideas from fellow hams since they are the ones who use these antennas on a daily basis.

The antenna presented in this article came about through a request from a commercial telemetry company, AC Daughty Inc. in New Jersey. It had a very interesting request which I am sure is also shared by the ham community. AC Daughty Inc. makes telemetry equipment that transmits on the commercial UHF band (465 MHz) in a meshed network. Its application transmitted low power (less than +30 dBm). In the extreme, they would link 10–15 miles per hop. They needed more than just a rubber duck antenna or ground plane antenna. Here is a condensed summary of the specifications:

1. The antenna needed to be low cost (under $30).
2. It needed a gain of at least +5 dB over a $^1/_4\lambda$ whip that was placed on top of the transceiver metal cabinet.
3. The antenna had to withstand extreme outdoor weather conditions with winds over 100 mph and harsh winter conditions in New Jersey.
4. Absolutely no radials (or other protruding elements) due to increased wind load and birds perching on them. With hundreds deployed in a meshed network, they had to be maintenance free. I was told that just one field service call cost the company over $200.

AC Daughty basically wanted what every ham desires—low cost, high performance, and good reliability. The high wind load requirement, cost, and reliability eliminated a multi-element beam as a solution. It is unlikely that one could build a multi-element beam without complex machined parts for the target price. Also, each one would then need to be individually adjusted for best performance and periodically checked for detuning. In the northeastern United States, an exposed gamma match (as used in a beam antenna) would only last, at

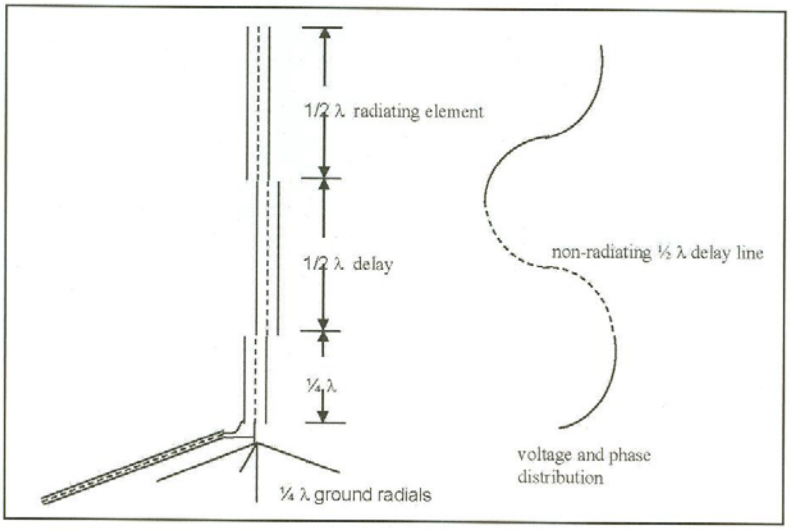

Figure 1. A 2-element collinear, using a ground plane as the root antenna. The voltage and phase are shown on the right.

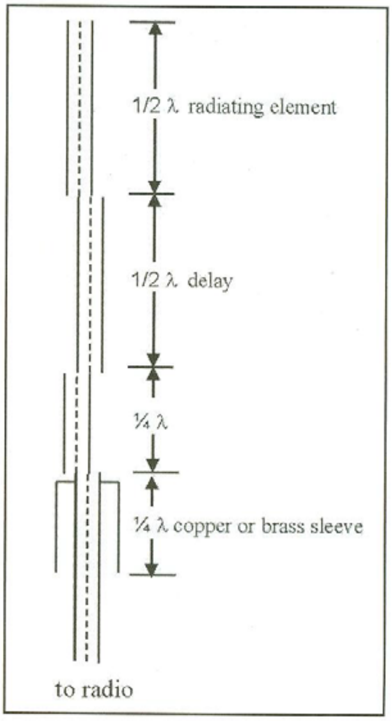

Figure 2. Many commercial antenna manufacturers use the $^1/_4\lambda$ sleeve in place of the radials for both durability and a slightly lower angle of radiation. Due to the high impedance at the end of the $^1/_4\lambda$ sleeve interacting with the coax shield, SWR of this configuration is usually high.

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best, a few years. The company's meshed network would have hundreds of these installed. Maintenance had to be kept to minimum since labor and transportation costs traveling to each site could easily become the dominant cost of the system. The engineer in charge, although not a ham, was very familiar with various antenna designs and their performance. He stressed several times, "no radials" because of the poor reliability. I could relate to that. Years ago I owned a Ringo® Ranger® and it had great performance, but radials and too many little protruding elements limited its life span. It lasted about five years until it was too difficult to maintain due to the aluminum radials breaking off.

In this article I will review some of the traditional methods of achieving omni-directional gain used by the ham community and commercial antenna manufacturers. Using these principles and with a novel delay line, a very low cost, easy to construct, high performance antenna has been achieved using easily obtainable parts. The antenna is completely enclosed in a 4-foot 3/4-inch PVC pipe. Measurements are compared to a rubber duck, ground plane, and standard 1/2λ J-pole. This antenna achieved a +5 dB gain over a ground plane and about +3 dB of gain over a single element J-pole.

Methods of Achieving Omnidirectional Gain

Historically, there are limited approaches to achieving omnidirectional gain. The J-pole gives about 2.1 dB over an isotropic radiator. The design goal was to achieve +5 dB over the rubber duck which was mounted on the metal transceiver cabinet. One could approximate this as a ground plane antenna. With this specification, it did not appear that a straightforward J-pole configuration would meet the specifications. It fell short by about 3 dB. The first step was to search the historical literature on how commercial manufacturers achieve omni-directional gain. The most common tried-and-true method is the collinear design made popular in the 1960s [3,4]. This configuration is commonly used for commercial base stations as well as repeaters. Virtually all commercial antennas with omnidirectional gain are based on the multi-element collinear as shown in figure 1. It basically works in the following way:

The first 1/4λ element works like a typical ground plane. The voltage plot is shown to the right of the antenna. If one were to

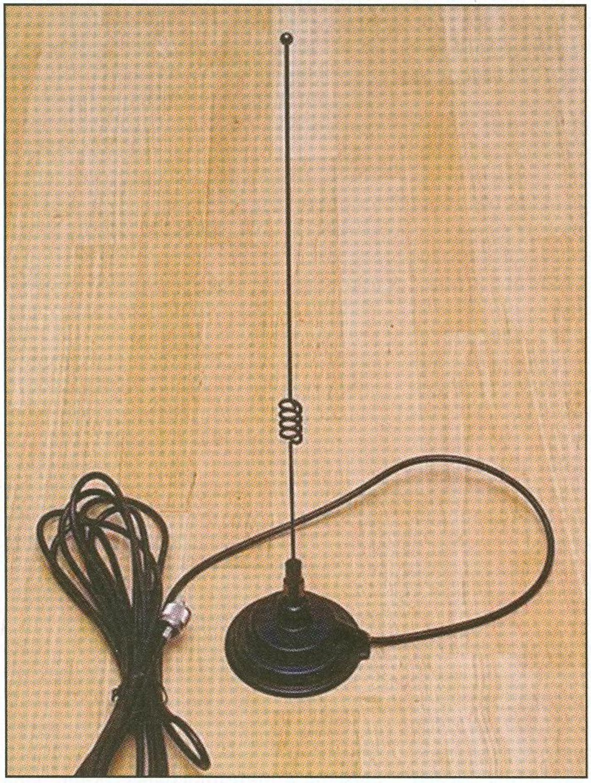


Photo 1. A very common configuration that claims gain at UHF. Measured results were minus 4–6 dB.

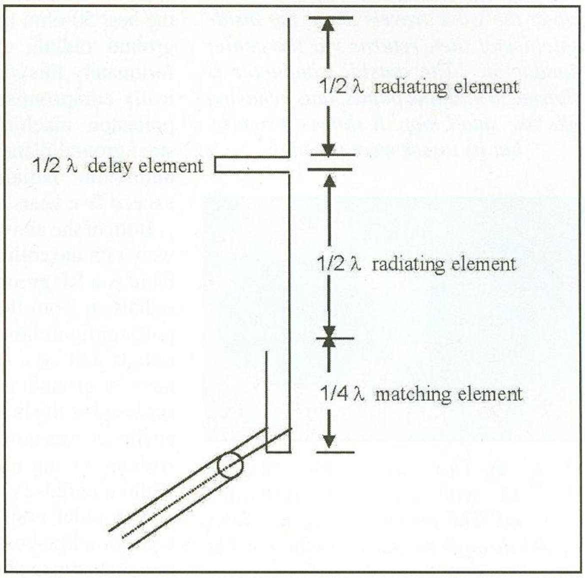


Figure 3. Known as the Super J®, this configuration consists of two 1/2λ in phase. The 1/2λ delay is achieved by using two 1/4λ elements at 90°.

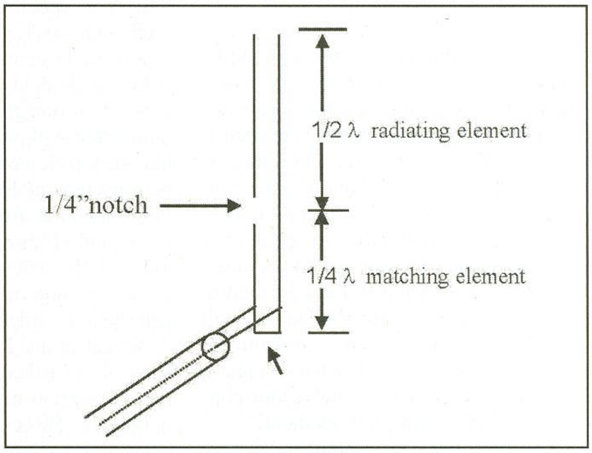


Figure 4. Typical dimensions for a J-pole at UHF constructed from 300-ohm twinlead. This is good starting point for the 2-element collinear.

Photo 2A. This is a shorted $^1/4\lambda$ loop made of RG174A with the outer insulation removed. This provides for a total delay of $^1/2\lambda$. Using the principle of skin effect the wave travels down the inside shield and then returns via the center conductor. The outside conductor is shorted at multiple points, thus behaving like one small loop. It showed promise, but its losses were too high.

Photo 2B. This is a $^1/2\lambda$ loop made of RG174A with the outer insulation removed. This provides for a total delay of $^1/4\lambda$ through the inside conductor. The outside conductor is shorted at multiple points, thus behaving like one turn small loop. This configuration should minimize radiation at UHF but the insertion loss was too high.

simply extend another $^1/2\lambda$, it would be out of phase with the main $^1/4\lambda$ driven element. This would not achieve gain due to phase cancellation. What is needed is a non-radiating $^1/2\lambda$ delay line. This is achieved by using the shielded outer conductor as the first $^1/4$ radiating element with the inner conductor as a ground reference. Then at $^1/4\lambda$ the shield and inner conductor are swapped and cascaded to a $^1/2\lambda$ coax. This second piece ideally will not radiate. When it comes out from the other end, the wave will be back in phase with the driving element and is then connected to a radiating $^1/2\lambda$ element.

This principle can continue indefinitely for a multi element phased array, but the point of diminishing returns occurs at about four.

Unfortunately, the design described above uses ground radials, which my client specifically did not want. To hide ground radials, several manufacturers use a fold back of $^1/4\lambda$ as shown in figure 2. This is sometimes known as a coaxial antenna. They often use a $^1/2$-inch copper or brass pipe and then feed the coax line through the inside of the pipe. This technique certainly works and solves the problem of the protruding ground radials, but I have found that low SWR is difficult to achieve due to the inherent coupling to the outer shield of coax being too close to the pipe. From my experience, the best 50-ohm match occurs with four ground radials drooped at 45°. Unfortunately, this configuration is mechanically compromised and requires some precision machining for high-quality steel ground plane rods. The lifespan of aluminum radials usually does not exceed five years.

Both of the above configurations work well with the collinear approach because there is a RF ground reference (from the radials or from the $^1/4\lambda$ sleeve). The J-pole configuration does not have ground radials and as a consequence does not have a ground reference that can be accessed at the bottom $^1/4\lambda$ section. The challenge was how could one obtain gain without having a ground reference and without radials?

A popular configuration that I have seen for a low-cost dual band configuration is shown in photo 1. Although this is the mag-mount mobile version, one could apply the same principles to a base station antenna. I know of at least three manufacturers that offer this antenna at under \$30. The specifications claim $^1/4\lambda$ at VHF and $^1/4\lambda$ UHF with a delay line of $^1/2\lambda$ from the center coil and a $^1/2\lambda$ as the collinear element. The theory behind this antenna is that the center coil will not radiate but will provide for $^1/2\lambda$ delay so that the top element will be in phase with bottom element. I have measured three of these antennas from different manufacturers and all three suffered 4–6 dBs of loss at UHF. They all performed well as a $^1/4\lambda$ antenna on VHF but had dismal performance at UHF.

At that point, I started to look at the Ringo® by Cushcraft®. This is also sometimes known as the Super J® [5] as shown in figure 3. This configuration uses a $^1/2\lambda$ delay line by configuring a right angle (90°) delay element between first $^1/2\lambda$ and the second $^1/2\lambda$. This delay element consists of a $^1/4\lambda$ going out and $^1/4\lambda$ returning. The radiation would be 90° out of phase of desired vertical radiation of the antenna. Also, the $^1/4\lambda$ delay line is balanced with currents going in equal but opposite directions, so some cancellation occurs between the forward and reflected waves from the coupling of the two lines. This contributes to the desired poor radiation of the delay line. The drawback of the Super J configuration is the physical construction. One does not have a simple, low cost, reliable method of physically attaching the two radiating elements and the phasing element. For this reason, it is primarily a "ham" antenna and will not survive the rigorous requirements of a commercial antenna.

Background on the J-Pole

To appreciate the design of the new gain antenna, a short review of the theory behind a J-pole is necessary. The basic J-pole antenna, constructed of 300-ohm twinlead, (figure 4) works in the following way:

The radiator is a half-wave vertical configuration, much like a dipole. What separates this design from a vertical dipole is the method of feeding the half-wave element. Because the feedline in a conventional dipole is center fed, the radiation pattern is disrupted due to the coax feeding the dipole element at right angles. The result is a radiation pattern that is off center since there is usually a tower or some kind of support structure which acts as a reflector parallel to the antenna. The J-pole resembles that of a true ideal vertical dipole with minimal disturbance from the feedline.

A question often asked is why does the J-pole achieve gain over a conventional ground plane? A simple explanation is that a J-pole is a true $^1/2\lambda$ vertical antenna. The counter element is 180° from the radiating element. In a ground plane antenna, the counter elements are the ground radials, which are between 90° and 135°. This arrangement will result in a higher angle of radiation.

The J-pole works by matching a high-impedance (the ends of the dipole) to a low-impedance point (50 ohms in practice). In a $^1/2\lambda$ antenna, the ends are high impedance and the center is the low impedance point. If one wants to match the ends to a $^1/2\lambda$ vertical dipole then it must be a high-impedance point. This condition is satisfied with a $^1/4\lambda$ shorted stub at one end and open at the other. The

50-ohm tap point is about 1/2 inch from the short for UHF[1,5].

The New Design

For a no-ground radial design, the J-pole is certainly a good choice. It has about a 1.5 dB gain over a ground plane. This is a great start. The trade-off is that it is 1/2λ taller than a ground plane and 1/4λ taller than a coaxial antenna. Fortunately, at 70 cm this is less than 6 inches.

In the traditional collinear design as shown in figure 1, one had a clever access to a ground reference which is not available in the J-pole. This ground reference is needed in the traditional collinear to suppress the radiation of the out-of-phase radiation. How does one achieve this without the ground reference? The Ringo® (or Super J®) accomplishes this task by using a 1/4λ element going out and 1/4λ element coming back in at 90° of the vertical radiators as shown in figure 3. The radiation pattern of the delay line is therefore orthogonal to the two collinear elements. The weakness of this approach is that this delay element is fully exposed, protruding out of the main elements.

Some of the lower-end commercial designs achieve the phase delay with an LC circuit. This is not optimum due to losses and tolerance as the antennas age. It is very difficult for the average ham to build and test LC circuits at VHF or UHF. To minimize radiation from the coil requires unlimited patience to determine the exact dimensions. I personally constructed numerous coils using recommended dimensions but none succeeded in any appreciable antenna gain. Some even suffered a net loss. The new design presented here uses no inductors or capacitors and thus reproducibility and durability over time should be superior over the LC approach.

Of the designs I studied, I chose the Super J as a starting point because it seemed to be the easiest to construct, although it did not meet the physical durability requested by the client. Sure enough, when I followed the directions in the *ARRL Antenna Handbook* and adjusted it for lowest SWR, signals from repeaters were on average 3–4 dBs stronger compared to a ground-plane. This validated the claims of this design. To obtain consistent results, I was on top of my roof accessing a repeater 10 miles away and using my HP8591E spectrum analyzer down in the shack.

The key to a successful 2-element collinear is to minimize the radiation of the 1/2λ delay element. I tried several methods to achieve the 1/2λ delay using a J-pole as the baseline antenna. One was with a 1/4λ RG174a coax shorted at one end with the insulation removed. Using the principles of skin effect, I coiled up the 4 1/2-inch stub and soldered it as one piece. Thus, the outside of the coax would behave as a 1/2-inch one-turn inductor but the inside would see a "balanced" transmission line with 1/4λ going down the inner shield and the center conductor would be the 1/4λ return path as shown in photo 2A. The diameter of the coil would just fit right over the twinlead of the J-pole antenna. This seems clever, but measurements could not confirm any appreciable antenna gain when it was used as the delay element. Turns out the losses are quite severe, since the RG174 coax was now being driven by a high impedance and not the intended 50 ohms.

Another method that failed was using a 1/2λ coax (with outer insulation removed) coiled up as one turn with the outer shield all soldered together as shown in photo 2B. The center conductor was used as the delay line and it was hoped the coiled-up outer shield would not radiate. The result showed some promise but did not provide

Photo 3. This is a close-up of view of the interface between two J-pole pieces using RG174 coax. Four Amidon® Corp. FT-23-61 ferrites were inserted through the RG174 coax to minimize common mode currents.

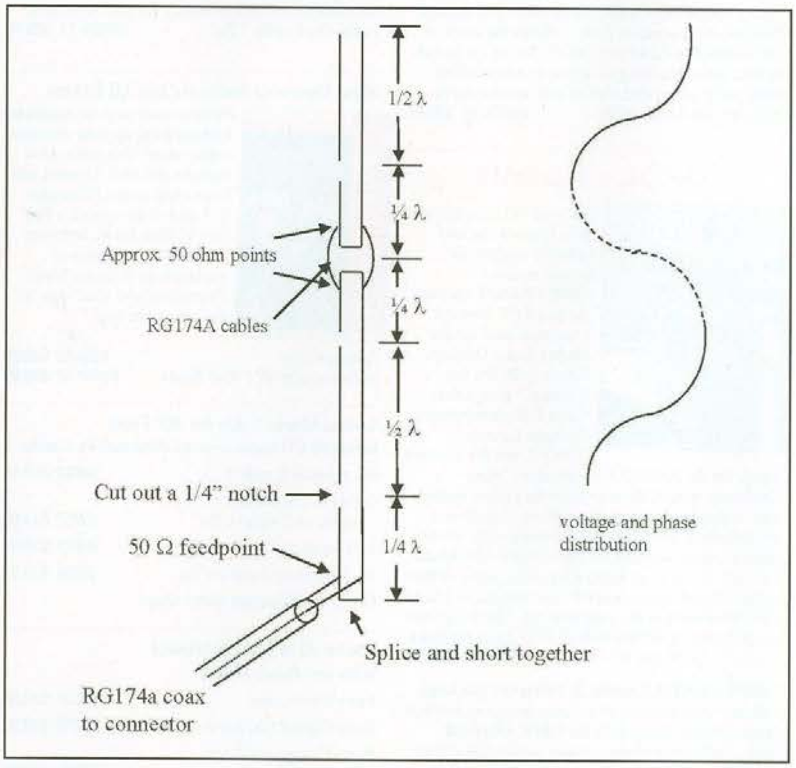


Figure 5. The 2-element UHF phase collinear with the voltage and phase given on the right. Dimensions are given for insertion into 3/4-inch 200 PSI PVC pipe.

the desired gain of 3–4 dBs. The losses were just too large inside the coax since it was meant for 50 ohms matching and the ends of the delay line needed to be in 1000s of ohms to interface with the ends of the J-pole. To be successful, what was needed was a low-loss $^1/_2\lambda$ delay line that did not radiate and that could also fit into a $^3/_4$-inch PVC tube. I concluded this was not trivial.

The most successful technique was to use the 300-ohm twinlead as the delay element. As a balanced line, the 300-ohm twinlead will give much lower loss when the line is mismatched and also will be a poor radiator. In principle, I used a shorted $^1/_4\lambda$ stub virtually identical to the one on the bottom that drives the antenna. This would just be launching the antenna back into a transmission line identical to the method that was used to feed the antenna from the bottom. From there, one locates the 50-ohm tap point and then feeds it back into an identical J-pole as shown in figure 5. Photo 3 shows how the two J-pole antennas are connected with RG174 coax cable inserted through four Amidon FT-23-61 RF ferrrites. We found no measureable difference in performance with or without the ferrites. In theory, the ferrites should suppress the common mode currents on the outer shield of the RG174.

Method of Construction

The antenna is inserted into 4 feet of $^3/_4$-inch 200 PSI PVC pipe as opposed to Schedule 40 (aka 400PSI). My graduate students have done extensive testing and found that it has the best RF characteristic compared to other plastic pipes on the market. Coincidently, it is also the least expensive, because it is about one-half the thickness of the ubiquitous Schedule 40 material. The wider diameter of $^3/_4$ inch also allows for easy mounting of an SO-239 or an N connector at the bottom end cap. In the construction of the antenna, I found that it was easiest to first construct two independently working J-poles at UHF. Then with one working, add a $^1/_4\lambda$ shorted stub at the top end. Adjust the $^1/_4\lambda$ stub until adding it at the tip of the first J-pole makes virtually no changes in SWR at the operating frequency (e.g., 445 MHz). A stub too long will lower the resonant frequency and a stub too short will raise the resonant frequency. To check the SWR, it must be reinserted into the PVC pipe for the actual measurement. This is because the PVC pipe has a different velocity factor compared to air. The resonant frequency will always drop slightly when inserted into a PVC pipe. After the exact dimensions of the $^1/_4\lambda$ shorted stub are determined, all that remains is to solder the second $^1/_2\lambda$ dipole as shown in Figure 5.

When sliding the antenna into the PVC tubing, I found no need to anchor the antenna once inside the tubing. The 300-ohm twinlead is adequately rigid and will not bend once inside the tubing. Also, be sure to give about 10 inches of RG174 at the bottom before connecting to the SO-239 (or N) connector for mounting. This is because the quarter-wave matching stub is very sensitive to surroundings, such as an antenna mast. The antenna should be clamped only at the bottom 10 inches to assure optimum performance.

Measured Data versus EZNEC Modeling

To determine the antenna's performance, we both modeled the antenna on EZNEC and took careful measurements. John Stanley, K4ERO, performed the modeling on EZNEC. This was not an easy task given the antenna configuration. An ideal two-element collinear separated by $^1/_2\lambda$ is easy to model and is shown in Figure 6A. It shows a gain of 5.4 dBi. However, building such an antenna would be impossible. The ideal model assumes that the elements are perfectly driven with an infinitely small generator with no lead in coax and perfect matching. Obviously, this ideal is an unrealistic but good starting point.

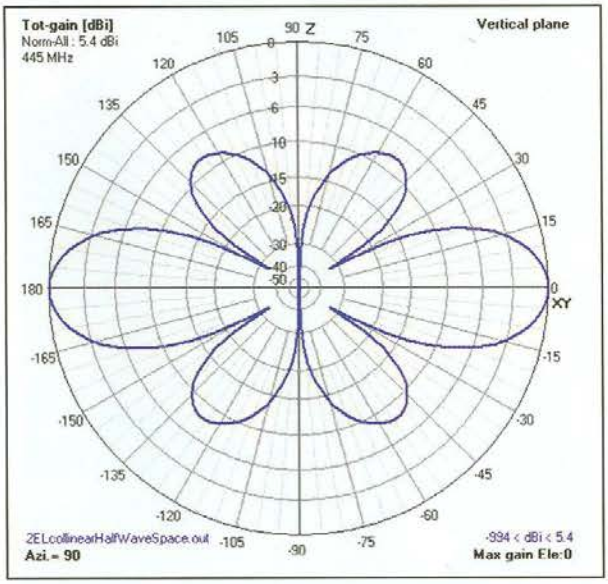


Figure 6A. Ideal simulation of a 2-element collinear separated by $^1/_2\lambda$.

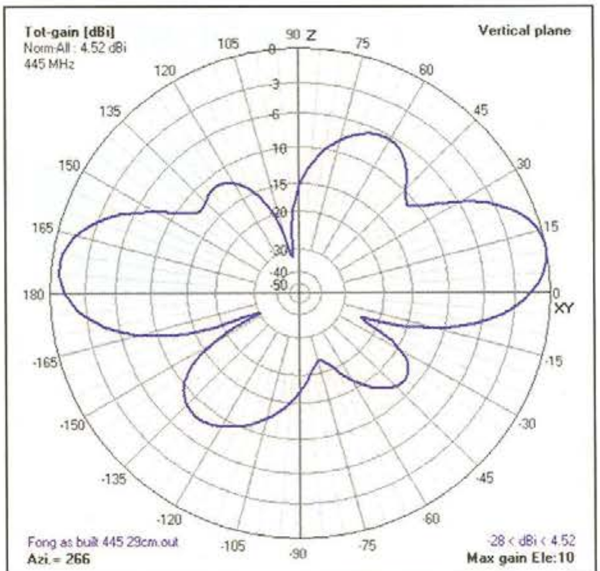


Figure 6B. EZNEC simulation of the 2-element collinear. The model includes all of the $^1/_4\lambda$ matching elements as well as coax interface of the two active elements. It also includes the electrically disconnected portions of the twinlead that physically remain as part of the antenna.

	Ground Plane	J 1-element J-pole	J 2-element collinear
Theoretical	1.35 dBi	2.1 dBi	5.4 dBi
EZNEC (as modeled from figure 5)	1.35 dBi	2.1 dBi	+4.52 dBi
EZNEC (adjusted) using ground plane as the reference point`	0 dB (ref)	+0.75 dB	+4.05 dB
Measured	0 dB (ref)	+1.78 dB	+4.98 dB
	Reference Ground Plane	**Standard J-pole**	**2 element collinear**
	relative dB	relative dB	relative dB
	–68.5	–66.3	–63.32
	–68.19	–66.2	–63.42
	–68.47	–66.63	–63.25
	–67.91	–66.5	–63.37
	–68.38	–66.89	–63.21
Average	–68.29	–66.504	–63.314

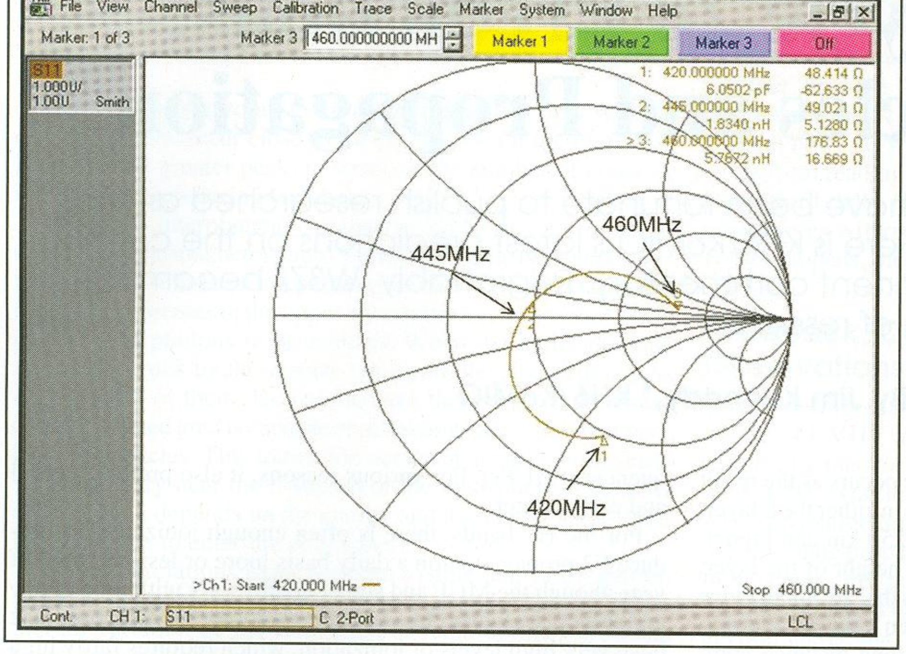
Table 1. Relative gain to a ground plane as measured with a repeater 10 miles away. Each entry was taken five times and what is shown is the average value.

A more realistic and much more complex EZNEC model is needed to include the $^{1}/_{4}\lambda$ matching section at the bottom $^{1}/_{2}\lambda$ delay line in the middle. The small piece of RG174A connecting the top and bottom sections of the antenna are also included in the model. In addition, the cutout pieces on the twinlead (which are not electrically part of the antenna but remain physically) will affect the final pattern. The EZNEC pattern of the full antenna is shown in Figure 6B.

One is reminded that EZNEC is only a modeling program. It is not perfect but gives very good "relative" guidelines. For example, the RG174 coax line that connects the top and bottom half as shown in figure 5 varies in length. It is part of the $^{1}/_{2}\lambda$ phase delay line. EZNEC had determined that 29 cm was the optimum length. Through many experiments, 6 cm resulted in the highest gain.

The input impedance of the antenna was measured with the Agilent 8364B network analyzer and the results are shown in figure 7. Although the matching is not perfect at 445 MHz, it is more than adequate. This antenna was extensively tested in a live airlink. The transmitter (W6VB) was located 10 miles away at 2800 feet (latitude 37.3° and longitude 122.09°). It was completely line-of-the site of our test antenna. All mea-

Photo 4. Here is my daughter, Tessa Fong, KJ6QXM, next to the completed antenna mounted on our roof.



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Marker: 1 of 3    Marker 3 460.000000000 MH
1:   420.000000 MHz    48.414 Ω
          6.0502 pF   -62.633 Ω
2:   445.000000 MHz    49.021 Ω
          1.8340 nH    5.1280 Ω
> 3: 460.000000 MHz    176.83 Ω
          5.7672 nH    16.669 Ω
>Ch1: Start 420.000 MHz    Stop 460.000 MHz
Cont.   CH 1: S11   C 2-Port
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Figure 7. This is a network analyzer plot of S11 taken with an Agilent 8364B network analyzer. The antenna is tuned for 445 MHz. It is not perfect, but certainly very close at 445 MHz.

surements were taken five times within two hours on a clear day at 83° Fahrenheit. This exact measurement-taking is critical because propagation varies with humidity and temperature. Measurements were confirmed by four of my graduate students, all with Masters of Engineering degrees.

The antenna was mounted in a clear spot on top of a one-story A-frame building as shown in photo 4 with my daughter Tessa Fong, KJ6QXM. It is 18 feet above the ground. All antennas tested were mounted within a ±$^1/4$-inch error. Extreme care was taken that all participants confirmed the readings on the spectrum analyzer and hardware setup.

Table 1 shows the results of the various configurations as measured from my roof accessing the W6VB repeater. The results are the average of five measurements for each entry. The instrument used was an Agilent 8591D spectrum analyzer. We measured about +5 dB of gain over the reference ground plane and approximately +3 dB over the single-element J-pole. This agrees well with the theory. To achieve anymore appreciable gain, one would need to double the number of elements for each +3 dB. We did not construct a 4-element collinear, but there no reason why this trend would not continue.

This configuration is not just limited to the UHF band; the dimensions can be scaled to the VHF 2-meter band as well. The only drawback is that at VHF, the antenna is $1^3/4\lambda$ long, which at 2 meters is $3^1/2$ meters (about 10 feet).

If you wish a sample of this antenna, I can construct (or have a graduate student construct) one of these antennas cut to the frequency of your choice. The cost is $40. Please e-mail me at <edfong@ieee.org>.

Acknowledgements

I wish to thank John Stanley, K4ERO, for his help in the EZNEC modeling of the antenna and also my graduate students Randel Blake, Meni Jayaswal, Jessica Le, and Paul Lazar in testing the antenna. Special thanks are given to my daughter Tessa Fong, KJ6QXM, for helping me build many of the prototypes.

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