# Ninety-Eight Percent Plastic Yagi Antenna for Six Meters

*An experiment in building an inexpensive but effective antenna.*

In the year 2018, I decided to get back on the six-meter band, after a long hiatus.  I like to build antennas, so I began looking around for an appropriate design.  I became interested in the four-element Yagi antenna designs for 144, 222, and 432 MHz, using folded dipole driven elements [1], by Rick Campbell, KK7B.  A version scaled for the six-meter band would make a nice, modest-sized antenna with a boom length of ten feet, and having good front-to-back (F/B) ratio.

## Design Considerations

Back in the days when I lived out in the countryside where electrical noise is low, I didn't want very good F/B ratio, as I deemed receiving off the back of the beam to be advantageous on a normally uncrowded band like six meters.  But now that I am living in town, there are troublesome noise sources, such that a clean pattern and good F/B are desirable.  On a boom length of ten feet, a three-element Yagi design can provide a similar forward gain to a four-element design, but I am not aware of a three-element design that produces as good F/B ratio.  Using the construction method described below, the advantages of the fourth element come at an additional cost of only a few dollars.

I began researching sources for aluminum tubing for the antenna, and to my consternation, I found no local sources of ten-foot length. Many antenna builders use shorter lengths of telescoping tubing and the builders join these to reach the required lengths, but I also know that aluminum joints can be problematic in terms of preserving good electrical connection. Aluminum surfaces are strongly prone to oxidation, even when they are seemingly well-connected mechanically. I investigated some on-line sources for the full-length aluminum. When I added up the prices including the shipping costs, and I added more costs for the various brackets and mounting hardware, I found the total cost was getting very close to that of commercial antennas. That seemed to defeat one of the advantages of building the antenna myself.

When shopping for the aluminum in local hardware and home improvement stores, I noticed that polyvinylchloride (PVC) tubing was readily available in ten-foot lengths at very low prices as compared to aluminum. Although PVC is certainly more “floppy” than aluminum, I began thinking of using the PVC as support for wire to be strung inside to form the elements of the Yagi. In particular, I noticed the grey PVC tubing that is sold for use as conduit for electrical wiring. Presuming that the grey color would probably be more resistant to damage from the ultraviolet (UV) light of the sun as compared to the whitish PVC used for plumbing, I decided to use the grey, which is claimed to be UV resistant. For the elements, I chose the “1/2 inch” size conduit, which is about 0.845 inches in outside diameter. In looking for something for the boom, I noticed some dark grey schedule 80 (rather thick wall) “1 inch” PVC pipe, about 1.32 inches in outside diameter, in 10-ft length, that appeared it might be suitable. I chose it.

I began thinking of the risks of using the PVC material. Its use for support in non-vertical installations has been discouraged by various builders. It certainly would violate many of the rules for good strong Yagi design laid down in the book, *Physical Design of Yagi Antennas* [2], by David Leeson, W6QHS. Would it survive wind storms? Would it stand up to the winters, which are certainly not the worst, but can be moderately bad, here in the mountains of Virginia? Would it rapidly decay in the sun? I expected some initial droop in the elements and boom, but would the droop continue to increase until the antenna folded nearly double? I decided that since the material is cheap, I would have little to lose except some time invested, and it would be an interesting experiment to try it.

In planning the design of the elements, I became concerned about how the PVC might alter the electrical length of the wire inside. I don’t have access to an electromagnetic field solver that could give a quantitative answer to this problem. I tried using a dip meter, but I could not get good coupling and the element had such a broad resonance that I could not determine anything useful. Also, I recognized that “fatter” elements, as compared to mere skinny wire, would probably provide broader bandwidth and less-critical length tolerances, as well as lower losses. So I began to think of covering the non-driven elements with adhesive-backed aluminum tape of the sort used for sealing joints in metal ductwork. The electrical skin depth in aluminum at 50 MHz is about 11.6 micrometers, which is less than half a thousandth of an inch. The aluminum portion of the tape is about 2 thousandths of an inch thick, which is more than four skin-depths. Thus, the tape is essentially as conductive at 50 MHz as aluminum tubing of any greater thickness. I selected the 3M type 3340 foil tape, which is advertised for use on dryer vents (hot service) as well as for cold weather uses. The tape is available in several widths, with 2.5 inch width being common and inexpensive, so I used this width, even though it is not quite wide enough to surround the full circumference of the PVC element.  I installed the tape with the gap, about a quarter-inch wide, at the bottom of the element, for best weather and UV protection of the PVC.  With virtually the full circumference covered, I could treat the elements as simple 0.85 inch diameter cylindrical conductors, with negligible error, in an antenna analysis program.

Regarding the design of the folded dipole driven element, I planned to slip some twin-lead, of 300-Ω characteristic impedance, inside the PVC conduit.  I would bring the twin-lead conductors out through drilled access holes near the center of the element for attaching the feedline and tuning mechanism.  I planned to do this by first dropping some strings through the holes down to the open end, then attaching the strings to the conductors of the twin-lead, and pulling the twin-lead in such that the conductors emerged from the holes.  The twin-lead would be installed in two pieces, each piece being half the overall length, one from each end.  However, I discovered that twin-lead, which used to be ubiquitous, could no longer be purchased locally.  I could order it, but I didn't want to wait, and I decided instead to form the parallel wire line with some #12 stranded insulated electrical wire, with outer diameter about 0.13 inches.  The wire would be installed on the outside of the PVC conduit.  Due to the presence of the wire insulation and PVC conduit, I would not know exactly what length to use, but I would let the tuning mechanism (described later) bring the driven element to resonance (zero reactance).

To begin the detailed design, I used Rick Campbell's dimensions for the 144.2 MHz version, and scaled these to 50.2 MHz.  The element diameter scaled to 0.359 inches, and as I planned to use a diameter of about 0.85 inches, I did some manual "tweaking" of lengths and spacings, using the antenna analysis program, EZNEC [3] (an old version 4.0), to get a more-nearly optimal solution for my elements by trial and error.  The EZNEC program has provision for modelling insulated wire, so I took advantage of this for the driven element, but I had no way of including the effect of the PVC conduit supporting this element.  Also, I planned to wrap the wires for the folded dipole driven element in helical fashion around the PVC conduit such that the wires would "hug" the conduit so as to keep the wires well-supported and consistently spaced on opposite sides of the conduit.  Variable wire spacing due to loose wire could cause the input impedance to vary, so I wanted to keep the spacing consistent.  Although EZNEC has provision for helical wires, I was not sure I could properly model this arrangement of the driven element wires in EZNEC, with the close spacing, and also get the ends correctly connected.  I instead used straight wires in the folded dipole driven element modelling.  Since the currents are in the same direction in the two adjacent conductors at any point along the length of the folded dipole, a few twists in the conductors around each other have virtually no effect on the radiation characteristics.  When building the actual antenna, I shortened the driven element and added a tuning loop to bring the resonance close to that of the model.  (See the Tune-up section for details.)

The as-built lengths of the antenna elements and the element positions are shown in Table 1.

According to the modelling results, the free-space gain should be about 9.3 dB with respect to an isotropic antenna.  The F/B ratio should be about 28 dB, and the horizontal beam-width should be about 53° at the -3 dB points.  Other folks might apply more effective optimization to get a bit better result, but I judged this result sufficient for my purposes.

## Construction Details

I wanted a low-cost method of attaching the elements to the boom without significantly weakening the boom. A single bolt could attach an element to the boom, but this arrangement would allow the element to pivot such that the element could no longer be counted on to remain perpendicular to the boom. I needed something to interpose between the element and the boom to assure the perpendicularity. The PVC conduit for the elements has an expanded end, such that sections can be telescoped together to form longer runs. I cut off the expanded ends when I cut the elements to length. I realized that short sections of these otherwise-scrap expanded ends could be worked into items that would preserve the needed perpendicularity. These are functionally analogous to the metallic items sometimes called “saddles” or “nests” which are used with antenna mast U-bolts to secure a mast pipe to another item. I am unaware of an established name for the items I made, so I am calling these “cross-saddles”.

To make the cross-saddles, I cut four half-inch long cylindrical sections from the expanded ends of the conduits. These were a convenient diameter between that of the elements and boom. Using a rotary grinder on a Dremel® tool, I ground two semicircular notches into one face, and two semicircular notches into the other face. These were oriented such that the axis of the two notches on one side was perpendicular to the axis of the two notches in the other face. Figure 1 is a photograph of the cross-saddle, showing the arrangement of the notches. Figure 2 shows the cross-saddle in place between a PVC tube representing the element on top and a cardboard tube representing the boom underneath. If I had a machine shop, I could have made the cross-saddles precisely and interchangeably. But since I was working by hand, I did trial fits, placing the cross-saddles between the boom and element, using a carpenter’s square to check the angle, and making small alterations with the grinder to get the desired right angle. I made the radii of curvature of the notches for the element a bit smaller than the radius of the element. Likewise, I made the radii of curvature of the notches for the boom a bit smaller than the radius of the boom. These measures insured that the corners of the notches made a tight fit to the two tubes, preventing any wobble. Then one bolt, passing through the element, down the axis of the tube of the cross-saddle, and through the boom, was sufficient to firmly secure each element in place. I used stainless steel ¼-20 machine screws 3-inches long, with stainless lock nuts with nylon inserts and stainless flat washers on the top of the element and bottom of the boom at each of these four locations.

To drill the holes in the elements and boom, I used a hand-held electric drill with a ¼ inch bit. I placed the boom on blocks on a flat floor and placed a cross-saddle on the boom, with the cross-saddle centered at the spot where the element was to be attached. Next I placed an element on the cross-saddle, used a punch to form an indentation in the center of the element, and then drilled down through the element and boom, passing through the axis of the hole in the cross-saddle. I temporarily installed the machine screw and nut, and placed spacer items (typically, books) under the ends of the attached element to hold the element parallel to the floor. Before drilling the hole for the next element, I placed spacer items of the same height under the ends to assure the element would be mounted in the same plane as the first element. Then I proceeded to assemble, drill, and attach as before, and continued to follow the same procedure with the remaining elements. Using this hand-assembly method, the elements are assured to be in the same plane and perpendicular to the boom, but the cross-saddles will not be interchangeable. Before disassembling, I labelled each cross-saddle to identify its associated element, and marked the front upper notch so it could be re-assembled in the same position and orientation later. I also marked the upper surfaces and right-hand ends of the elements, and marked the upper surface of the boom, since the drilled holes are not precisely vertical and centered. I used this method to first attach the three non-driven elements. I delayed the drilling for the driven element until after tune-up, to allow for some re-positioning that might be needed to get a good match for the driven element.

To avoid any possible tearing of the aluminum tape when drilling, I drilled first and then applied the tape to the PVC reflector and director elements after disassembly. I laid the tape down in one continuous strip on the upper side of the element and wrapped the tape around the element so the gap would be on the underside. Using a wood dowel, I rubbed the tape firmly all over to assure a good bond everywhere between the tape and PVC. Once the tape was in place, I removed the bit of tape over the drilled hole using a utility knife.

In the case of the driven element, it would not be taped, but would have wire applied, out to each end and back, to form a folded dipole. To keep the wire consistently spaced and hugging the PVC, I installed the wire with two full rotations around the PVC support, in each direction from the center out almost to the ends. At one-half inch from each outer end, the wire passes through a hole drilled through the PVC element. The PVC conduit was cut about one inch longer than the overall length of the folded dipole to accommodate the holes. Figure 3 is a sketch (not to scale) of the driven element, showing the routing of the wires, plus the tuning loop, balun, and feedline. The wires are pulled tight, and the wire ends are secured to sheet-metal screws that are screwed into the PVC conduit. These screws are also the attachment points for the tuning loop and feedline, as shown in the figure. After tune-up, I applied silicone room-temperature vulcanizing (RTV) sealant to the screws and to the open end of the feedline including the shield and center conductor to provide weather protection and prevent water ingress. As a precaution, I applied two plastic tie-wraps, equally-spaced, around the wires and PVC conduit, on both halves of the driven element, just to assure the wires remained on opposite sides of the support tube. With the helical installation of wires pulled tight, I’m not at all sure this step was necessary, but it provided cheap assurance.

Rather than buying a metallic mounting plate to attach the boom to the upright, I purchased an inexpensive plastic cutting board, 8” x 10” in size, about ¼” thick, which had good stiffness and strength. It was white in color, so I painted it black for additional UV protection. I drilled holes in it to accommodate four television antenna u-clamps, two clamps for the upright support pole and two for the boom.

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## Finishing touches

I didn’t like the looks of the red printing on the aluminum tape, so I removed the printing by rubbing with a cotton ball dipped in acetone. (If you do this step, be sure to follow appropriate safety precautions, including wearing gloves and working in an area of good ventilation, away from ignition sources, when handling the acetone.)

I didn't want insects taking up residence inside the elements or boom, so I plugged the ends of the elements and capped the ends of the boom. (I certainly didn't want the insects to get confused and have difficulty finding the way home when I rotated the antenna!) Wooden plugs cut from 5/8" diameter dowel, sanded around the circumference to reduce the diameter slightly, fit snugly in the ends of the elements. Standard PVC caps with a portion of the sleeve cut away to avoid interference with the elements, worked well on the boom. I drilled a small weep hole on the underside of each end of the elements and boom, located just inside the plugs and caps, to prevent any water or moisture that might get in from pooling in the ends.

To provide balanced drive to the folded dipole, I liked the simple approach adopted by Rick Campbell. I formed a balun with five Wurth #74270060 WE-AFB EMI suppression axial ferrite beads strung on RG-8X coaxial feedline adjacent to the feed point of the folded dipole. Each bead is 18 mm long, by 14.1 mm outer diameter, by 6.3 mm inner diameter. The inner diameter is just large enough to accept the RG-8X feedline. The bead is formed of a nickel-zinc material with initial relative permeability of 620. Using a vector antenna analyzer, I measured the impedance of a bead at 50.1 MHz, with one turn of wire looped through the hole, to be 152 + j 83 ohms. This is about 173 ohms total magnitude. Handling the feedline anywhere below the balun produces no change to the reflected power, and the horizontal radiation pattern of the completed antenna appears to be symmetrical, so I believe the balun is working as intended. Other combinations of ferrite beads or snap-on ferrites summing to about 750 ohms impedance, total, or more, at 50 MHz should work as well in this application.

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## Final Adjustments and Tune-up

As it would be a nuisance to change the length of the folded dipole to achieve resonance, I began thinking of other methods. Experimenting in EZNEC, I found that adding inductance in the folded dipole wire immediately across from the feed point had about the same effect as adding inductance in series with the feed. Thus, if the folded dipole is cut to the short side of resonance, the feed point will appear capacitive, and a wire hairpin shape or loop shape inserted in the center of the opposite wire will add the needed series inductance to achieve resonance. As an initial hardware experiment, I attached the dipole wire (with no tuning loop) temporarily to the PVC support conduit using tape. I found that at the initially-calculated length, the dipole indeed resonated low in frequency, indicating it was inductive at the feed point. I scaled from there to a shorter length that would make the feed point capacitive, and proceeded to build the folded dipole in final form. I chose to space the holes that the wires pass through at the ends of the dipole 110-9/16 inches apart, as noted in Table 1. This length turned out to be somewhat shorter than it needs to be, but the proper resonant frequency is easily achieved by means of the tuning loop.

I attached the Yagi, pointed skyward, to a wooden step ladder for the final tune-up. I had permanently attached all the elements to the boom except for the driven element. I attached the driven element for test with nonconductive duct tape so the element could be moved forward or backward a little to provide another degree of freedom to bring the feed point impedance to 50 ohms resistive. As it turned out, the calculated mounting point worked very well. For the tuning loop, I used an eight-inch length of the relatively-stiff #12 insulated wire, beginning with it in a hairpin shape, and expected to spread or squeeze the sides together to achieve the necessary inductance.  At that time, I didn't have an antenna analyzer, but I did have a return loss bridge.  For the signal source and indicator, I used a tunable signal generator feeding the return loss bridge, with an rf power meter attached to the bridge's return loss port.  The load port of the return loss bridge fed the Yagi through a short length of coax strung with ferrite beads for the balun.  The adjustment then proceeded with the goal of nulling the power indicated at the return loss port.  When adjusting the tuning loop, the resonance remained on the high-frequency side until I formed the loop into a circle as shown in Figure 3.  I could have increased the wire length and retained the hairpin shape, but the circle did the trick, achieving a return loss of about 30 dB at a frequency of 50.140 MHz.  A return loss of 30 dB works out by calculation to be an SWR of 1.065:1. Following the tune-up, I permanently mounted the driven element, drilling the hole for the mounting bolt per the method covered previously, and applied the sealant to the electrical connections.

As an afterthought, I became concerned that a heavy bird might perch on the tuning loop and bend it, so I added a piece of scrap plastic between the loop and the boom to support the loop.  Had I thought of this possibility at tune-up time, I could have formed the loop in a manner such that it would be lying directly against the boom for support.

Now that the antenna has been permanently installed on the chimney of my house, I occasionally check the SWR at the transceiver end, using an antenna analyzer.  The analyzer reports 1.05:1, which works back to a number close to the 1.065 figure at the antenna when the coax loss is taken into account. Thus, the antenna match probably did not change much during the process of final assembly and installation, and has not changed much since.

## Conclusions, including pros and cons

Yes, for the fun of it, I calculated the volumes of the components making up the antenna, and found that the antenna is about 98% plastic by volume, with the remaining 2% being metal.  (Oops, I didn't count the wooden plugs and the enclosed air!)

The total cost of materials for the antenna, including the mounting hardware that attaches to the upright pole, plus the ferrite beads for the balun, was about $57.

Building with the PVC is inexpensive and easy, but it does produce a droopy antenna if no additional support is provided.  I deliberately added no additional support in order to observe the droop.  The droop in the elements is minor, but the droop in the boom looks "sad".  I have scaled a recent photo, taken at a distance from a position up the street, of the antenna to determine the droop in the boom at the locations of each element.  The first director is highest, being close to the mounting point.  With respect to the first director, the reflector is down about 6 inches, the driven element is down about 1-½ inches, and the second director is down about 14 inches.  While this result may sound horrible, the effect on the performance of the antenna is negligible.  When modelling the droopy versus non-droopy antenna in EZNEC, the droopy result is only 0.12 dB down in forward gain, and the front-to-back ratio is actually somewhat better: about 3 to 4 dB higher.  The modelled free-space antenna pattern in the vertical plane shows some asymmetry due to the droop, but the vertical pattern in the real world is very asymmetrical anyway due to the presence of ground. When modelled over ground, both results look very similar. The droop has increased in the one and a half years since installation. I'm not sure whether the amount of droop is stabilizing over time. Regrettably, I previously failed to take comparable photos from the same location. In any case, the droop can be easily prevented by several inexpensive and simple means, such as adding UV-resistant antenna rope guys in tension from the boom ends to the apex of the upright pole, or adding PVC braces in compression from below. Another method would be to use dual ¾ inch PVC schedule 80 tubes for the boom, one above the other, with the ends bolted together, to form an arrangement analogous to an I-beam. Of course an aluminum boom would work very well, at somewhat more cost. There are suggestions to be found on-line [4, 5] of other methods for stiffening PVC pipe, but many of these would add weight, and some are of dubious value. Perhaps the best cheap alternative suggested is bamboo.

I intend to wait until the droop becomes a significant detriment before I apply a guy rope to support the boom.

Regarding durability, the antenna has stayed up through two winters. That means it is not big enough, right? It has not yet been exposed to a severe ice storm, but it has been exposed to some snow storms and some ice loading from freezing rain (ice build-up did not exceeded a quarter-inch). Regarding winds, it hasn't been exposed to hurricane-force winds, but it has survived without damage a couple of strong wind storms that have toppled large trees in the neighborhood and have broken large tree branches. The antenna may be like the reeds versus the oak in the old Aesop's fable – the reeds flexed in the wind storm and survived, while the oak tree stood mighty and stiff, until it was blown over. Regarding heat, our summer days have been as hot as the upper nineties in air temperature, with solar loading in addition. The foil tape is showing no signs of delaminating from the PVC. There are no signs of degradation other than the droop that was discussed previously. So far, the antenna continues to perform well in the moderate climate we experience here in Virginia. I would caution that I have no data that says the antenna won't wilt in very hot climates such as those found in the desert southwest. I would suggest that some of the selected PVC tubing be suspended from its middle as a trial before others commit to this antenna for use in very hot climates.

I do notice that during a rain storm or during a snow storm when the snow sticks to the driven element, the resonant frequency of the antenna shifts downward, raising the SWR to above 2:1. Later, the SWR returns to normal once the water or snow is gone. This shift is not a significant problem for my old Heathkit SB-110 with a pair of 6146 vacuum tubes in the final amplifier, as this rig has tuning and loading controls that can be adjusted, if needed, to compensate for the effect. However, this shift may be an issue for solid-state rigs without some means of output tuning. I presume that had I proceeded with my original plan to locate the folded dipole driven element inside the PVC tubing, this shift would be reduced, but I have done no experiments to back up this supposition. There is no reason a similar antenna could not be built with a non-folded driven element matched with a technique such as a gamma match, if desired.

On-the-air performance has been pleasing. The antenna displays the expected clean pattern. Best distance contacts (DX) so far have been single-sideband (SSB) contacts to England and France, using my

Heathkit SB-110 barefoot with less than 75 watts output, when I was lucky to catch a couple of multi-hop sporadic-e openings across the “pond”.  (I haven’t tried FT-8 or any of the other weak-signal modes.)  Not bad for a few pieces of cheap plastic!  Of course, the antenna may collapse tomorrow, but I have gotten my money’s worth in experimentation and on-the-air fun.  I can suggest it to those who are looking for an inexpensive antenna with modest size and gain, for use in regions that have moderate climatic conditions.

## References

[1]  Rick Campbell, KK7B, “Square Four Aerials”, QEX, Jan/Feb 2018, pp23-26.

[2]  David B. Leeson, W6QHS, *Physical Design of Yagi Antennas*, 1st ed., The American Radio Relay League, 1992.

[3]  EZNEC antenna modelling software available from developer Roy Lewallen, W7EL, at **www.eznec.com**.

[4]  See https://forums.qrz.com/index.php?threads/cheap-easy-way-to-firm-up-20-length-pvc-pipe.327996/

[5]  See https://cr4.globalspec.com/thread/80328/Keeping-3-4-and-1-2-PVC-From-Sagging

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| **Element** | **End-to-end Length (inches)** | **Distance from Reflector (inches)** |
|---|---|---|
| Reflector | 116-1/2 | 0 |
| Driven Element | 110-9/16 | 28-1/2 |
| First Director | 108-5/16 | 57-7/32 |
| Second Director | 98-7/8 | 118-5/8 |

Note:  The driven element length is the total linear distance between the outer holes where the driven element wires pass through the PVC support.  The actual total folded dipole wire length differs somewhat from twice this number.

**Table 1.  Element Lengths and Locations.**

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List of figures to follow:

## Figures

Figure 1.  Cross Saddle

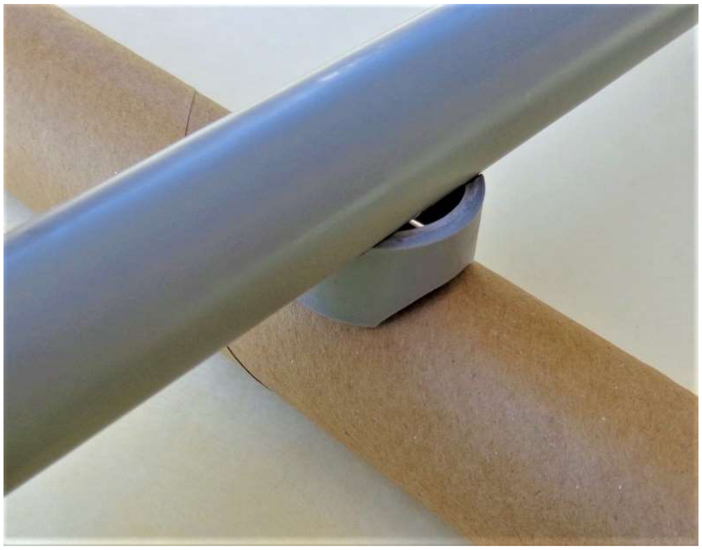

Figure 2.  Cross Saddle Fitted Between Element and Boom.
(A cardboard tube simulates the boom in this picture.)

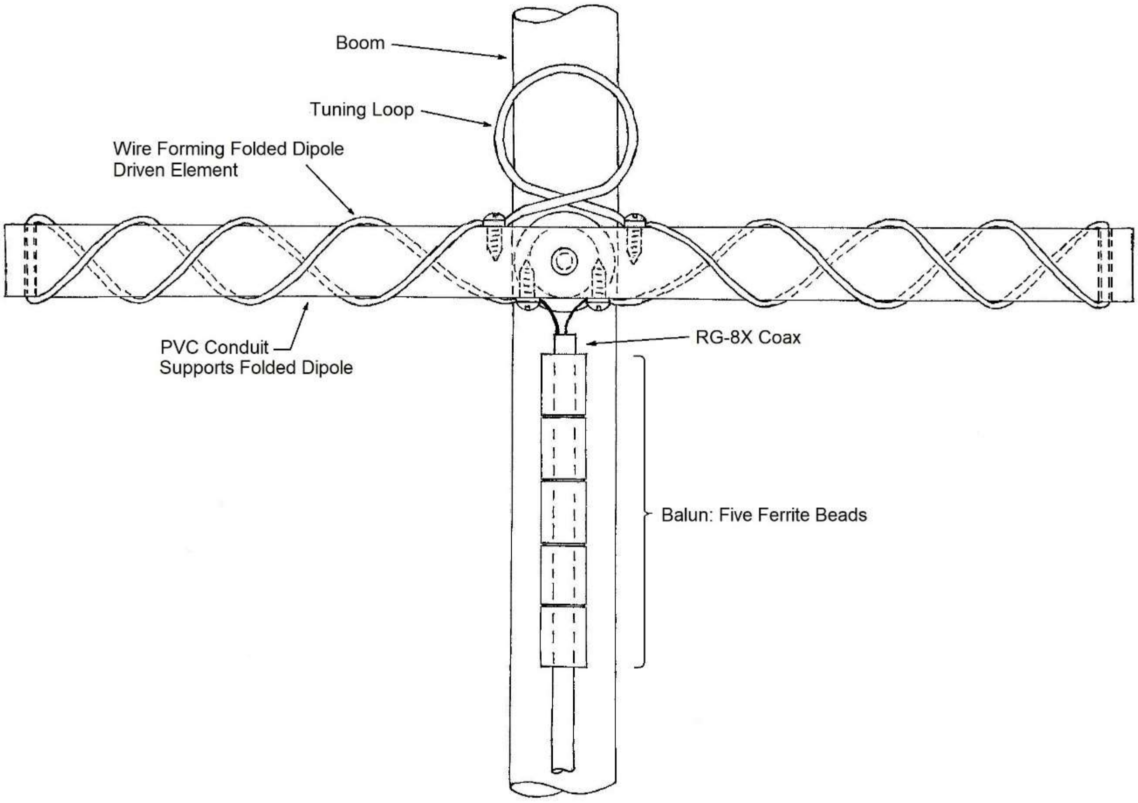

Figure 3. Driven Element and Feed Matching Detail.
(The horizontal scale for the driven element is greatly compressed to illustrate the spiral wraps along the full length.)

Optional Photo.  This could become a Figure 4:  The Completed Antenna Following Installation.