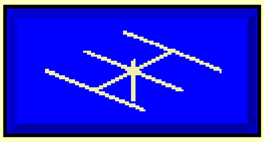
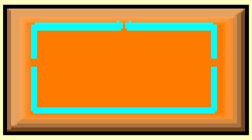


CAP Emergency-Beacon Direction-Finding Antennas



L. B. Cebik, W4RNL (SK)

The Civil Air Patrol has acquired a new urgency to monitor the emergency radio beacons of downed aircraft. These beacons operate at 121.5 MHz, with a strong third harmonic at 364.5 MHz.

I have long held CAP in high regard, since in the 1950s, my father and mother were CO and Exec for the Bridgeport, CT, squadron. Indeed, among my parents and two brothers, I was the only family member not to obtain a pilot's license, although I did serve the USAF in the late 1950s and early 1960s as an air traffic controller. I guess I always wanted to be able to tell my brothers where to go.

When asked if I had any designs adaptable to the new requirement, not only to monitor the emergency beacons, but to perform direction finding (DF) work in the field to locate downed aircraft, I came up with a pair of serviceable designs. Each design has versions for 121.5 and 364.5 MHz, exact 3:1 scalings. In addition to being good DF antennas, an added requirement was that the antennas may be assembled and disassembled, the latter need a function of having to carry them in aircraft to a search site.

A good DF antenna--short of a Doppler multi-antenna DF array--needs to have an adequate forward gain lobe and a deep rear null. The forward gain acquires the signal. However, the deep rear null allows a more accurate determination of the direction to the signal, since the null is much sharper, that is, narrower in terms of the headings at which the signal disappears or is weakest. Like all CAP skills, it takes practice to use a DF antenna effectively.

We shall divide our work into 3 parts. First, we shall look at a simple design--a Moxon rectangle--that is smaller: only 35" by 13". Then, we shall examine a 3-element Yagi. It is larger: 49" by 30". These numbers apply to the 121.5-MHz version. The 364.5-MHz antennas are exactly 1/3 size. Whichever frequency we choose, each design has advantages and disadvantages. Finally, we shall examine some construction suggestions, many of which apply to either design.

DF Moxon Rectangles for 121.5 MHz and for 364.5 MHz

The Moxon rectangle is a simple 2-element array composed of a driver and a reflector. Because it folds its element ends toward each other, it obtains a smaller footprint than a comparable 2-element Yagi. As well, the combined coupling of the parallel elements and the tail tips provides a deep front-to-back ratio that provides a good DF rearward null.

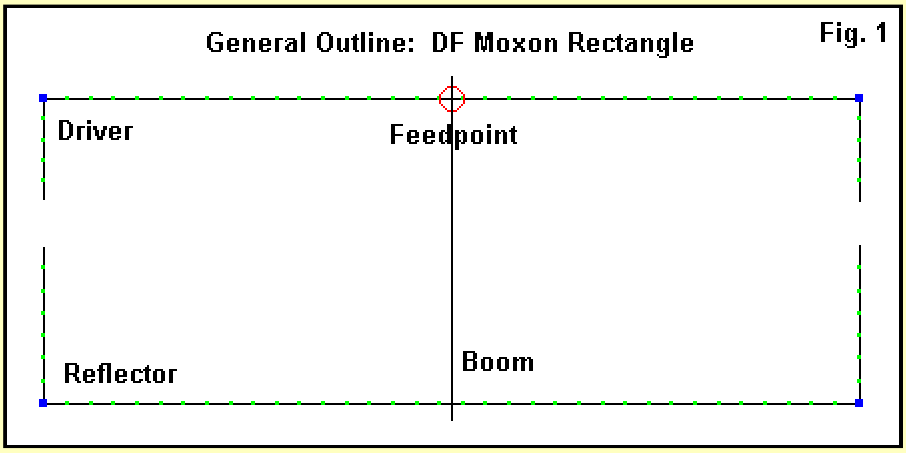

General Outline: DF Moxon Rectangle

Fig. 1

Fig. 1 provides the outline of the Moxon rectangle. The proportions apply to the versions for both frequencies. The following table provides the dimensions in inches for each frequency. A is the total side-to-side length. B is the length of the forward or driver tail. C is the gap between tails. D is the reflector tail. E is the sum of B, C, and D, giving the total front-to-back dimension.

……

DF Moxon Rectangle Dimensions

Dimension	121.5 MHz	364.5 MHz
Diameter	0.375	0.125
A	34.77	11.59
B	4.36	1.45
C	1.87	0.62
D	6.74	2.25
E	12.97	4.32

……

The Moxon dimensions are dependent upon the element diameter, so they will be somewhat off if you choose a different material. We shall discuss my recommendation for 3/8" diameter 121.5 MHz elements in the construction section. The most critical dimension is the gap between tail tips. They need to be well aligned and maintain their spacing during antenna use.

The Moxon rectangle has modest gain with a broad forward lobe. The following performance table applies equally to the 121.5-MHz and 364.5-MHz versions. The gain is for free-space and is provided as a comparison with the Yagi design to come later.

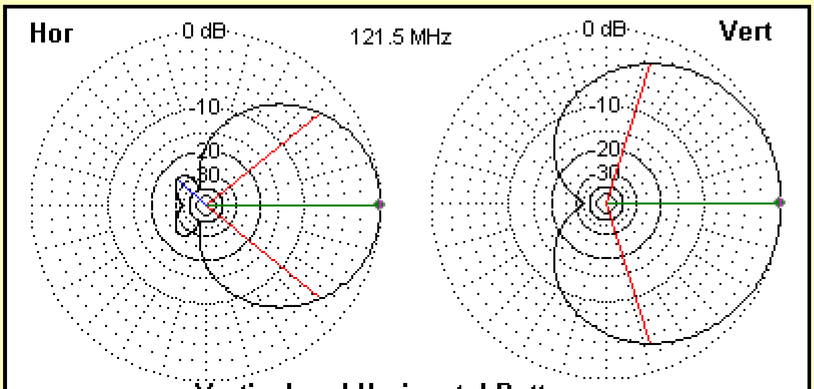
……

Modeled Performance Data: DF Moxon Rectangle

Category	Performance
Free-Space Gain in dBi	5.9
180-Degree Front-to-Back Ratio	34
Horizontal Beamwidth, Degrees	79
Vertical Beamwidth, Degrees	144
Feedpoint Impedance, R+/-jX Ohms	54 - j0
50-Ohm SWR	1.08

……

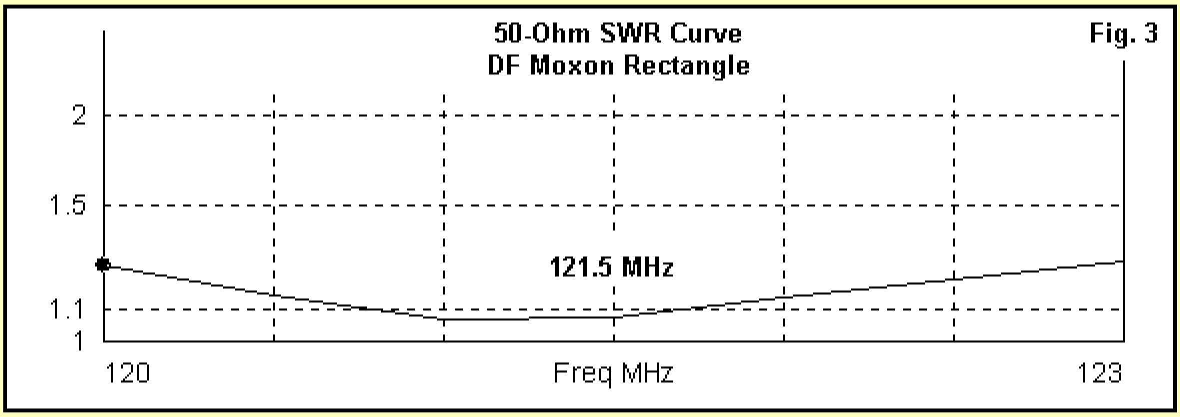
The Moxon rectangle supplies moderate gain in a very broad forward lobe, whether held vertically or horizontally. (With a downed aircraft, one may have to hold the antenna in either manner--or at an intermediate angle--for the strongest forward signal.) The direct front-to-back ratio provides a deep rear null. **Fig. 2** shows the patterns for both horizontal and vertical orientations of the antenna.



Vertical and Horizontal Patterns
DF Moxon Rectangle

Fig. 2

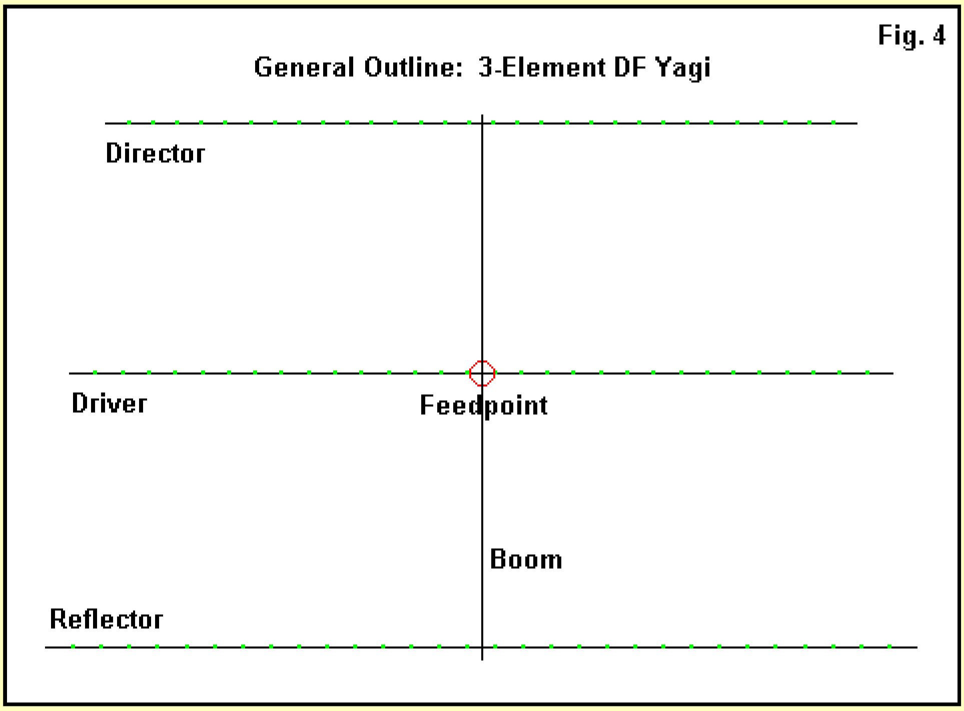
The Moxon has less gain than a 3-element Yagi, but it is smaller and lighter to wield. As well, its design allows direct connection of a 50-Ohm coaxial cable with no matching considerations. Since we use the antenna only in receiving applications, we do not need to consider a balun device. **Fig. 3** shows the SWR curve from 120-MHz to 123 MHz. A similar curve, centered on 364.5 MHz would apply to the smaller antenna.



The Moxon is one route to effective DF work, if the gain is adequate to the field situation. However, if we need more forward gain to acquire the emergency beacon signal, we should turn to a larger array.

3-Element DF Yagis for 121.5 MHz and for 364.5 MHz

Standard Yagi designs strive for maximum forward gain from a given number of elements and boom length. However, we may also design a Yagi for maximum front-to-back ratio, sacrificing some gain for the good DF null to the rear. That is the operative design specification that produces the 3-element Yagi outlined in **Fig. 4**.



Note that the driven element is fairly well centered between the reflector and the director. The following table provides the dimensions for both frequencies, again using 3/8" elements for 121.5 MHz and 1/8" Elements for 364.5 MHz. Because we need two spacing columns, one for inter-element spacing and the other for cumulative spacing, we divide the dimensions into separate tables for the two frequencies. All dimensions are in inches.

. . . .

3-element DF Yagi Dimensions

Element	Length	Spacing	Cumulative Spacing
121.5 MHz (0.375" diameter elements)			
Reflector	48.66	-----	-----
Driver A	44.29	15.31	15.31
(Driver B)	46.00	15.31	15.31
Director	42.11	13.92	29.23
364.5 MHz (0.125" diameter elements)			
Reflector	16.22	-----	-----
Driver A	14.76	5.10	5.10
(Driver B)	15.36	5.10	5.10
Director	14.04	4.64	9.74

. . . .

With the dimensions shown, the Yagi--whichever the frequency--has the performance characteristics shown in the table that follows.

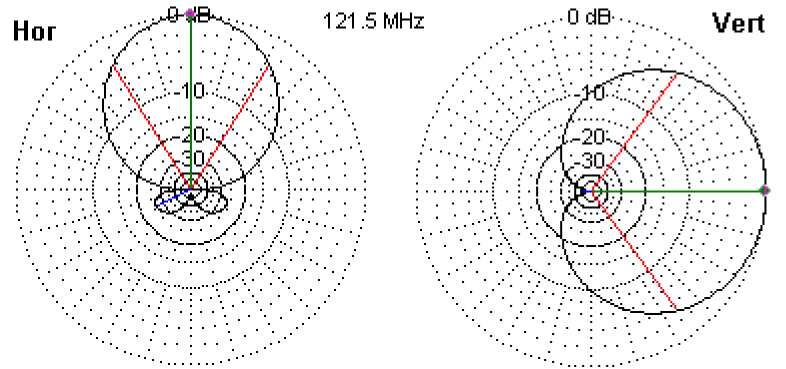
. . . .

Modeled Performance Data: 3-Element DF Yagi

Category	Performance
Free-Space Gain in dBi	7.7
180-Degree Front-to-Back Ratio	45
Horizontal Beamwidth, Degrees	65
Vertical Beamwidth, Degrees	108
Feedpoint Impedance, R+/-jX Ohms:	
Driver A with matching stub	51 + j2
Driver A 50-Ohm SWR	1.05
Driver B without matching stub	32 + j2
50-Ohm SWR	1.55

. . . .

The gain of the Yagi is nearly 2 dB greater than for the Moxon rectangle. The rear nulls of both are so deep that there is no practical difference in the two numbers for this category. The Yagi forward beamwidth in either a horizontal or a vertical position is considerably narrower than the Moxon. Hence, for the added antenna area and weight, we obtain more gain and a somewhat better ability to stay on course when pointing the antenna at the target. **Fig. 5** clearly shows the narrower beam angle of the Yagi, relative to the Moxon.

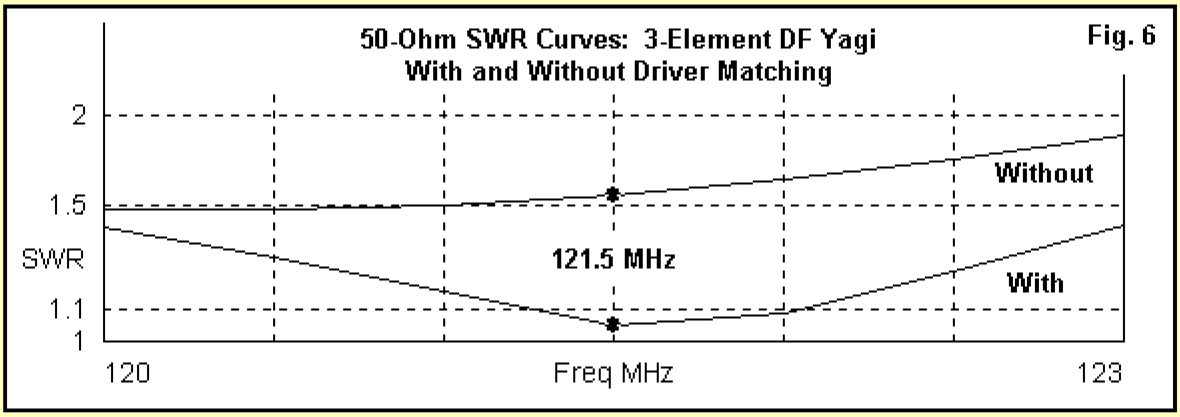


Vertical and Horizontal Patterns
3-Element DF-Yagi

Fig. 5

You have a choice between two drivers. They differ in length but use the same spacing from the reflector and director. Driver A is designed for use with a shorted stub placed across the feedpoint terminals. It is a 37.5-Ohm transmission line stub constructed from parallel section of RG-59 or other 75-Ohm coaxial cable (or even some old 75-Ohm parallel transmission line). Driver B is the length if you choose not to use a matching section.

The matching section allows a near-perfect match between the feedpoint and a 50-Ohm main feedline, using the Driver A length. With the alternate length, B, the SWR is about 1.55:1, which is adequate for almost all purposes and simplifies construction. **Fig. 6** shows the comparative SWR curves for the two versions of the antenna.



The following table lists the physical lengths of shorted stubs using two different velocity factors. The 0.8 value applies to most foam insulation versions of RG-59 or similar 75-Ohm cables. 0.67 applies to standard solid dielectric cables. Note that when paralleling cables for a lower impedance, we cut each to the specified length and tie the braid to the braid and the center-conductor to the center-conductor. Of course, at the shorted end, we tie everything together. To tie lines together means to establish a good physical junction that we then solder and seal. Dimensions are in inches.

. . . .

Driver A Matching Shorted-Stub Lengths

Length	**121.5 MHz**	**364.5 MHz**
Electrical: VF = 1.0	**14.90**	**4.97**
Foam: VF = 0.8	**11.92**	**3.97**
Solid: VF = 0.67	**9.98**	**3.33**

. . . .

Because constructing an accurate short stub of paralleled transmission line at 364.5 MHz is quite tricky and more than a little bit finicky, I recommend that you use Driver B for the upper frequency antenna. For the 121.5-MHz version, you have your choice.

The Yagi is bigger, heavier, but performs somewhat better than the Moxon. However, either is capable of giving good performance within the gain needs of the situation.

Building a DF Antenna

A DF antenna for the field must be as light as feasible, durable in use, but able to be disassembled for transport in a small package. Although these requirements are not easy to implement, we have a major advantage. Since the antenna will remain disassembled except during use, we need not concern ourselves too much with eliminating contact between dissimilar metals. That fact opens up some potentials of the local home center hardware sections.

Let's begin with the 3-element Yagi for 121.5 MHz. I recommend the use of 3/8" elements because we can obtain good 6063-T832 aluminum tubing from standard mail order sources, such as Texas

Towers. It comes in 6' lengths for UPS shipping, so 3 lengths will meet our needs.

Note that the boom is shorter than the elements. Therefore, if we can have a boom with the element centers permanently attached, we can take off the outer ends of the elements and pack them in line with the boom for a transport package about 30" long. See **Fig. 7** for the general idea of how this might work for the director and the reflector (as well as for the Moxon reflector).

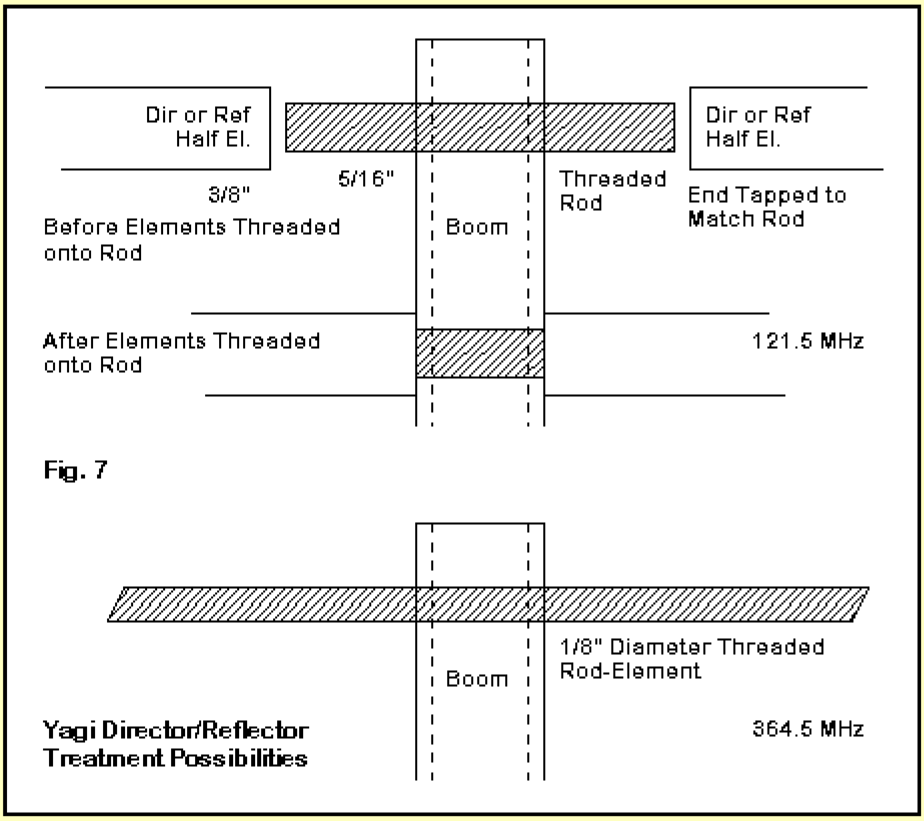


Fig. 7

Yagi Director/Reflector Treatment Possibilities

The boom should be 1/2" nominal PVC, which has an outer diameter close to 1". We shall treat the driver element separately, so let's begin with the reflector and the director. Obtain some threaded brass rod, 5/15" in diameter. (Steel is fine, but harder to cut, while aluminum is hard to find.) Cut two 3" or so lengths. Drill the boom just under 5/16" and either tap the hole for threads that match the rod or use the rod itself to cut threads. Install the reflector and director threaded rods in the PVC.

Now cut two pieces of 3/8" aluminum tubing in half. Tap the ends to create 5/16" threads to match the rod. Do not tap much beyond the end of the threaded rod projections from the PVC (about 1") or you will create a weak point in the element. Now thread the elements on the rod projections. Measure the total length of the reflector and the director so that the tip-to-tip length equals the dimension chart. Trim the ends.

Of course, I am omitting from each step the need to have clean smooth ends. The threads need to be especially clean, since we do not wish to destroy the interior threading of the tubes with metal burrs. The outer ends need to be smooth for operator and bystander safety.

We can use the same system on the smaller 364.5-MHz Yagi. However, lets use threaded 1/8" brass rod for both elements. After tapping the boom at the correct positions, we can simply thread the element into place. Since this antenna is only 16" by 10", once assembled, it can stay assembled for transport. So a drop of epoxy at the boom-element junctions should hold things in place permanently.

The driven elements require different treatment. See **Fig. 8** for some ideas.

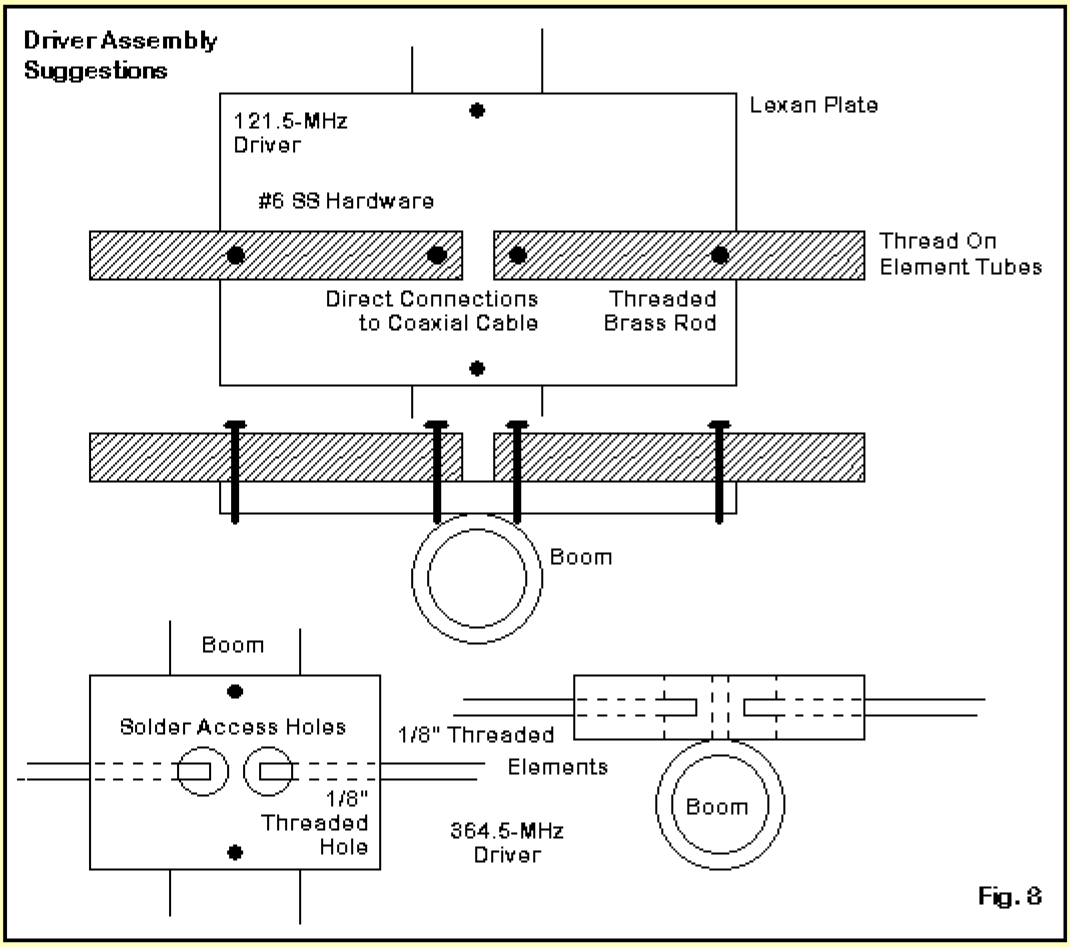


Fig. 8

For the driven element of the 121.5-MHz antenna, we shall need a non- conductive plate, perhaps a 2" by 4" piece of 1/4" Lexan, plexiglas, or similar. The 4" dimension projects to the sides of the boom. Fasten the plate to the boom with sheet metal screws into the boom--or use nuts and bolts. Lock the nuts with sealer, since they will stay in place.

From the 5/16" brass rod, cut two 3" pieces. With a drill press, drill a pair of holes to pass through the rod and into each side of the plate. We now have two rod sections with a small gap between them and extending over the plate ends. Tap two more sections of aluminum tubing, place them over the rod ends, and trim to length--either A or B, depending on your choice.

The brass rod will accept solder. Therefore, you may solder the main feedline directly to the rod at the gap--the braid to one side and the center conductor to the other. For this operation, it pays to remove the rod from the plate and use a temporary wood plate instead. The heat of soldering may deform the plastic material. Alternatively, you can install solder lugs under the bolts closest to the gap and use these for attaching the feedline. When you re-assemble the driver plate, if you use a matching stub, you can tape it to the boom. There is no need in this antenna to waste coax connectors.

The 364.5-MHz antenna requires somewhat different treatment. A 1/2" thick plate of plastic will serve as the feedpoint and driver mount. We only need a piece about 1.5" wide by about 2" side-to-side. Use screws through holes in the block to attach it to the boom.

The trickier part is the element mount. Drill a hole (it can be threaded to match the brass rod) from one side of the block to the other. Or drill separate holes from each side limit inward. Now drill a larger hole on each side of the center line to give you access to the half element that you will insert or thread into the long holes. Use these holes to solder the transmission line to the two halves of the driver. Solder quickly and carefully with a well-heated iron to prevent damage to the plastic block. I am assuming you are using Driver B and only need to trim the length so that the driver matches the dimension sheet from tip-to-tip.

You may coat soldered connections with Plasti-Dip or similar material for weather protection. The only step left is to add a handle. For the small Yagi, you can use a PVC coupling--either cemented or threaded--and add PVC sections of your choice to make a convenient handle. Remember that you may have to use the antenna at any angle from vertical to horizontal.

The large Yagi can also use an end handle, although the weight may be more tiring. An end handle lets you stand behind the antenna which creates less pattern distortion. However, for taking null readings, you may have to hold it overhead.

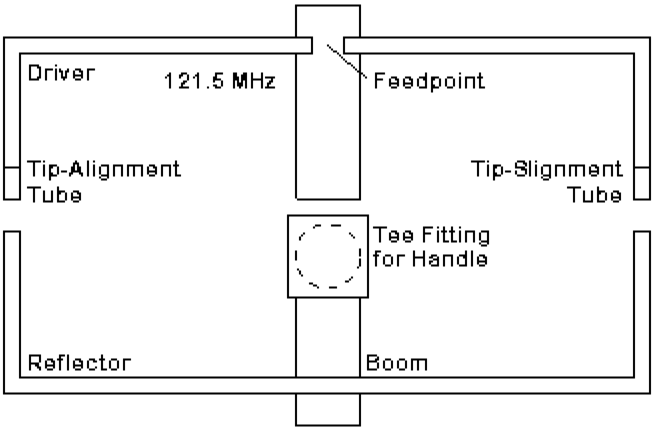
Alternatively, you can break the PVC boom and add a Tee fitting (making sure that the reassembled boom maintains the correct element spacing). From the Tee, you can add PVC fittings of your choice to create the most comfortable grip to keep the antenna overhead. Height does make a difference in both forward signal acquisition and in null determination.

The Moxon rectangle can use many of the same techniques as the Yagi. For 121.5 MHz, the threaded brass rod at the reflector allows you to attach the reflector halves without going around corners through the element hole. At the forward or driver end, the brass rod permits soldering directly to the coax able pig-tails. PVC makes a good boom, with the same handle-fitting considerations as on the larger Yagi.

The key is bending corners. However, most plumbers tubing benders will handle up to 3/8" material. Go slowly to prevent crimping. If necessary, fill the tube with fine sand before bending. Use slow and steady pressure.

Allow excess tubing at both ends of each half element. Then fit the pieces together to align the tail tips and assure measurements. From the boom center line, each driver should measure a total of 1/2 A plus B, and each reflector should measure 1/2 A plus D. Use a small piece of nylon tubing or similar to keep the tips aligned and properly gapped.

The 364.5-MHz Moxon can use the same driver assembly method as the Yagi for that frequency, except that the ends will bend pack. You can use a single piece of brass rod for the reflector if you use a rear handle. Simply cut a slot into the boom rear and align all of the pieces, including the tips with the positioning nylon tubing. Since the smaller Moxon will be a unit, you can then use epoxy at the slot-to-reflector junction to fix the position. Then add couplings for a rear handle.



Splitting a Moxon Rectangle for Transport

Fig. 9

For the larger Moxon at 121.5 MHz, consider a Tee fitting at the boom center for a centered vertical handle. See **Fig. 9**. Cement only one side of the Tee onto the boom. Since the nylon tip tubes can slide off and since one side of the boom can slide off, you can break the Moxon into 2 pieces for bagging and transport.

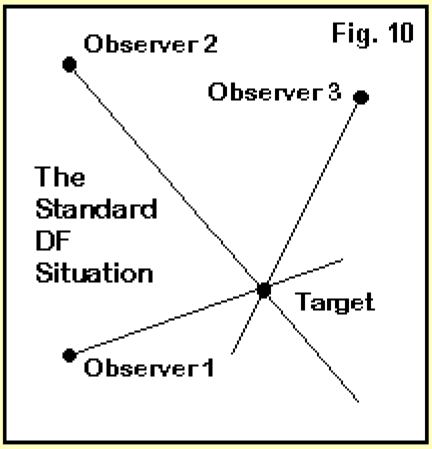
I have debated whether to add more than the three sketches of these construction ideas. I decided not to do so. The sketches are only suggestions of some, but certainly not all, ideas. You will have to adapt them to local circumstances in any event. Therefore, anything that is not perfectly clear in words, you will have to think through, and that may open to you many new ideas to use materials to which you have access and with which you have some facility.

So these notes present at least two types of antennas, with complete dimensional data, that will serve the beacon monitoring and direction finding needs for most CAP filed operations. There are other antenna systems that you might use, but these are inexpensive and amenable to basement or garage shop construction at a small cost using easily obtained materials. Nevertheless, cheap does not mean careless. The utility of the antenna in the field, both in terms of performance and durability, will depend on the care that you use in construction. Pooling talent is a good way to obtain the best construction.

Eventually, commercial antenna makers will discover that there is a market for antennas of these types or similar ones, given the intensification of the requirements on CAP and possibly other agencies for monitoring and field antennas for the beacon frequencies. Until then, these designs provide a nice challenge for the home workshop--not to mention a very important public service from CAP and other volunteers.

A Note on 2-Observer DF-Fixing

Radio direction finding (DF) remains an art filled with maps and grease pencils in many circles. The standard technique, illustrated in **Fig. 10**, shows a target--with a radiating emergency beacon or other radio signal--at the center of an array of observers.



Each observer takes a reading and conveys it to a central location. There, a map reader who knows the location of each observer draws a heading line from that observer across the map. Where the lines intersect must be the target.

Initial observations are often limited to single approach area, so the differences between heading readings may be small. Under these conditions, the single-dot target becomes a target area.

Since the initial approach area may often be restricted, let's see if we cannot develop a different approach to the problem of locating the target. The approach will be based on taking reading on the fly with the use of highly directional antennas and accurate compass work. This phase of the work is always a limiting factor in any target location operation. We require the most accurate heading--usually taken by reference to a deep null in the antenna pattern--accompanied by the most accurate possible compass reading.

In the late 1950s, USAF control towers were fitted with a UHF DF device to give the bearing of any radio transmission used by USAF pilots on any of the UHF channels. If the pilots navigation receivers were out, we could steer him toward the base. About 1960, two interesting things occurred. First, Sgt. Achee (my memory does not have his first name on file) and I developed a 1-station DF-fix calculator and submitted it through channels. Second, the idea, while praised, was not acted upon, because the DF gear was systematically removed from control towers. However, our tests with aircraft stationed at the base (Webb AFB in Big Spring, TX, now closed) proved the technique to be sound.

The technique we used was to create an initial bearing. Then we had the plane fly for 1 minute at right angles to the heading. The airspeed and time gave us the distance flown. We took a second bearing. Finally, we calculated the distance of the aircraft from the base. Back then (1959-60), we modified a circular slide rule with the necessary scales to make the calculation a 30-second affair.

Now suppose that we have two ground observers fitted with highly directional antennas and compasses. Further, let them be have two other small pieces of gear: a GPS receiver to determine highly accurate positions and a pocket-size programmable calculator. If our target is a downed aircraft with a radiating beacon, we can achieve the same DF fix on the fly.

Since I do not have access to CAP or USAF training materials dealing with locating downed aircraft, the following notes may be replicating an existing wheel. However, on the chance that the notes might be useful, I'll go through the procedure anyway. Who knows where the ideas may not yet be known and hence prove useful.

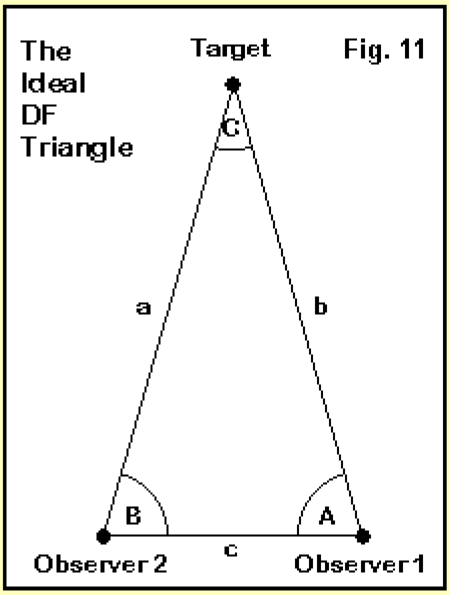


Fig. 2 sets forth an idealized situation of 2 observers, each roughly equidistant from the target. Each observer takes a heading to the target. If the two headings are close to identical, then the first step is to send one of the observers at a roughly right angle to the heading for a specified distance, perhaps 1/10 the initial estimate of the possible distance from the target. When the second observer takes a new reading, the triangle will be a closer approximation to the ideal.

At this point, we know several things of very great interest.

- 1. From either (or both) GPS readings or known positions, we know how far apart the two observers are. That is, in terms of our triangle in **Fig. 2**, we know side c.
- 2. From the difference between the two readings of the target heading, we know the angle C.
- 3. From our right angle maneuver, we know that the distances between observers to the target are about the same. In other words, side a = side b.

That is all of the information that we need to do a rough calculation of the position of the target in terms of its distance from the observers--remembering that we already have the headings.

The key is a much overlooked simple trig relationship called the law of sines:

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} \qquad (1)$$

The letter designations correspond to those in **Fig. 2**.

Under the assumption that the two sides, a and b, are about the same length, we can calculate angle A (or angle B), since it is one half the difference between 180 degrees and angle C. Hence, we can calculate the approximate length of side a from the following equation.

$$a = \frac{\sin\left(\frac{180 - C}{2}\right) \cdot c}{\sin C} \qquad (2)$$

We can plug this equation into a programmable calculator. We only need to enter the difference between the readings of the two observers and the distance apart of the two observers, and a distance to the target will emerge. Together with the headings, we can place the target--at least well enough for the observers to leap forward toward it.

The benefit of the technique is that it does not require transferring data to a map--not always an easy task in the field. As well, even if initial readings are not precise, the observers can move at least 50% of the way toward the target at the highest feasible field speed before taking the next set of readings.

An Example

Suppose that we let the distance between observers by 5 (in whatever units you choose). Also suppose that the difference between headings taken by the observers is 20 degrees. The sine of 20 degrees is 0.3420, as any pocket calculator will tell.

Assuming that both observers are about the same distance from the target, then angle A (or angle B) will be (180-20)/2 or 80 degrees. The sine of 80 degrees is 0.9848.

If we plug this information into equation (2), the calculator gives us a result of 14.398 in the same units as we used for the side c value.

As a check, the ratio of side c to sin(C) is 14.6199. The ratio of our calculated side a to sin(A) is 14.6202.

The smaller the value of angle C, the higher the potential error. As we initially noted, the readings of the observers with respect to the heading to the target also affect the reliability of the results.

Nevertheless, the technique does allow two observer teams to proceed at a fairly rapid pace toward a target with almost instantaneous checks on their positions with respect to the target. The technique cannot overcome canyons, cliffs, and other impossible terrain, but it might help speed the process of locating a target without having to transfer data to a map while on the move.

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