Design of Yagi Antennas

BY FREDERICK W. BROWN*, W6HPH

This article covers basic end-fire array theory and presents, for the first time, a design method for Yagis that will produce maximum gain.

YAGI type antennas have a strong appeal to the amateur because, within a limited gain region, they yield more gain for the amount of space consumed than most any other form of array. None the less, there seems to be some mystery as to how Yagis work and little practical knowledge available (outside of a tedious cut-and-try procedure) for building high performance models.

The experimenter who builds a Yagi from dimensions published in a magazine article or handbook will almost always be disappointed in the results if he bothers to measure gain by the honest method[1]. The published design usually falls far short of optimum performance because more often than not the dimensions were arrived at by guesswork in the first place; and the gain was then usually checked (if it was checked at all) by a measurement procedure of doubtful veracity. Factory made Yagis are little better, in fact some are evidently made directly from dimensions published in the handbooks.

The method outlined here, if properly applied, gives *optimum* performance *every* time. What's more, it does not require element pruning and the whole process is accomplished almost in less time than it takes to tell it.

But before getting into practical Yagi design, let's be sure we understand some of the elementary principles involved.

How They Work

Yagis belong to a class of antennas known as *end-fire arrays*, most of which can be conceptually separated into two parts: a *launcher* and a *slow-wave structure*. For the case of a conventional Yagi, the launcher is customarily a dipole-reflector combination, and the slow-wave structure a string of directors. This configuration is usually the most practical in terms of such things as weight and wind resistance, but is by no means the only form an end-fire array may take.

For instance, a corner reflector or horn may be used for the launcher, and one of the most effective Yagi designs from a bandwidth standpoint uses a V antenna launcher[2]. The slow-wave structure also may take many different forms, such as a dielectric rod or any form of artificial dielectric (a string of directors may be regarded as an artificial dielectric structure).

*Star Route, Idyllwild, Calif.

[1]Brown, F. W., "How To Measure Antenna Gain," *CQ* Nov. 1962.

[2]Reynolds, D. K. "Broadband Travelling Wave Antennas" 1957 *IRE National Convention Record*, Part 1.

It is important to understand how any antenna achieves gain. Because it is a passive device, it can only radiate as much power as is fed into it. Gain comes about by taking power that would otherwise be wasted in a wrong direction and concentrating it in the desired direction. Gain therefore implies directivity and there can be no such thing as an antenna with gain in all directions (in 3 dimensions).

Looked at from a receiving standpoint, we know that the signal delivered to the receiver is proportional to the gain. Since the power delivered to the receiver is extracted from the passing electromagnetic wave, it is logical to view the receiving antenna as an aperture with a given "capture area."

Suppose, for instance, we have a receiving antenna with a capture area of 2 square meters. If the incident electromagnetic wave has a field strength of 3 micro-micro watts (or more correctly, 3 picowatts) per square meter, our antenna would deliver $2 \times 3 = 6$ picowatts to the receiver. (That may not sound like much power, incidentally, but 6×10^{-12} watts is really a fairly strong received signal).

Since we know from reciprocity that the transmitting and receiving gains are identical; gain, directivity, and aperture must go hand in hand and contrary to what is often believed we never have one without the other[3].

For a broadside type of array, the relationship between gain and aperture is intuitively evident since the effective aperture is approximately equal to the physical area (for a well designed antenna), and the signal delivered to

[3]Almost never. Actually it is possible to have directivity without gain if the antenna is inefficient (lossy). Most practical antennas, however, exceed 90% efficiency.

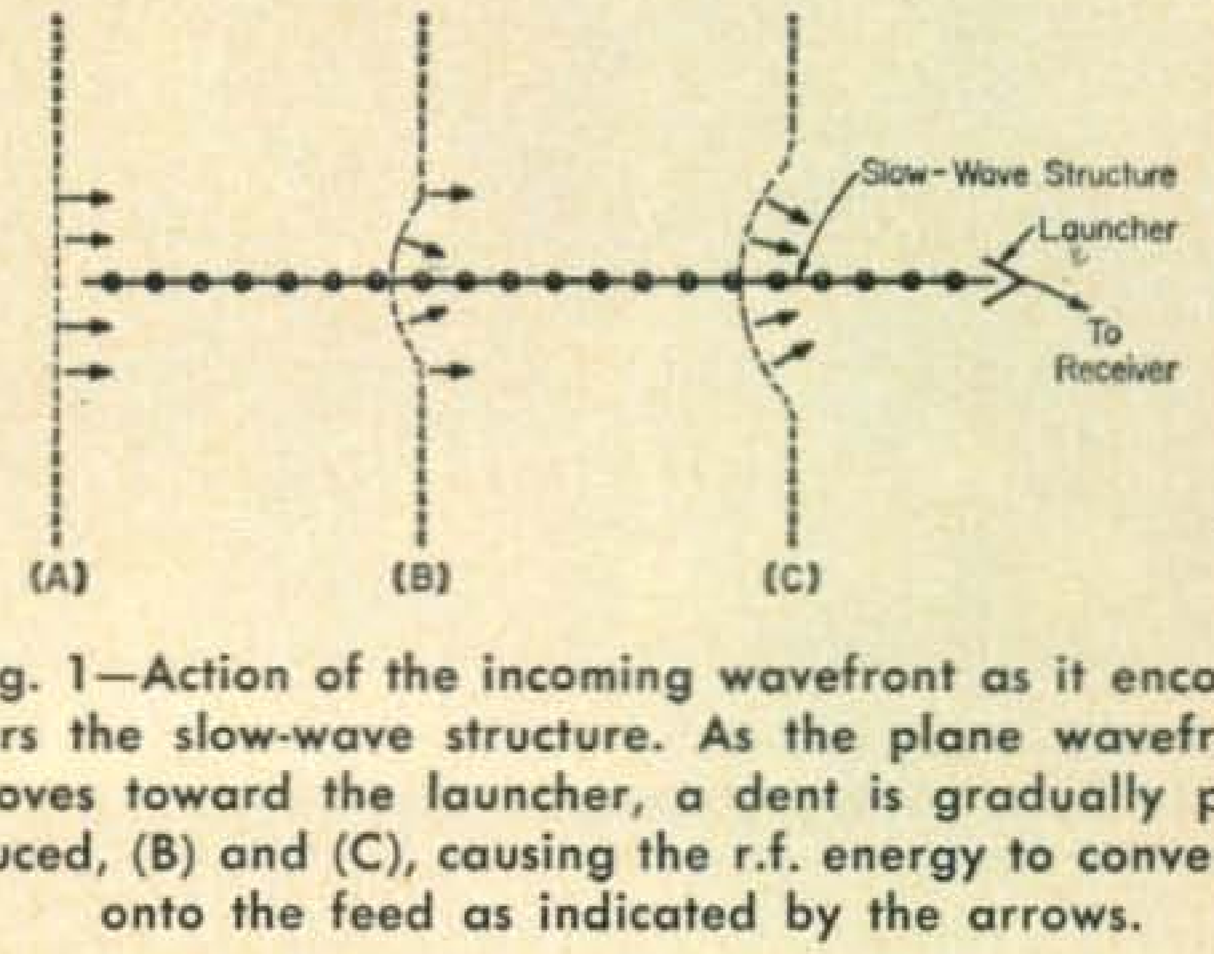


Fig. 1—Action of the incoming wavefront as it encounters the slow-wave structure. As the plane wavefront moves toward the launcher, a dent is gradually produced, (B) and (C), causing the r.f. energy to converge onto the feed as indicated by the arrows.

the receiver is simply proportional to this area.

There is some uncertainty, however, as to just how the end-fire array acquires its large aperture; which, of course, it must have if it exhibits gain. We often hear the incorrect statement, "The Yagi makes a good transmitting antenna because of its power gain, but is ineffective for receiving because of its small capture area." Looking at the Yagi head-on (as does the incoming signal), it is understandable how this misconception arises, for all we see, in effect, is a half wave dipole, and would expect an aperture similar in magnitude. How, then, is the large aperture achieved?

Remember that the end-fire array consists of a slow-wave structure placed ahead of a launching (or catching) device (fig. 1). Notice what happens to the incoming wavefront as it moves toward the launcher. That part of the wavefront near the slow-wave structure is slowed down, making a dent or depression in the wavefront (fig. 1b). Now since the direction of propagation for an electromagnetic wave is always normal (perpendicular) to the wavefront, the effect of the dent is to focus the r.f. energy onto the launcher (fig. 1c), thereby greatly increasing the signal delivered to the receiver. In very naïve terms, we might say that the Yagi actually "sucks in" the r.f. Hence its large effective aperture or capture area.

Viewed as a transmitting antenna, just the reverse action takes place, the launcher radiates a spherical wave, but that part of the wavefront near the slow-wave structure is retarded, producing an approximately plane wavefront at the end of the array. Because the direction of energy flow is normal to the wavefront, all of the power in this front will be radiated in approximately the same direction—the condition that gives rise to directivity and gain.

From this simplified and qualitative explanation we might jump to the wrong conclusion that the more the wave is slowed down, the greater will be the gain. Actually, there is an optimum value of wave velocity (or phase velocity) which depends on the array length. Any departure from this optimum (especially a lower velocity) will result in reduced gain. The optimum velocity is that which will produce a phase shift at the end of the slow wave structure of about 180° over what would occur in free space. Figure 2 gives

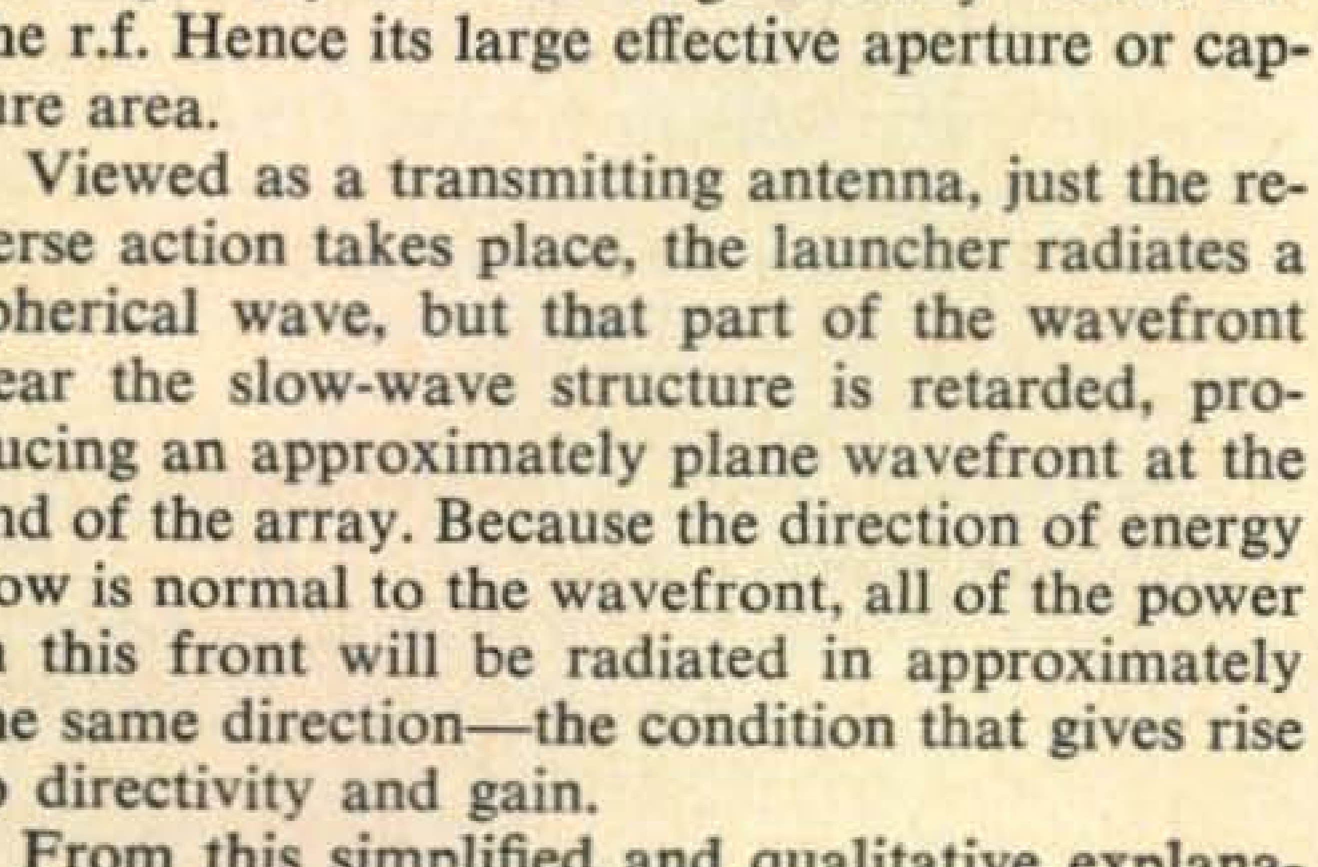


Fig. 2—Chart showing how the optimum phase velocity increases with length for a yagi. Free space velocity (velocity of light) is indicated by the dotted line.

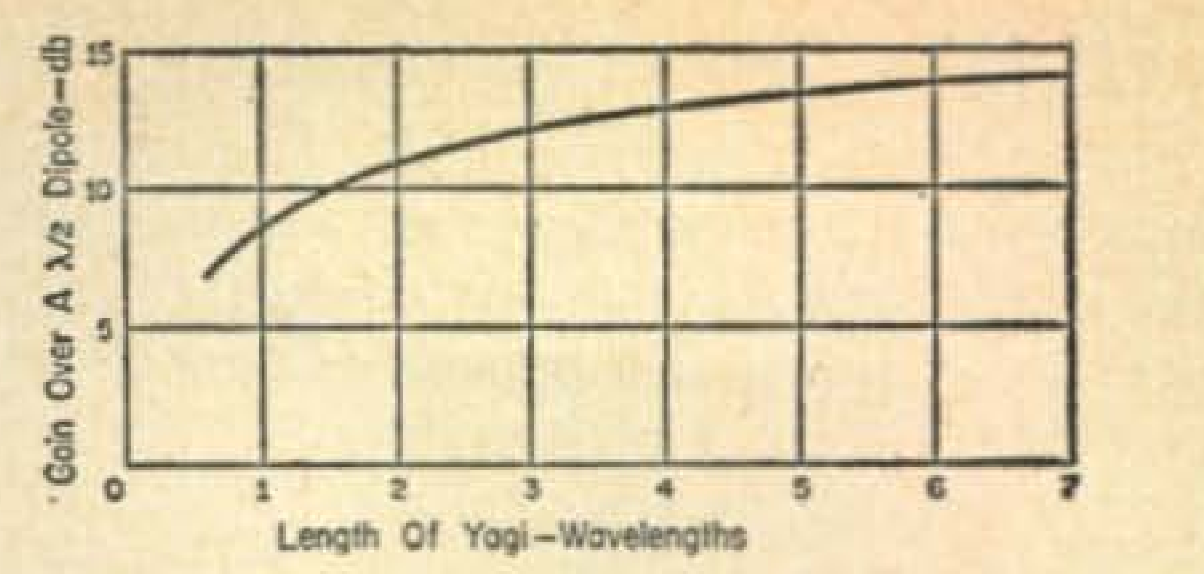


Fig. 3—Chart showing the relationship between maximum attainable gain and length for a yagi antenna. After Ehrenspeck and Poehler.

the optimum phase velocity as a function of array length (measured from the feed point to the far end). Notice that as the array length increases, the optimum phase velocity approaches that of free space. But free space velocity is just what we have *without* a slow-wave structure; i.e., with the launcher alone. So in the very narrow interval between free space velocity and optimum phase velocity, the gain must change from that of the launcher alone to maximum gain for a Yagi of that length. Since the interval becomes narrower as the array length increases, it is not surprising that long Yagis are much more critical to design and adjust than are short Yagis.

The power gain of a classical end-fire array is proportional to length; so ideally 3 db should be added to the gain every time the length is doubled. In practice, however, this 3 db is seldom realized, and in fact is never realized for long Yagis. Figure 3, after Ehrenspeck and Poehler[4] shows the relation between gain and length that may be expected for Yagi antennas. This curve is considerably lower throughout its extent than would be indicated by many Yagi antenna gains claimed in the past. These optimistic gain figures, however, are explainable in terms of the measurement techniques adopted[1]. Figure 3 was determined under precise laboratory conditions and has been experimentally confirmed elsewhere. It can be accepted as the maximum attainable gain for a Yagi of given length.

Notice in fig. 3 that the rate of growth of gain vs. length diminishes with increasing length. A short or moderately long broadside array of dipoles will show less gain than an equal length Yagi. Its rate of growth (power gain is directly proportional to length for a broadside array) does not diminish as rapidly, however, resulting in a crossover point beyond which the Yagi shows *less* gain than an equal length broadside array. This crossover occurs at about 10 wavelengths for a broadside array of half wave dipoles; at about 6 wavelengths for a broadside array of full wave dipoles; and at about 2½ wavelengths for a broadside array of half wave dipoles backed up by reflectors. Of course, both the dipole-reflector array and the full wave dipole array are somewhat clumsier than a Yagi of equal length, but the comparison does show that a point of diminishing return exists for very long Yagis.

[4]Ehrenspeck and Poehler, "A New Method for Obtaining Maximum Gain from Yagi Antennas," *IRE Transactions on Antennas and Propagation*, October, 1959, page 379.

Design Technique

We have seen that the most important parameter involved in the design of end-fire arrays is the phase velocity. For the case of a Yagi, this velocity is determined by four factors listed here in order of their relative influence:

(1) director length
(2) director spacing
(3) director diameter
(4) boom diameter

The phase velocity is lowered by increasing element length, element diameter, or boom diameter; or by decreasing the spacing.

It is important to realize that there are unlimited combinations of these four factors that can yield one and the same phase velocity and only one factor need be controllable in order to construct a Yagi with optimum phase velocity and maximum gain. Of the four, the one that lends itself to easiest control is the second: element spacing. An optimum Yagi may be constructed from directors of fixed length by simply adjusting the spacings for maximum forward gain. Shorter directors will require closer spacings and consequently more elements per unit length. Although there is no gain advantage to either close or wide spacing, since gain depends only on the total array length, a close spaced array does have a slight bandwidth advantage that is purchased at the expense of increased wind resistance.

Figure 4 shows the recommended experimental setup for making optimum Yagis. The directors are laid across wooden rails and can be slid back and forth by means of a notched stick. The spacings are adjusted for maximum received signal from a signal source[5] placed sufficiently far away to meet the distance requirements[1].

The rails upon which the elements rest are designed to have as little effect on the wave velocity as possible. They are made from thin wood and are oriented so that their wide dimension is normal to the electric field. Also, the rails are kept as far as possible from the element ends

[5]Brown, F. W., "A Solid State Signal Source for 144, 432, and 1296 Mc." *CQ*, May 1961, page 32.

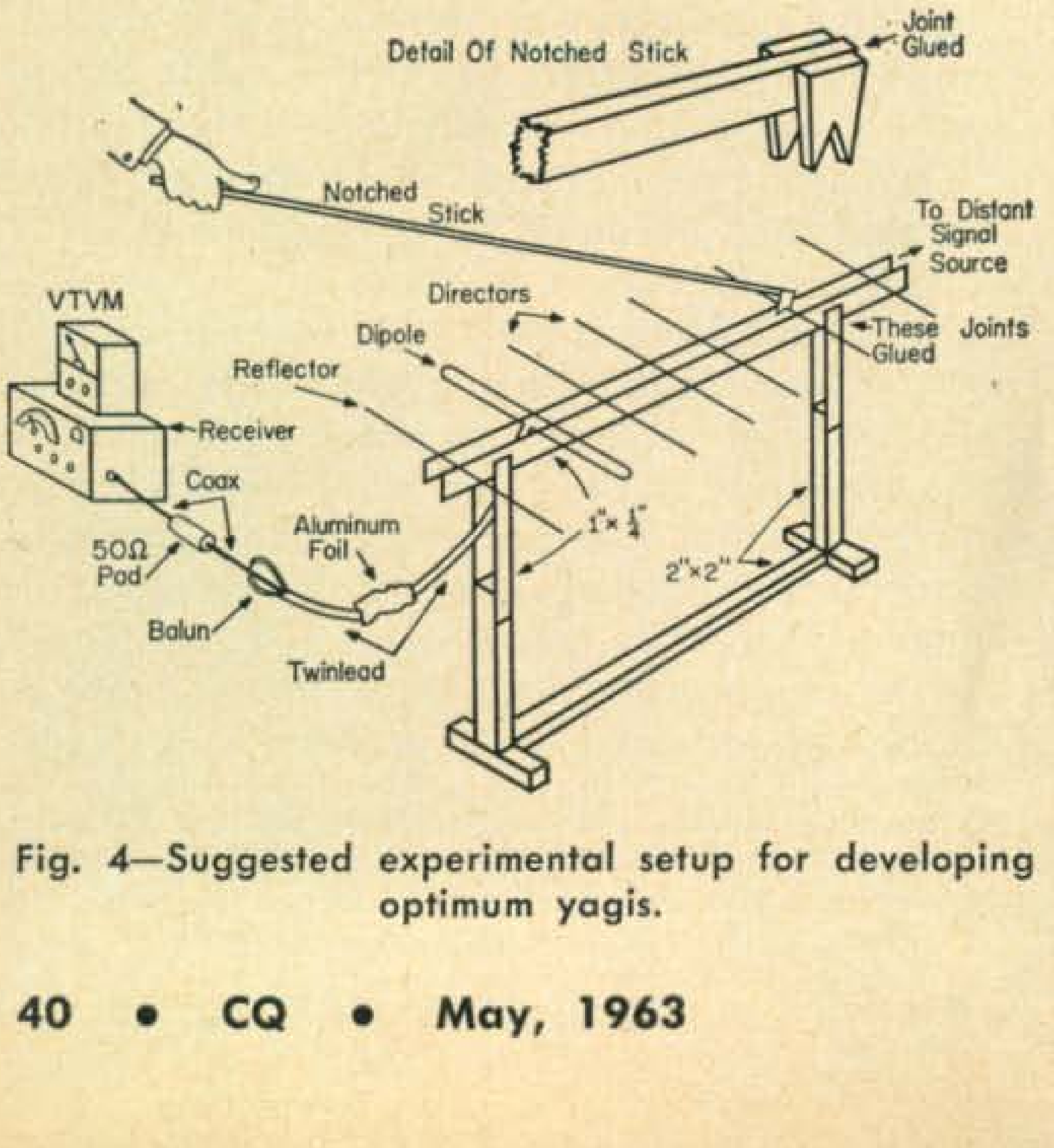


Fig. 4—Suggested experimental setup for developing optimum yagis.

where voltage gradient is maximum. The frame supporting the rails should hold the Yagi at least its boom length above the ground. It should be constructed so as to place as little material as possible near the antenna, and joints near the rails should preferably be made without nails or screws.

The adjustment procedure should be carried out at a site reasonably free of reflections, ideally an open field.

An attenuator pad[1] placed in the transmission line to the receiver is usually necessary to insure a matched load for the antenna, and to wipe out any r.f. stage gain variation due to impedance changes.

Since small differences in signal strength are practically invisible on an S-meter (due to its logarithmic nature), a v.t.v.m. connected to the receiver second detector should be used for the signal indicator. A.v.c., of course, is turned off. If the detector is operated in its square law[1] region, an additional 2 to 1 magnification of small gain changes is provided.

The procedure for determining optimum element spacings is as follows:

(1) With everything ready as in fig. 4, set the dipole and reflector in place and connect to the receiver. Optimum reflector spacing is always ¼ wavelength, regardless of the number of directors used. Notches for the dipole and reflector may be cut in the rails since these elements will not be moved. Tune in the signal and set the r.f. gain control for about 1 volt d.c. output.

(2) Place the first two directors ahead of the dipole and, standing well behind the reflector, adjust the director spacings with the notched stick for maximum meter reading. At this point the dipole may be matched to the line (only the first few directors will affect the dipole impedance). If a folded dipole and twin lead transmission line are used, a quick and easy match may be achieved with aluminum foil wrapped around the twin lead. Simply adjust the foil (position and length) for maximum meter reading.

(3) Add the third director, placing it well out in front of the first two, and then adjust all directors for maximum signal starting with the second. Go over all spacings at least twice since there is some interaction; and then readjust the match. Beyond this point the match should need no further readjustment.

(4) Add the fourth director, again placing it well ahead of the others and adjust all directors starting with the third, then the second, the first, and finally the fourth.

(5) Proceed as in (4) with the other directors, repeaking all every time a new one is added. You will find the average spacing increases as the array length increases, in agreement with fig. 2. When a new director is added, it is placed well ahead of the others to make room for this increased spacing.

(6) That's about all there is to it. When the Yagi reaches the desired length (remember fig. 3), simply measure the spacings and drill the boom accordingly. As mentioned before, the boom will have a slight effect on the phase velocity, and may or may not significantly affect the gain, depending on the boom diameter, material, and the array length. The boom's effect may be tested by temporarily laying it atop the directors and noting its influence on the received signal. Remember that the wooden rails also have a slight slowing effect on the wave which will at least partially compensate for the boom's presence in the final model.

The only remaining problem is to permanently match the dipole to the transmission line. Measurements at 432 mc indicate that the dipole impedance is reduced to about one half by the presence of the parasitic elements. This reduction is much less than has been reported elsewhere, probably because of the different design methods employed. A 2 to 1 s.w.r. is easy to match with the aluminum foil technique. There is more than one position along the line, of course, where the foil will eliminate standing waves. The correct position is that nearest the dipole. When the proper length and position have been found, the foil section may be wrapped with tape and the whole thing doped with paint to make it weatherproof.

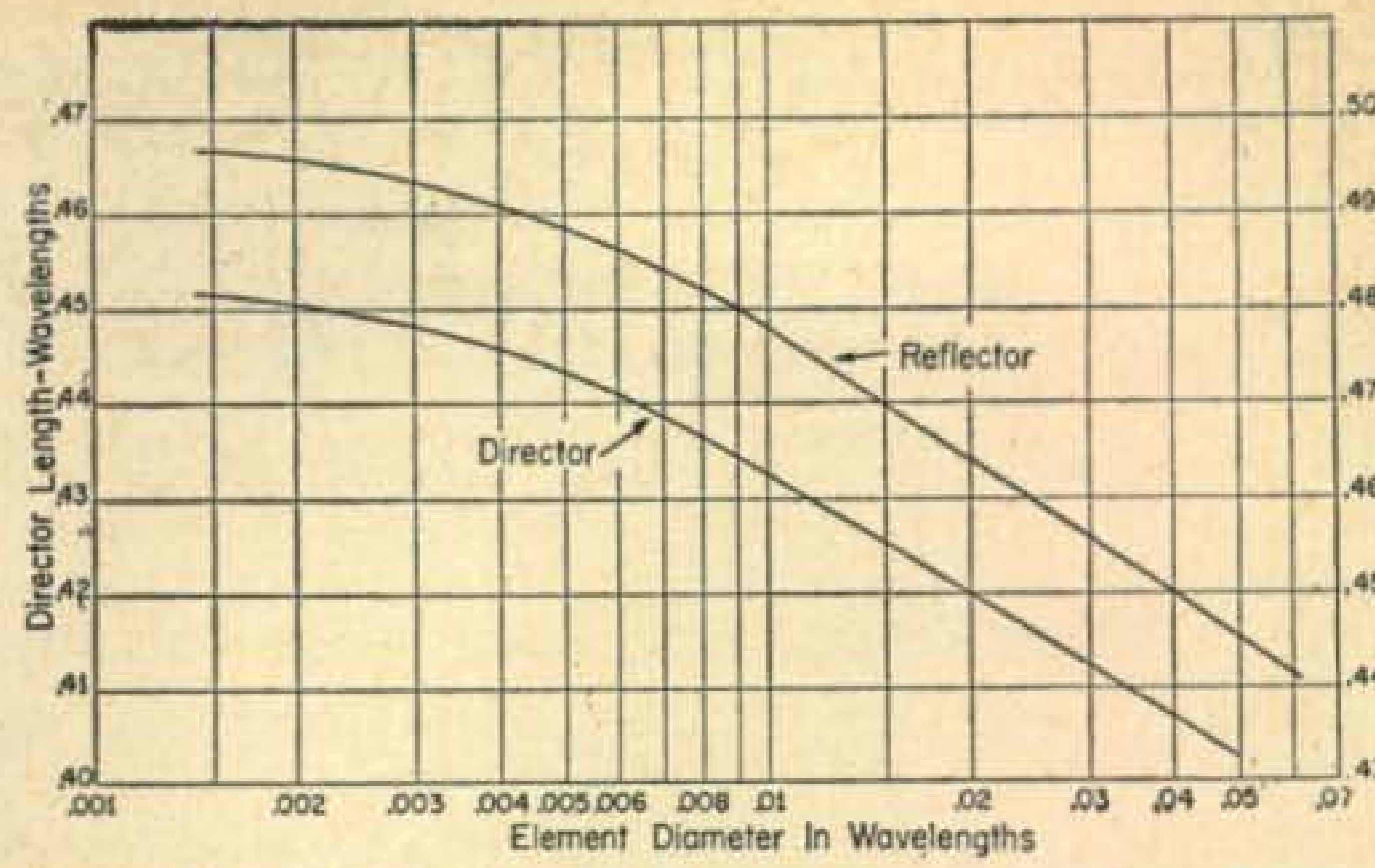


Fig. 5—Director and reflector lengths may be determined from the chart above.

As mentioned earlier, director lengths are not critical within certain limits. A good value for the director lengths, as a function of their diameter, is given in fig. 5. All directors are made the same length, there is no advantage whatever to progressively shortened directors. Ehrenspeck and Poehler[4] have found that director spacings greater than 0.4λ result in a sharp drop in gain. Accordingly, if the spacings turn out to be greater than 0.4λ, it would be wise to shorten all directors by a few percent and start over.

Optimum reflector length is likewise not too critical, and a good value for the reflector length as a function of its diameter is also shown in fig. 5. ■

A Simple Mobile Accessory Cutoff Circuit

BY JACK MYERS*, W5KKB

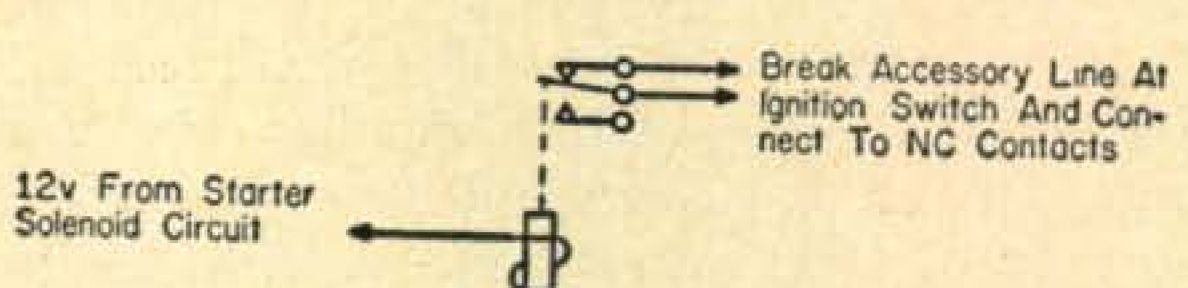
SINCE the starter takes a very large slug of current from the auto battery, it is desirable to have all accessories turned off during starting. Some cars have a special ignition switch so that accessories are cut off when the switch is in the start position. However, many cars do not have this feature.

In the author's Corvair the radio, wipers, back-up lights, heater and air conditioner are controlled by the ignition switch, also any mobile rig that may happen to be installed. On any given trip, 3 or 4 of these accessories are usually on. When the car is stopped and then re-started it is advisable to turn off these accessories, particularly the air conditioner or mobile rig. However, to turn off these items and then turn them back on every time the car is started is rather troublesome.

The simple circuit shown eliminates the problem by turning off the accessories when the engine is being started. One heavy duty relay is used. It must be rated for the full accessory current and have normally closed contacts. Although a commercial unit is specified, any surplus 12 volt d.c. relay meeting those specifications would be satisfactory.

The leads which carry the full accessory current should be of wire the same gauge or heavier than that used for the auto ignition switch wiring. ■

*443 Centenary Drive, Baton Rouge 8, La.



This simple circuit relieves the battery of the accessory load current when starting the car. The relay is a Potter Brumfield PR5D. Any surplus relay with a 12 volt coil, whose contacts can handle up to 25 amps, will do as well.