VERTICAL ANTENNAS

Part I

BY CAPTAIN PAUL H. LEE, *W3JM (ex-W3JHR)

This is the first of a series of articles on the subject of vertical antennas which will be published in this magazine during the next year. Basic principles are presented in this chapter. Subsequent chapters will cover feed methods, arrays, stacked verticals, broadband types and physical design factors.

IN spite of the fact that there have been many articles written on vertical antennas, including several by myself[1,2,3,4,5], there are, no doubt, many amateurs to whom their operation is a bit mysterious. There are some amateurs who emphatically and categorically state that verticals are no good without really knowing what they are talking about. But please, I am not trying to sell vertical antennas to the exclusion of other types; I am just trying to spread a bit of knowledge, and we can stand having a bit spread around in amateur radio these days.

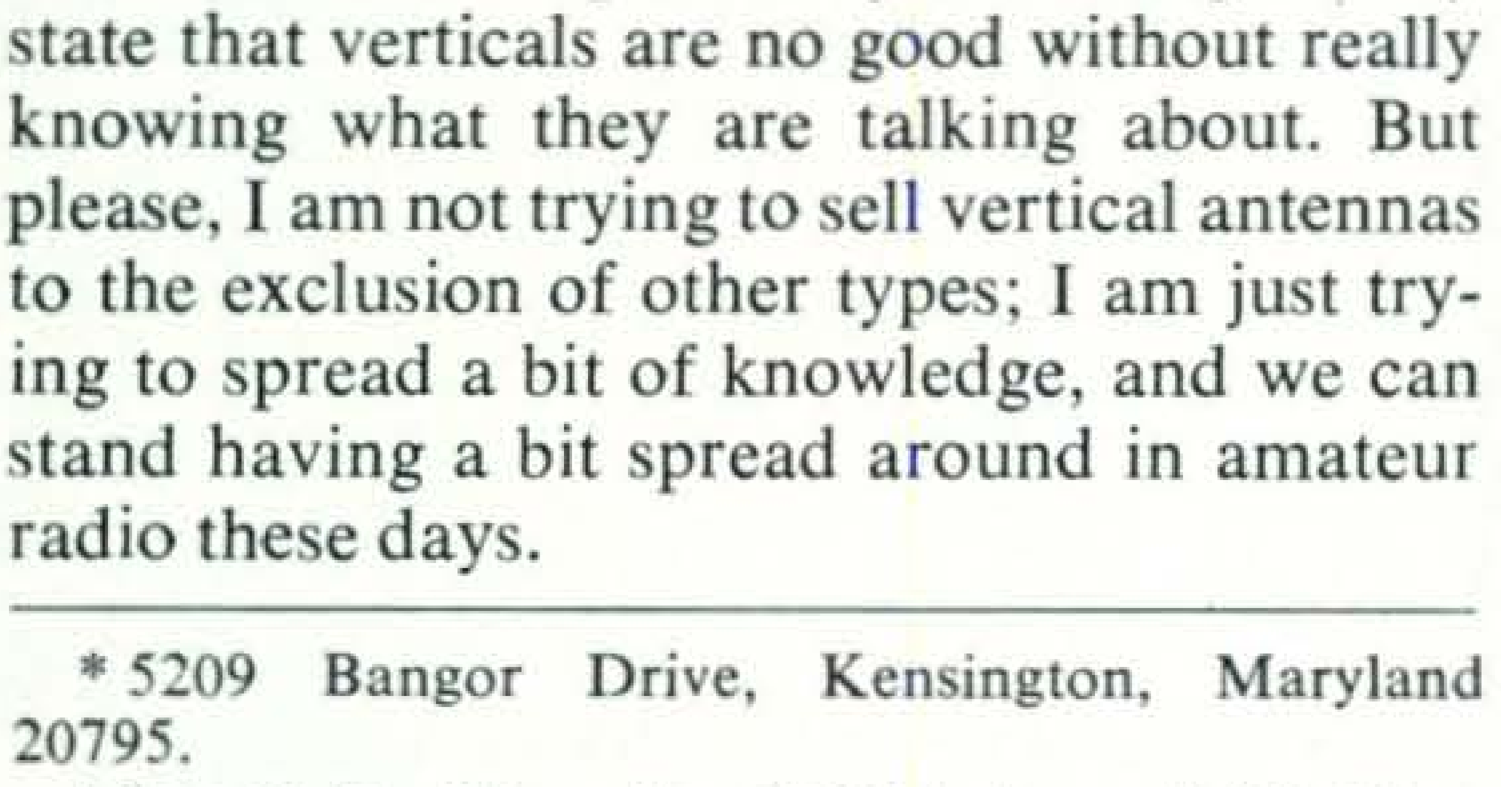

Fig. 1—The theoretical vertical radiation patterns for vertical antennas of ¼, ½ and ⅝ wavelengths in height.

For many years I have found the field of antenna design, in conjunction with propagation study, to be a very fascinating one in which to work, both in naval communications and in civilian consulting radio engineering. Now back in uniform, on active duty in the Navy Department, Washington, D. C., I have much to do with shipboard antenna problems as head of an office which is directing an extensive program of fleet communications improvement. At our service in this endeavor we have the output of years of experience in our naval electronics laboratories and many interesting and valuable contributions from commercial industry. Antenna design is one of the most important factors in the planning of any communications system. In this business one cannot afford to tolerate an "NIH" (Not Invented Here) attitude, nor to say that something is no good. An open mind is the mark of an intelligent man. In this series of articles I plan to discuss many aspects of vertical antennas, from some basic theory right on through actual designs, practical configurations, advantages and disadvantages and results to be expected.

Fundamentally, a vertical antenna is nothing but a horizontal antenna turned up on end. Let us go one step further and rule out the vertical dipole at some distance above earth for practical reasons, and consider the case of the vertical antenna fed at its base against a ground system. For purposes of analysis, this can be considered as a dipole whose lower half has been cut off and replaced by a ground plane. For some purposes the concept of a mirror image (imaginary lower half below ground) is useful. One can say quite truthfully that the total power radiated in free space by a dipole (either vertical

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* 5209 Bangor Drive, Kensington, Maryland 20795.

[1] Lee, P. H., "Four Band DX Antenna," *CQ*, Nov. 1953, p. 20.

[2] Lee, P. H., "Mark II Four Band DX Antenna," *CQ*, July 1960, p. 28.

[3] Lee, P. H., "Optimum Antenna Design For DX Communications," *CQ*, Nov. 1962, p. 49.

[4] Lee, P. H., "Mark III DX Antenna," *CQ*, Dec. 1962, p. 43.

[5] Lee, P. H. "Mark IV DX Antenna," *CQ*, Feb. 1967, p. 60.

See page 126 for New Reader Service

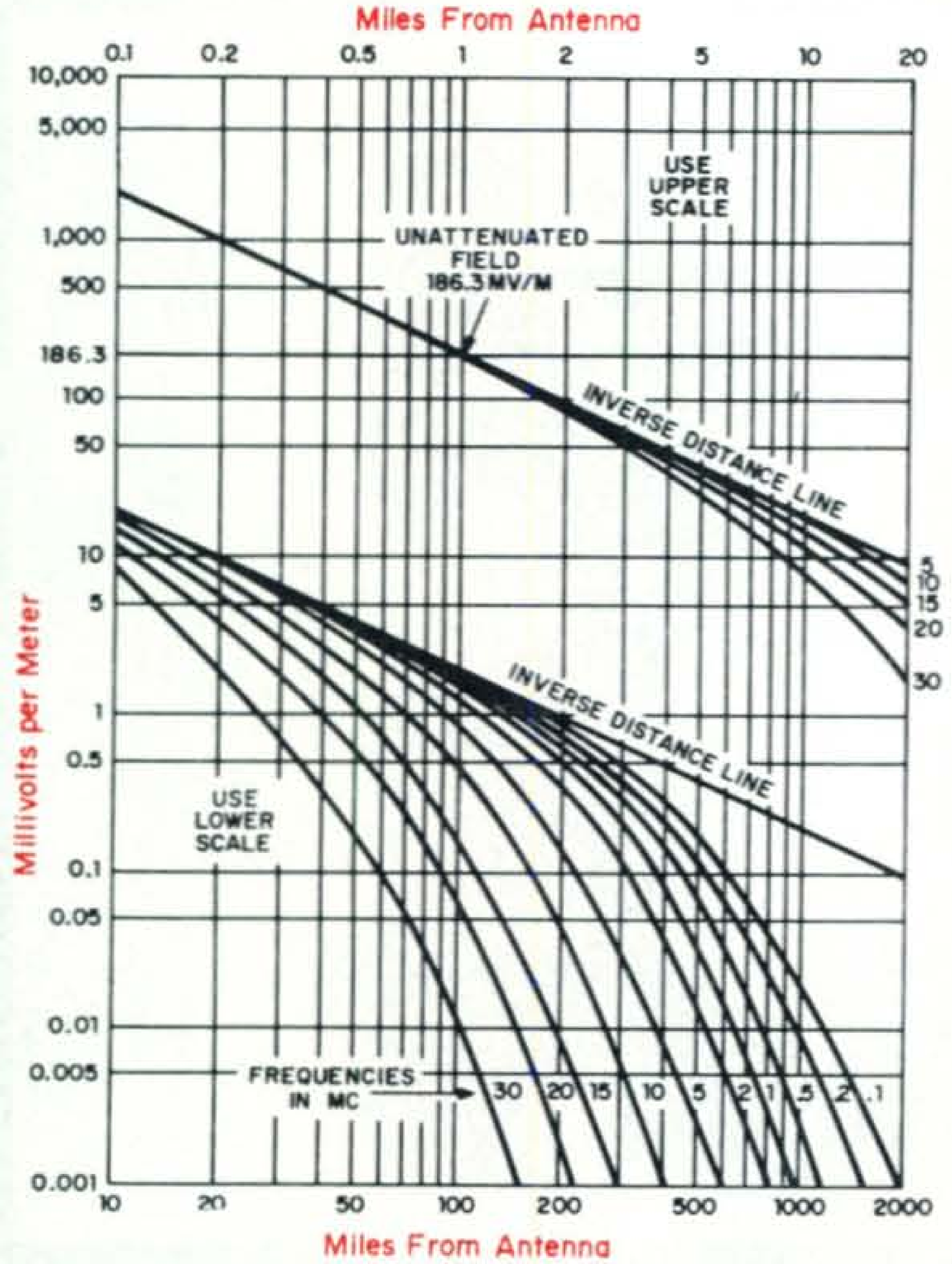

Fig. 2—A plot of ground wave field intensity versus distance from the antenna for various frequencies over sea water based on a radiated power of 1 kw.

or horizontal) has now been concentrated in the upper hemisphere only. Thus it is commonly said that, considering only the upper hemisphere, the radiation from the ground based vertical is 3 db above that from a free space dipole. This is true in one special case, and that is the case of a perfect ground plane with no loss. No such thing exists in actual practice. It can be closely approximated by sea water, or by an extensive copper screen. However, in these two cases there will still be some loss, although minimal. The loss will depend to some extent on frequency. Model studies have shown that for sea water or a large copper ground screen, the vertical radiation pattern of a ground based vertical antenna closely approaches that of the theoretical case.

Vertical Radiation Patterns

What are theoretical vertical patterns of ground based antennas of various heights? They are shown here in figs. 1(A) through 1 (C). It will be noted that as antenna height increases, the ground wave or low angle lobe increases until it reaches a maximum at ⅝ wavelength height. As this height is exceeded, the low angle lobe shrinks very fast, the high angle lobe increases rapidly, and the antenna becomes useless for communications where low angle radiation is required.

Some authors have discussed at length the effect of ground reflections on the vertical pattern, and have stated that all low angle radiation is either absorbed or reflected out of phase, thus making verticals useless for low angle communications. The example invariably used to prove this is one in which the vertical is a dipole, suspended in the air some distance above earth. The center of the dipole is considered to be the theoretical center of radiation. How one is to feed this antenna from a practical standpoint is never mentioned. However this antenna does lend itself very well to a mathematical analysis which can be done by hand or by computer, which shows that ground reflections do occur, and that the vertical pattern has zones of cancellation and reinforcement of radiation, as one would expect. There is an excellent discussion of this in one of the references[6] which is obtainable from the Superintendent of Documents, Government Printing Office, Washington, D. C. at a cost of $1.25. However, this antenna is hardly a practical configuration. It is an entirely different case from that of the practical, base fed vertical whose ground system is a part of the actual radiating system. For an analysis of this type, consider the theoretical center of radiation to be at earth level, and that the ground system is a part of the antenna system, a lossy part to be sure, but still an inseparable part of it. (The vertical dipole mentioned above has no ground system, nor any connection with earth. That point is always overlooked.)

Ground Attenuation

Ground is lossy. Loss increases with frequency. Ground wave radiation thus decreases with frequency. Figure 2 is a plot of ground wave versus distance for various frequencies, over sea water where ε is 80 and σ is 5 mhos per meter. Figure 3 is a similar plot over "good ground", where ε is 15 and σ is 10 mmhos per meter. Figure 4 is the same plot over "poor ground," where ε is 5 and σ is 1 mmho per meter. (ε is the dielectric constant, and σ is the conductivity.) From these plots it can be seen that at l.f. and m.f. ground losses are fairly reasonable. This is why the FCC considers that the vertical radiation patterns closely approach theoretical at frequencies in the m.f. broadcast band. In

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[6] "Siting Criterea For HF Communication Centers," *National Bureau of Standards Technical Note 139.*

past consulting work for broadcast clients before the FCC many skywave patterns have been computed based on this premise, and it might be added that there are literally thousands of actual skywave measurements on file which show this premise to be realistic. Skywave interference ratios between co-channel stations are computed on this basis. Ground wave coverage and directional patterns are similarly based. More will be said about that later.

It can be seen that at frequencies of interest to amateurs, 2, 4, 7, 14, 21 and 28 mc, ground wave attenuation over earth increases greatly with frequency. Thus from a ground based antenna, the ground wave will be quite strong within two or three miles, but will rapidly attenuate as distance increases, until it finally becomes useless. There is no such thing at h.f. as 50 to 100 mile ground wave coverage, as occurs in the m.f. broadcast band. Because of these ground losses the vertical pattern from a vertical antenna at h.f. will show considerable "suck-in" at low angles, as shown in fig. 5. The exact patterns will depend on frequency, with more suck-in and loss at higher frequencies.

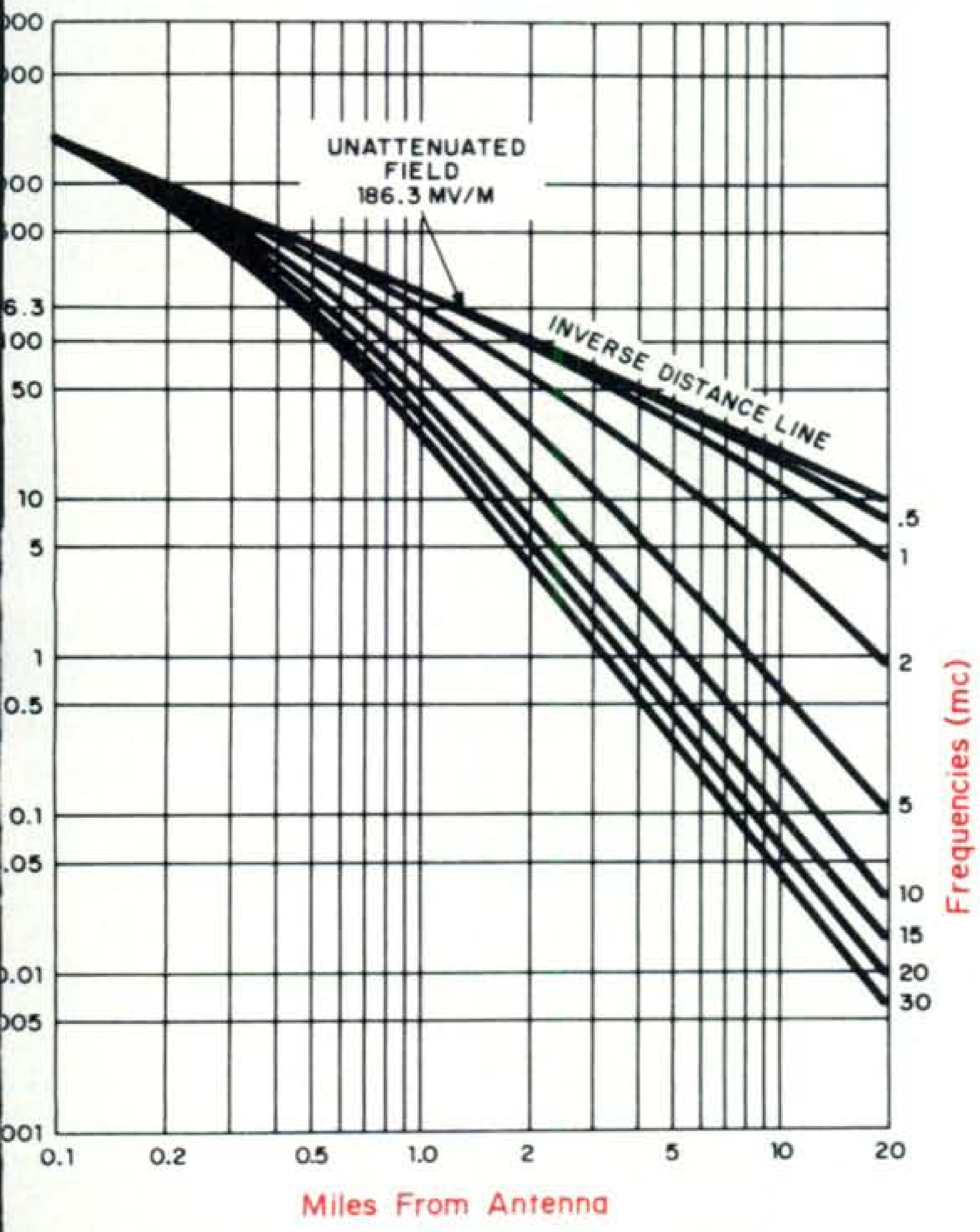

Fig. 3—A plot of ground wave field intensity versus distance from the antenna for various frequencies over "good ground" where $\varepsilon = 15$ and $\sigma = 10$ millimhos per meter, based on a radiated power of 1 kw.

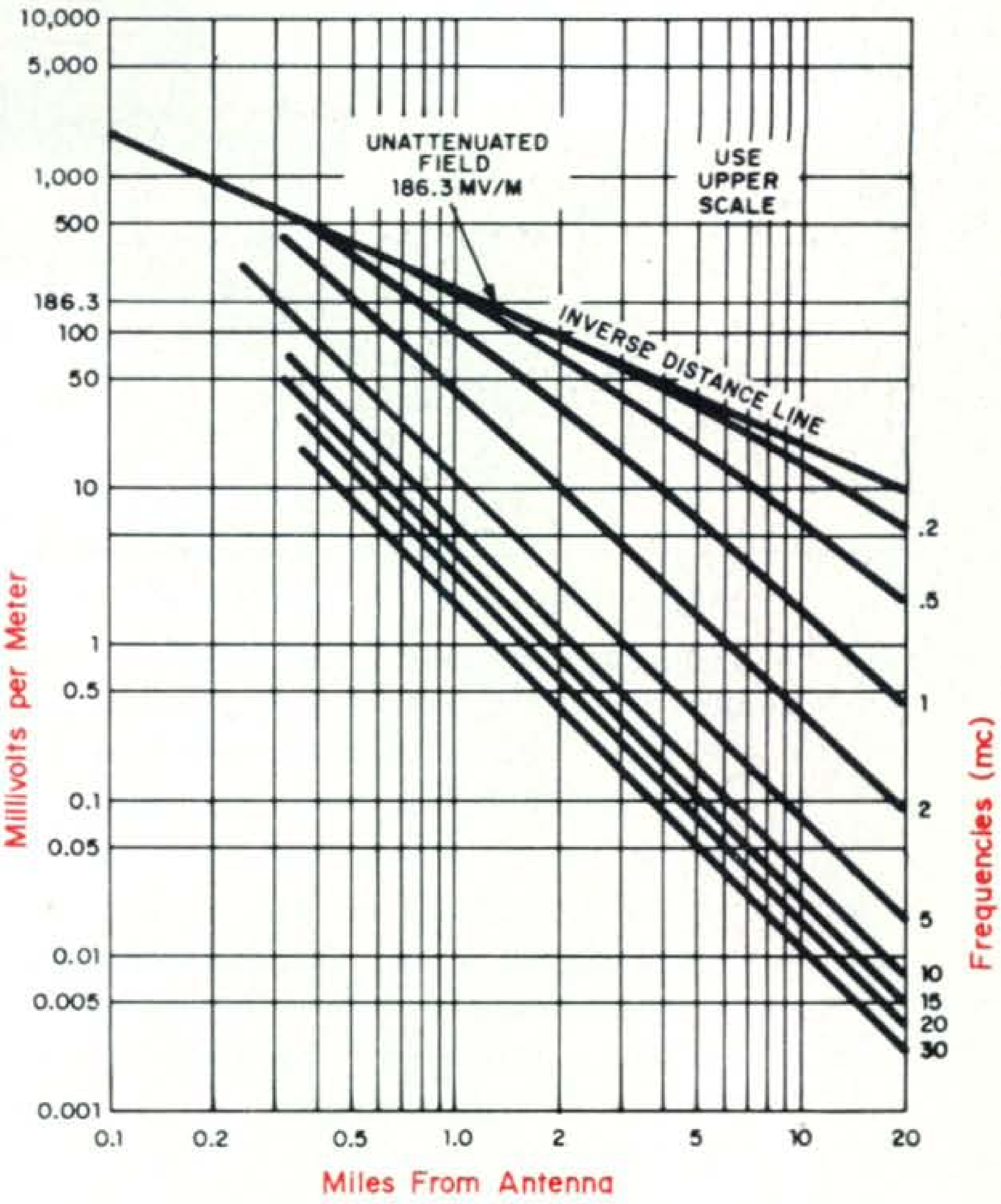

Fig. 4—A plot of ground wave field intensity versus distance from the antenna for various frequencies over "poor ground" where $\varepsilon = 5$ and $\sigma = 1$ millimhos per meter, based on a radiated power of 1 kw.

Thus it is apparent that it behooves the amateur who uses a vertical antenna to install as good a ground system as possible to minimize the losses. He who lives on the ocean beach or other body of water is indeed fortunate, for his local ground losses will be much less than those of the poor soul on a city lot surrounded by buildings, trees, etc.

The vertical radiator with ground system is thus more efficient at the lower amateur frequencies, such as 2, 4 and 7 mc. It is simply a matter of losses. The vertical radiator with counterpoise or metal ground plane is therefor used at higher frequencies. One does not see v.h.f. or u.h.f antennas sitting on the ground, with buried ground planes. However, buried ground systems are used up through 28 mc with good success. More will be said about ground systems and their effect on radiation efficiency later.

Gain

Meanwhile, let's talk about the subject of "gain." What is antenna gain? We hear it mentioned many times on the air, and see it quoted (or misquoted) in advertisements. To have gain, one must start with something and

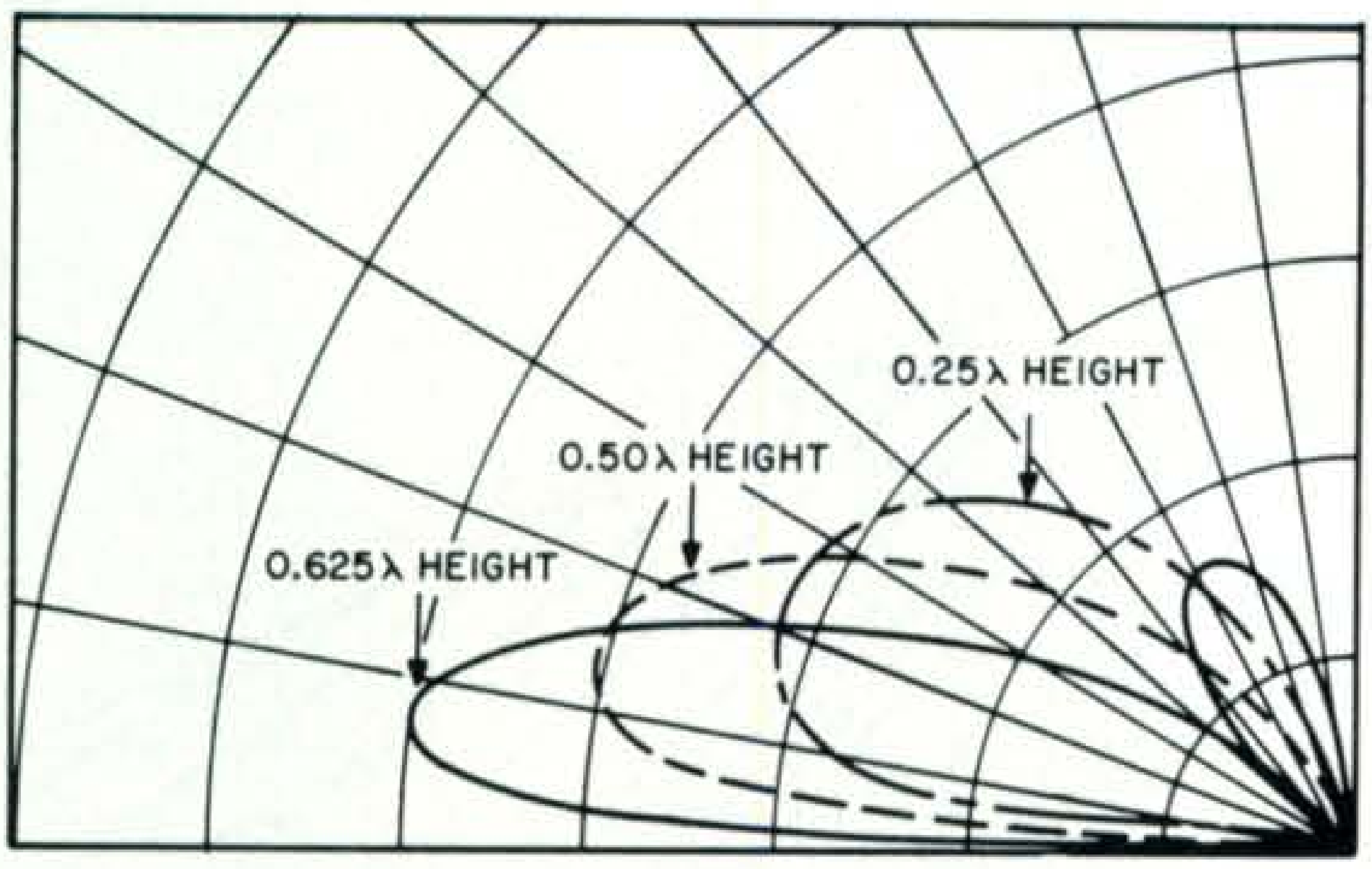

Fig. 5—Ground losses cause "suck in" of the vertical radiation pattern of the vertical antenna. The effects are shown above for antennas of various wavelengths.

then compare something else to it. What is the start, in antenna work? What is the basis of comparison? What is this "isotropic" antenna we hear about — so many db above isotropic? An isotropic antenna is a theoretical zero length point source. It can never exist. However, it is used as a theoretical and mathematical basis for comparison. In reality, what else could one use? The isotropic antenna is one which radiates equally in all directions. For a given power input, it will produce a certain radiated field intensity at a given distance from it, in all directions. A plot of its radiation pattern is a perfect spherical surface, with the point source at the center of the sphere. Every *practical* antenna, which must have finite length, thickness, and distance from earth, will produce a pattern which is not constant in all directions. Thus the practical antenna is said to possess gain (or loss) in certain directions when compared to the isotropic antenna. *Gain is meaningful only when referred to a specific path or direction.* Directional gain is defined as the ratio of the power that must be radiated by an isotropic antenna to the power being radiated by the test antenna under consideration, to develop equal field intensities from the two antennas in a certain direction. Consider that the isotropic spreads power over the entire spherical surface. The directional antenna, on the other hand, concentrates power in a certain area of the sphere's surface. This concept is shown in fig. 6. Thus for equal field intensities at point "X" within the area illuminated by the beam, the power in the isotropic must be considerably greater than that in the test directional antenna. This power ratio between the two is equal to the gain of the directional antenna. It can be seen that there is an inverse relationship between gain and areas illuminated, for a certain fixed power. There is a simple method of computing the gain of a directional antenna.[7] The number of "square degrees" area in the surface of a sphere has been computed to be 41253. Keeping in mind the relationships mentioned above, divide this number by the number of "square degrees" in the beam of the directional antenna between the half-power points, and the result will be a close approximation of the power gain of the directional antenna, in the direction of the beam. Consider the 3 element horizontal Yagi antenna, whose beam width is about 60 degrees in the horizontal plane,[8] and about 30 degrees in the vertical plane, for a height above earth of ½ wavelength. The approximate area within the half-power limits is 1800 square degrees.

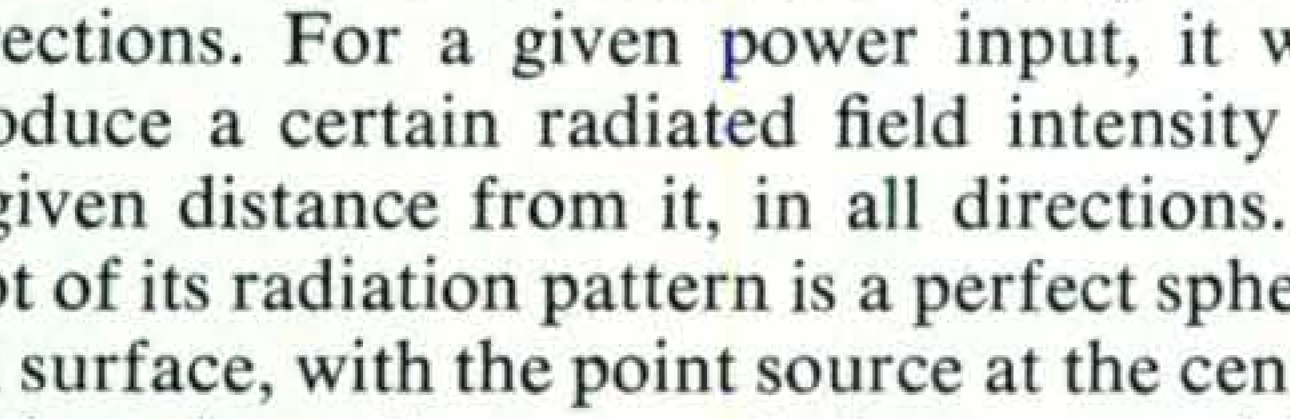

Fig. 6—Comparison of radiation pattern of an isotropic versus a directional antenna.

$$\text{Power gain} = \frac{41253}{1800} = 22.9,$$

or 13.60 db above isotropic

Note that I said *above isotropic*, the theoretical antenna which cannot exist. Sometimes, without much thought, the horizontal dipole is used as a reference. But this can be very confusing, because its radiation varies with direction, both in the horizontal and the vertical planes, and with distance above earth. Thus, a manufacturer can easily confuse an amateur by saying simply that his beam has so much gain in db. Gain with reference to what? To isotropic? To a dipole? In what direction? At what vertical angle? At what height above earth? The "gain above isotropic" figure is always more impressive to the reader, because in the direction of its main lobe the dipole has several db gain with refer-

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[7] Terman and Pettit, *"Electronic Measurements,"* Second Edition p. 436.

[8] Kraus, J. D., "Antennas," *McGraw-Hill*, p. 321.

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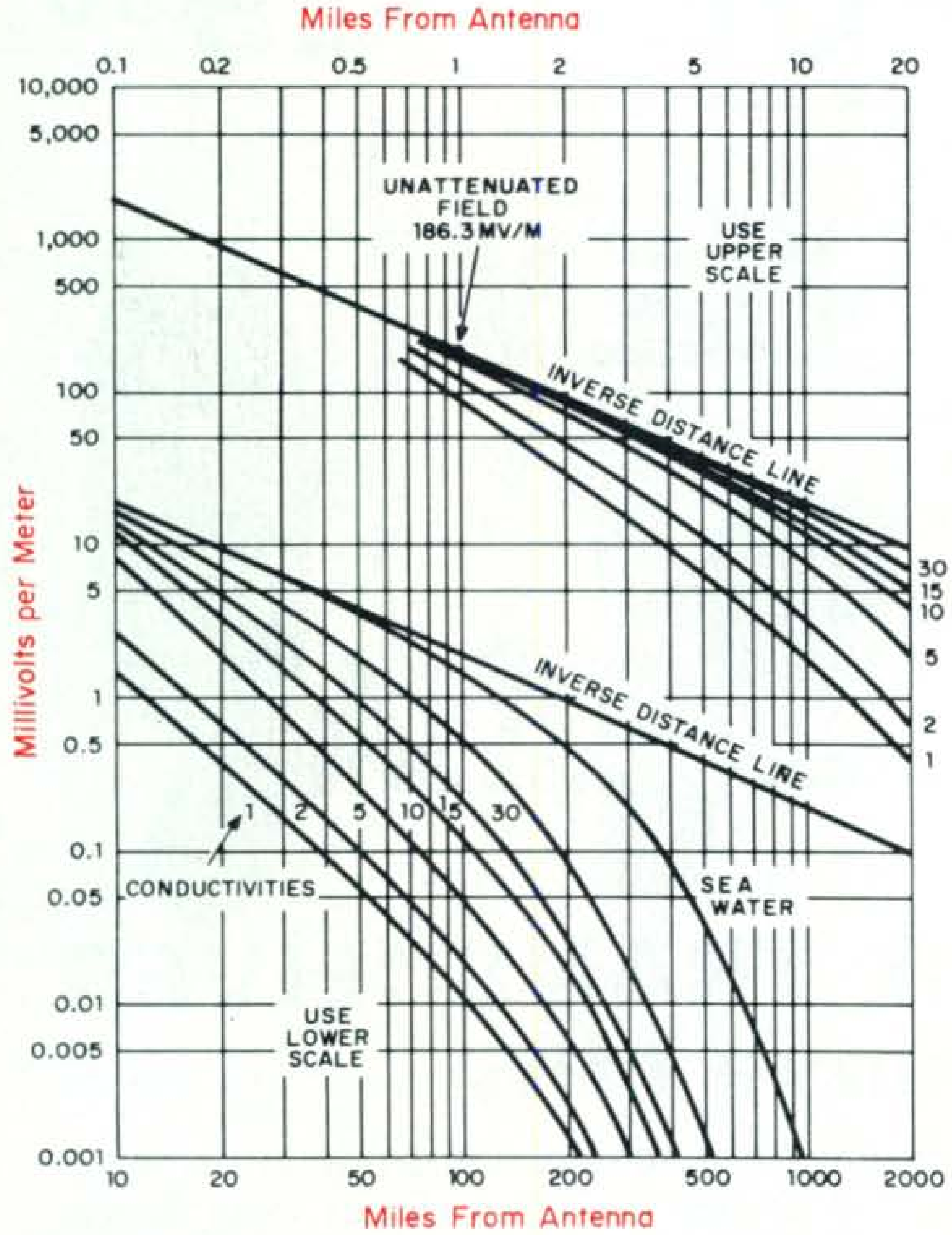


Fig. 7—A plot of ground wave field intensity versus distance from the antenna for 970 to 1030 kc. The unattenuated field is 186.3 mv/m at one mile for a radiated power of 1 kw. The dielectric constant ε is 15 and the conductivities σ are shown in millimhos/meter.

ence to isotropic. Thus gain figures quoted by manufacturers have to be considered with care, with special attention to the fine print. Don't be fooled by gain figures; ask the question, "Gain with reference to what?" You may be surprised at the answer. Some beams, especially miniature ones, have little gain above a dipole, possessing only *directional discrimination.*

We might be inquisitive, not to prove any thing but to simply find the answer, and compute the gain of a ⅝ wave vertical antenna.

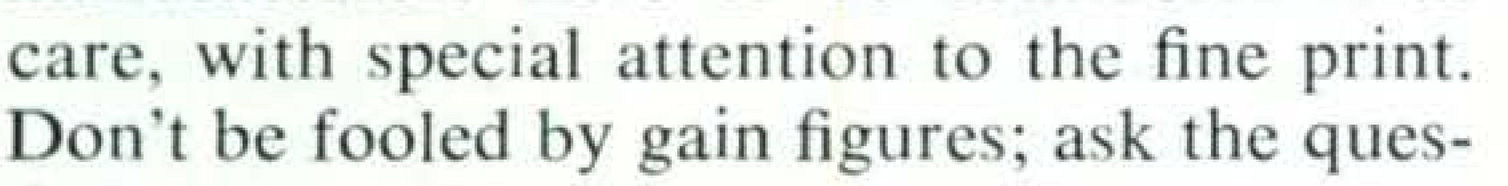


Fig. 8—Theoretical vertical patterns for antennas of 0.25, 0.5 and 0.625 λ heights.

We must decide on a reference, which by rights should be isotropic. The vertical beamwidth to be expected is about 15 degrees. Since the horizontal spread is a full 360 degrees, the approximate number of square degrees is 5400.

$$\text{Power gain} = \frac{41253}{5400} = 7.63$$

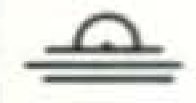
or 8.84 db above istropic

Note that I again said *above isotropic,* the theoretical antenna which cannot exist. Thus by computing the gains of individual antennas with reference to isotropic, their gains relative to each other may be determined. The above computations show a relative gain of 4.76 db for the Yagi over the ⅝ wave vertical, but *in different main lobe directions.* The lobe from the ⅝ wave vertical is lower than that from the Yagi.

Gain is meaningful only when considered with reference to a particular communications path and set of propagation conditions. This factor can never be overlooked. A simple illustration will suffice. Antennas designed for the tropical broadcasting bands to produce skywave coverage over a certain Latin American country or two usually are horizontal dipoles at a low height above ground, thus producing only high angle skywave lobes. They are useless for long distance communications. They are designed that way intentionally, to restrict coverage. Thus, one cannot say that one antenna is no good, or that another is the perfect answer. Each type has its own specific application, designed to fit certain systems requirements.

There is another way of determining the efficiency of a vertical antenna. As a basis of evaluation in this case, it has become standard practice throughout the years to use the "unattenuated field intensity at one mile" as the reference for field intensity measurements. This figure is the basis for all plots such as those in figs. 2, 3, 4 and 7. It is a figure of merit which can be accurately determined by a carefully made series of field intensity measurements, taken along a number of radials (usually at least 8) and out to considerable distance from the antenna. Each set of radial measurements is then plotted in a field intensity plot such as that in fig. 7. From knowledge of the ground conductivity in the area (shown in fig. 11) the plotted curve can be fitted against one of those in fig. 7, and the actual unattenuated field being radiated can be determined. The curves of fig. 7 show field intensity versus distance for various ground conductivities, with the *standard unattenuated field of 186.3 mv/m at a mile for one kilowatt radiated power*. Figure 7 is an adaptation of one of a series of such figures from the FCC rules for various frequencies in the m.f. broadcast band. It is used merely as a convenient example. Similar curves can be plotted for frequencies in the h.f. range.[9] As may be seen, figs. 2, 3 and 4 are a partial plot of such. There is a direct relationship between them and fig. 7.

One may ask the origin of the "186.3 mv/m at one mile" as a standard of vertical antenna efficiency. This figure is the unattenuated field at one mile for a theoretical zero-height point source current element on a ground plane. The derivation of this figure is given in one of the references.[10] The table below shows the relationship between the zero height point source current element and the isotropic. The current element is, of course, something which cannot exist in practice.

Type	Pattern	mv/m at 1Mile (1 kw)	Power Gain	DB Gain
Isotropic	⊙	107.6	1	0
Half Isotropic		152.1	2	3.01
Current Element		186.3	3	4.77

Practical antennas have finite height. Figure 8 shows the vertical patterns which can be computed for antennas of various heights. It may be seen that this figure is the same as fig. 1, but plotted with field intensity values. The theoretical unattenuated field at one mile along the horizontal plane may be read for each. They are as follows:

Height of antenna	*Unattenuated field at One Mile (1 kw)*
0.25 (¼)λ	196 mv/m
0.50 (½)λ	236 mv/m
0.625(⅝)λ	276 mv/m

Thus it may be seen that the 0.625 (⅝) wave antenna produces the greatest ground wave field, and the lowest main lobe. Figure 8 is taken directly from the FCC rules. The values shown are theoretical maximums. Antennas with adequate ground planes and low losses will closely approach these values, as will be seen shortly.

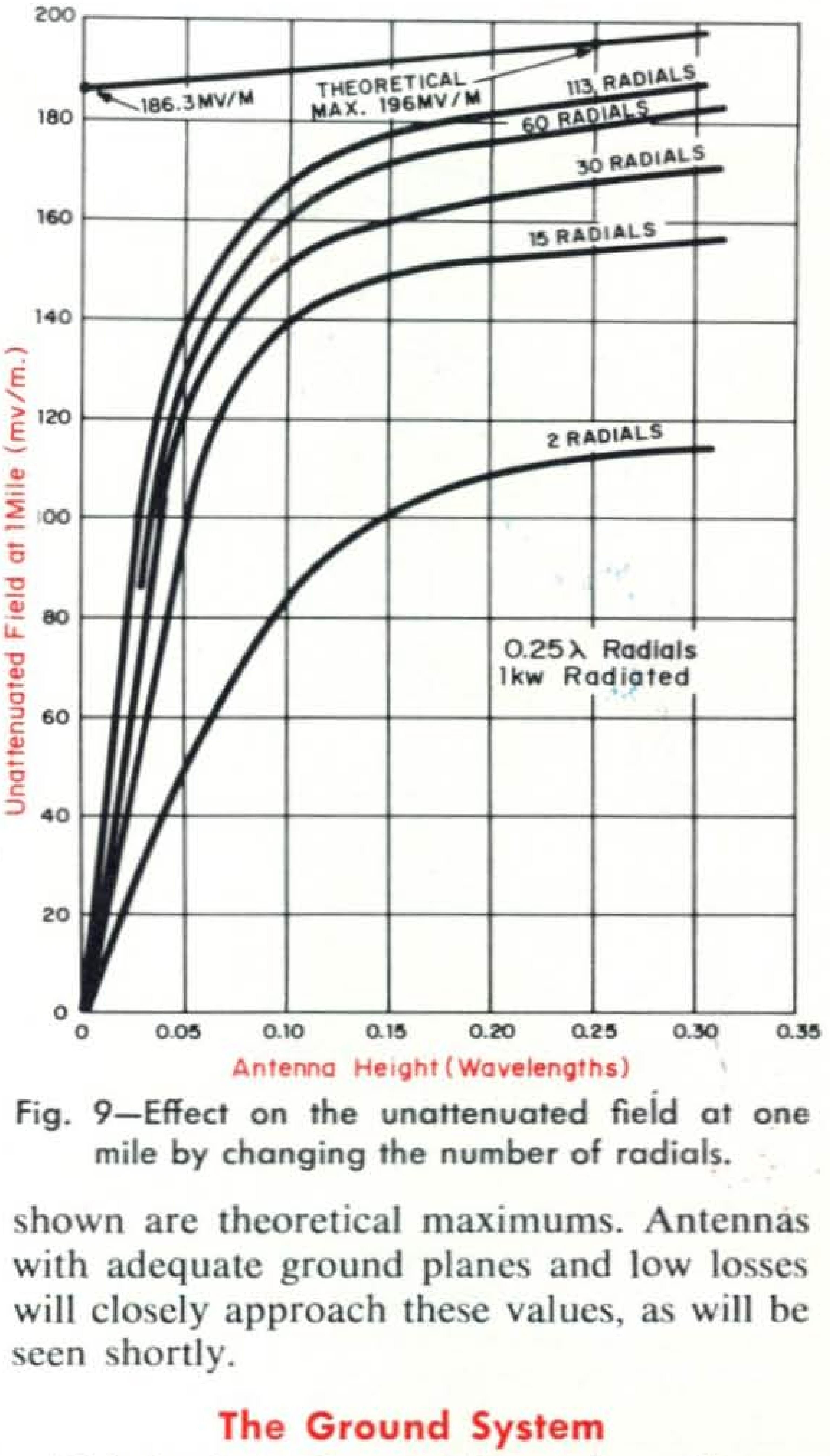


Fig. 9—Effect on the unattenuated field at one mile by changing the number of radials.

The Ground System

This leads to the next item of my discussion, which is the ground system. There have been several good articles published in past years on the subject of ground systems and their effect on antenna efficiency and other parameters. One of the best, which we in the business consider to be the "bible", is by G. H. Brown.[10] It was based on an extensive experimental program of actual field measurements by RCA Laboratories. It covers such factors as numbers and lengths of radials, depth of burial, ground currents, losses, radiation resistance, and other factors. The development of the figure of 186.3 mv/m is shown. Figure 9, based on this reference, shows a factor of interest to amateurs, which is the effect of changing the number of radials of a fixed length. Figure 10 shows another such factor, the effect of varying the length of the radials, for certain fixed numbers of radials (15 and 113). A study of these figures shows that radiation efficiency is greatest for a large number of long radials, but it can be seen that the curves flatten off and that there is an area of diminishing returns where the percent

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[9] Norton, K. A., "Calculation of Ground Wave Field Intensity Over a Finitely Conducting Spherical Earth," *Proc. of I.R.E.*, Dec. 1941, p. 632.

[10] Brown, G. H., et al, "Ground Systems As A Factor In Antenna Efficiency," *Proc. of I.R.E.*, June 1957, p. 735.

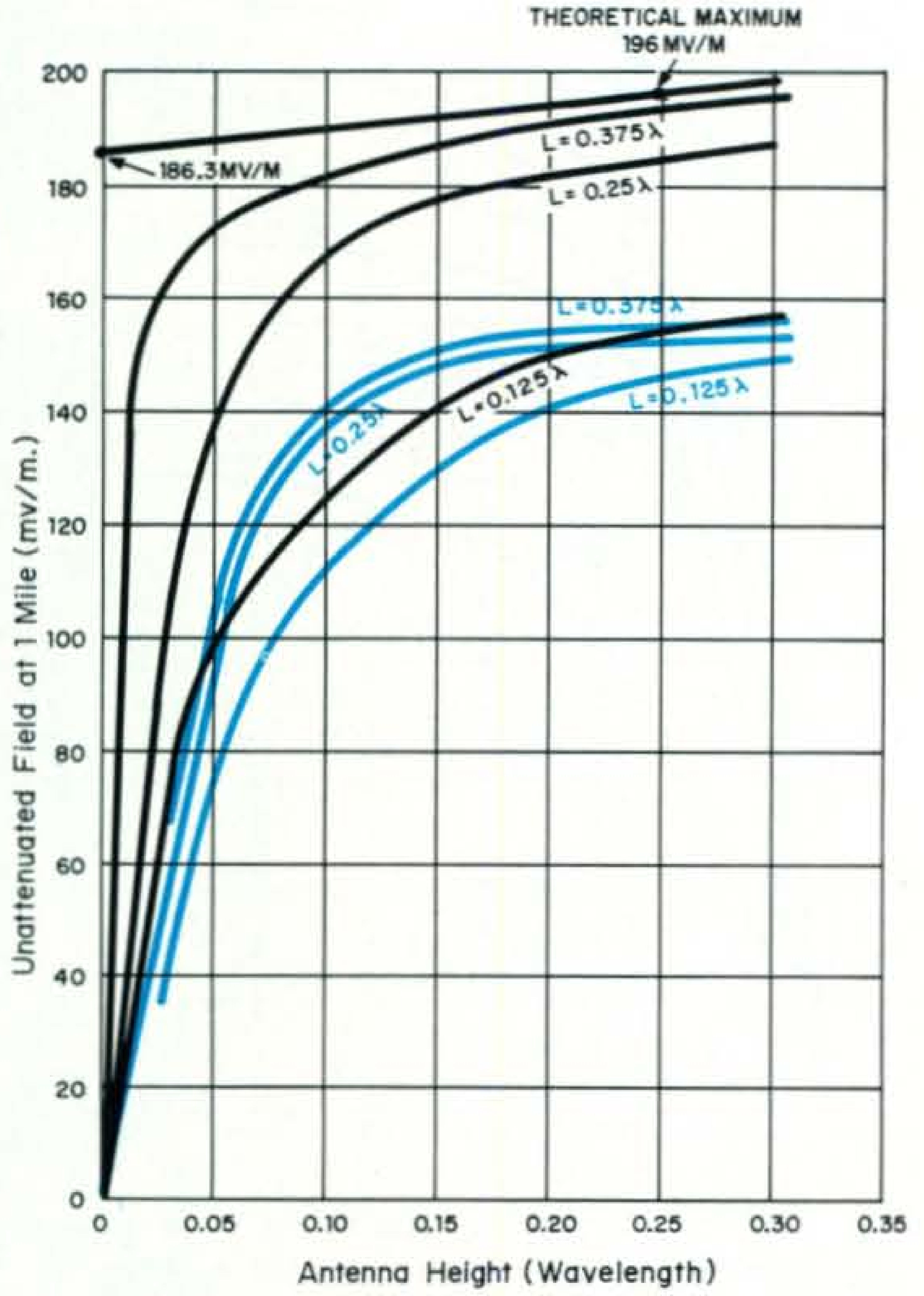


Fig. 10—Effect upon the unattenuated field strength at one mile by varying the length of the radials. The radial lengths, L, are specified in wavelengths. Black curves are for 113 radials and the colored curves are for 15 radials.

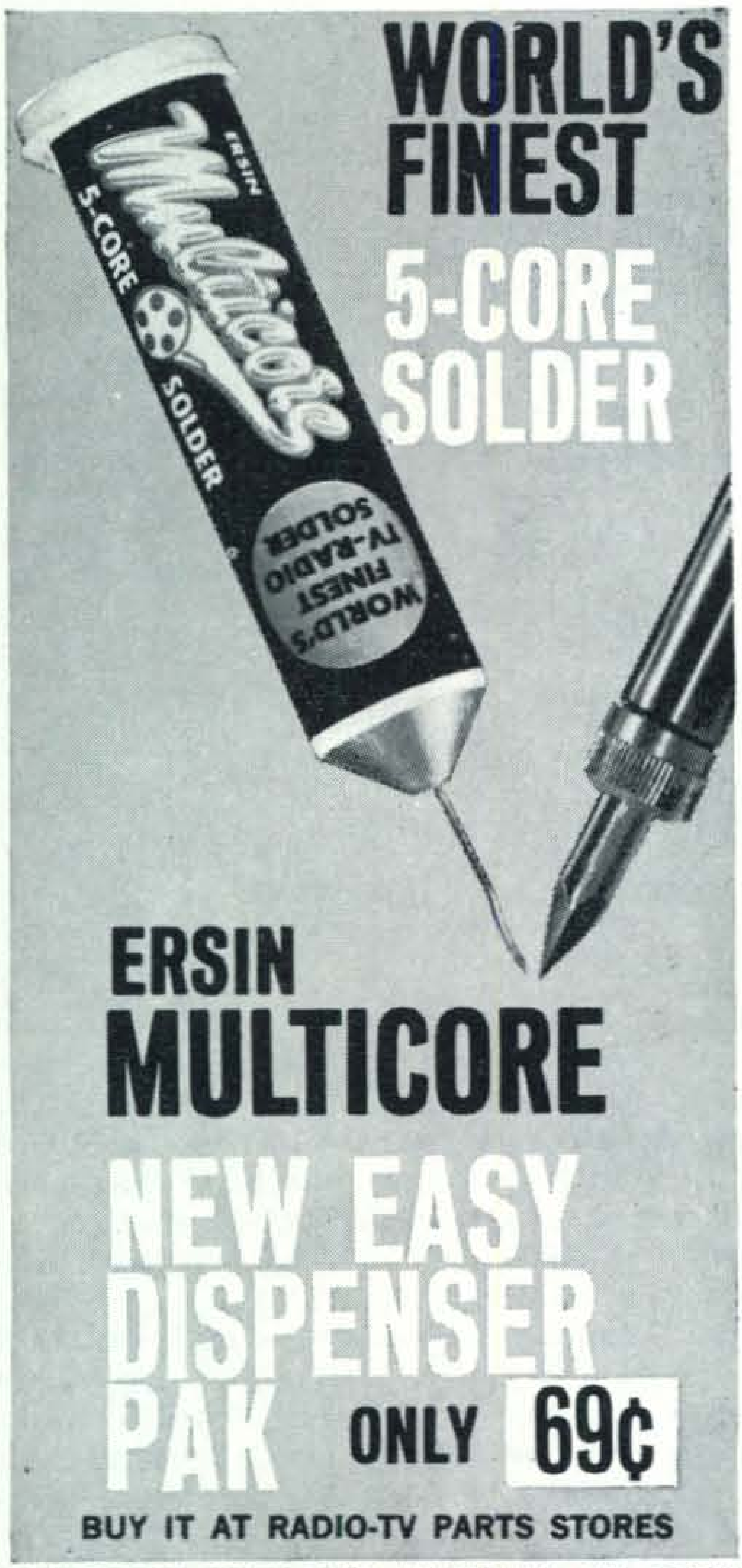
increase in efficiency is not really worth the added cost of copper in the ground. FCC rules require that broadcasters use at least 120 radials ¼ wave long. Many stations better this. For the average amateur, 16 is a reasonable and economical number. Doubling the number will not double the radiation efficiency.

It should next be realized that the unattenuated field determined by measurements is the "starting out" radiation from an antenna of given height. It is less than the theoretical field by amount which is determined by the losses in the ground system, as shown in figs. 9 and 10. It is also affected by losses in the antenna itself, and by the presence of buildings, wires, and other absorptive elements in the vicinity of the antenna. This is especially true at h.f., where losses in the immediate vicinity may be quite high, as some of those objects approach an appreciable size in terms of wavelength. He who has a good, clear site is fortunate. Then, as the signal proceeds further from the antenna along the surface of the earth, it is attenuated even more by ground losses, causing the considerable suck-in of the low angle radiation, especially at the higher frequencies.

Figure 11 is included for those who are interested in knowing something about

[*Continued on page 120*]

Fig. 11—Estimated effective ground conductivity in the United States. The numbers represent estimated effective ground conductivity in millimhos/meter. The conductivity of sea water, while not shown, is assumed to be 5000 millimhos/meter.



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Central & South Asia	*Nil*	07-09 (1) 09-11 (2) 11-13 (1) 17-19 (1) 19-21 (2) 21-22 (1)	22-04 (1) 04-08 (2) 08-11 (1)	*Nil*
South-east Asia	*Nil*	07-08 (1) 08-10 (3) 10-12 (2) 12-15 (1) 18-20 (1) 20-22 (2) 22-00 (1)	22-00 (1) 00-02 (2) 02-04 (3) 04-06 (2) 06-08 (3) 08-10 (2) 10-13 (1)	02-06 (1)
Far East	13-15 (1)	08-09 (1) 09-11 (2) 11-13 (1) 13-14 (2) 14-16 (3) 16-18 (2) 18-21 (1)	18-20 (1) 20-22 (2) 22-00 (3) 00-02 (4) 02-04 (3) 04-06 (2) 06-09 (3) 09-11 (2) 11-14 (1)	01-02 (1) 02-05 (2) 05-06 (1) 02-04 (1)*
Pacific Islands & New Zealand	11-13 (1) 13-18 (2) 18-19 (1)	08-10 (1) 10-11 (2) 11-13 (3) 13-15 (2) 15-17 (3) 17-20 (4) 20-21 (3) 21-22 (2) 22-00 (1)	16-18 (1) 18-20 (2) 20-01 (4) 01-05 (2) 05-07 (4) 07-10 (2) 10-12 (1)	21-22 (1) 22-00 (2) 00-05 (3) 05-06 (2) 06-07 (1) 23-01 (1)* 01-04 (2)* 04-06 (1)*
Aus-tralia	13-16 (1) 16-19 (2) 19-20 (1)	06-08 (1) 12-14 (1) 14-17 (2) 17-19 (3) 19-21 (4) 21-22 (3) 22-00 (2) 00-02 (1)	19-21 (1) 21-23 (2) 23-04 (4) 04-06 (3) 06-08 (4) 08-09 (2) 09-12 (1)	23-01 (1) 01-03 (2) 03-05 (3) 05-06 (2) 06-07 (1) 01-06 (1)*
North-ern & Central South America	08-10 (1) 10-12 (2) 12-14 (1) 14-16 (2) 16-17 (1)	07-08 (1) 08-12 (2) 12-14 (3) 14-17 (4) 17-18 (3) 18-20 (2) 20-22 (1)	08-10 (2) 10-13 (1) 13-15 (2) 15-17 (3) 17-23 (4) 23-02 (3) 02-05 (2) 05-08 (3)	19-20 (1) 20-23 (2) 23-02 (3) 02-04 (2) 04-05 (1) 20-00 (1)* 00-02 (2)* 02-03 (1)*
Brazil, Argen-tina, Chile & Uru-guay	08-12 (1) 12-14 (2) 14-16 (3) 16-18 (2) 18-20 (1)	05-06 (1) 06-08 (2) 08-12 (1) 12-14 (2) 14-16 (3) 16-20 (4) 20-22 (3) 22-23 (2) 23-00 (1)	13-15 (1) 15-17 (2) 17-18 (3) 18-23 (4) 23-00 (3) 00-02 (2) 02-04 (1) 04-06 (2) 06-09 (1)	20-22 (1) 22-01 (2) 01-04 (1) 21-02 (1)*
Mc-Murdo Sound, Antarc-tica	16-18 (1)	14-16 (1) 16-20 (2) 20-21 (1)	15-17 (1) 17-18 (2) 18-00 (3) 00-03 (2) 03-06 (1)	20-21 (1) 21-23 (2) 23-03 (1) 03-05 (2) 05-06 (1)

Vertical Antennas

[*from page 24*]

ground conductivities in the United States. It is taken directly from the FCC rules. This map is based upon thousands of field intensity measurements made and on file with the FCC. It will be noted that some of the midwest states have ground conductivity as high as 30 mmhos/meter. On the other hand, mountainous areas are quite low in conductivity, around 2 or 4 mmhos/meter.

In the next chapter, the impedance characteristics of vertical antennas of various heights and the circuits used for tuning or matching them to the power source will be discussed.

[*To be continued*]

See page 126 for New Reader Service

VERTICAL ANTENNAS

Part II

BY CAPTAIN PAUL H. LEE, *W3JM

This is the second in a series of articles on a subject which has never before been treated in depth in an amateur magazine. The first chapter in last month's issue covered basic principles. This one deals with base impedances and methods of feeding and matching.

THE input (base) impedance of an ungrounded vertical antenna which is being fed against a ground plane is dependent on several factors. The one factor which has the greatest effect is of course the height of the vertical radiator. The height is usually mentioned in terms of wavelengths. In the first chapter vertical radiators of 0.25, 0.50 and 0.625 wavelengths height were discussed from the standpoint of their radiation characteristics. It is of interest, however, to plot the base impedance of vertical radiators of all heights from 0.10 through about 0.65 wavelengths height so that the variations may be noted in detail.

The second factor which affects base impedance is that of height (length) versus thickness (diameter). It is customary in texts to define this in terms of the ratio *length/diameter* (*L*/*D*). If one considers the vertical radiator being fed against a ground plane as an open-ended, unbalanced, lossy transmission line, which it actually is, it will be realized that it must have a characteristic impedance like any other transmission line. The magnitude of this characteristic impedance is determined by the conductor size and spacing. In the case of the vertical antenna (considered as a transmission line) the spacing (position of the vertical conductor relative to the ground plane) is fixed. The only factor which can then be varied, to have an effect on the characteristic impedance, is the vertical conductor's diameter. The effect on the characteristic impedance of changing diameter can be computed. Several authors treat this, but perhaps Schelkunoff[11] is one of the best references.

Radiation Resistance

If this unbalanced transmission line could be terminated in its characteristic impedance at its far end, one would see the characteristic impedance when measuring at its input connection. However, it cannot be terminated. It must remain open-ended. Thus it has standing waves on it, and it radiates. When speaking of it as "lossy", this does not refer to its inherent I^2R losses. This refers to the fact that power put into it is "lost" or radiated into space. This power is represented theoretically as the power dissipated in a *radiation resistance*, R_r. For a good discussion of the concept of radiation resistance, see Laport[12]. The radiation resistance of an antenna cannot be measured. It can be computed with considerable accuracy. The radiation resistance times the square of the current at the point of reference is the radiated power. This radiated power can be determined quite closely by making field intensity measurements along

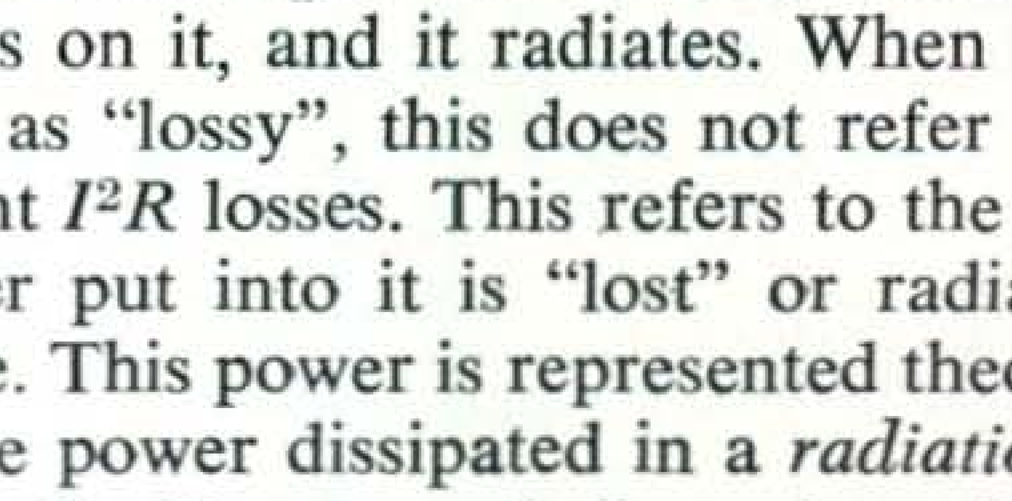

Fig. 12—Equivalent circuit of an antenna system. The total antenna resistance, R_a, is equal to the sum of R_L, R_d and R_r.

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* 5209 Bangor Drive, Kensington, Maryland 20795.

[11] Schelkunoff and Friis, "*Antenna Theory and Practice*," John Wiley and Sons.

[12] Laport, E. A., "*Radio Antenna Engineering*," McGraw Hill.

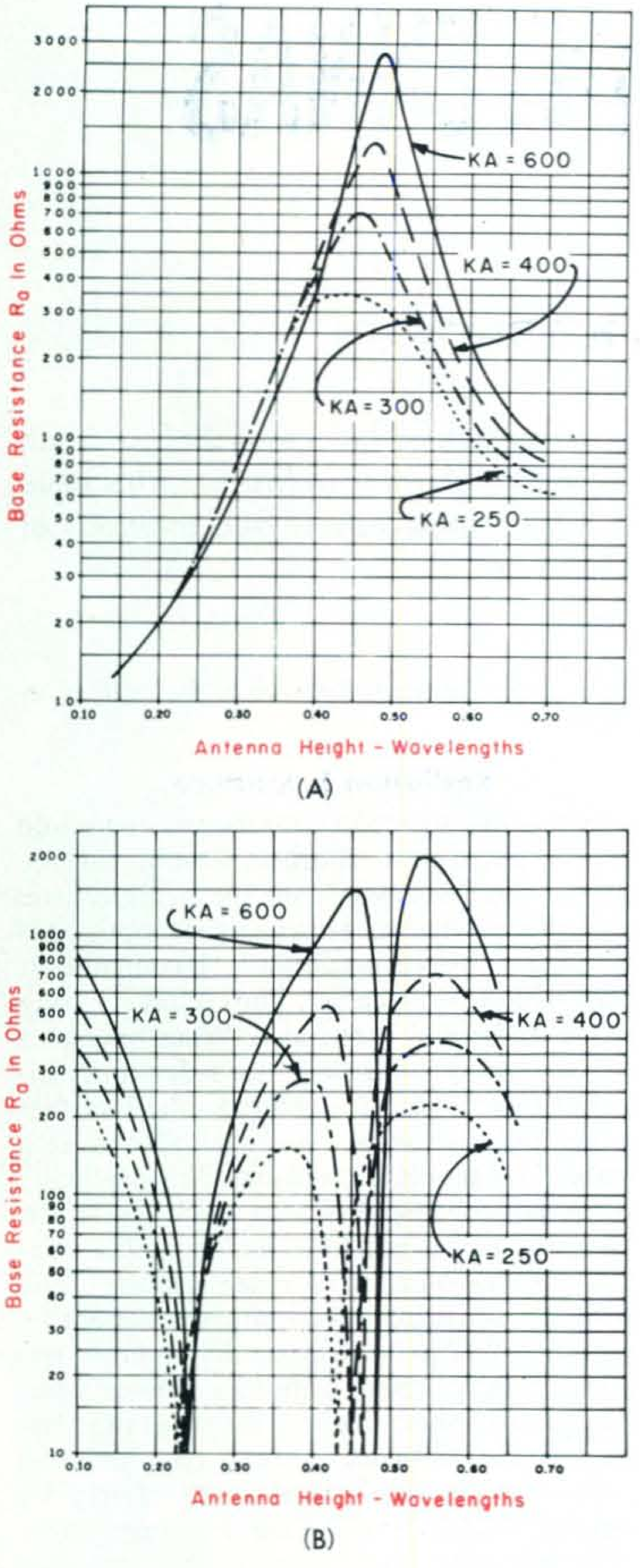

Fig. 13(A)—Vertical antenna base resistance *versus* antenna height in wavelengths for different values of characteristic impedance, K_a. (B)—The plot of the base reactance versus antenna height for the same values of K_a.

radials at varying distances out from the vertical radiator, plotting them on field intensity paper, and determining the unattenuated field intensity at one mile, as discussed earlier.

When measuring into the antenna, one sees the total antenna resistance, R_a, which is composed of several parts. This is depicted in fig. 12, which shows the equivalent series circuit of an antenna possessing some inductive reactance. These parts are the radiation resistance R_r, the ohmic loss resistances R_l and the dielectric loss R_d. In the m.f. and h.f. cases, the R_r is quite large, and it makes up most of R_a. In fact, in a well designed installation, the several loss resistances are usually neglected. However, at l.f. and v.l.f., where the vertical radiator is a small part of a wavelength, R_r is very small. In fact, at v.l.f. it is often as small as a fraction of an ohm. When this is combined with fractional ohm loss resistances, efficiency is reduced considerably. At v.l.f. it requires very special care in design, plus many model studies, to obtain an efficiency as high as 50% or so. Not so at h.f., however. We are up in the range of tens and hundreds of ohms for R_r.

The standing wave configuration on a vertical radiator will depend on its height. The base input impedance will, therefor, show variations with respect to frequency. The magnitude of the peak excursions of impedance will depend on the radiator's characteristic impedance. This fact is shown in fig. 13(A) and 13(B), which are plots of R_a and X_a, respectively. They are plotted separately for clarity. The family of curves shows the effect of varying the characteristic impedance of the radiator. Characteristic impedance is denoted by the factor K_a which can be computed from the following equation:

$$K_a = 120 \log \frac{L}{D} - 120$$

Values of K_a have been computed as follows:[11]

L/D	10	50	100	200	300	600	1000
K_a	323	516	599	682	731	814	875

By reference to fig. 13(A) and 13(B) it can be seen that a thin vertical radiator exhibits greater variations of impedance than does a thick one. (This is true of any antenna.) We make use of this fact in designing broadband antennas, which will be covered later.

Bandwidth

This brings up the subject of antenna bandwidth. The bandwidth of an antenna is dependent upon the rate of change of reactance versus the rate of change of resistance, with frequency. It may be seen that the thick antenna, the one with the lower K_a, will have a

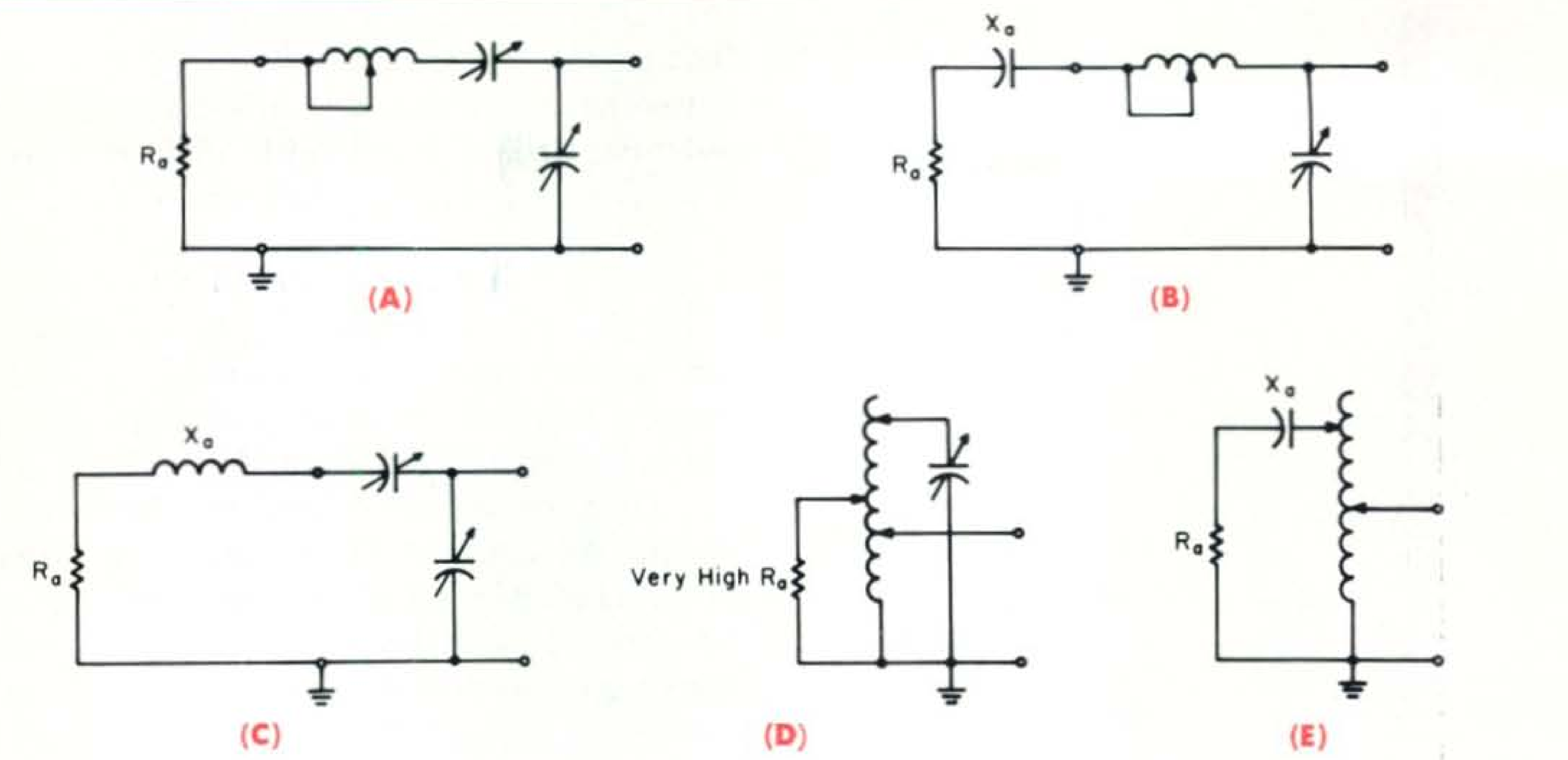

Fig. 14 (A)—Matching unit for an antenna with R_a-j X_a=R (low)-jX_c. (B)—Matching unit for a $\lambda/4$ resonant antenna with a low R_a only. (C)—Matching unit for an antenna with R_a+JX_L. (D)—Matching unit for an antenna with a very high R_a, $\lambda/2$ resonance. It is difficult to match well and should be avoided if possible. (E)—Matching unit for an antenna with a high R-jX_c (higher than coaxial line impedance).

greater inherent bandwidth than the thin one. For practical purposes, operating bandwidth is the band of frequencies centered about the tuned resonant frequency, enclosed within certain v.s.w.r. limits which depend on other factors such as transmission line capabilities, transmitter v.s.w.r. tolerance, modulation r.f. passband response requirements, *etc*. A figure which is commonly used is the bandwidth to the "3 db down" power limits. There is a very good discussion of antenna bandwidths in Laport.[12]

In the l.f. and v.l.f. cases, bandwidth restrictions can seriously limit an antenna's transmission capabilities unless special designs are adopted to increase bandwidth. These restrictions are caused by the high Q of these antennas. With very high capacitive reactance and very low resistance, the l.f. or v.l.f. antenna is a high Q device. There are special designs, which will be covered later, which improve the bandwidth of these antennas, but at the expense of efficiency. One may ask why we need greater bandwidths at l.f. and v.l.f. than heretofore. The reason is that we are gradually converting to multichannel teletype transmission systems at these frequencies, to increase our traffic handling capabilities, and such systems require greater bandwidth than the old method of single channel keyed c.w.

At m.f. and h.f. we are not worried too much about bandwidth, except that in the case of some m.f. directional arrays, the coupling and branching networks may in some cases restrict the antenna system's bandwidth, and cause loss of sideband modulation frequency response, unless special design precautions are taken. It is for this reason that the FCC requires the consulting engineer to measure and plot R_{in} and X_{in} for a directional antenna system, versus frequency. At h.f. there is no such problem. In the h.f. case bandwidth is important from the standpoint of avoiding retuning of the antenna when shifting frequency, which is very desirable in military and commercial installations.

Reference should again be made to figs. 13(A) and 13(B). Now that we have the plots of impedance versus frequency (plotted in terms of height of radiator in wavelengths), we can state the following general rules for the kind of base impedance which will exist:

Height	*Base Impedance*
Less than 0.25λ resonance.	$R - jX_C$
0.25λ resonance.	$R + jO$
0.25λ physical length.	$R + jX_L$
0.25λ resonance to 0.50λ resonance.	$R + jX_L$
0.50λ resonance.	*R (Very high) (Not recommended)*
0.50λ physical length.	$R - jX_C$ *(High)*
0.50λ physical length to 0.625λ electrical length.	$R - jX_C$

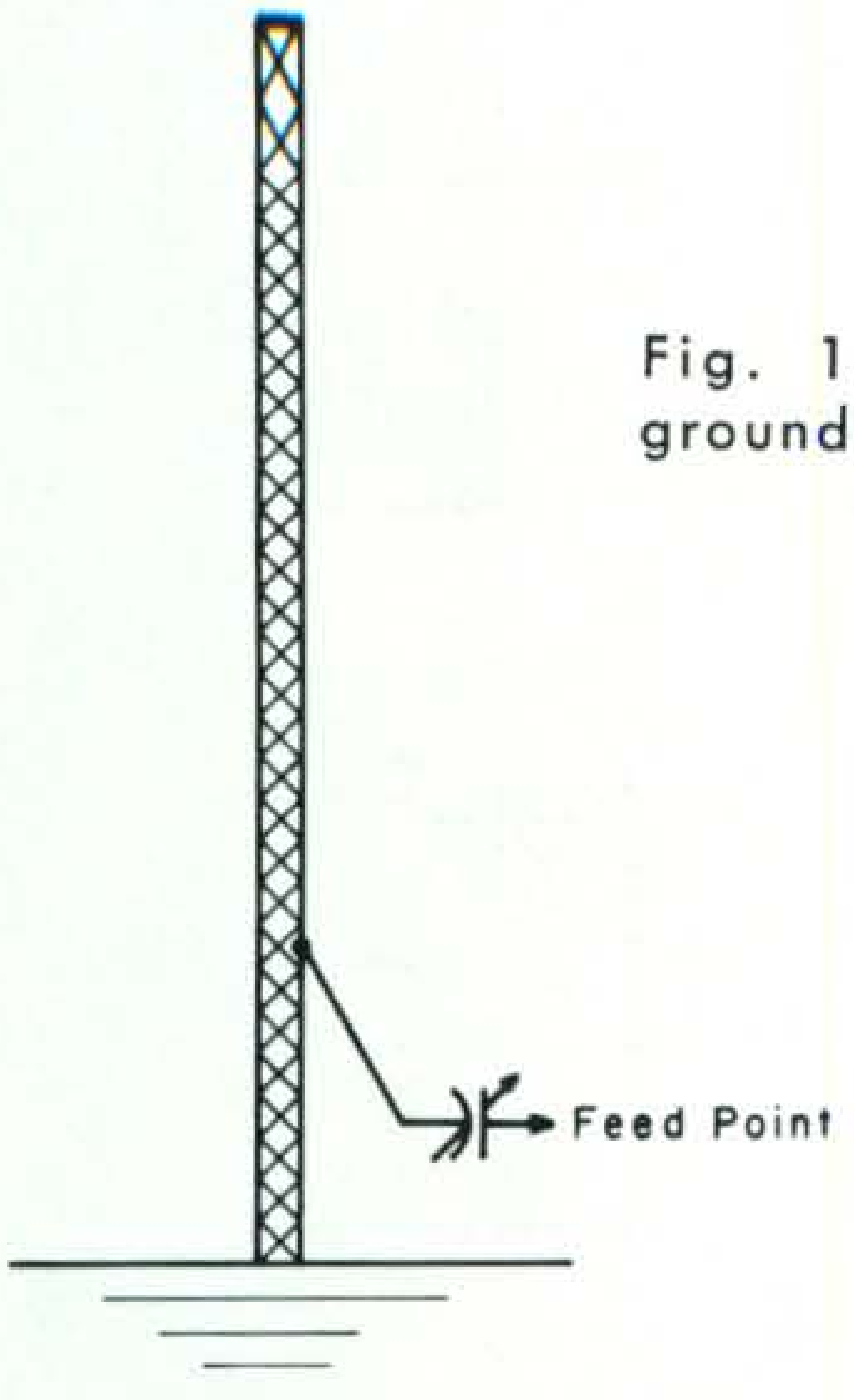

Fig. 15 — Shunt fed grounded base vertical antenna.

It will be noted that the resonant length is always less than the physical length by an amount which is inversely dependent on the *L*/*D* ratio.

Tuning And Matching Networks

This leads to the next topic, which is the tuning and matching networks required to resonate and match the antennas of heights shown in the preceding impedance summary, to a known source. In modern times the known source has come to be the nominal 50 ohm coaxial line, although 70 ohm line is sometimes used. The matching networks are quite simple, and are shown in figs. 14(A) through 14(E). The values of the reactances required in each case may be calculated by use of r.f. network theory as shown in Terman.[13] In general, if the antenna input reactance is $-jX_C$, inductive reactance $+jX_L$ will be required in the network to tune it, and *vice versa.* The network also simultaneously transforms the antenna input resistance into a value which matches the characteristic impedance of the transmission line.

Where an antenna is fed through a tuning and matching unit of this type, the *total antenna system reactance* must be taken into account in bandwidth computations. This total value includes not only the antenna's own input reactance versus frequency, but also the effect of the reactances in the matching unit as they vary with frequency. The computation of this is not difficult, although perhaps a bit laborious. The simplest approach is to actually tune up the matching unit with antenna attached, and then measure the matching unit's input impedance versus frequency. There are certain "tricks" with networks which can be employed to improve antenna. system bandwidth and give lower v.s.w.r. over a range of frequencies.[14]

Shunt Fed Verticals

In the previous paragraph we spoke of tuning and matching a series fed, ungrounded, vertical radiator. Now let's consider the case of the grounded base, shunt fed vertical radiator. There have been several excellent articles on this subject.[15,16] The shunt fed configuration is shown in fig. 15. Simply stated, a tap is brought off the vertical radiator at a distance above ground and it is used as a feed point, having its input impedance matched to the characteristic impedance of the transmission line. In some cases it is possible by trial and error to adjust the tap's vertical position on the radiator so that the input impedance is $50 + jX_L$, thus permitting an easy match to 50 ohm line by use of only a series capacitor of equal reactance. This adjustment, however, can be quite tedious and critical, especially when hanging on the side of a tower or mast, and it is much simpler to use a matching network of proper reactance values. This type of feed has been used in many broadcast installations. It has been proven by actual full scale model studies and field intensity measurements[15] that use of this feed method is just as efficient as is series feed, and that the horizontal radiation pattern is not distorted by the presence of the sloping feed wire. By both mathematical analysis and actual radiator current meaurements[15,16] it has been shown that current distribution on the shunt fed radiator closely approaches that of a series fed radiator, and that the vertical radiation pattern is not appreciably different.

A similar arrangment, and one most often used by amateurs, is the "gamma" match or "omega" match, similar to that used on the driven element of Yagi arrays. This is shown in fig. 16. This principle was used in the feed arrangements for the Mark III and the Mark IV DX antennas which were published some time ago.[17,18] A feed rod is connected to the radiator at a suitable point some distance

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[13] Terman, F. E., *"Radio Engineering Handbook,"* McGraw Hill (first edition).

[14] Lee, P. H., "Broadband 80 Meter Feed for the Mark III," *CQ*, March 1964, p. 43.

[15] Morrison, J. F., Smith, P. H., "The Shunt Excited Antenna," *Proc. of the I.R.E.*, June 1937.

[16] Badoux, P., "Current Distribution and Radiation Properties of a Shunt Excited Antenna," *Proc. of the I.R.E.*, June 1940.

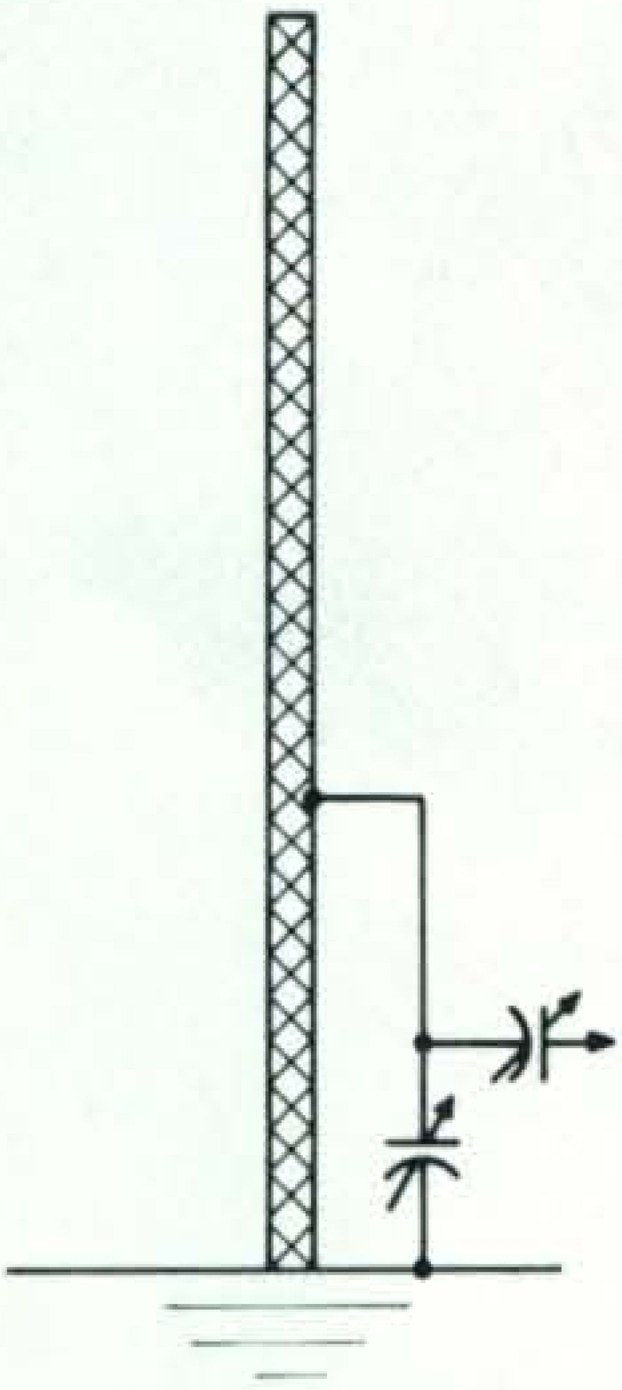

Fig. 16 — Omega fed grounded base vertical antenna.

above ground, and it is brought down the side of the radiator rigidly supported on standoff insulators. It is fed at its bottom end. It must always be considerably less than ¼ wavelength for its input impedance to be of a reasonable value. Note my experience with the 7 mc feed on the Mark IV[18]. The input impedance will always measure $R + jX_L$, because the short section of transmission line (feed rod plus the portion of radiator concerned) thus formed is less than ¼ wavelength and shorted at its top end. Matching then becomes a question of adjusting the several capacitive reactances in the matching unit. The R term of the input impedance may be quite low. The values in the Mark III and Mark IV articles[17, 18] are typical.

If the feed rod (or wire) runs all the way to the top of the vertical radiator, the whole thing becomes a folded unipole antenna and was used as a feed in the Mark IV for 2 and 4 mc.[18] This type will be discussed in detail later.

Ground Bus

There is one additional point that should be made very emphatically in connection with the shunt fed and gamma or omega fed antennas. That is that the ground bus from the tuning unit to the base of the radiator should be heavy and low loss. On the Mark IV I used a ¼″ by 1″ *aluminum* bar (to avoid use of dissimilar metals). This bus carries considerable current, especially where the R term of the feed point impedance is low. For 1 kw in the antenna (2 kw p.e.p. transmitter input), with a feed point R of 10 ohms, there would be 10 amperes current flowing in this bus (and in the feed rod as well). The capacitors in the matching unit should be large enough to withstand the voltages developed across them.

Each method of feed has certain advantages and disadvantages. The series feed has the advantage of simple matching when the antenna base impedance is capacitive, by means of a single tapped coil, as in fig. 14(E). A simple variable matching unit with a bandswitching arrangement can be built to tune a series fed radiator at several frequencies. However, unless a 3-legged self-supporting tower is used, the series fed radiator must usually be guyed because it has to be insulated from ground. Of course one may use small self-supporting whips for short verticals.

On the other hand, the grounded base radiator is quite easy to make self-supporting. Short, light weight ones can be set right in the ground itself, and tall heavy ones can be set in concrete. Very tall ones must usually be guyed. The grounded base permits other circuits to be run up the tower or mast without any special choke coils or other isolation devices. Such circuits would be tower lights, rotary beam motor control cables[18], and in some cases even the coaxial lines for v.h.f. or u.h.f. antennas can be run up a grounded vertical radiator without isolation. This latter idea has been used in several broadcast tower installations where a.m., f.m. and c.a.t.v. antennas utilize the same tower structure.[19]

Feed rod construction is simple. Even multiple feed rods are not difficult to install and adjust[17, 18] for feeding the vertical radiator on several frequency bands. Jasek's "Antenna Engineering Handbook"[20] is a veritable gold mine of information on vertical radiators (and on other types also), and especially on some of the schemes we have been discussing. It also provides an excellent source of additional references, listed at the end of each chapter.

The next installment will deal with electrically short vertical radiators, and ways of matching to them.

[*To be Continued*]

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[17] Lee, P. H., "The Mark III DX Antenna," *CQ*, December 1962, p. 43.

[18] Lee, P. H., "The Mark IV DX Antenna," *CQ*, February 1967, p. 60.

[19] Gureckis, P. V., "A Simple Method of Isolating CATV Antennas On Standard Broadcast Towers," *Broadcast Management-Engineering*, January 1968.

[20] Jasik, H., "*Antenna Engineering Handbook*," McGraw Hill.

VERTICAL ANTENNAS

Part III

BY CAPT. PAUL H. LEE, *W3JM

In Part III of this series, the author discusses short vertical antennas, their limitations and ways to overcome these limitations. Several practical designs and methods of feeding are shown.

SHORT vertical antennas are of interest to many amateurs. Every mobile whip antenna is short, much too short, at frequencies in the 7, 4 and 2 mc bands. Also, not everyone is blessed with sufficient clear space for erection of horizontal dipoles at those frequencies. For such amateurs, the short vertical is a solution which may be attractive, especially for use on 4 or 2 mc. This discussion is for those who care to know something about how such antennas can and do work, and what their limitations are.

Since this type of antenna is electrically short, something has to be done to lengthen it so that it will resonate and take power from the transmitter. One of the simple ways of resonating a short antenna is by use of a series loading coil at the base of the antenna. Why is a coil used? Reference to figs. 13(A) and 13(B) of Part II of this series[21] will show that the input impedance of an antenna shorter than ¼ wavelength consists of a fairly low resistance and a capacitive reactance. The shorter the antenna, the lower the resistance and the higher the reactance. Thus, the shorter the antenna, the more loading coil is required, and, since loading coils have inherent loss resistance, the lower will be the efficiency of the antenna system. Remember these facts, for we shall talk about them later on.

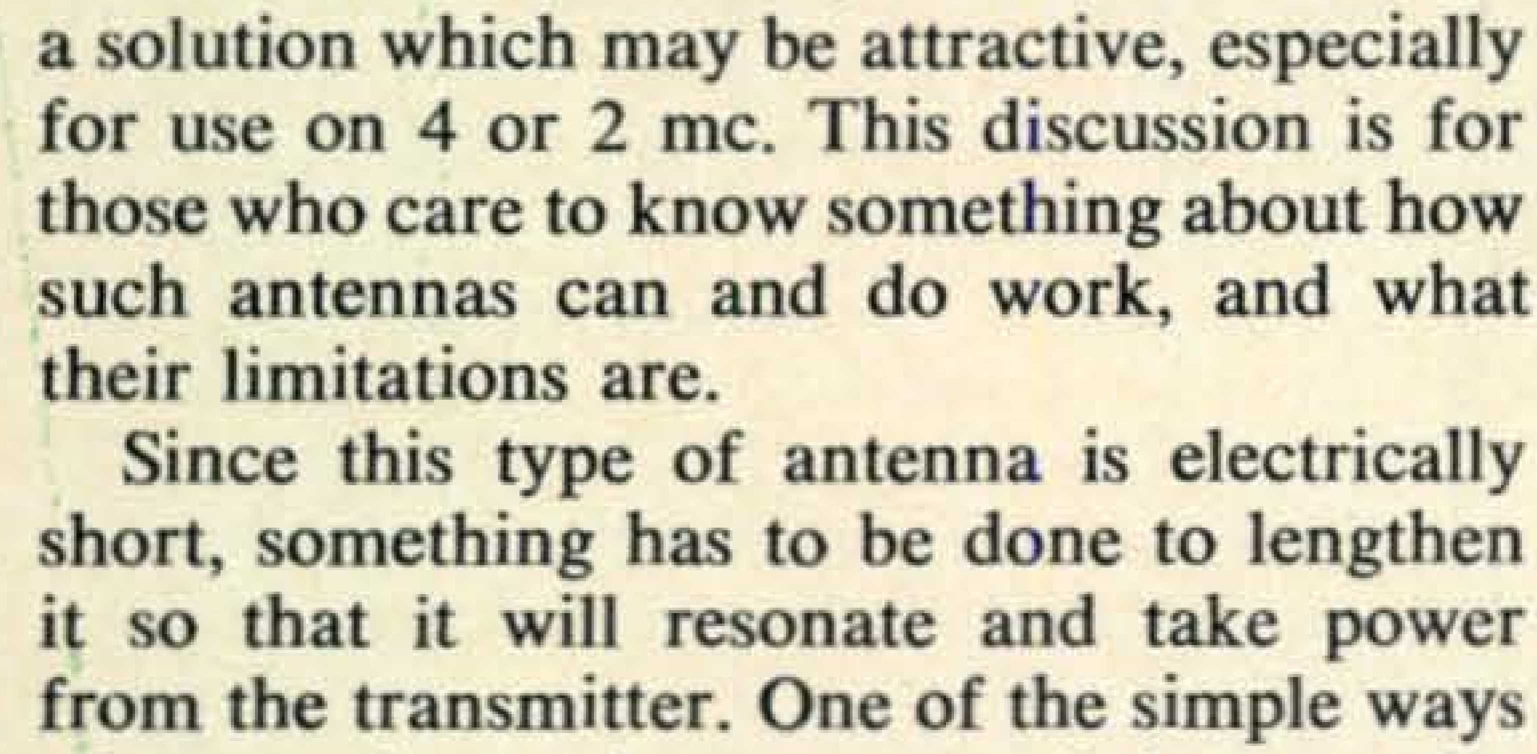

Fig. 17—Top loading a vertical by the use of guys. The rear guys, also broken by insulators, are not shown for the sake of clarity.

One of the common forms of short antennas is the mobile whip. Early mobile whips were built with base loading coils, and for changing bands it was possible to change loading coils by unscrewing the whip and the coil from the spring mount. These worked after a fashion, but were quite inefficient at 7 and 4 mc. They were inefficient because the current distribution on the vertical whip was poor. With the antenna in resonance the point of maximum current, or "current loop", was at the bottom of the loading coil. In any antenna, the portion which carries the greatest current does most of the radiating. Thus with the base loaded whip, the greatest current was in the loading coil, merely creating an inductive field, while a relatively small current was flowing in the whip itself. The answer to this dilemma was to make the whip in two parts, and put the loading coil up in the whip itself, thus giving at least the bottom portion of the whip a chance to carry some appreciable antenna current and do some radiating. Most mobile whips today are made in this fashion. You can see them in the ads in this and other magazines, and in distributor catalogs. In spite of all the claims made by the manufacturers, however, even this type of whip which is so very short elec-

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* 5209 Bangor Drive, Kensington, Maryland 20795.

[21] Lee, P. H., "Vertical Antennas, Part II" *CQ*, July 1968, p. 25.

trically is quite inefficient on 7, 4 or 2 mc. Factors which contribute to the inefficiency are lack of adequate ground plane, losses in the loading coil, and the short length of the portion of the radiator carrying greatest current.

Top-Loading

A better approach to the problem of increasing the radiation from a short antenna is by use of top loading. In some cases of m.f. and l.f. high power installations, an actual top hat has been constructed on a tower by using steel structural members, supporting a horizontal web of connecting wires. A much more practical approach is the use of the upper portions of top level guys as top loading by connecting them to the tower and breaking them with insulators a certain distance down from the top. There have been many studies made in an effort to determine optimum configurations of top loading cable length, angle of top loading cables from the tower, number of top loading cables, and interconnection of the lower ends of the top loading cables. One of the most extensive of these was done by Smith and Johnson.[22] That article contains many graphs of resistance and reactance for various top loading guy configuration, plus discussions of the effects of insulator losses and ground system losses. The results of this study showed that substantial gain in radiated power can be realized by this "umbrella" type of top loading. Connection of a wire skirt around the lower ends of the top loading cables shortens the length of cables required to produce a particular result. In cases of high power at l.f., use of the skirt wire reduces corona losses. Top loading gets the current up in the antenna, where it belongs.

Another study which showed substantially the same thing was one made on a 1200 foot tower at Forestport, N. Y.[23] Optimum configuration of top loading cables for maximum resistance and lowest reactance (best efficiency and bandwidth) is shown in fig. 17. The tower is shown being guyed in six directions at the 1040 foot level, with the guys at a 45 degree angle with the tower. A skirt cable is used, and between each pair of guys there are two additional top loading cables, thus making a total of eighteen top loading cables. The top loading portion of each guy is 805 feet long. The study shows the 1200 foot tower to be resonant (zero reactance) at 80 kc with this top loading configuration. Now, scaling the dimensions down for use on 2 mc, the tower height becomes 48 feet, and the top loading guy cable length becomes 32 feet. This is a reasonable size for amateur use on 2 mc. For 4 mc these dimensions would be halved. The importance of an adequate ground system under such a radiator cannot be overemphasized. As shown in Part I of this series,[24] the number and length of radials has great effect on radiation efficiency, especially in the case of short vertical radiators.

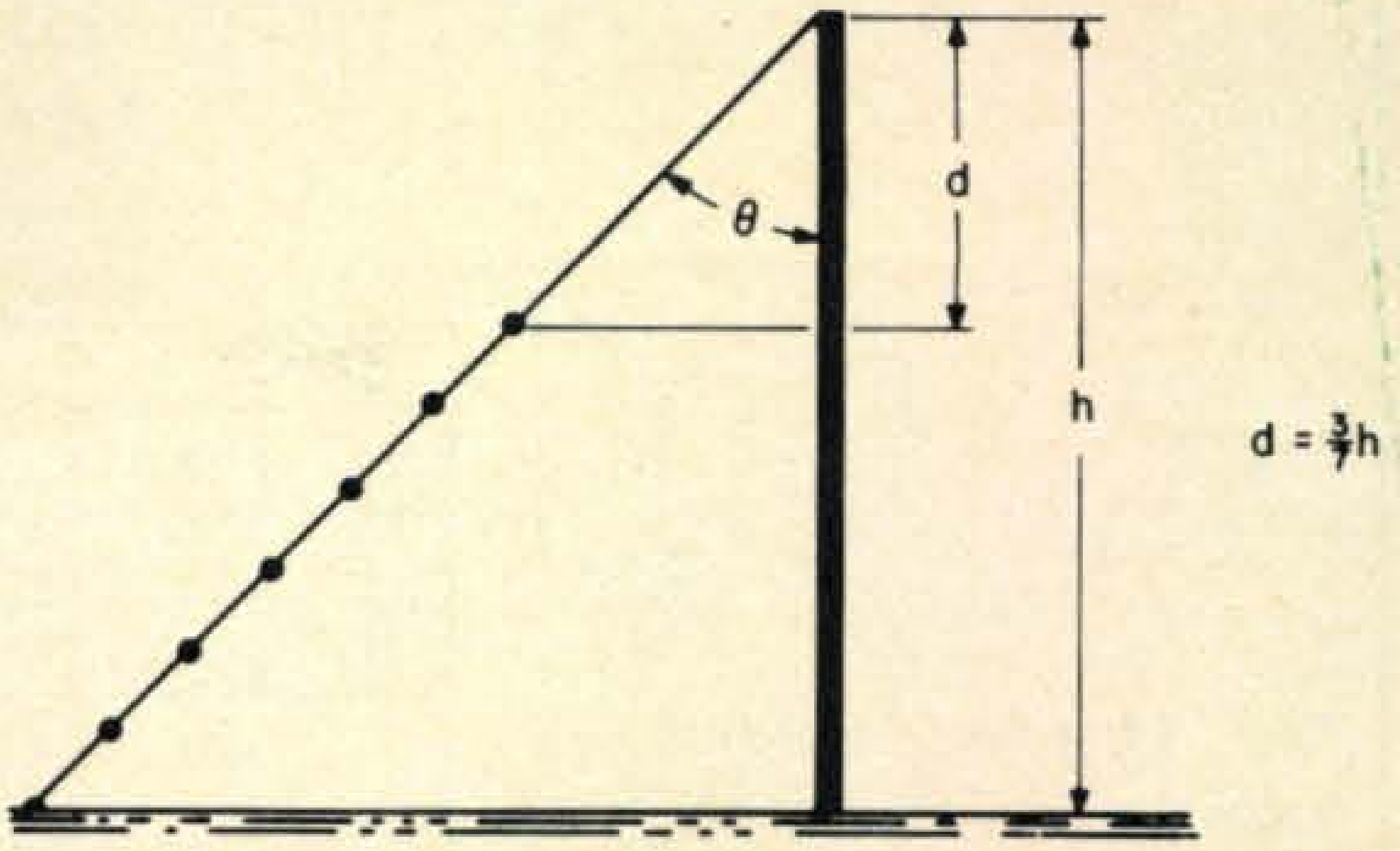

Fig. 18—Critical dimensions for the top loaded antenna.

Belrose conducted a study of top loading parameters[25] and determined that radiation resistance was maximum when $d = 3/7h$

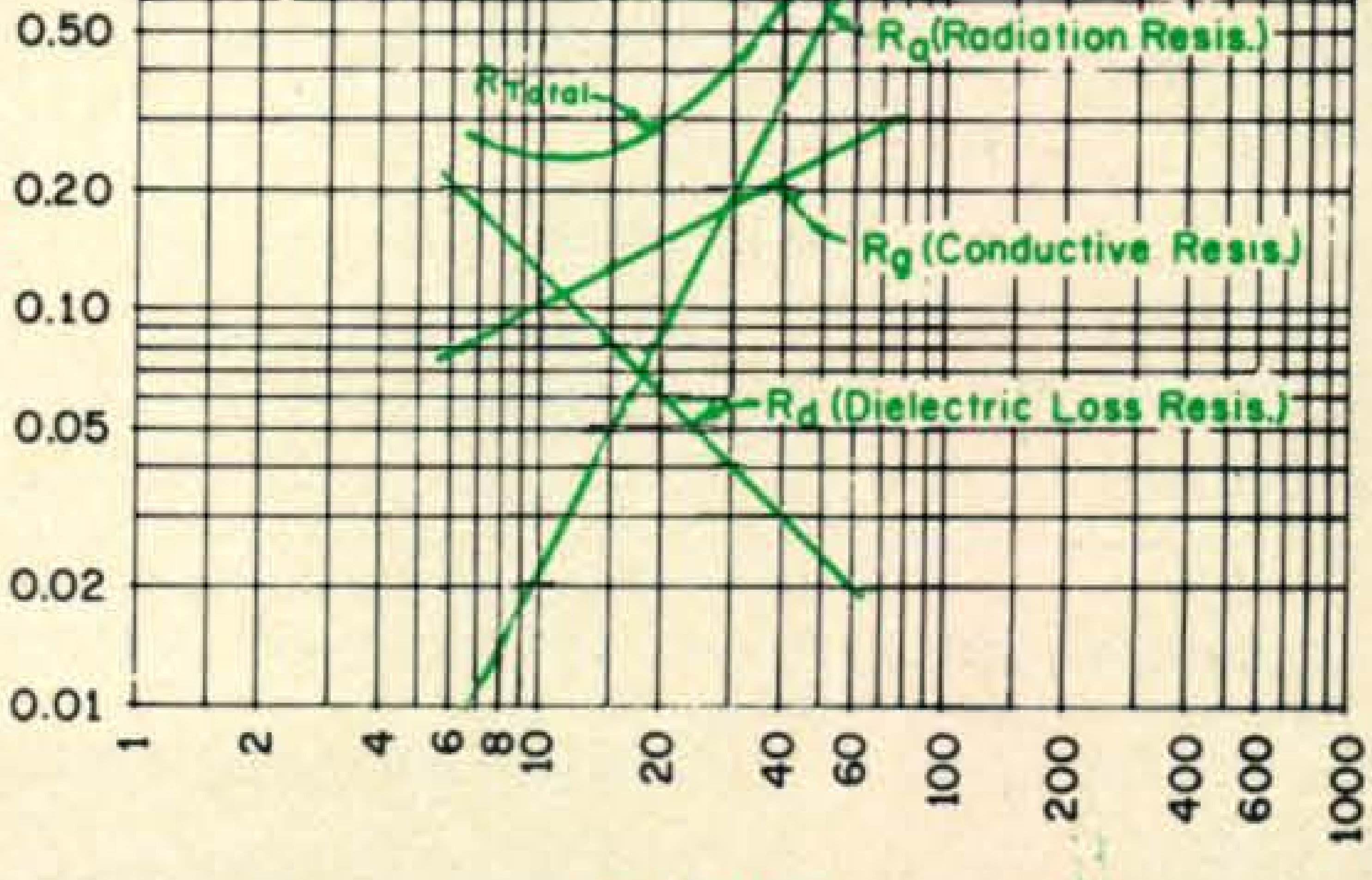

Fig. 19—Resistive Components of a v.l.f. antenna.

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[22] Smith, C. E., Johnson, E. M., "Performance of Short Antennas," *Proc of IRE,* Oct. 1947.

[23] "Forestport Antenna Study," Technical Report 42-F Contract AF 30 (602)-2588, 31 Jan. 1962. Available to defense contractors through D.D.C. (Unclassified)

[24] Lee, P. H., "Vertical Antennas, Part I," *CQ,* June 1968, p. 16.

[25] Belrose, *et al,* "Engineering of Communications Systems for Low Radio Frequencies," *Proc of IRE,* May 1959.

Type A **3 Guys**
Type B **6 Guys**
Type C **6 Guys With Skirt Wire**

Type	H	L_1	L_2	S	d_1	d_2
A	.124λ	.122λ	.172λ	.013λ	.0012λ	.000187λ
B	.104λ	.102λ	.144λ	.011λ	.0010λ	.000156λ
C	.081λ	.079λ	.112λ	.0036λ	.00078λ	.000121λ

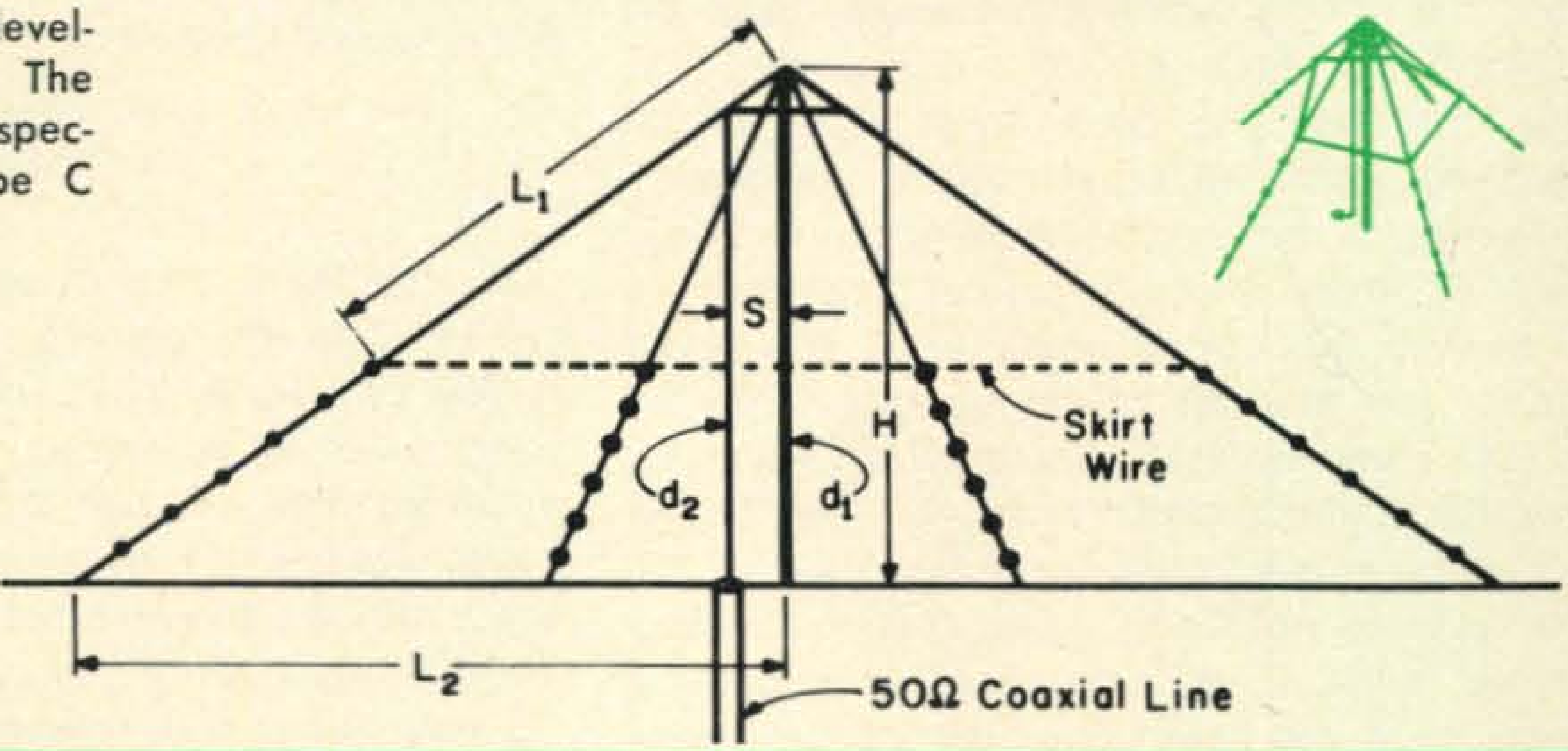

Fig. 20—Top loaded Folded Unipole developed at the N.O.L. The insert shows a perspective view of a Type C antenna.

and Θ is 45 degrees, in fig. 18. It can be seen that this confirms the results of the Forestport study. Smith did the design work for the 837 foot vertical radiator used on 173 kc by the Voice of America at Munich, Germany.[26] In this case Θ was made approximately 55 degrees, and twelve top loading cables 512 feet long were used. The measured base impedance was $29.5 + j135$ ohms. The measured unattenuated field at one mile was 178.9 mv/m for 1 KW, which is quite good efficiency. Scaling this antenna for 2 mc use, its height would be 73 feet, and the top loading guy cables would be 44 feet long. As may be seen from the measured base impedance, the vertical radiator is slightly over ¼ wave in electrical height, the reactance being positive. There have been other studies made on this subject, some of which are those by Monser[27] and Gangi.[28]

Resistances

Unless one goes to the amount of top loading used on the Munich antenna, the resistance will be low, and the reactance will be capacitive. As will be seen from fig. 13(A) of Part II,[21] the base resistance of an antenna shorter than about 0.15 wavelength is less than 10 ohms, and the shorter the antenna the lower the resistance, and the higher the negative reactance. Adding the optimum top loading to the Forestport tower, while it brought the reactance to zero (resonance) at 80 kc, left the resistance at only 4 ohms. In other words, top loading is effective in reducing capacitive input reactance of a vertical radiator which is quite short, but it does not have much effect on input resistance, which remains quite low. This means that antenna system Q is quite high, and particular care must be paid to keeping losses to a minimum. Base input resistance includes losses, of course.

The reasons for this can be seen in fig. 19, which shows the composite resistance characteristics of a v.l.f. antenna which is extremely short electrically. The loss components R_g and R_d are considerable when compared to radiation resistance R_a. R_g is conductive resistance, which represents power lost in conductors and earth due to current flow. R_d is dielectric loss resistance, which results from hysteresis losses in insulators, nearby trees, vegetation, and wood or masonry. John Walter, one of our experts in the v.l.f. and l.f. field, has written an excellent paper on this subject.[29] It may

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[26] Smith, *et al*, "Very High Power Long Wave Broadcasting Station," *Proc of IRE*, August 1954.

[27] Monser, G. F., Sabin, W. D., "Antenna Design for Maximum L. F. Radiation," *Electronics*, June 3, 1960.

[28] Gangi, *et al*, "Characteristics of Electrically Short, Umbrella Top-Loaded Antennas," *IEEE Transactions on Antennas & Propagation*, Vol. AP-13, No. 6, Nov. 1965.

thus be seen that it behooves the antenna designer to make the radiator as tall as possible, so that radiation resistance may be high enough to make the losses of little consequence when compared with it.

Folded Unipole

So far in this chapter we have been speaking of series fed vertical radiators. There is another way in which the efficiency can be improved, and that is by use of the folded unipole principle of feed.[30, 31] We shall not go into the details of how a folded unipole works as that subject is well covered in the references. Let it suffice to say that the folded unipole is the upper half of a vertical folded dipole, with the lower half replaced by a ground plane. If you are not using one on the amateur bands, you probably are using one as the driven element of your home TV antenna. They are very common in this application.

The folded unipole feed principle may be easily applied to the short, top loaded vertical radiator. The transformer action of the folded unipole is used to give a more favorable input resistance than can be obtained with series feed. Another thing that the folded unipole feed does is to reverse the sign of the input reactance. The input reactance of a series fed tower shorter than ¼ wavelength is always capacitive. This means that a series loading coil (spoken of in high power as a *helix*) must be used to resonate the tower. With folded unipole input the feed point reactance is always positive. (Consider the tower and feed wire to be a shorted transmission line less than ¼ wave long. Its input reactance is positive.) Thus the folded unipole may be fed with a simple low-loss capacitive feed network, rather than through a loading coil or helix which is lossy. Also, because with the folded unipole feed the resistance will be stepped up by transformer action and the reactance will usually be lower, the Q of the antenna will be lower, and its bandwidth will be greater, than with series feed.

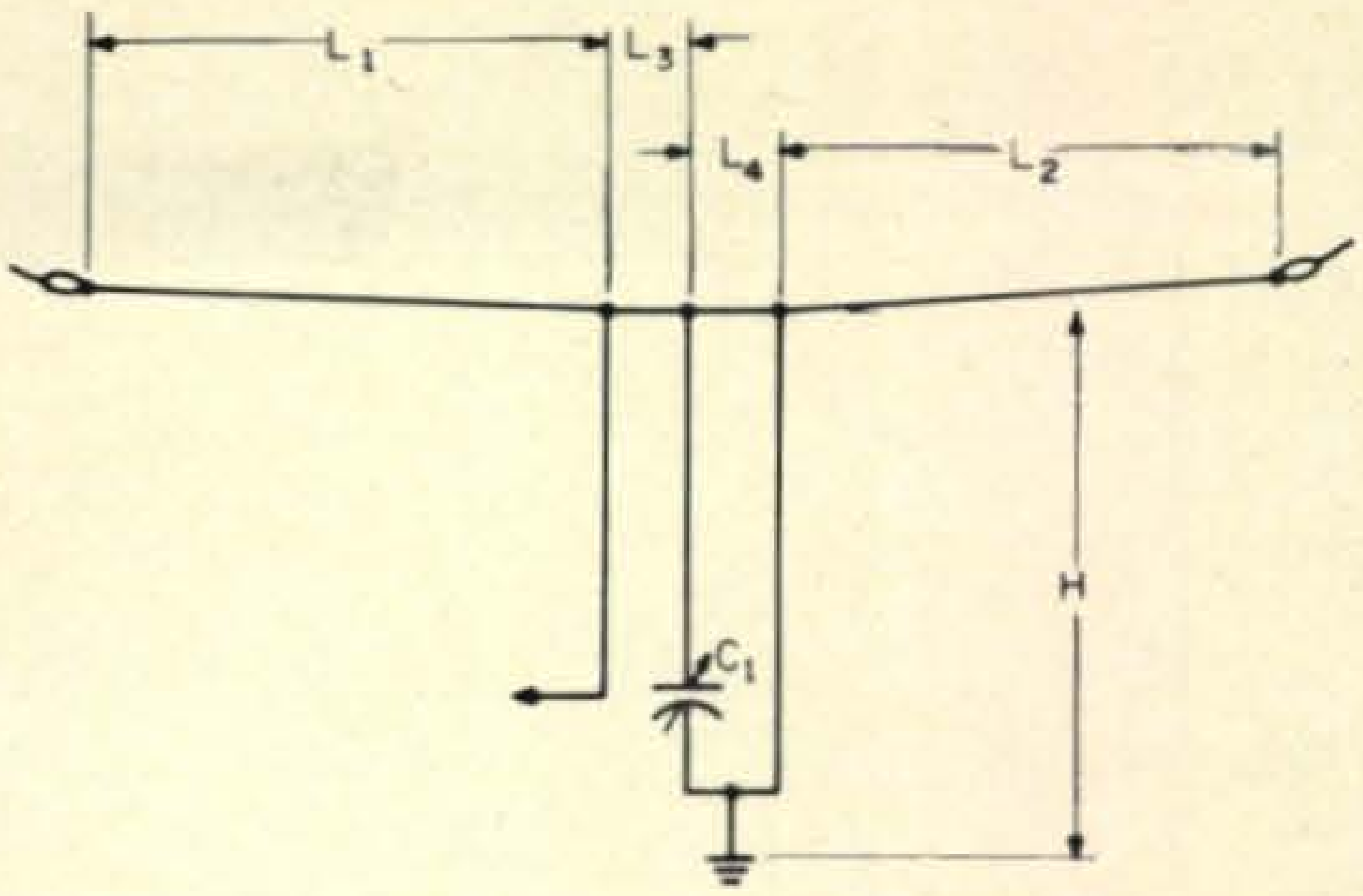

Fig. 21—Configuration of the UG® antenna. The dimensions are given in the text.

Studies of this type of feed have been made by the Naval Ordinance Laboratory, Corona, California in an effort to reduce the size of l.f. antennas for ship and shore use.[32, 33] A simple design which evolved is shown in fig. 20. Dimensions are shown in the accompanying table in terms of wavelength. It may be seen from the table that height H can be lower when 6 guys with skirt wire are used (Type C). Other dimensions are also smaller with Type C. For 2 mc use, a Type C configuration would have the following dimensions:

$H = 39.8$ feet
$S = 50.5$ inches
$L_1 = 39.1$ feet
$d_1 = 4.6$ inches
$L_2 = 55$ feet
$d_2 = 0.72$ inches

For 4 mc the above dimensions can be halved. The antenna can be fed with 50 ohm coaxial line.

Type UG

Another allied type of antenna which was developed several years ago is one called the Type UG.®[34] This type was devised to improve the feed point impedance and the bandwidth of some of the "inverted L" or "T" antennas used at l.f. The configuration of the Type UG is shown in fig. 21. Typical dimensions for 2 mc would be:

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[29] Walter, J. C., Capt. USNR (Ret.), "Practical Analysis of LF and VLF Antenna Resistance," *Naval Engineers Journal*, Feb. 1966.

[30] Leonhard, *et al*, "Folded Unipole Antennas," *IEEE Transactions or Antennas and Propagation*, Vol. AP-3, No. 3, July 1955.

[31] Monser, J. G., "Calculating Folded-Unipole Antenna Parameters," *Electronic Industries*, Jan. 1960.

[32] Walters, A. W., "Antenna Miniaturization," (Naval Ordnance Lab., Corona, Calif.) in *"A Decade of Basic & Applied Science in the Navy,"* Supt. of Documents, U.S. Government Printing Office, Wash., D.C.

[33] Seeley, E. W., "Small Antenna Study," NOL, Corona, Calif. Unclassified Report. (Not available for public distribution.)

[34] "Engineering Appendix-Type UG Antenna." Private communication from John H. Mullaney & Associates.

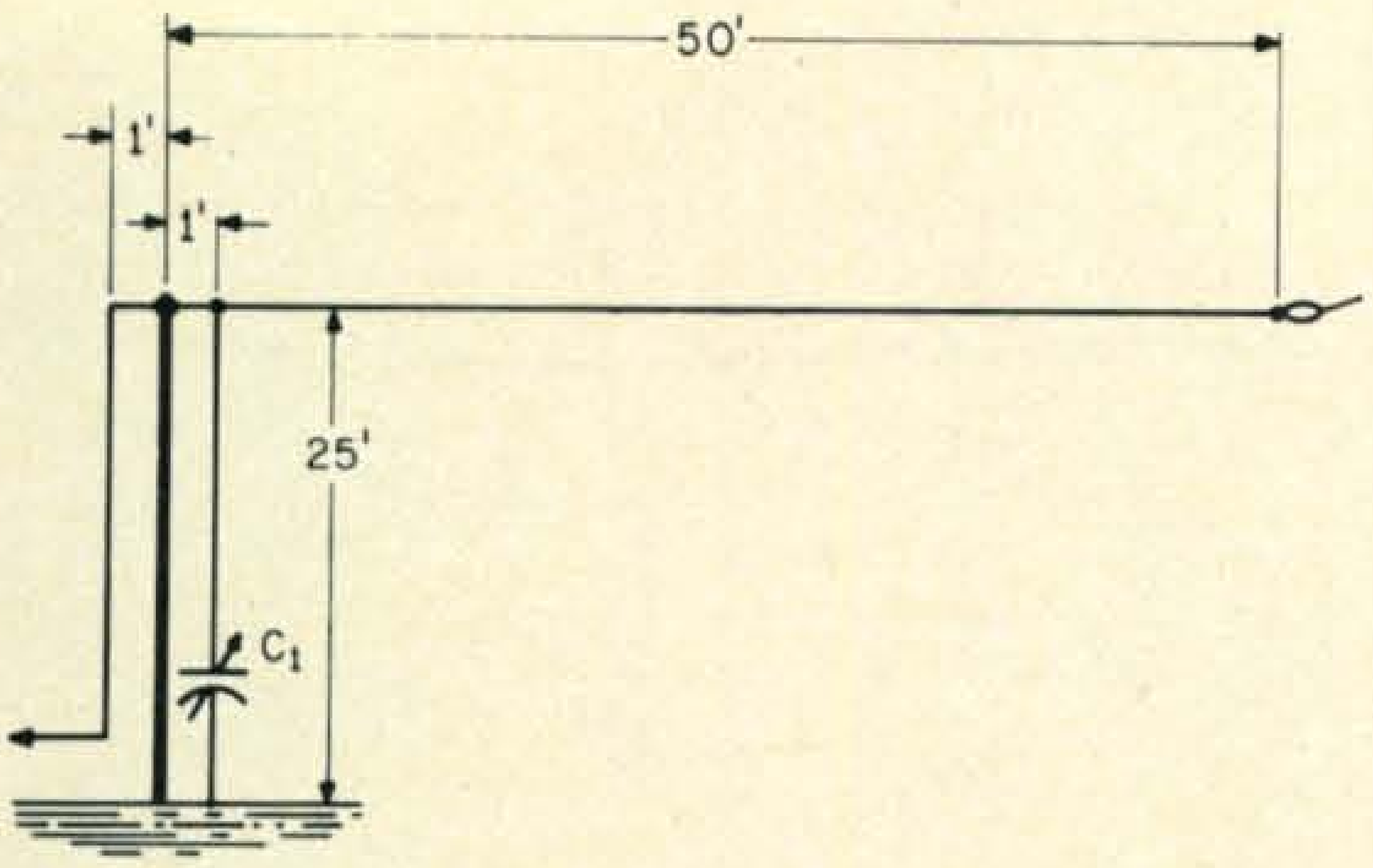

Fig. 22—Configuration of an end fed UG® antenna.

$L_1 = 25.0$ feet
$H = 25$ feet
$L_2 = 25.0$ feet
$L_3 = L_4 = 1$ foot

The feed can also be applied to one end, if desired, as shown on fig. 22.

By study of these two figures it will be seen that the transformer action of the folded unipole has been made variable by the use of an extra downlead and capacitor C_1. In tuning up this antenna for a specific frequency, C_1 is varied until a favorable feed point impedance $(50 + j\ x)$ is seen at the feed point. This may then be matched to the coaxial line by use of the matching techniques described in Part II. One word of warning, capacitor C_1 should be a high voltage type if powers of 1 KW or so are used. Considerable current flows in this wire, and also in the grounded vertical wire, when the antenna is tuned up. In fact, the grounded vertical wire does not have to be a wire at all. It can be a metal mast such as a short tower or pipe, suitably guyed, and well-grounded at its base. Ground connections linking tuning unit, mast or tower, and C_1 should be heavy and well-made. I used an aluminum pipe mast for my end fed Type UG. The downleads should be rigidly mounted to the mast.

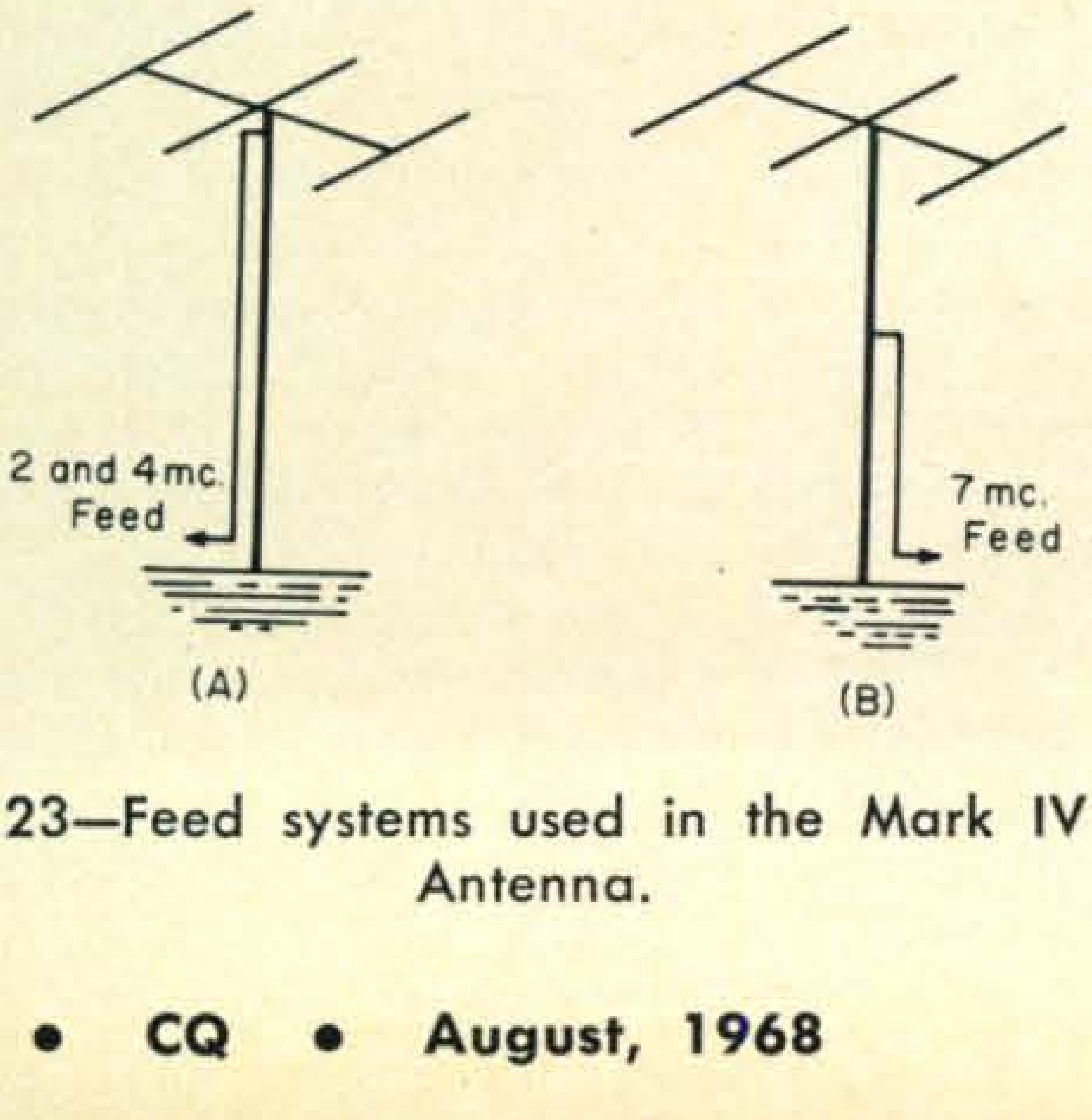

Fig. 23—Feed systems used in the Mark IV DX Antenna.

Another possible way of using the folded unipole feed principle for a six-band antenna was described in the article on the Mark IV DX Antenna.[35] In this one, which is still in use, the 40 foot tower is used as a top-loaded vertical radiator on 2, 4 and 7 mc, and the tri-band beam on top of it is the top-loading. On 2 and 4 mc the tower is fed as a true folded unipole, with the feed line going to the top of the tower. On 7 mc this tap point is too high, and therefor a feed rod is connected to the side of the tower at the 20 foot level. The schematics of these two feed arrangements for 2, 4 and 7 mc are shown in figs. 23 (A) and 23 (B) respectively. This antenna is ideal for the amateur who has a beam on a tower of reasonable height in his backyard, and who would like to get on 2, 4 or 7 mc without putting up wire antennas.

NORD

There is yet another type of short vertical antenna which has recently come into use. This is the NORD®. The original NORD was designed for shipboard use, for radio broadcasting in the m.f. band in European waters. It has since been built for shore use at high power, in the l.f. band. To date, NORDs are in use at Naval Communication Stations in Japan, Guam, Philippines, Hawaii and Annapolis, Md., providing l.f. multichannel transmitting capability. A schematic of the NORD is shown in fig. 24. A center tower is used, with its base grounded. The tower is fed by the folded unipole method, with a feedwire going to the top of the tower. The upper set of guys (three of them) is connected to the tower, and they extend out to three short perimeter towers, where they are secured to strain insulators. From these the cables drop down to tuning units which consist of capacitors.

For sake of clarity in fig. 24, the perimeter towers are not shown. The NORD is basically nothing but three over-coupled tuned circuits with a common element, the center tower. The purpose of the NORD for l.f. is to provide sufficient bandwidth for multichannel teletype transmissions, while still retaining reasonable radiation efficiency. The electrically short series fed tower cannot do this at

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[35] Lee, P. H., "Mark IV DX Antenna," *CQ*, Feb. 1967, p. 60.

high power. Its Q is very high and its bandwidth is limited. Also, with top-loading, the top-loading guys are corona-limited due to the very high voltages which are developed on them. The NORD has no such problems. By adjusment of the capacitors C_a, C_b, and C_c, optimum bandwidth and/or efficiency can be obtained, with reasonable input impedance being provided by the folded unipole feed. For Naval l.f. purposes we require bandwith. For amateur c.w. and voice at h.f., efficiency is paramount. The NORD can fulfill both of these, by suitable adjustment, in a tradeoff of efficiency for bandwith or vice versa. By going to the NORD at l.f. we have rid ourselves of the high voltage helix with its inherent losses, and its bandwidth limitations. The input coupling unit with the NORD can be nothing but low loss capacitors. In fact, in the high power NORDs vacuum capacitors are used throughout.

A full-size NORD, designed for 50 to 150 kc., now in use, has dimensions as follows:[36]

Height of center tower—450′.

Height of perimeter towers—150′.

Spacing of center to perimeter towers—500′.

For use on 2 and 4 mc by amateurs, the NORD would not have to be so short electrically. It could have the following dimensions:

Height of center element—30′.

Height of perimeter supports—10′.

Spacing of center to perimeter—33′.

This antenna would have excellent efficiency on both bands. Guy tuning capacitor values would have to be determined by experiment, but should be of at least 1500 mmf total capacity, adjustable in steps, with a portion variable. The input impedance at the feed point will be $R + jX_L$ of a reasonable value, and this can be matched to coaxial line by a simple capacitor network. The antenna is tuned by connecting an impedance bridge to the input, then starting with the guy tuning capacitors at minimum they are brought up in value simultaneously until a good $R + jX_L$ is obtained. It may be possible to obtain $50 + jX_L$, in which case only a series capacitor will be required for matching to the line. Heavy ground busses must be used to link perimeter tuning units with the center tower.

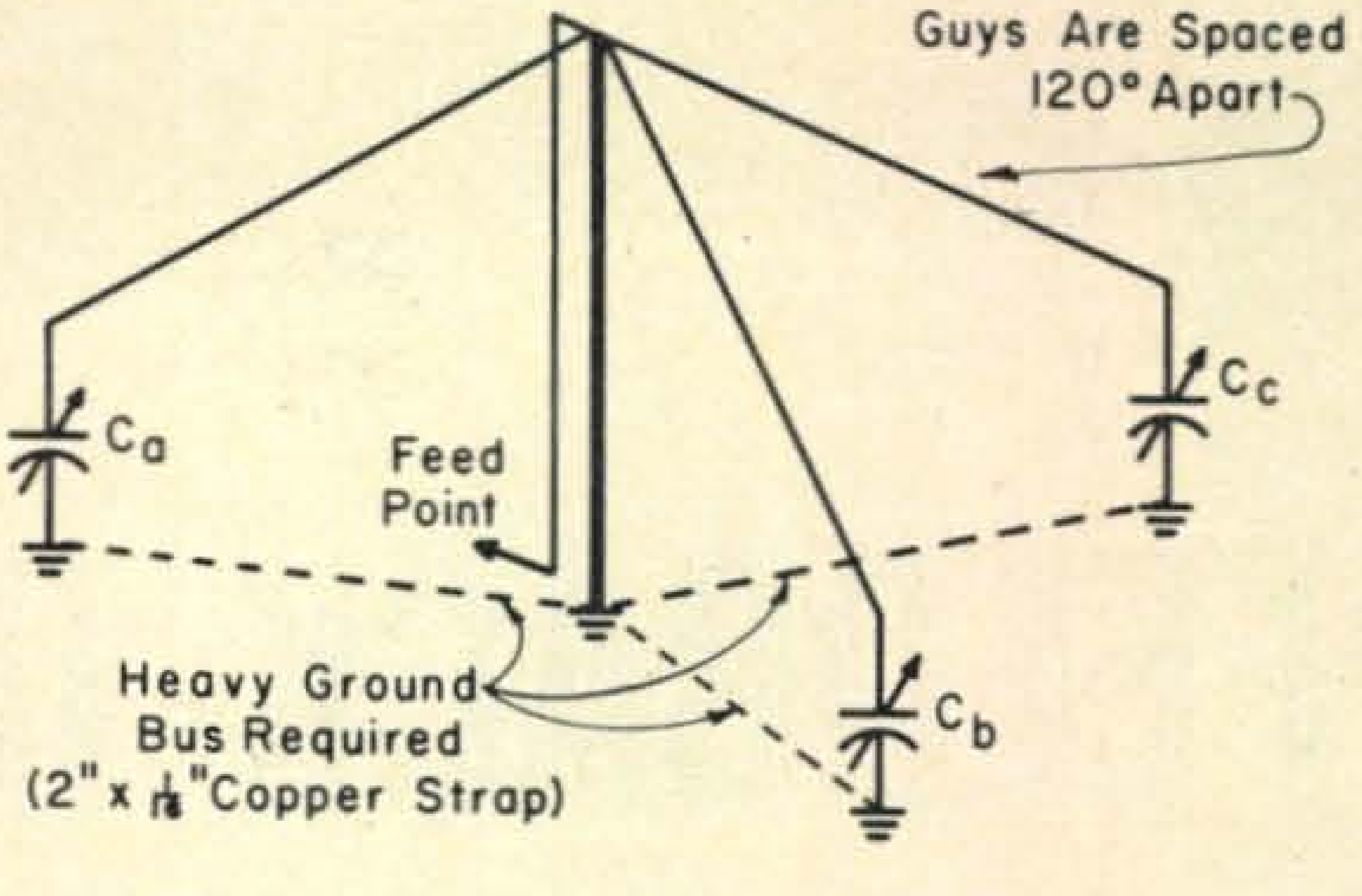

Fig. 24—Layout of the NORD® Antenna. A heavy ground buss is needed, at least a 2″ × 1/16″ copper strap.

There is another type of short vertical radiator that can be used at h.f., and this is the wound whip. These are made commercially by the Shakespeare Co. in South Carolina. A wire is wound around and imbedded in the outside of a fiberglass whip. The winding greatly increases the electrical length of the antenna. In fact, one might consider it to be a loading coil which has been stretched out to become *the* antenna itself. Whips of this type find great use on small boats, fishing craft, yachts, etc., for use with ship-shore radiotelephone in the 2 to 3 mc band. Any amateur can easily build one by winding wire around a bamboo pole, wrapping the thing with waterproof tape, and varnishing it. Such an antenna would suffice to handle several hundred watts, but for 1 KW or more I would not recommend it. Considerable voltage can be developed between turns in some places on the whip, and it could easily go up in smoke.

Slinkey

For low power there is another similar type, fed in the folded unipole manner. This one can be made of a child's "Slinky Toy", the coiled steel spring which stretches itself and "walks" downstairs by itself. The spring can be stretched out on any suitable support such as a fiberglass tube, anchored in place, and fed like a folded unipole, against ground. Its length can be varied to produce almost any input impedance and degree of loading desired. Such an antenna, experimentally built, would be an ideal thing for indoor use, or sticking out from an apartment window, suitably supported. It offers endless opportunity for the enterprising amateur to surprise himself with the amazing results which can be obtained. Communications have been maintained between this area and ZS stations

[*Continued on page 114*]

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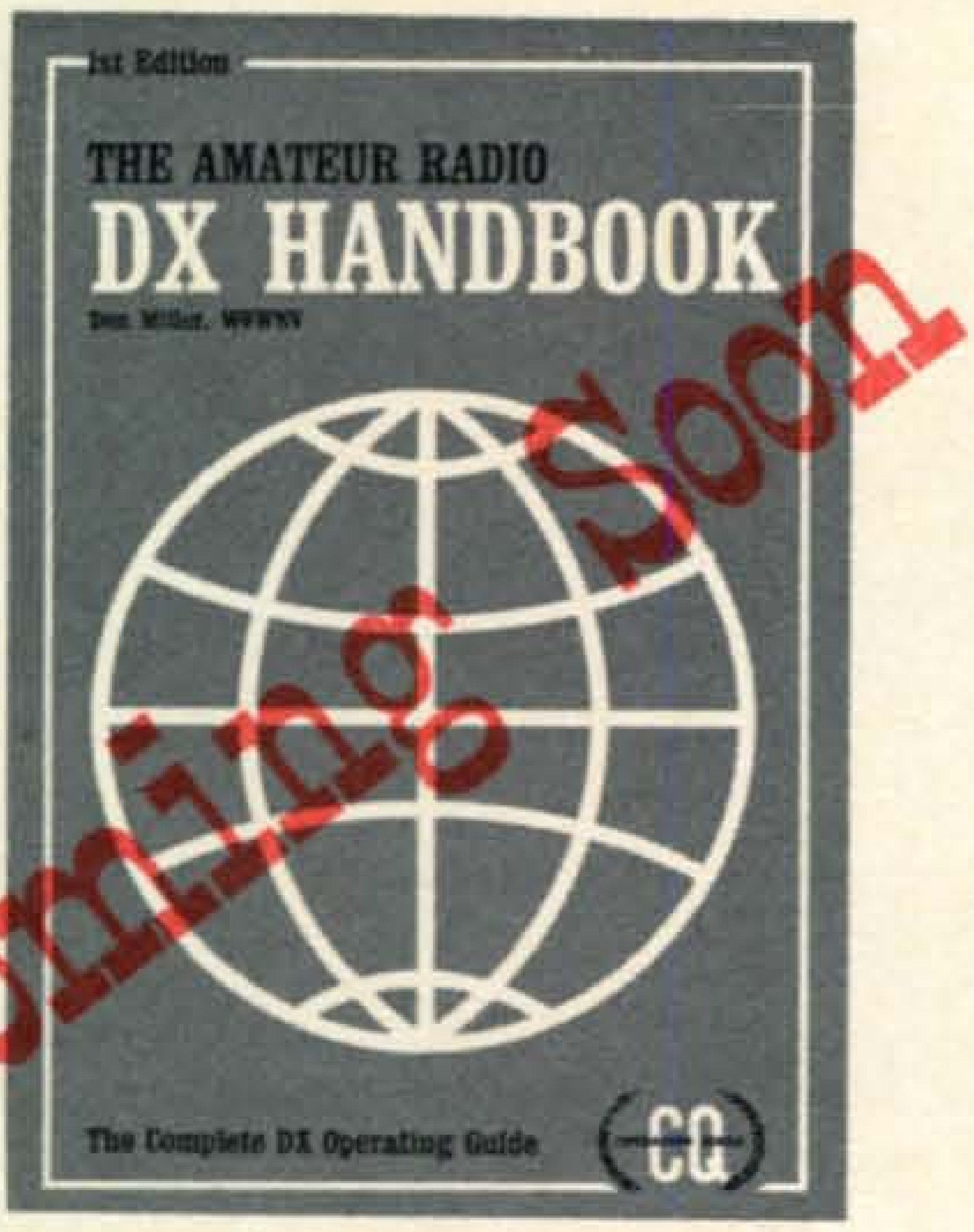
[36] "NORD Antenna Model Report," Private communication from John H. Mullaney, Multronics, Inc.



Scratchi [*from page 13*]

ing by the bed. When she seeing I can heering her, just like a woman, she starts talking—all about how she coming up in desert and finding me, and how the rest of the RRRR crowd are helping get me to a car and to the hospital, and how on acct. she finding me she winning the hidden xmitter contest, for which she getting big trophy with horse on top, and how she now being new member of RRRR's and how everybuddy liking her new clothes, and wasn't it all so wonderful, and doctor saying he think he getting out all cactus spines, and I can going home next day, and for me not to worrying, and when I feeling better she will making it all up to me for that wonderful day I giving her.

So that's why I standing up to riting you, Hon. Ed. And Lil says that tomorrow we going out and having fun on a real nice picnic. Hon. Ed., how much you want to bet that Lil decides we ought to go on horseback?

Respectively yours,
Hashafisti Scratchi

Vertical Antennas [*from page 57*]

and other DX locations using a short "Slinky" on 21 mc s.s.b. The little thing never ceases to amaze me.[37]

To sum up this chapter, there are many ways in which the serious amateur can use short vertical antennas and obtain good results. One need not be limited by space or height restrictions in getting on 2, 4 or 7 mc. A major consideration is the ground system, however. Reference to figs. 9 and 10 of Part I (4) will show the importance of having sufficient radials of great enough length when the antenna is shorter than 0.15 wavelength. The shorter the antenna, the more important the ground system becomes in obtaining the highest possible radiation efficiency.

The types UG and NORD are covered by patents held by John H. Mullaney, and the "Slinky" technique is covered by a patent application pending. This does not prevent any amateur from building one for his own use, however.

In Part IV of this series, we shall discuss driven vertical arrays of two or more elements, which can be used to produce and control directional radiation patterns. There are amateurs who are using such arrays at h.f. with considerable success.

[*To be continued*]

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[37] Private communication from John H. Mullaney, Multronics, Inc.

VERTICAL ANTENNAS

Part IV

BY CAPTAIN PAUL H. LEE,* W3JM

n this fourth part of a series, the author discusses directional antennas. Basic esign principles are explained, a sample design is worked out, and methods f power division and phasing are shown. Amateur band configurations are covered.

IN past years there have been articles in this agazine and others on directional arrays sing vertical elements. These have been of oth types, driven arrays and parasitic arrays. or the most part these have been fixed rrays, with several elements which could be witched in or out to change the direction of e pattern. It is natural that a horizontal agi array, which can be put up in the air n a tower thus requiring practically no real state, and which can be easily rotated to any irection, is in the majority. However, for the , 4 and 7 mc bands, Yagi arrays are somehat impractical because of their size. Thus here has been some interest in vertical arrays hose direction of radiation can be switched. here are several rather simple configurations f element spacing and phasing which lend hemselves to this concept. It is the purpose f this part to explain how vertical arrays ork, to show several simple configurations, nd to show how the elements of an array can e fed power of the proper phase and magniude to produce the desired pattern.

M.F. Broadcasting Arrays

What is the purpose of a directional array? n the most widely used application, which is n.f. broadcasting, these arrays are usually sed to produce nulls in the horizontal pattern (and sometimes also in the vertical pattern) o protect the service area of a co-channel tation (and often an adjacent channel staion) from interference. Coincidentally, the tation's transmitter site is so located that the nain lobe (or lobes) of the pattern falls over he station's desired service area, insofar as possible. Thus at m.f. the main purpose is protection of other stations from interference, not production of forward gain. Such an array often has several nulls in its pattern, one for each station to be protected. The patterns are carefully designed, by application of proper phasing and current ratios to the vertical elements, to produce specific levels of field intensity in the nulls. The FCC always imposes specific levels of field intensity, which shall not be exceeded, towards the stations to be protected. Thus, it is the consulting engineer's job not only to design the pattern to fit these limits, but to assure himself that the array will be stable and remain in critical adjustment during changes in weather and ground conditions from season to season. Proper design of the phasing and branching networks enters into this latter consideration.

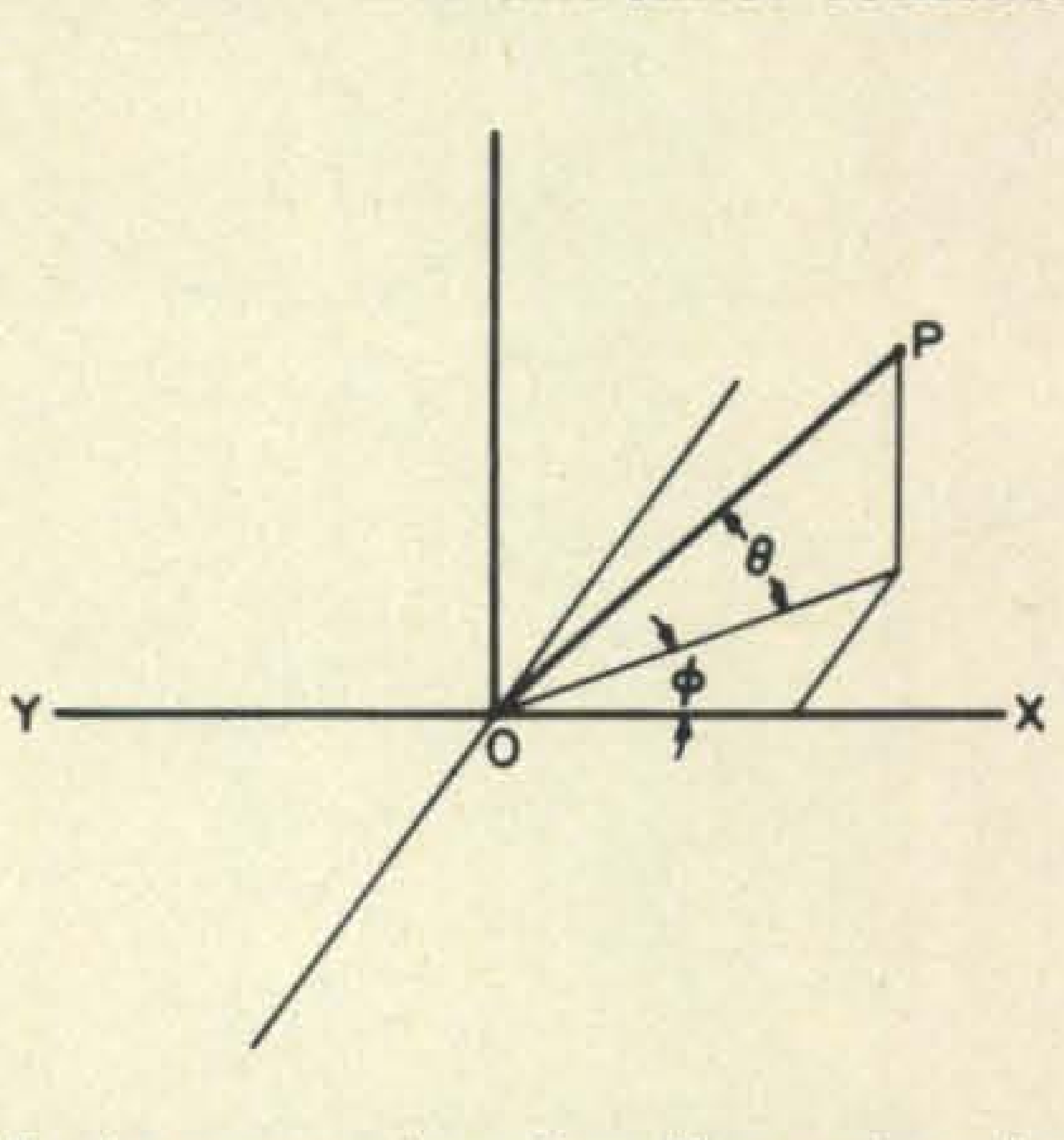

Fig. 25—A perspective view illustrating the equation that permits the determination of the radiation to be expected in the direction of point *P*. In this drawing θ represents the vertical angle of *P*, Φ the azimuth angle of *P*, *XY* is the line of towers and the array is located at O.

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* 5209 Bangor Drive, Kensington, Md. 20795.

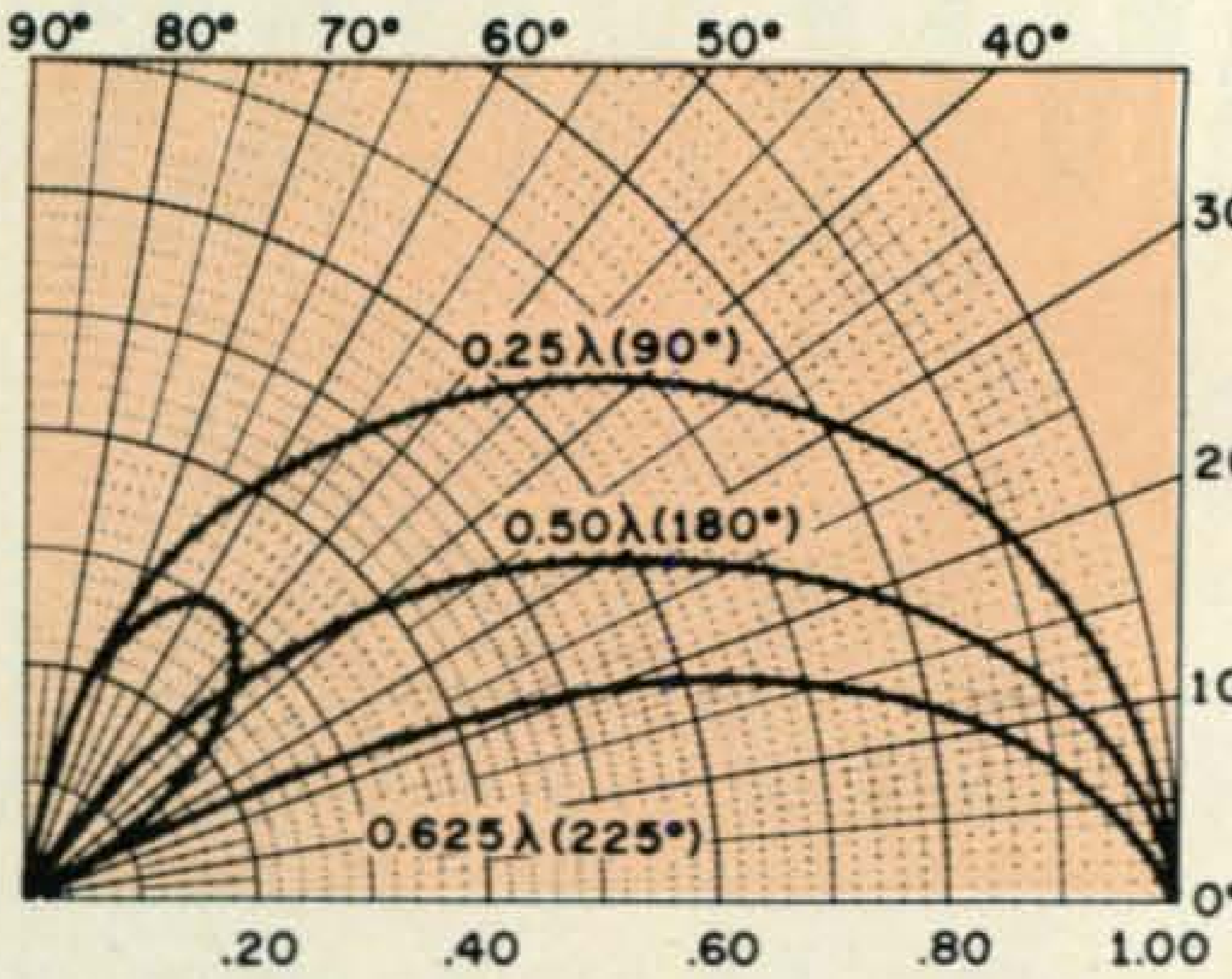

Fig. 26—Plot of the factor f (θ) for towers of ¼, ½ and ⅝ wavelengths height.

Amateur Use

For amateur use, however, we are not concerned with the absolute value of radiation in the nulls. Our main purpose is forward gain, usually in only one direction. Thus we can employ a more simple array of fewer elements, usually in-line, and content ourselves with obtaining forward gain and not worrying about depth of the nulls, nor about absolute pattern stability therein. Patterns can more simple, with one main lobe (or possib two). For reasons of propagation, such arra for amateur use will usually be employed 2, 4 or 7 mc, although they can be used f the higher bands as well, instead of ho zontal Yagis.

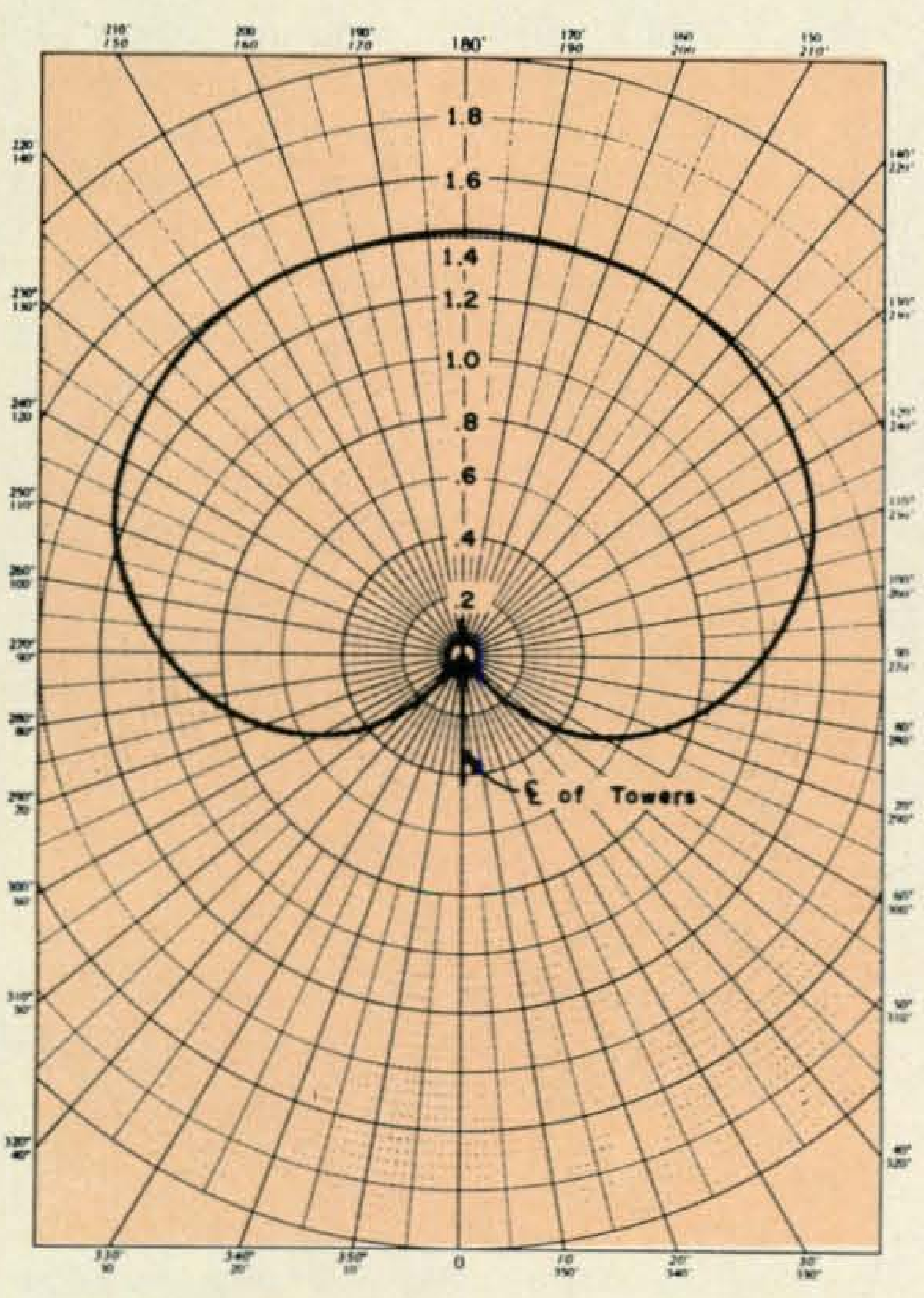

Fig. 27—Ground wave pattern from a directional array consisting of 2 elements of equal height, spaced 90°, equal element currents and a phase angle of 90°. The r.m.s. of the field pattern is normalized to 1.0.

Review

It is well to run through some of the bas mathematics for directional arrays, so that v all know what we are talking about. Figu 25 shows a perspective view which illustrat the following equation, which gives the rad ation to be expected in the direction of ar point *P* in space from a simple two-eleme array. The line of towers is shown as *X* *S* is the spacing between towers. The hor zontal or azimuth angle of point *P* from th line of towers is indicated as ϕ. The vertic angle of point *P* above the ground plane is i dicated as θ. The phasing of the currents the two elements is shown as ψ, and *R* is th current ratio between the two elements. Th field intensity at point *P* is thus equal to:

$$E = Kf(\theta)\sqrt{\left(\frac{1+R^2}{2R}\right)+\cos\,(S\cos\phi\cos\theta+}$$

This can also be written as:

$$E = Kf(\theta)\left(I_1\,\underline{/0^\circ} + \frac{I_2}{I_1}\,\underline{/S\cos\phi\cos\theta+\psi}\right.$$

K is a constant which is used to convert t mv/m, and which depends on the r.m.s. valu of the pattern, the power used, and the heigh of towers to be used. The factor $f(\theta)$ depend on the tower height *G* in degrees, and whic is computed from the following formula:

$$f(\theta) = \frac{\cos G - \cos\,(G\sin\theta)}{\cos G}$$

For example, the $f(\theta)$ for a tower height of ⅝ wavelength (225°) is as follows:

θ°	$f(\theta)$
0	1.000
10	.883
20	.582
30	.219
40	−.119
50	−.260
60	−.292
70	−.250
80	−.138
90	.000

See page 134 for New Reader Service

he minus sign is nothing to worry about. t merely shows that the radiation in the ninor lobe is 180 degrees out of phase with hat in the major lobe. Figure 26 shows this (θ) plotted, along with similar plots for ower heights of ¼ wavelength (90°), and ½ wavelength (180°). It will be seen that his plot is the same as that of fig. 1 in Part I f this series.[38] This is where the vertical patterns come from, right from the above equaion for the value of $f(\theta)$.

Thus, for our two element array, we can ompute the field intensity which will be radited towards any point P in space. Now if oint P lies in the horizontal plane, vertical ngle θ is zero, and since cos 0° is unity, it alls out of the equation. Also, $f(\theta)$ is unity, nd it falls out. Thus the horizontal or ground vave pattern equation is:

$$E = K\sqrt{\left(\frac{1+R^2}{2R}\right) + \cos\left(S\cos\phi + \psi\right)}$$

This can also be written as:

$$E = K\left(I_1\ \underline{/0^\circ} + \frac{I_2}{I_1}\ \underline{/S\cos\phi + \psi}\right)$$

If the currents in the two towers are made equal, the equations simplify to:

$$E = K\sqrt{1 + \cos\left(S\cos\phi + \psi\right)}$$

which can also be written as:

$$E = K\left(1\ \underline{/0^\circ} + 1\ \underline{/S\cos\phi + \psi}\right)$$

The azimuth angle of the null can be computed from the following relationship:

$$\text{'os}\ (S\cos\phi_N + \psi) = -1, \text{ or}$$
$$S\cos\phi_N + \psi = \pm 180^\circ, \text{ solving for } \phi_N$$

The pattern is symmetrical about the line of owers, and there will be a pair (or in some ases two pairs) of nulls for a two tower rray.

The pattern for a simple array of two towers whose spacing is ¼ wavelength (90°) and whose phasing is 90° is shown in fig. 27. Currents are equal. The figure is normalized to an r.m.s. of 1.0 for the pattern. Maximum radiation is only 1.42, which is a power gain of about 2, or 3 db.

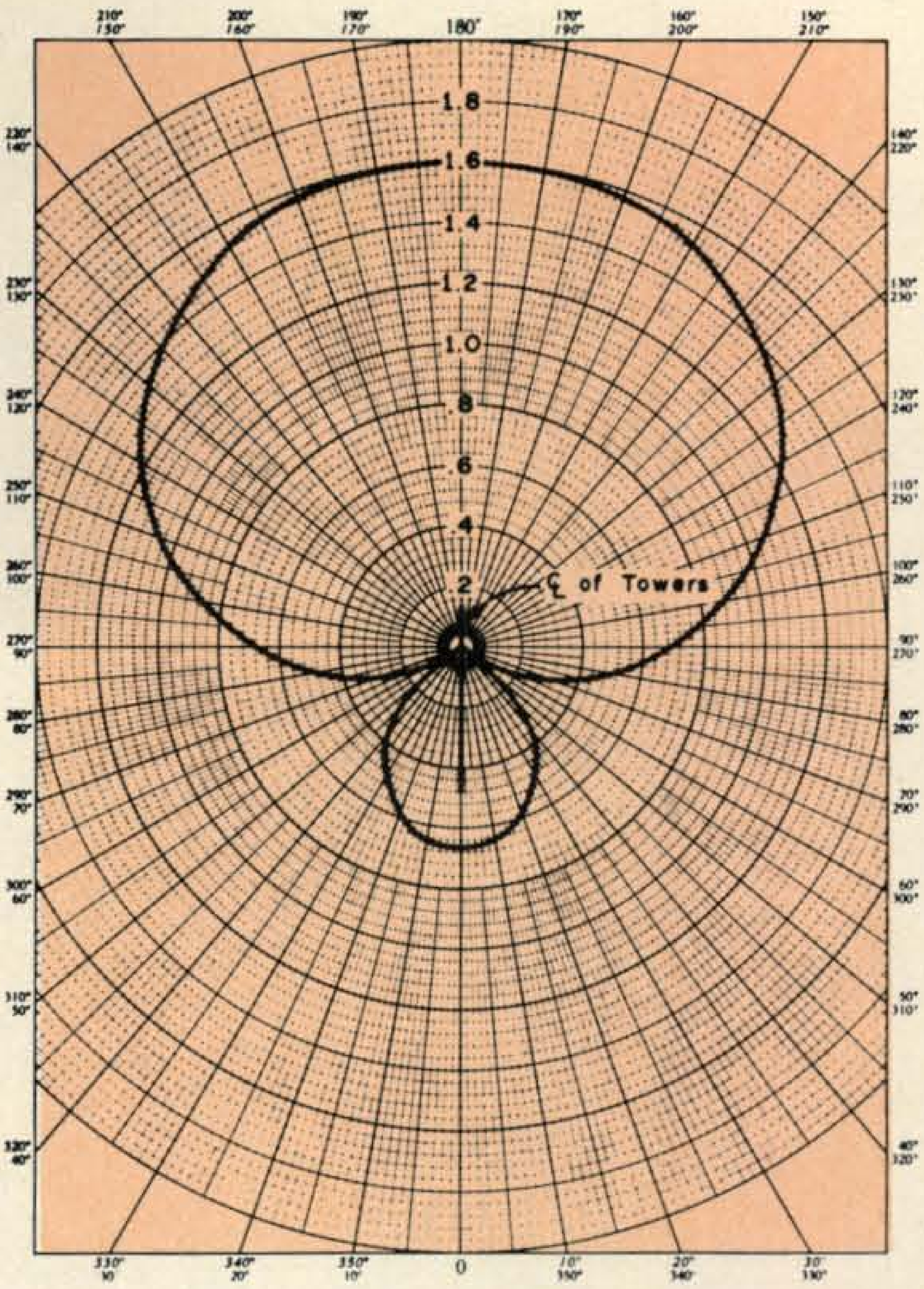

Fig. 28—Ground wave pattern from a directional array consisting of 2 elements of equal height, spaced 90°, equal element currents and a phase angle of 135°. The r.m.s. of the field pattern is normalized to 1.0.

Figure 28 shows a plot of radiation for a pair of towers spaced 90° but phased 135°. It will be noted that a small back lobe has

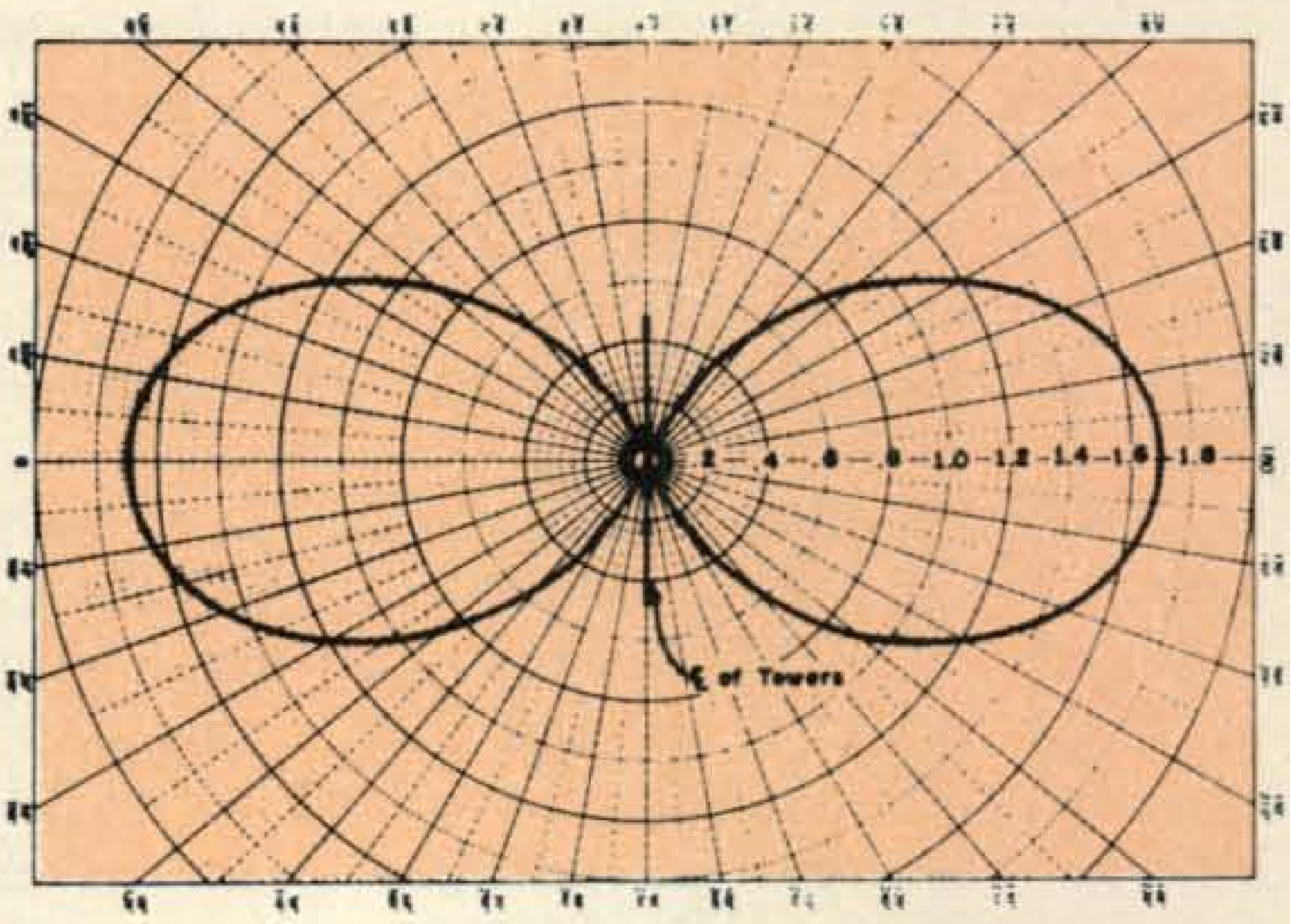

Fig. 29—Ground wave pattern for 2 elements of equal height spaced 180°, equal element currents but with zero degrees phase angle.

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[38] Lee, P. H., "Vertical Antennas, Part I," *CQ*, June 1968, page 16.

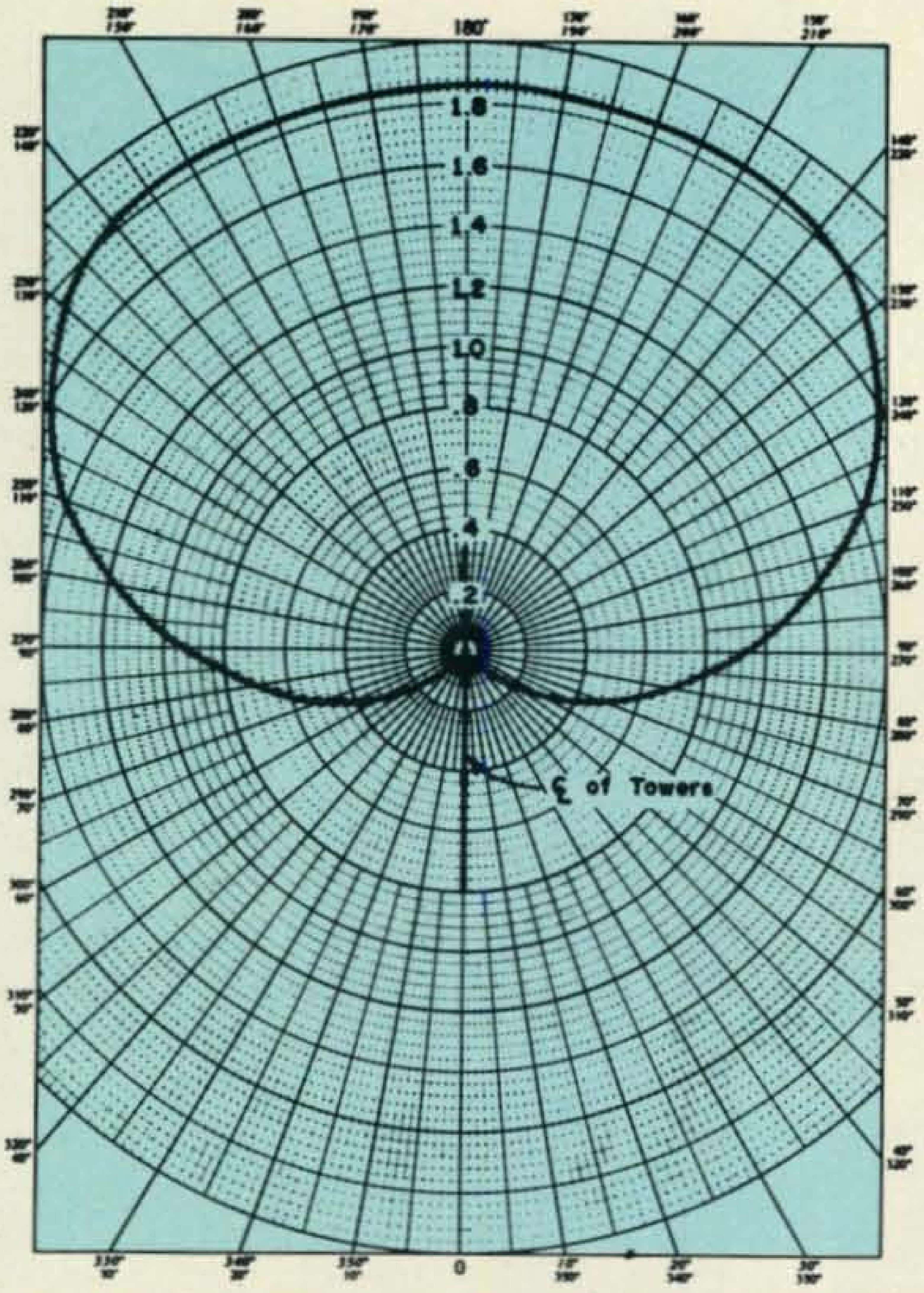

Fig. 30—Ground wave pattern from a directional array comprising three elements of equal height, spaced 90° in line with $I_A=1.0$, $I_B=2.00$, $I_C=1.0$, $\psi_A=0$, $\psi_B=90°$ and $\psi_C=180°$. The r.m.s. of the pattern is normalized to 1.0.

appeared, and there are two nulls, symmetrically placed on either side of the line of towers. The voltage gain of this one is 1.6, and the power gain is 2.56, which is 4.08 db.

Figure 29 shows the pattern from a pair of towers spaced ½ wavelength (180°), and operated in phase. Note that the direction of the main lobes has shifted from that of the line of towers to a broadside direction. Voltage gain is 1.7, power gain is 2.89 or 4.62 db, and we have two nulls in the line of towers. If the spacing is increased beyond 180°, and the phasing maintained at zero, a small lobe will appear in each of the nulls in the line of towers, in this pattern. Thus there will be four nulls instead of two.

The maximum possible gain with two towers for a pattern whose main lobe is in line with the line of towers is a voltage gain of 1.725, or 4.74 db, and this occurs with spacing of 30° and phasing of 165°. For the broadside pattern (two lobes), maximum gain is 1.82, or 5.2 db, and this results from a spacing of 210° and phasing of zero degrees. (With this spacing there will be a very small minor lobe in each null.)

Multiple Towers

So much for two tower configurations. I will be seen from the above statements tha gain is somewhat limited, and the lobes ar quite broad, especially in the in-line case How can we increase gain? The answer is t increase the number of towers to three, o even four. It is not intended that this text g into all the various complicated arrays whic can be formed. We shall simply state that i the case of an in-line array such as that whos pattern is shown in fig. 27, if a third tower i added at a spacing of 90° from one of th others, making it three in line with 90° spacing, the pattern of fig. 27 can be "squared, or multiplied by itself, to produce the patter shown in fig. 30. The equation for such pattern is:

$$E = \sqrt{[1 + \cos\,(S_2 \cos \phi_2 + \psi_2)] \times [1 + \cos\,(S_3 \cos \phi_3 + \psi_3)]}$$

For the in-line case, $\phi_2 = \phi_3$. The transitio from the two tower case to the three towe case is shown diagramatically in fig. 31. Current in each tower is assumed to be unity. I will be seen that we start with two pairs o towers, each spaced and phased 90°, but w end up with three in line, whose phasing are entirely different, which produce the pattern of fig. 30.

Unsymmetrical Patterns

If the three towers are not to be in line making an unsymmetrical pattern, ϕ_2 will differ from ϕ_3. Or perhaps the spacing and phasing of the second pair will not be the same a those of the first pair, making an entirely different result. It can be seen, therefore, tha there are an almost infinite number of configurations, which produce all kinds of strange looking patterns. There is a very fine book[39] by Carl E. Smith which shows hundreds o possible configurations. The same author ha written another book[40] which goes into th design of directional antennas in great detail covering not only two and three tower cases but also those with four or more towers. Th mathematical principles for the more complicated arrays are the same as those for th simple arrays, but the computations are mor laborious and time-consuming, unless one has a computer available.

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[39] Smith, Carl E., "Directional Antennas," *Cleveland Institute of Electronics.*

[40] Smith, Carl E., "Theory and Design of Directional Antennas," *Cleveland Institute of Electronics*

To get back to our three element array of fig. 30, we see that the voltage gain is now 1.86, and the power gain is 3.46 or 5.4 db. By adding the third tower we have gone from a gain of 3 db in fig. 27 to a gain of 5.4 db in fig. 30.

For our maximum possible case previously mentioned, where we had a two-tower gain of 4.74 db (the in-line case) with spacing of 30° and phasing of 165°, we could add a third tower and realize a gain of about 9 db. In this case, and referring to fig. 31 for guidance, I_A would be $1.00\underline{/0°}$, I_B would be $2.00\underline{/165°}$, and I_C would be $1.00\underline{/-30°}$. For the maximum possible gain in the broadside case, adding a third tower would result in about 10 db gain.

Field Intensities

In our discussion so far, we have normalized everything to 1.0. To obtain actual expected unattenuated field intensity at one mile from fig. 27 through 30, one must multiply by the factor *K*. For 1 kw into an array of ¼ wave elements, a value for *K* of 190 mv/m is reasonable. The FCC allows up to 7.5% power loss in the phasing and branching networks for m.f. broadcast directional arrays. When an array is tuned up and in adjustment, the proof of performance consists of making field intensity measurements on at least eight radials, and plotting these measurements on field intensity paper as described in Part I of this series.[38] The unattenuated field at one mile is then obtained from these plots, for each radial. These values are then plotted on polar paper like that in figs. 27 through 30, and if the array is adjusted properly, the polar plot of measured values should conform to the designer's original plot.

Feeding

How are such arrays fed? It is a well known fact that there are mutual interactions between elements. What causes this? What can be done in the design of the phasing and branching networks to take these interactions into account and to compensate for them? First, let us examine the interaction itself. There is a very good explanation in a paper by G. H. Brown[41] whom we have met before in this series of articles. When two vertical (or any other kind) antennas are close together, there exists at antenna number two a voltage which is produced by the current flowing in number one. Thus a current flows in number two due to the current flowing in number one. This curent is over and above the current which flows in number two due to its own connection to the source of power, and it bears a certain phase and magnitude relationship to the current in number one which causes it.

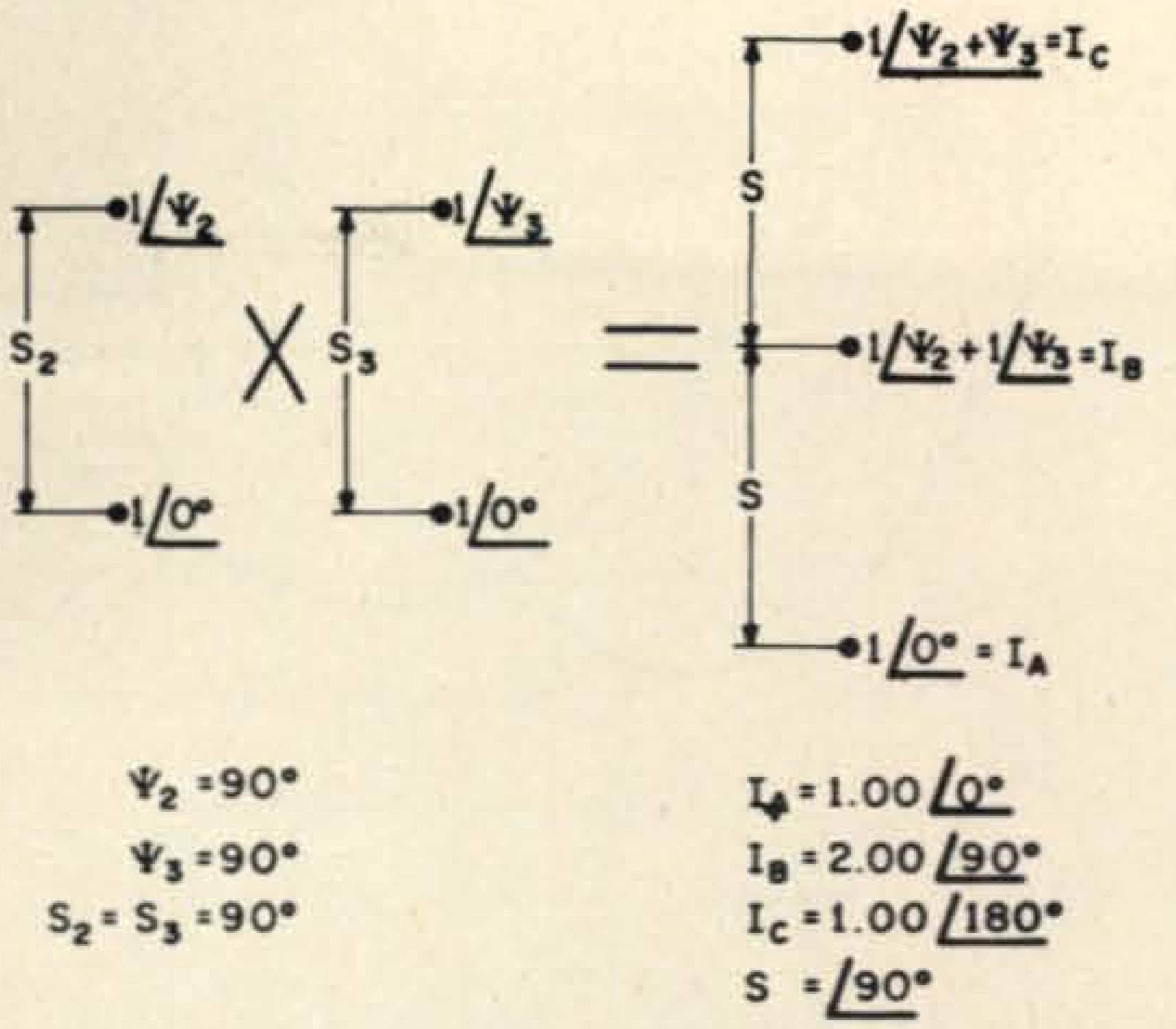

Fig. 31—Multiplication of two equal tower arrays to form a three tower array.

This phase and magnitude relationship is caused by the "mutual impedance" between the two antennas. The mutual impedance depends on the antenna heights and the spacing between them. Figure 32 is a plot of the resistance and reactance parts of the mutual impedance between two ¼ wave vertical radiators (referred to the current loop at the base of the antenna). Note that both resistance and reactance can be either positive or negative in sign. There are similar charts for other tower heights, both for towers of equal height and of unequal height, in Smith[40] and in Brown[41].

The array designer uses these charts in the initial design of the phasing and branching networks. Actually, in the field, the engineer can measure and compute the mutual impedance between two towers by measuring the change in self-impedance of one tower when the other is first open-circuited and then resonated to ground. He can then go to the second tower and repeat the process in reverse, if the towers are equal height, and he should get the same result (within a couple of percent). There is a formula[41] for this computation, but we shall not go into it here. The mutual impedance determined in the field by this method usually is quite close to that which can be read from a chart such as fig. 32.

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[41] Brown, G. H., "Directional Antennas," *Proceedings of the I.R.E.*, January 1937, pages 78-145.

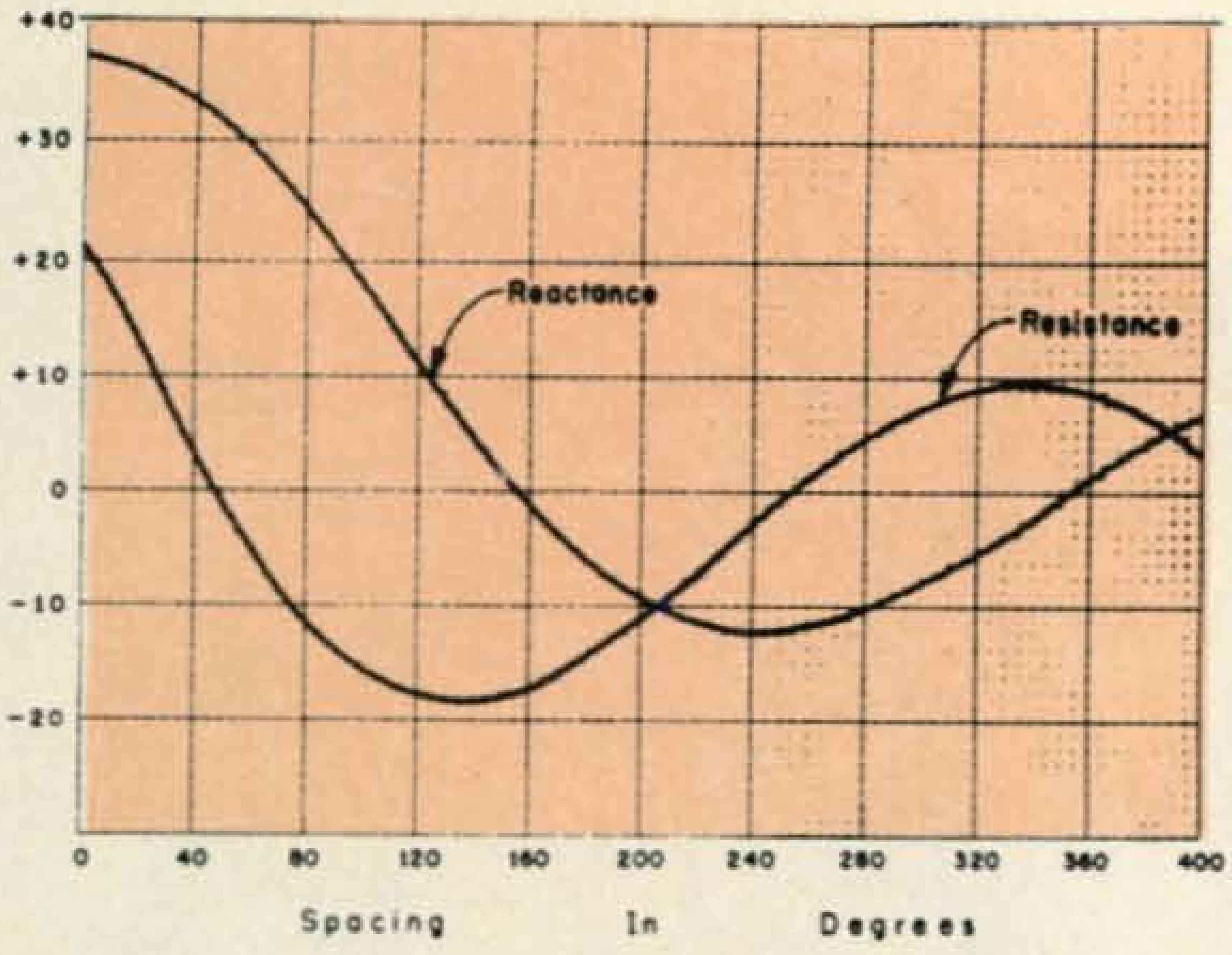

Fig. 32—Plot of mutual impedance between two quarter wave antennas over perfect earth. It is referred to the current loop at the base of the antenna.

Having found the mutual impedance either from the chart or by actual field antenna resistance and reactance measurements, the engineer can then determine the actual operating base impedance of each element of the array, when all the elements are connected to the system and handling power. This is something which cannot be measured by an ordinary radio frequency bridge, because the element or tower cannot be detached from the system for purposes of making impedance measurements. Detaching it destroys the effect of the mutual impedance and gives an entirely erroneous result. The operating impedance of a single element under power can only be determined by use of an s.w.r. bridge which will handle the power involved. One company, Delta Electronics of Alexandria, Va. makes one for m.f. use for powers up to 5 kw. This has become a very handy tool for the consulting engineer to use in the field. The operating impedance can be computed, however, by use of the following formulas:

$$Z_1 = Z_{11} + \left(\frac{I_2}{I_1}\right) Z_{21}$$

$$Z_2 = Z_{22} + \left(\frac{I_1}{I_2}\right) Z_{12}$$

where Z_1 is the operating impedance of tower 1, Z_{11} is the self impedance of tower 1 with tower 2 floating, I_2/I_1 is the ratio of currents, and Z_{21} is the mutual impedance from tower 2 to tower 1. Z_2 is the operating impedance of tower 2, Z_{22} is the self-impedance of towe 2 with tower 1 floating, I_1/I_2 is the inverse o the current ratio, and Z_{12} is the mutual impedance from tower 1 to tower 2. Theoretically, Z_{11} and Z_{22} should be equal, and Z_{21} and Z_{12} should be equal, and in a very carefully designed and constructed array this will be the case, within a couple of percent with equal height towers. However, during actual tuneup and adjustment, the engineer always measures and computes these factors both for a check on his initial design, and t show up any unforeseen defects in the array

Coupling Networks

It can be seen from the above equations that for most cases the operating base impedances of the towers will be different by an amount dependent on the magnitude and phase angle of the mutual impedance, and on the phase relationship and magnitudes of the tower currents. Thus, the coupling networks must be designed to match those operating base impedances to the transmission lines being used. Designing the coupling networks to match the self-impedance of either tower would result in considerable impedance mismatch as well as an erroneous phase shift.

A typical two-tower phasing and branching network is shown in fig. 33. The two transmission lines are tapped on a low-*Q* tank circuit, which is in turn tapped to provide a suitable load (usually 50 + *j*0 ohms) to the transmitter. This type of circuit is called "the jeep coil type," because of the fine adjustment coils marked "*X*." It is a very critical circuit to adjust, especially when three or more towers are being fed, because of the extreme interactions betwen individual adjustments.

A much better circuit in this respect is shown in fig. 34. This is called "the Ohm's Law type." It is much easier to adjust when three or more towers are used, because each tower is fed off a separate power divider coil, and the parallel combination of these, in series with L_s, is tuned by capacitor C_A to form a low-*Q* tank. The tank circuit's input impedance is usually set to be about 150 + *j*0 to 250 + *j*0 ohms, and this is matched to the transmitter, which usually likes to see 50 + *j*0 ohms, by a simple "T" network.

In the circuits shown in fig. 33 and 34, the amount of phasing to be contributed by the phasing networks and the tower coupling units is computed; the required component values are then determined by calculation, and the whole thing is then wired up and ested under power (low power at first). The engineer makes the required adjustments to ecure the desired phasings and current ratios, and checks the actual field intensity pattern by field measurements. Two-way radio is used, with a field car located in each null, calling in readings as adjustments are made, until the pattern is correct. S.w.r.'s on the ines are checked with the Delta Bridge, required impedance matching adjustments are made (which throws off the array adjustment somewhat), and the process starts all over again. Tuning up a two tower array can usually be accomplished in two or three nights of work (midnight to 6 A.M.), but a multi-element array with critical or deep nulls can take as long as three or four weeks of very tedious adjustments. By keeping a complete and careful log of all adjustments and their resulting field readings, the engineer can soon note trends, and know which way o go with the various adjustments, which always interact somewhat.

Amateur Use

While all of this is not applicable in detail o the amateur case, we have gone through it step by step to show the basic principles involved, so that you will have an understanding of all that goes into the design and operation of these arrays. Perhaps some of you will want to apply these principles to the design of your own arrays for 2, 4 or 7 mc. If so, you will find Smith[39, 40] and Brown[41] invaluable. It might also pay to visit one of your ocal broadcast stations which has a directional array, and look over the circuitry and discuss its design with the chief engineer. Note particularly the type of power dividing or branching network used ("jeep coil" or "Ohms Law"), how the phasing is accomplished (positive or negative networks), how the tower coupling units are designed, how the tower lighting circuits are brought across the base insulators (choke coils or Austin transformers), how the ground system is designed, and its extent, and, in general, how carefully put together the system is. Most of them are quite well designed and built; they have to be, to pass FCC inspection.

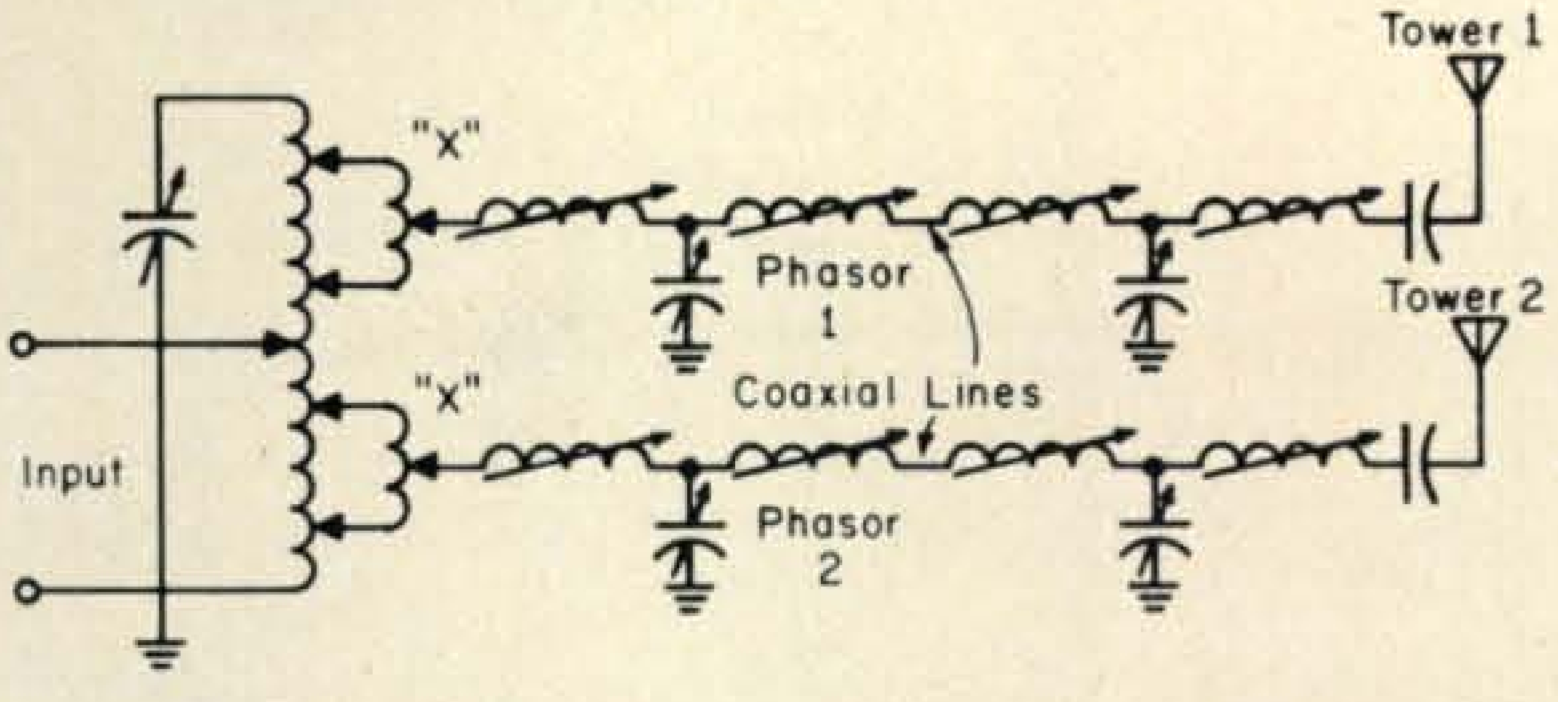

Fig. 33—A typical two tower phasing and branching network called the "jeep coil type."

Configurations

Now, for some simple configurations which lend themselves to amateur use, refer to figs. 27 and 29. For the array of fig. 27, the 90° phasing can be accomplished by making the coaxial lines 90° different in length. This is an old trick, often used, for phasing of any amount. A simple matching network is used at each tower, and the Ohms Law power divider is employed. See fig. 35 for a suitable circuit. For the array of fig. 29, if you want a broadside array which will fire in two opposite directions, the phasing is zero degrees. This is very easily accomplished by making the coaxial lines equal in length. In fact, the array is completely symmetrical, and the tower tuning units are alike. Again an Ohms Law network can be used.

For the maximum gain case mentioned previously, locate the towers 30° apart, make the coaxial lines about 135° different in length, and design the tower coupling units for the operating impedances involved. In this case, the effect of mutual impedance will be quite pronounced due to the close spacing,

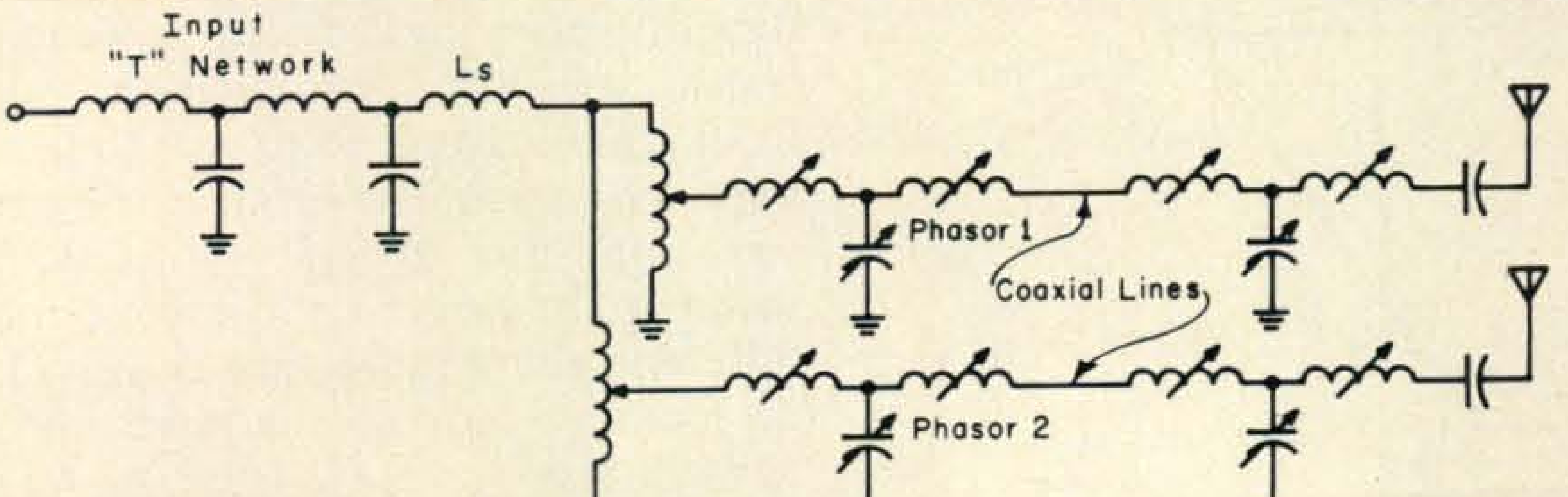

Fig. 34—An improved type of phasing and branching network called "the Ohm's Law type."

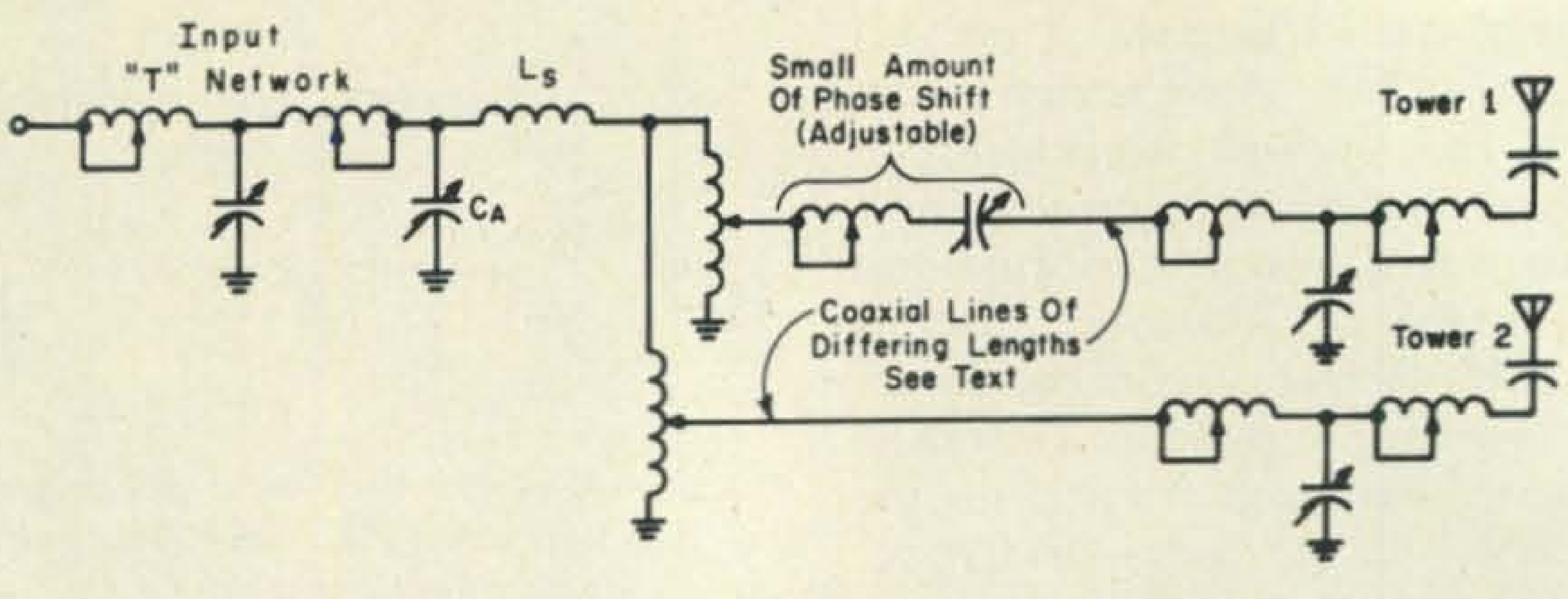

Fig. 35—Circuit of an Ohm's Law power divider suitable for amateur use.

and more attention will have to be paid to s.w.r. on the lines, and to matching. In the two previous cases, perhaps some mismatch and s.w.r. can be tolerated, with only a kilowatt and RG-8/U cable. In the maximum gain case, however, more care should be taken, if the gain is to be realized. For the 210° maximum gain case, we again have a completely symmetrical array, and with the great spacing the effect of mutual impedance is not going to be so apparent. A bit of s.w.r. can be tolerated here.

Radials

Each tower or radiator should have its buried ground system. These should be joined by a copper bus running between tower tuning units. This can be made of copper strap, or three or four ground wires twisted together. Where ground radials ovelap, they should be joined, as in fig. 36. The whole ground system should be one well-bonded unit, with no loose connections or unsoldered crossing wires. Refer to Part I of this series[38] for a discussion of ground system design and its effect on radiation efficiency. If I were going to build a directional array for 2, 4 or 7 mc, I would lay down at least 32 radials around each radiator, with the ground bus extending into the building and connecting to the branching unit and the transmitter.

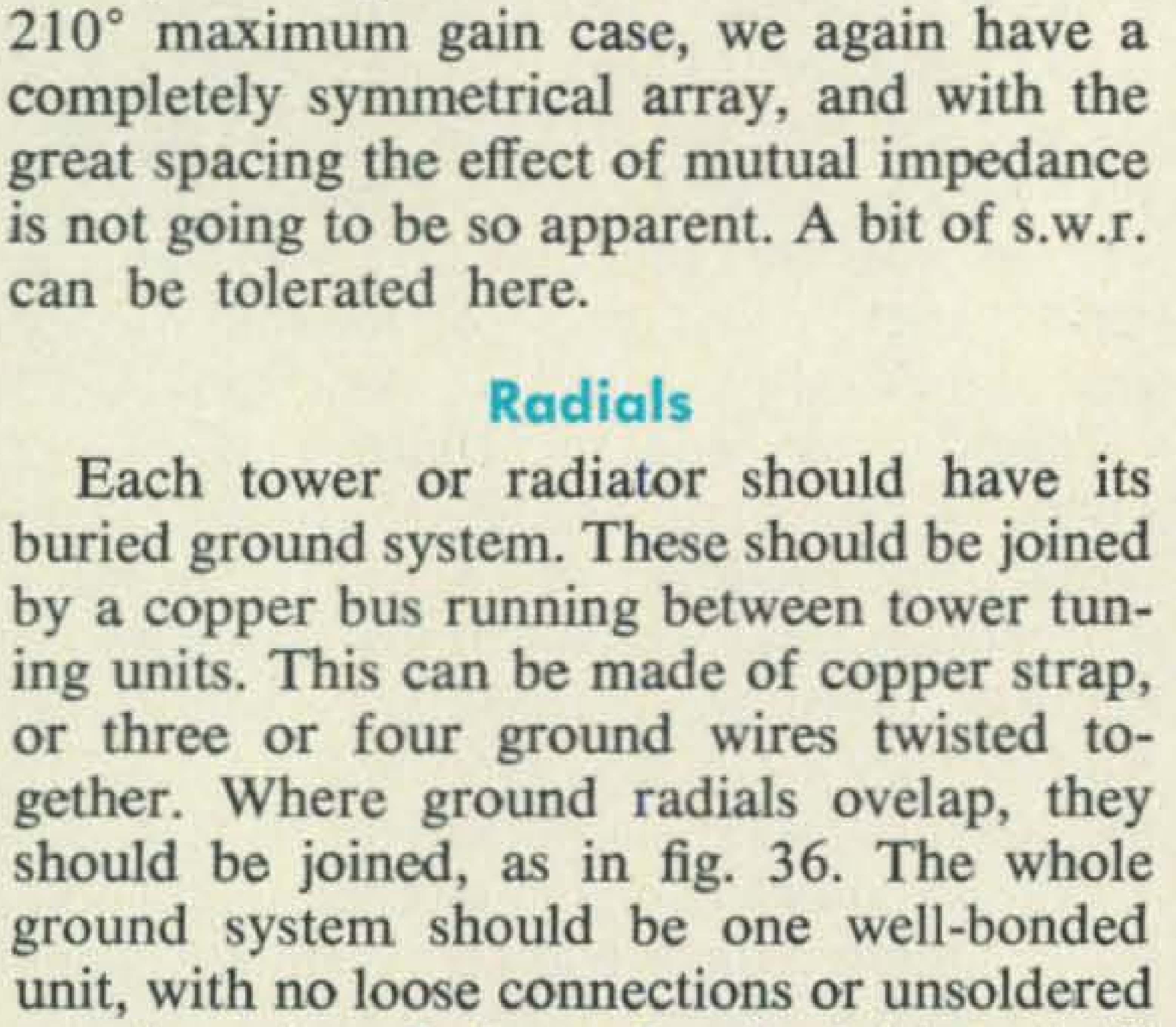

Fig. 36—A 32 radial ground system for a two-tower array.

Tower Phasing

One matter I have not touched upon here is the measurement of the tower phasing. For the amateur this will not be too important, inasmuch as the array can be tuned for maximum forward gain (or maximum rear rejection) without much attention being paid to exact direction of the nulls. In the m.f. broadcast case, however, the phasing is required to be logged and maintained within two degrees. There is one common method of measuring it, and that is by means of a current sampling loop located on each tower. Each loop feeds a length of coaxial cable (usually RG-8/U), which is attached in the building to a phase monitor. This is a rather expensive piece of equipment which is designed to read phase difference between two currents. The sampling loop also provides a means of reading tower current remotely, and the remote meter can be calibrated to track fairly closely with the tower base current meter. Most phase monitors have provision for reading up to six towers. There has recently been introduced a simple current transformer which can be inserted in the lead from coupling unit to tower, to provide a remote indication. However, in the case of some self-supporting towers with wide bases, the tower input current will give a considerably different phase indication than will the pickup from the loop on the tower. After all, the actual tower current is what we are after. The pickup loop is usually mounted slightly above

[*Continued on page 130*]

YLRL Convention [*from page 119*]
W2's EEO, OWL; WA2FGS; WB2YBA; W3's OLY, PVH; WA3ATQ; K4LMB; W4's BIL, HRC, ZDK; W5's UXW, RZJ, ZPD; K5's BNQ, JKV, YIB, JFJ, ECP, OPT; WA5MPM.

W6's MWU, BIS, YKU, QGX, VDP, DXI, ALL, BDE, AXX, CEE, PJU, LBO: K6's GU, JCL, BUS, HHD, KCI, ELO, DLL, RLR; WA6's AOE, PKP, WFZ, UBU, LWE, OGK, BNS; WB6BBO.

W7's HPT, NJS, LXQ, GXI, ULK, GGV, HHH, QYA; K7's BED, UBC, UJV, YFD, CHA, WVT, YDO, BII, KSF; KL7FJW.

W8's, RZN, UAP, TAY, LGY, WRJ; K8's ZNC, RZI, MZT, BDC, PXX, LHF, UXM, CEN, ITF; WA8's HWL, EBS, ZMU, ARJ, UYJ, FSX, CJP, GPO; W9's RTH, QGR, LYU; K9's ILK, HGY; WA9HLW.

W0's WZN, HEM, RAW, EVT, ZWL; K0's EPE, KHR, WZS, SPW, LCZ, EVG, WGL, JFO, BTV; WA0's FSK, KRB, KER, SSS, OIG, CSF, ECG, NNC, EXX, PPV; WN0UMB; WB6VJX/0.

Now we can enjoy many pleasant memories of "Our Big Date in '68"—and also look forward to 1972! ■

Vertical Antennas [*from page 44*]
the base in a ¼ wave tower, or at the voltage node (current loop) in the case of a tower taller than ¼ wave. The sampling loop is insulated from the tower, and its angular position is adjustable to vary the amount of pickup. The sampling line is brought down the tower on insulators, because it is usually buried from the base of the tower into the building. For the sake of easy reading of the phase monitor, it is customary to make all sampling lines of equal length, coiling up any excess in some out of the way place. This makes the monitor read correctly, without any "fudge factors." Perhaps some enterprising reader will build a phase monitor. It is not too difficult. Again, a visit to your local station may enable you to find a copy of a circuit diagram.

2 mc Vertical Arrays

With the increases of power recently granted in some areas of the country on 2 mc, and with crowded conditions on 4 mc, use of vertical directional arrays might pay off. This leads me to think about possible use of such an array here on the east coast to protect the Loran coverage areas, while still delivering a strong signal to the interior of the country. This might be an interesting point to explor with the FCC—whether the FCC would pe mit one using an array to protect Loran area to run increased power input over and abov that normally permitted in his area. Such a array could be easily designed and tuned u and with proper monitoring equipment could be every bit as effective as one for th m.f. broadcast band. If any of you have an thoughts on this subject, I would be happy t hear of them.

If you have enough land available, you ca put up a switchable directional array. Fo example, the array of fig. 29 can be used t provide coverage in six directions, by use o three elements spaced 180° on the corne of an equilateral triangle, and switched in o out by use of relays. The element would b used a pair at a time. Other interesting co figurations can be arranged, depending o the individual amateur's desired directions o communications.

(To be continued)

The readers attention is called to footno 10 in Part I. It should read "Proceedings o I.R.E., June 1937, page 753. Also, in fig. 1 of Part II, the designation of (A) and (B) reversed.

Signals From Satellites [*from page 34*]
the Doppler shift on the satellite's signal. Th relative velocity of the satellite with referenc to a listener on earth causes the satellite signal to change pitch in much the same ma ner that a train's whistle changes pitch as th train approaches and then moves away fro an observer at relatively high speeds. Th frequency on which the satellite is transmi ting will appear to increase as the satelli approaches, and decrease as it moves awa from the listener on the ground. The satelli is nearest to being overhead at the instant th pitch of its signal begins to decrease. At 2 mc the Doppler shift will be approximatel one kilocycle each side of the center fr quency, while at 136 mc the shift can be a much as six kilocycles, for satellites in orbi below a thousand miles.

With a suitable receiver and antenna, an the information contained in the followi list of trasmitting satellites, it should be po sible to tune into the wide, wide regions o space, and listen to the exciting sounds o the satellites as they flash signals back t earth.

VERTICAL ANTENNAS

Part V

BY CAPTAIN PAUL H. LEE, *W3JM

An antenna composed of vertically stacked vertical elements produces low angle radiation without wasting power in high angle skywave lobes. In this article of the series, the author covers the theoretical aspects of vertical stacking, and then describes some practical configurations.

In the previous parts of this series of articles, we have discussed vertical antennas composed of a single vertical element, whose height must be limited to ⅝ wave or less. For those who may be confused by the term "height," it is used to indicate the length of the vertical element or radiator. Figure 1 of Part I[42] and Figure 26 of Part IV[43] show the vertical radiation patterns to be expected from antennas of several heights. The pattern for a ⅝ wave vertical radiator is shown. It has a large low angle lobe, and a small skywave lobe. These vertical patterns result from the computation of the factor $f(\theta)$ as shown in Part IV.[43] If the computation is carried out for heights greater than ⅝ wavelength, it will be seen that the low angle lobe shrinks very fast, the skywave lobe increases rapidly, and the pattern becomes useless for long distance communications, as the height G is increased. Thus the statement that the height of the single simple element must be limited to ⅝ wave or less. Perhaps the statement should be qualified by saying that the vertical is most effective when producing low angle radiation for long distance communications. There are simpler antennas for short-hop, high angle skywave (such as a horizontal dipole close to ground).

Lowering The Angle

A look at the pattern of the ⅝ wave vertical shows, however, that some radiation is wasted in that high angle skywave lobe, and that the low angle lobe could be compressed even more and radiated at still lower angle, which is very desirable for long distance work.

Compression and lowering of the main lobe can only be accomplished by vertical stacking of in-phase elements. This is true whether the elements are horizontal or vertical. In the vertical element case, the array which results is called a vertical colinear array, since the elements are in line, or colinear. The vertical radiation pattern which results from a single two element colinear array in free space is shown in fig. 37. This array has a free space gain of 1.9 db over a dipole. The plot actually shows a vertical cross-section thru one side of the pattern. The whole pattern is actually a "doughnut", in three dimensions. The two element colinear in free space, when cut in half, becomes a ½ wave element working against a ground plane. The ½ wave pattern in fig. 26 (Part IV) is the plot of this antenna's theoretical radiation over perfect ground. The affects of imperfect ground on the vertical pattern, and the resulting suck-in at very low angles were thoroughly discussed in Part I.

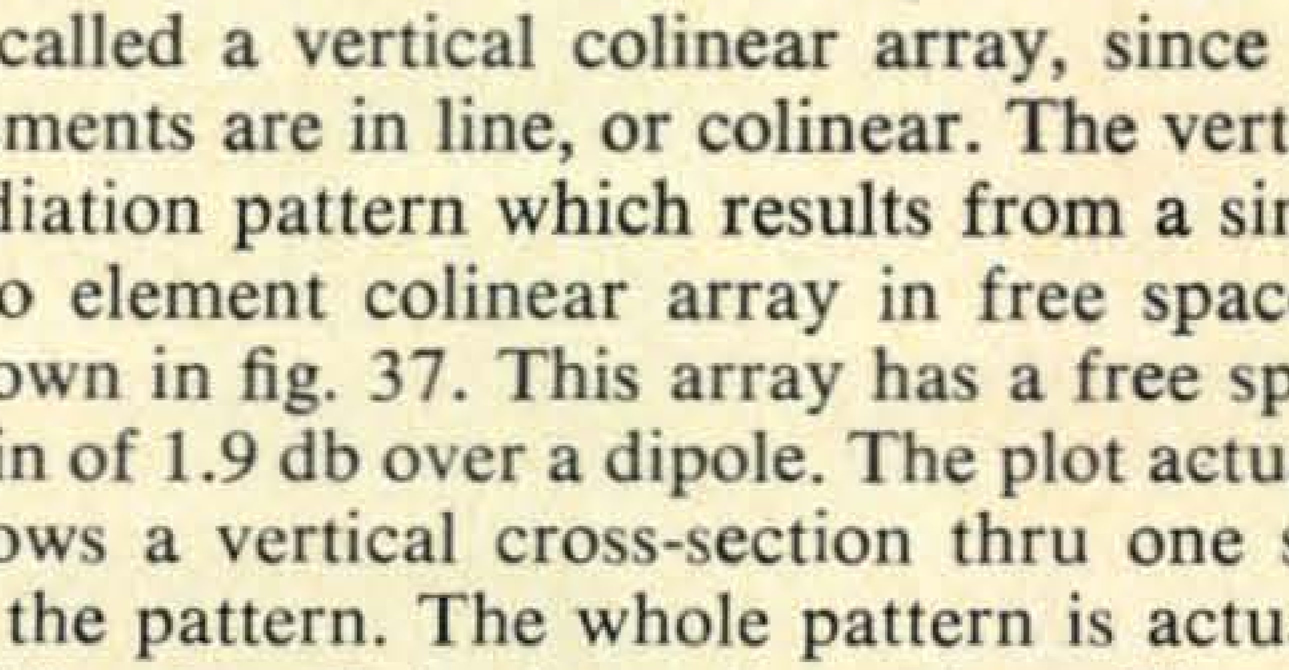

Fig. 37—Configuration and polar pattern of a two element colinear in free space.

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* 5209 Bangor Drive, Kensington, Md. 20795.

[42] Lee, P. H., "Vertical Antennas, Part I," *CQ*, June 1968, p. 16.

[43] Lee, P. H., "Vertical Antennas, Part IV," *CQ* Sept. 1968, p. 37.

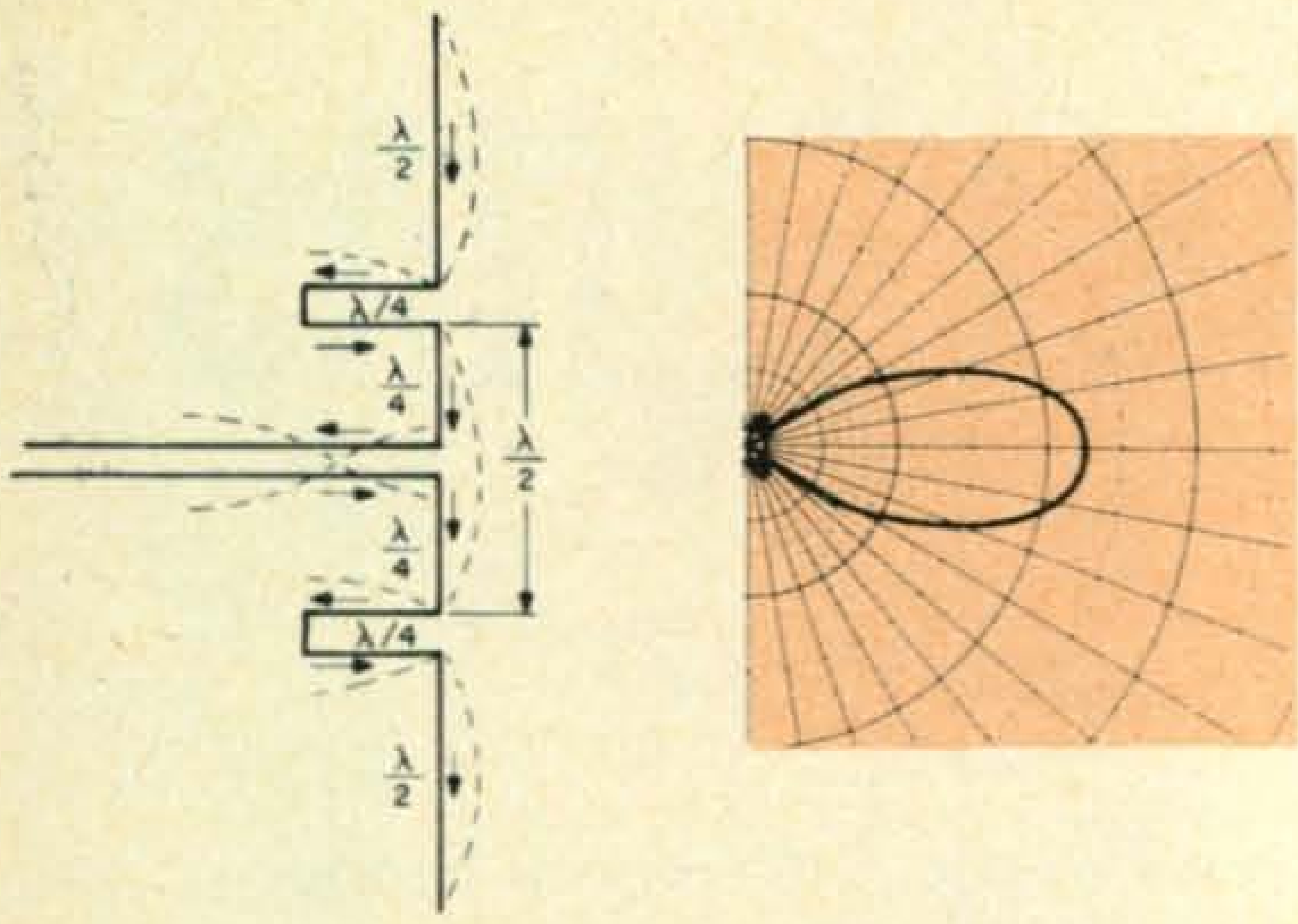

Fig. 38—Configuration and polar pattern of a three element colinear in free space.

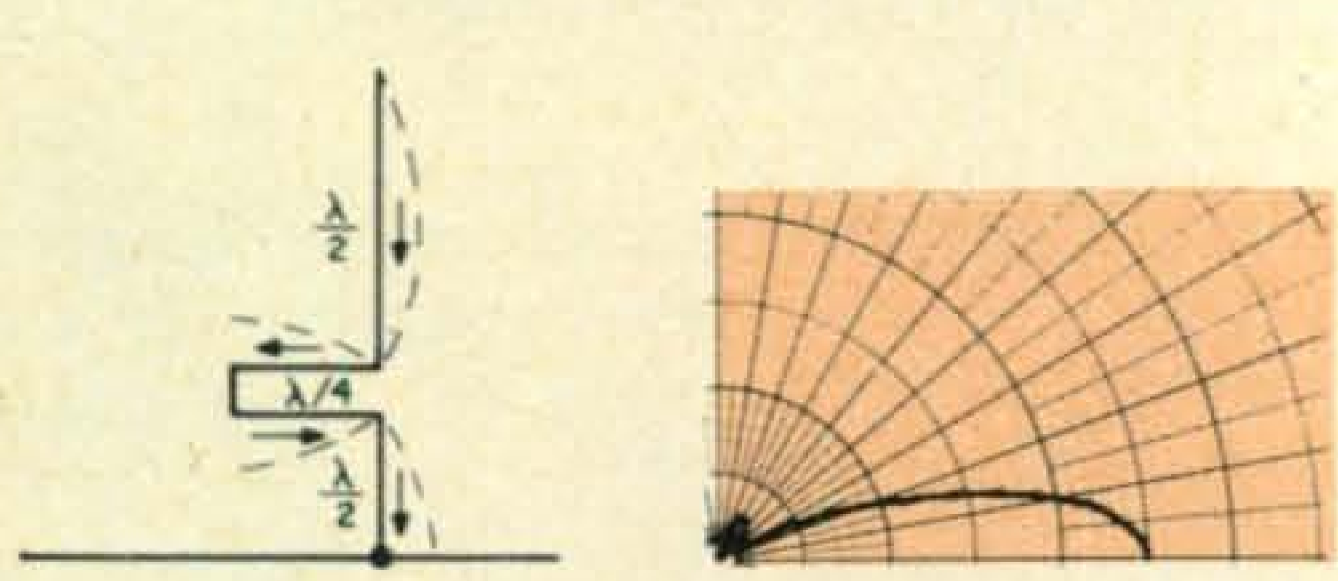

Fig. 39—Configuration and polar pattern of a 1½ element colinear over ground.

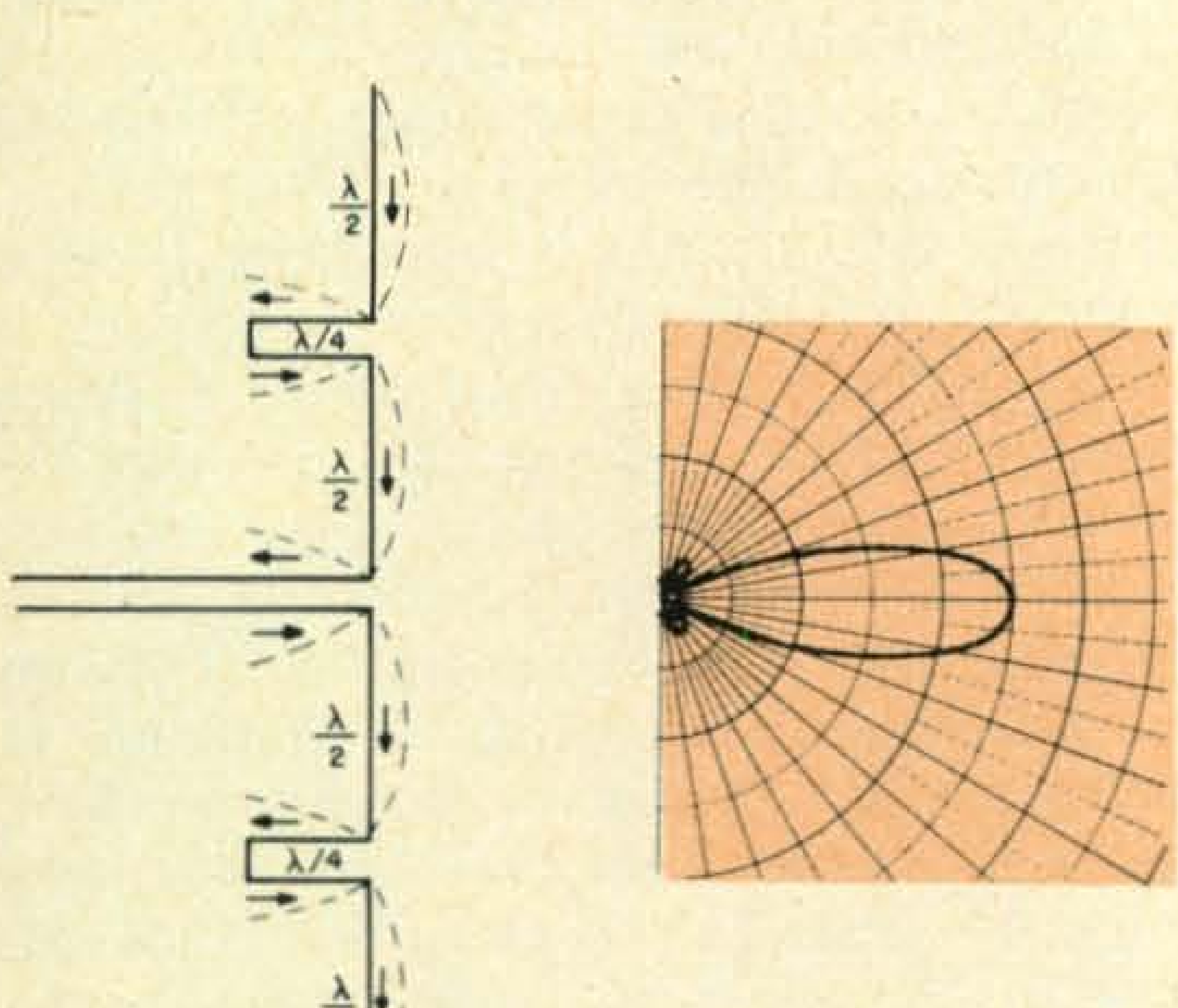

Fig. 40—Configuration and polar pattern of a 4 element colinear in free space.

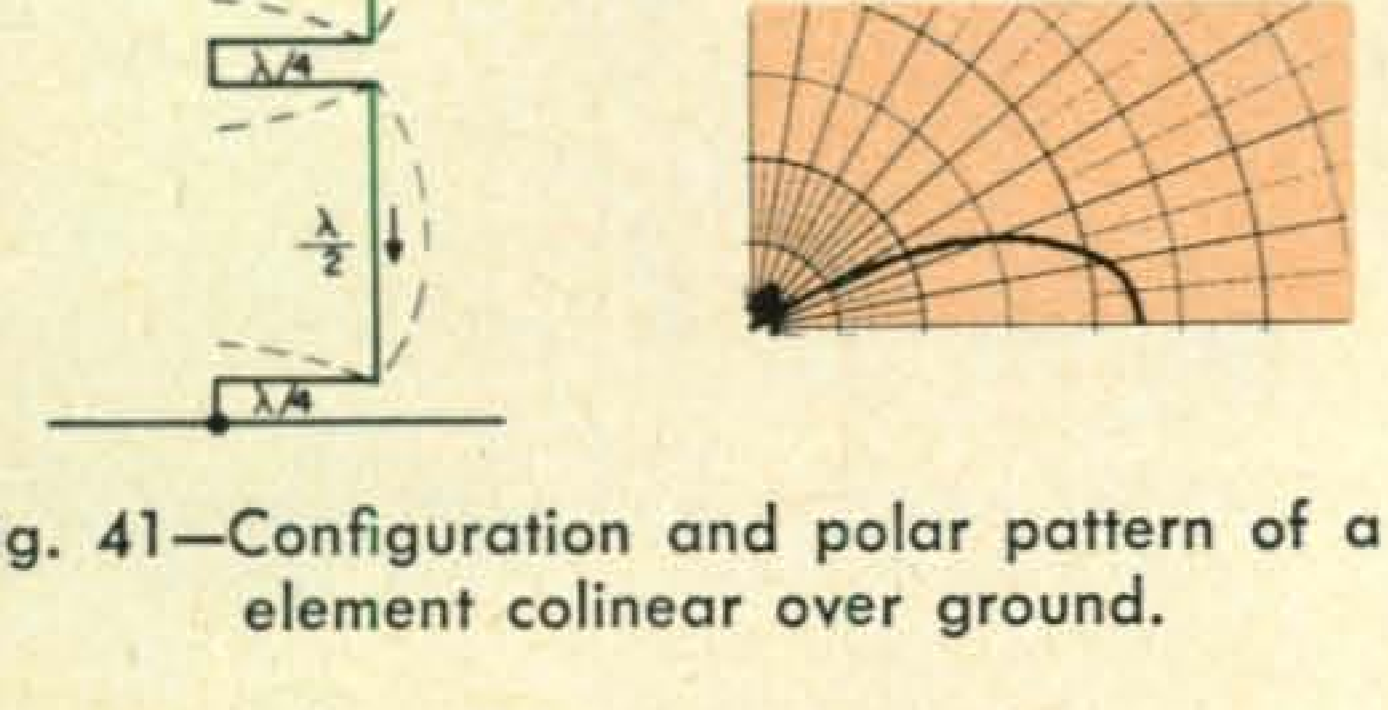

Fig. 41—Configuration and polar pattern of a 2 element colinear over ground.

Figure 38 shows the pattern for a three-element colinear in free space. It has a gain of 3.2 db over a dipole. It also can be cut in half, and operated against a ground plane. Now, however, one must be careful not to call this a ¾ wave antenna, for it is not that at all. It is a ½ wave element stacked above and operated *in-phase with* a ¼ wave element. Figure 39 is the vertical pattern of this antenna over perfect ground.

If we carry the vertical stacking further, we can make a four element colinear array, whose free space pattern is shown in fig. 40. The gain of this one over a dipole is 4.3 db. As in the previous cases, we can replace the lower half by a ground plane, and then we have two ½ wave elements stacked, *in-phase*. This is not the same as a full wave antenna, whose two halves would not be in-phase. Figure 41 is the plot of this antenna's radiation over perfect ground.

Practical Colinear

From a practical standpoint the free space configuration of any of these arrays is impossible to build and feed. It lends itself very nicely to textbook analysis, but it cannot be caused to produce the patterns shown, because of the presence of earth. The configurations which utilize a ground system as a part of the radiating system can be built, however, and the vertical patterns will conform closely to those shown in fig. 39 and 41, dependent on ground characteristics and frequency as discussed in Part I. The effects of ground system design at h.f., and particularly the effects on low angle radiation, have been quite well documented in three reports by the U.S. Navy Electronics Laboratory.[44,45,46] The U.S. Navy uses many vertical antennas at its shore radio stations, mostly in broadband configurations, and each one has its properly designed ground system. Briefly these reports show that greatly improved radiation at low angles will result when the number and length of ground system radials is increased, and that the improvement obtainable is a function of

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[44] "Ground System Effect on HF Antenna Propagation," Report 1346, *U.S. Navy Electronics Laboratory*, San Diego, 4 Jan. 1966 (Unclassified).

[45] "HF Extended Ground Systems: Results of a Numerical Analysis," Report 1359 *U.S. Navy Electronics Laboratory*, San Diego, 24 Feb. 1966 (Unclassified).

[46] "A Numerical Analysis of HF Extended Sector Ground Systems," Report 1430 *U.S. Navy Electronics Laboratory*, San Diego, 19 Jan. 1967 (Unclassified).

ground conductivity and frequency, with larger improvements being realized over poor ground (as would be suspected).

It may be seen from the above configurations and pattern plots that, within practical limits, the greater the number of vertical in-phase elements, the more the main lobe will be compressed and lowered, and the greater will be the gain. One such design, which carried the number of elements to a very high number, was the Franklin Antenna whose designer, C. S. Franklin, was very well known in the earlier years of radio communication in England. It was based on the principle that a vertical wire carrying uniform currents in-phase over its length is the ideal radiator for producing the lowest possible angle of radiation. In the Franklin Antenna, as described in two of the references,[47,48] each successive ½ wave length of wire is folded back on itself in such a way that the radiation from its central part assists the radiation from its neighbors. This is shown in fig. 42 which depicts the current distribution on a Franklin Uniform Aerial. The exact dimensions in terms of wavelengths are in fig. 43. The major portions of the currents are in-phase, and the resulting current distribution is almost the ideal of a uniform current. As a matter of historical interest, there is, in one of the references, [47] a very good photograph of a large Franklin Antenna array with reflectors at a Marconi station at Bodmin, Cornwall, England. This array consists of a series of vertical Franklin Antennas in line, with a reflector screen behind them. No gain figures are given for such arrays, but based on present designs of horizontal dipole curtain arrays of similar parameters, [49] the gain can be estimated at about 20 to 22 db. Such a Franklin array produces a narrow, low main lobe, broadside to the line of elements, by proper spacing and phasing of the elements.

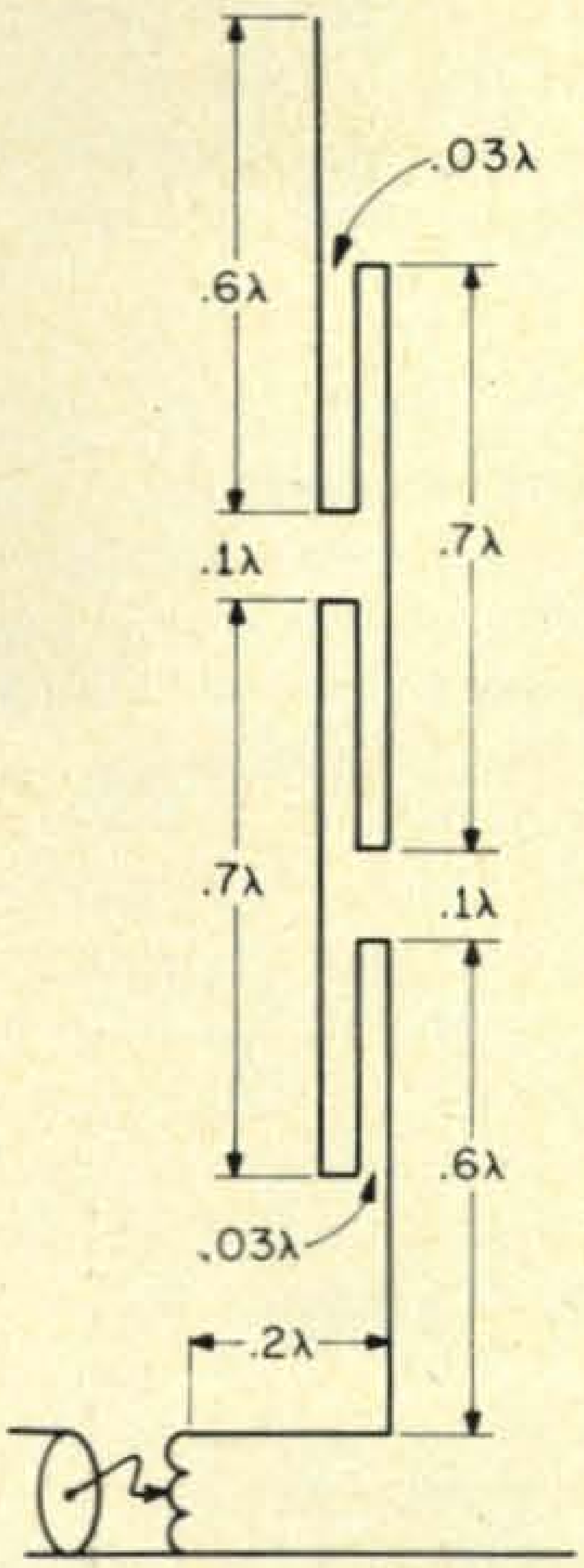

Fig. 42—Current distribution on a folded Franklin Antenna.

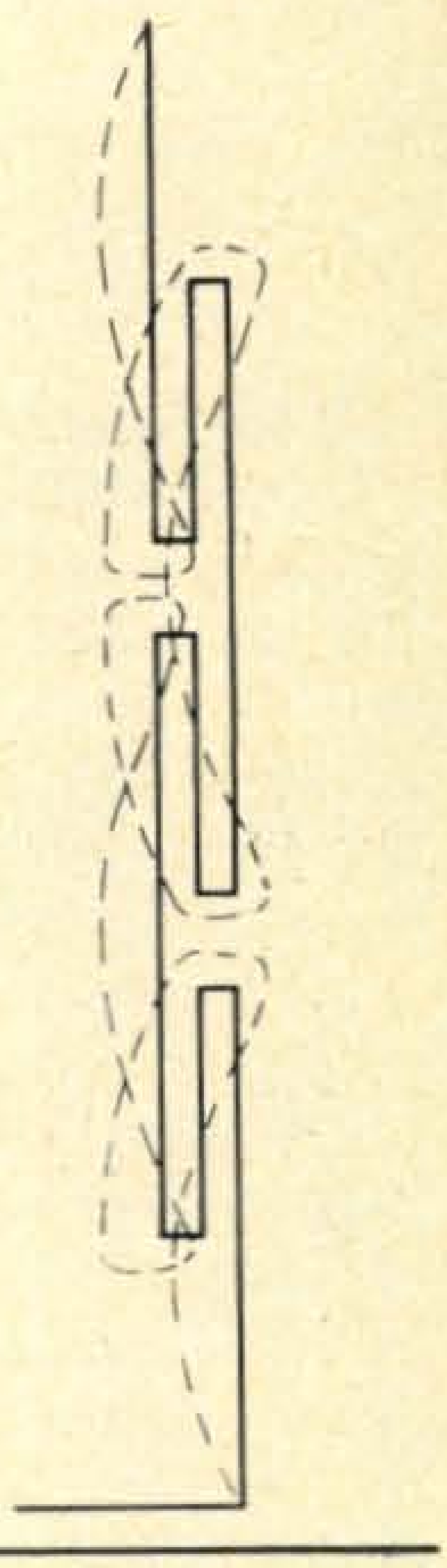

Fig. 43—Dimensions of a folded Franklin Antenna.

Franklin Antenna Applications

You might well ask, if this array is so good, why do the Voice of America, the BBC, Radio Free Europe, *etc.* not use it in preference to the horizontal dipole curtain arrays? The answer can be readily seen from the dimensions in fig. 43, which are very critical, and which make the Franklin Antenna a single frequency antenna. The horizontal dipole curtain array can, by use of broadbanding techniques in the design of the dipole elements and the feed system, be made to cover at least two adjacent high frequency broadcast bands, such as 7/9 mc, 11/15 mc or 17/22 mc, with one antenna. Also, the Franklin Antenna is a bit more inconvenient to construct and rig, and it is difficult to isolate the vertical tower supporting structures, due to the vertical polarization. Thus the broadcasters and others engaged in long distance communications have turned to broadband types such as curtains and rhombics, with horizontal polarization. It is not a matter of the polarization itself, but is a matter of operational and constructional convenience.

For v.h.f. or u.h.f. use, however, an amateur could easily bend up a Franklin Antenna out of stiff rod, and make it self-supporting and small in size, even though consisting of three or four ½ waves stacked. Figure 43 can be followed for design. If desired, the antenna can be fed against a ground plane, either by coaxial line directly (tolerating some v.s.w.r.), or via a suitable matching network

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[47] Williams, H. P., "Antenna Theory and Design, Vol. II," Pitman and Sons, Ltd.

[48] Ladner, A. W., Stoner, C. R., "Short Wave Wireless Communications," 5th Edition, John Wiley and Sons.

[49] Jasik, H., *"Antenna Engineering Handbook,"* McGraw Hill.

composed of small components. Reference should be made to Part II of this series for matching techniques.[50] This will make a very fine v.h.f. or u.h.f. antenna, with low angle radiation and worthwhile gain.

Phasing Methods

The Franklin Antenna accomplished the necessary phasing between ½ wave elements by means of lengths of transmission line (although folded in a peculiar manner). This is one way of accomplishing the phasing, as shown in figs. 39 and 41, by use of shorted ¼ wave stub lines. This is a bit impractical to rig mechanically, unless one has suitable supports for the vertical elements and for pulling off the wire stubs horizontally. There are two other ways which are more practical, and they are the use of tuned circuits and the use of coaxial sleeves. First, let's discuss the use of tuned circuits.

As you know, the ¼ wave shorted stub is the electrical equivalent of a parallel resonant circuit. Thus it can be replaced by a parallel resonant circuit, electrically. A vertical antenna consisting of ½ wave stacked over ¼ wave, or ½ wave stacked over ½ wave, or any other such combination, may be phased in this manner. The problem resolves itself into one of mechanical design, and weatherproofing the tuned circuit which must be mounted in the open on the mast or other support, or actually suspended in the antenna itself. One might think that such a tuned circuit would function as a trap, in the manner of traps used in multiband Yagi arrays, but it does not. The reason for this is that the length of the element beyond the tuned circuit is ½ wave resonant and it draws power through the tuned circuit. This is not the case with the length of the element beyond the trap in the Yagi. That short portion of the element in a Yagi cannot draw any power through the trap at the trap's resonant frequency. Thus the trap in the Yagi acts as an isolating device, not as a phase reversing device.

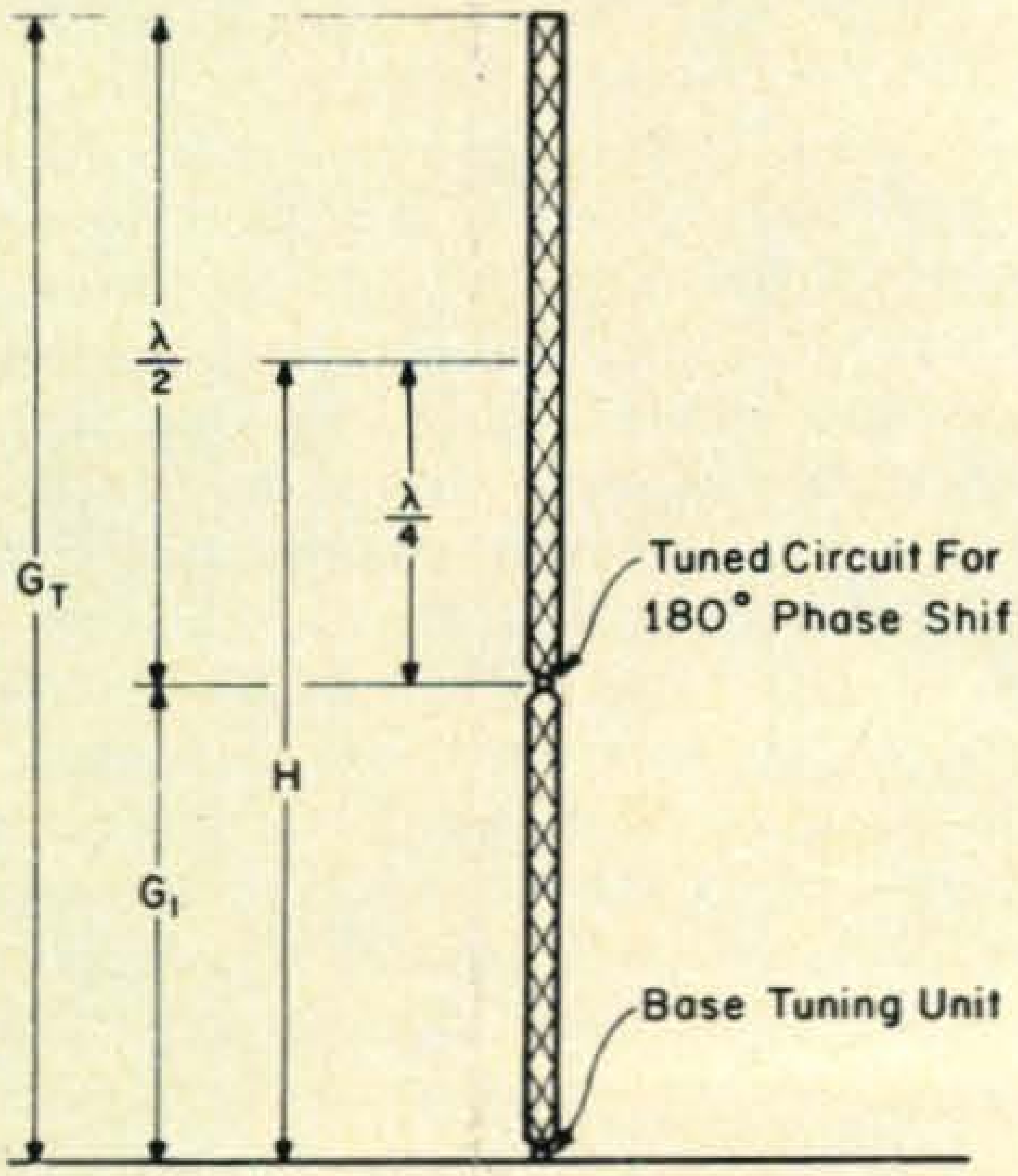

Fig. 44—Sectionalized vertical radiator isolated by a tuned circuit. Length G_1 is less than $\lambda/2$.

There have been some really large-size examples of vertical antennas with tuned circuits for phase reversal. Several examples of this are shown in *Jasek*[49] in the chapter devoted to medium frequency broadcast antennas. The design of sectionalized vertical tower radiators is shown. In such cases, the tower is actually broken at the proper height by insulators, across which the tuned circuit is connected. Of course such a structure must be very carefully designed mechanically, and suitably guyed as it is quite tall. The reference shows the design of a sectionalized antenna of overall height of 300° used at WHO, Des Moines. The upper 180° (½ wave) of the tower is actually isolated from the lower 120° by insulators, and fed through a phase reversal tuned circuit mounted up in the tower. The vertical radiation pattern of such an antenna is given by the following equation:

$$f(\theta) = \frac{2 \cos (90 \sin \theta) \cos (H \sin \theta) + \cos (G_1 \sin \theta) - \cos G_1}{\cos \theta}$$

where H and G_1 are defined in fig. 44.

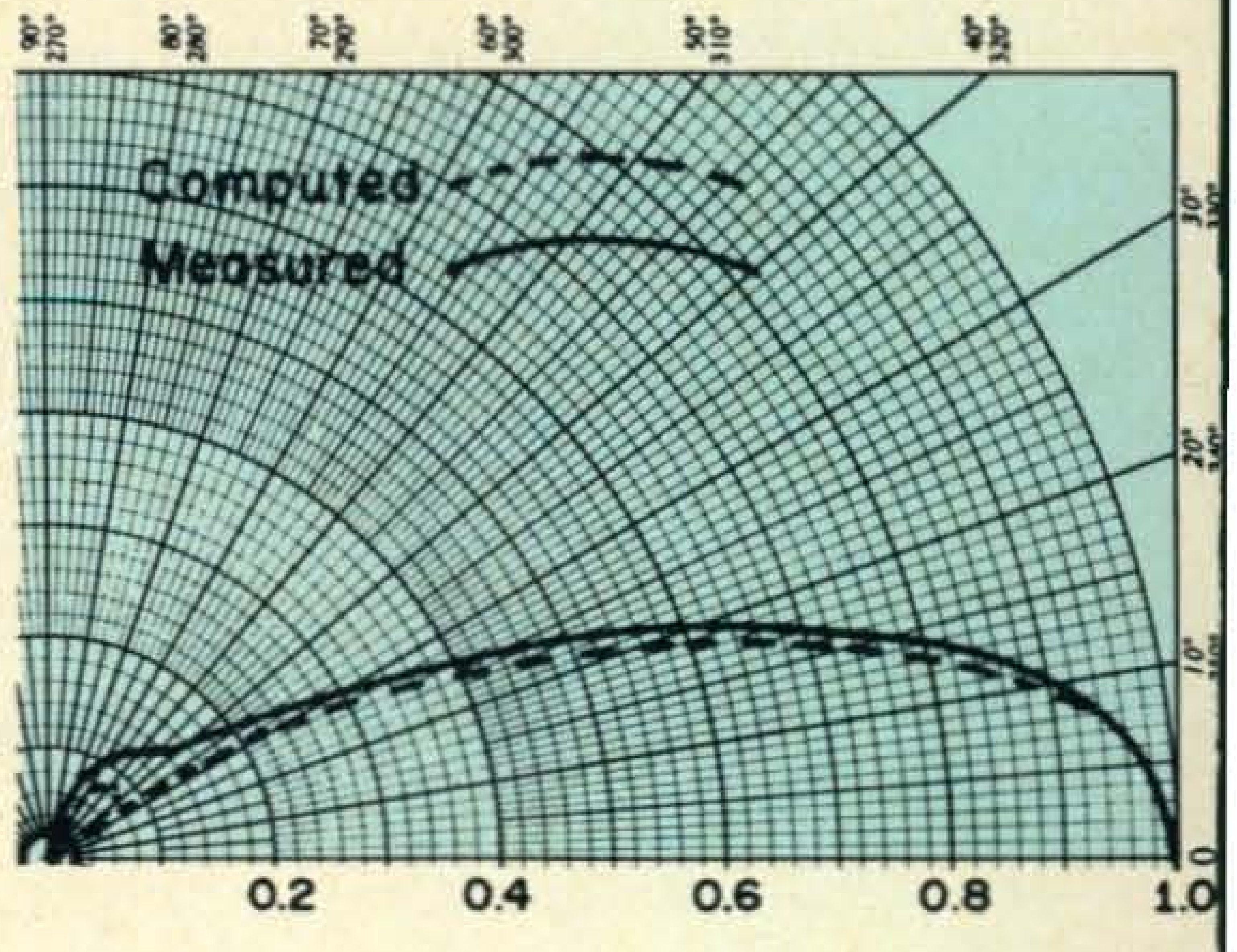

Fig. 45—Vertical patterns for 300° sectionalized radiator at WHO, Des Moines. This is a plot of $f\theta$ where θ is the angle above the horizon. The measured pattern is normalized to 1.0 maximum value for $\theta = 0$

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[50] Lee, P. H., "Vertical Antennas, Part II, *CQ*, July 1968, p. 25.

It may be seen that this is similar to the equation for $f\ (\theta)$ given in Part IV for a simple single vertical element. The vertical pattern of the WHO sectionalized tower is shown in fig. 45. There have been other such high power installations for m.f. and l.f. broadcasting in this country and in Europe. The tuned circuit must be built of suitable components and mounted in a weatherproof enclosure, as considerable r.f. voltage will exist across it.

Coaxial Sleeve

The other way of obtaining the required 180° phase shift is by the use of a coaxial ¼ wave sleeve. This is shown in fig. 46. The Mark III DX Antenna described in *CQ*[51] is an example of a design of this type for use at h.f. The design of antennas of this type is covered in detail in several of the references[47, 52]. Because of the mechanical problems connected with the design and mounting of the sleeve, such antennas are usually used for v.h.f. and u.h.f. where they can be physically small in size and easily supported. Some are even self-supporting, easily mounted on a mast. A coaxial sleeve on the Mark III was simulated by means of a wire cage, and it worked fine. Several readers did not quite have faith and confidence in the cage, and asked if they could build the sleeve out of sheet metal. I was a bit dubious as to their ability to install and support such a thing, and to maintain it in the face of problems of wind resistance, weight, *etc.*

Rigid Coax

Figure 47 shows a suitable design for v.h.f. or u.h.f. using rigid coaxial line. Several sleeves are used over the outer conductor of the line, for phase reversal. The lower sleeve, it will be noted, is mounted with its upper end open, and is shorted to the coaxial line at the bottom. It acts in this manner as a detuning sleeve or "choke," preventing antenna currents from flowing any further down the outer conductor of the coaxial line. No ground plane is required in this case.

The ¼ wave coaxial sleeve is really nothing but a ¼ wave shorted section of transmission line, configured coaxially *around* the vertical radiator, instead of being made of wire and pulled off horizontally from it. It is quite a simple and effective device. There are, however, certain design precautions which must be observed. For maximum radiation it is necessary to individually tune (adjust the length of) each antenna section and each sleeve. In the case of the ¼ wave wire stub, this is quite easy. In the case of the coaxial sleeve, the outer surface (nominal ¼ wave) cannot be made shorter than the inner sur-

[*continued on page 134*]

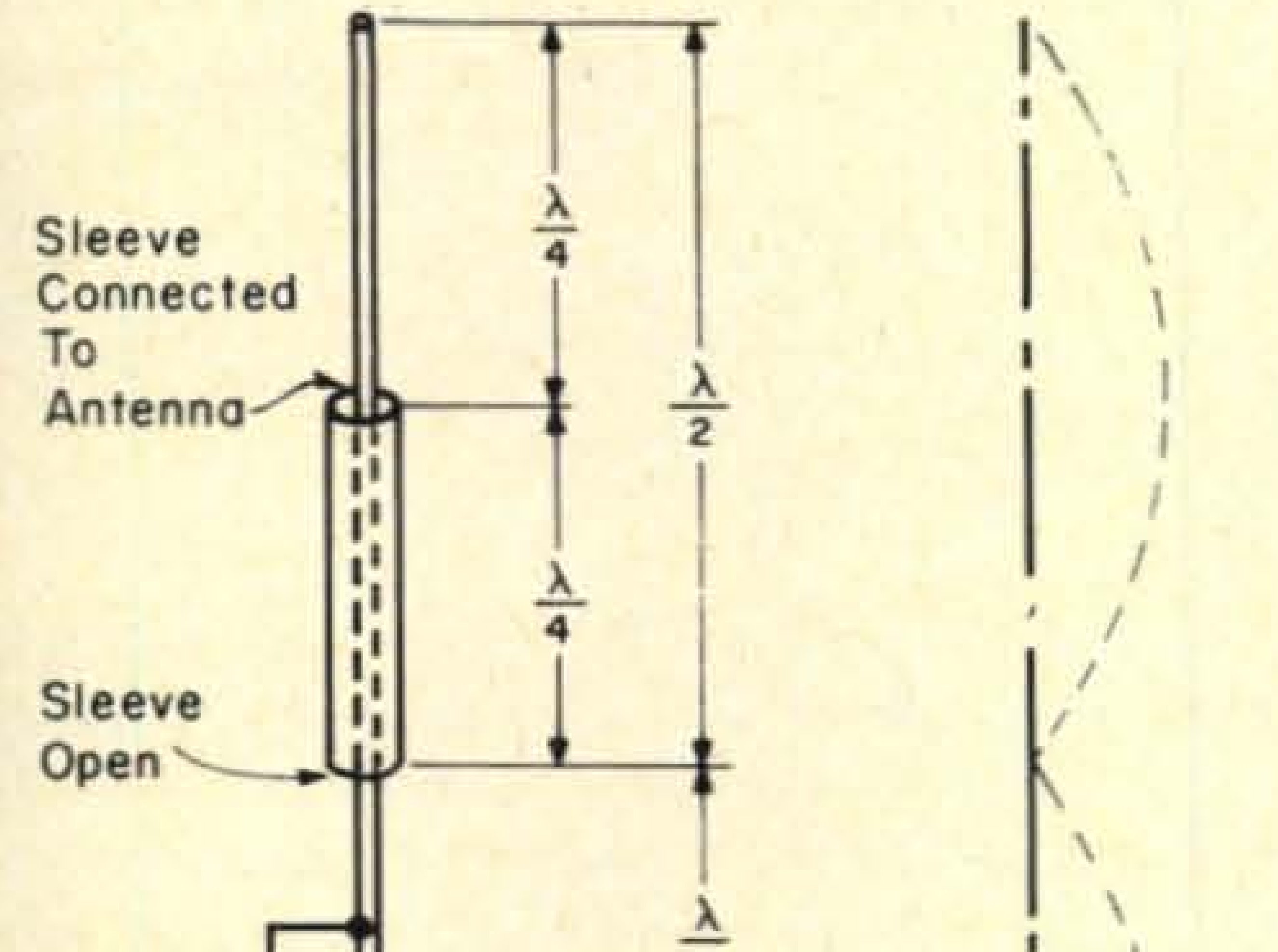

Fig. 46—A half wave over quarter wave in phase, with sleeve for phase reversal and its current distribution.

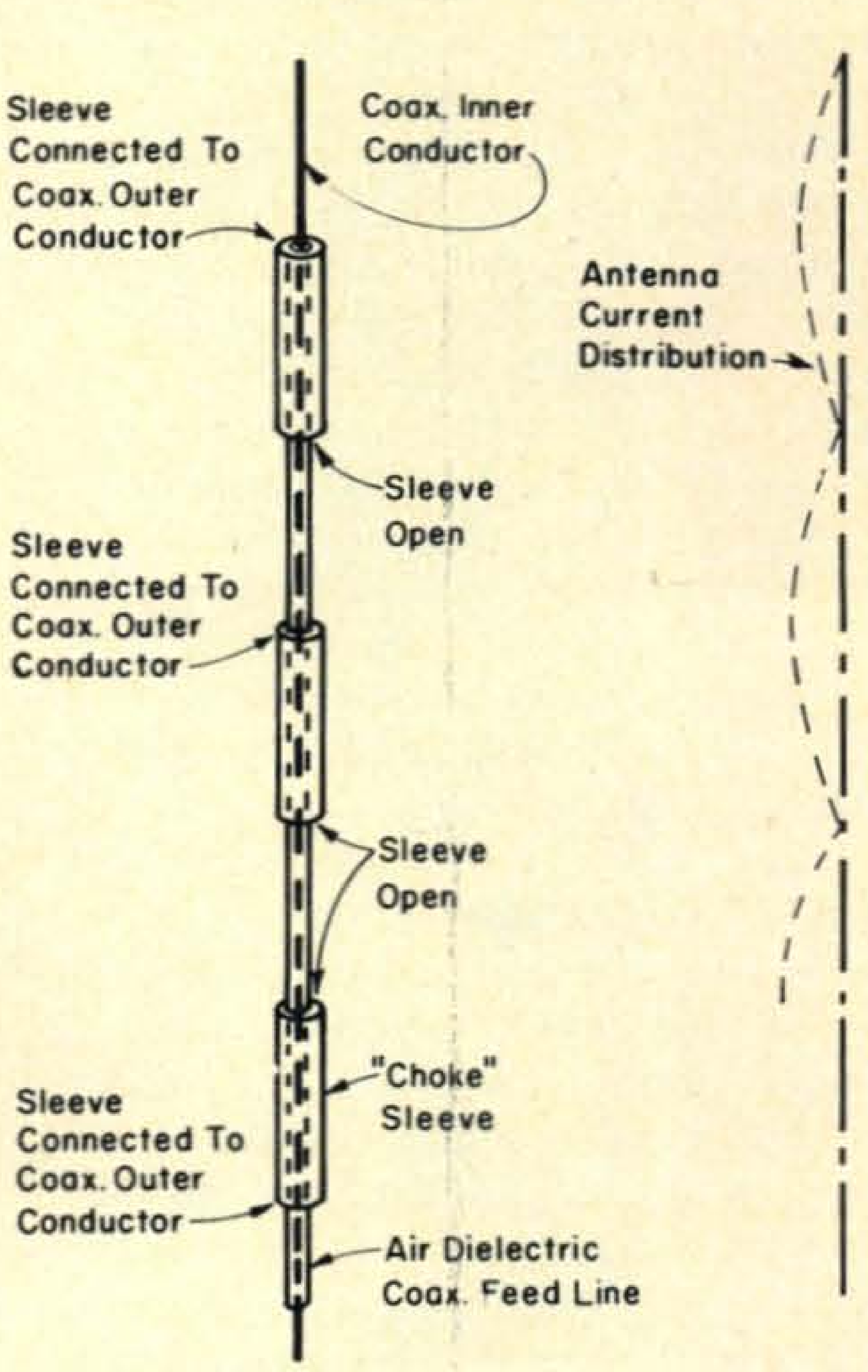

Fig. 47—Suitable design for a v.h.f. or u.h.f. colinear using rigid coax and sleeves as described in the text.

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[51] Lee, P. H., "Mark III DX Antenna," *CQ*, December 1962, p. 43.

[52] King, R. P. W. *et al*, *"Transmission Lines, Antennas and Waveguides,"* McGraw Hill.

signal increases. Retune the signal slightly to make sure it is peaked. A different peaking frequency may be chosen by changing the PITCH CONTROL switch. For maximum peaking and selectivity advance the REGEN. CONTROL until it is just under the point of oscillation. When the signal has been satisfactorily tuned in and peaked, turn the SELECTOR SWITCH to position 3. The signal should now trigger the neon lamp. The volume control on the S-S may now be adjusted to any desired volume without any background noise or interference. Tuning in a weak signal and running up the volume control on the S-S can result in quite a dramatic effect.

The operation of the DUAL SWITCH has been explained earlier.

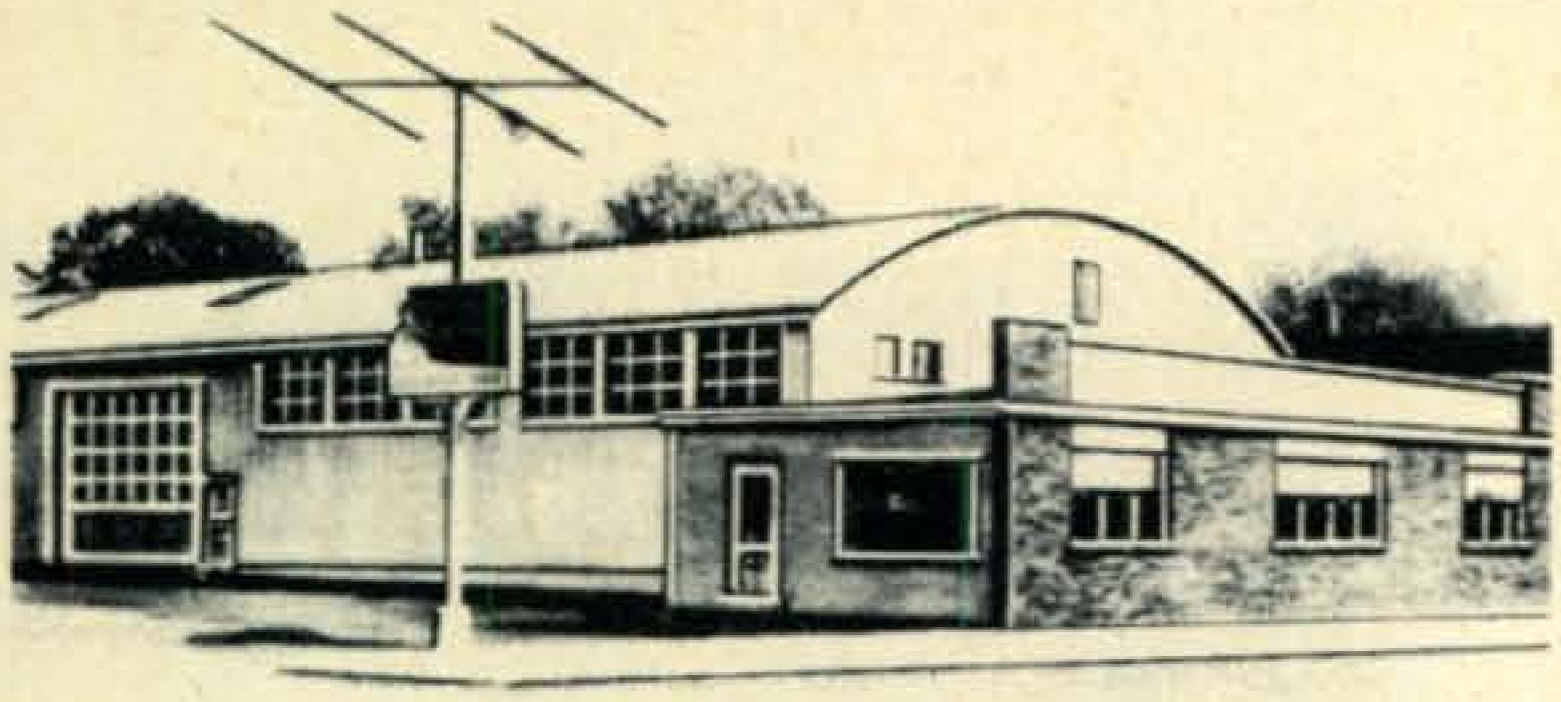
Miscellaneous

Construction, wiring and parts layout are not critical. The *high* impedance winding on the Regeneration Transformer (T_1) is used as the primary, and the *low* impedance winding as the secondary. As in any transformer feedback circuit, if oscillation does not occur, reverse the leads on one of the windings. If a transformer other than a Triad A-31X is used then R_3 and C_6 *may* have to be changed for optimum operation.

The REGENERATION CONTROL can be advanced further without going into oscillation when the SELECTOR SWITCH is in position 3. This means the control must be backed off slightly when returning to position 2. There is a certain minimum signal strength below which the S-S will not operate properly. This will become readily apparent after short experimentation, and can be usually overcome by turning up the gain on the receiver slightly. ■

Vertical Antennas *from page 47*]

face. A shorted stub of air dielectric coaxial line of ¼ wave electrical length will be very close to an actual physical ¼ wavelength. However, considering the outer surface of the sleeve only as an antenna, because of its considerable diameter and low L/D ratio it should be shorter than a physical ¼ wave to be ¼ wave resonant. Thus an apparently irreconcilable fact exists, which is that a ¼ wave section of sleeve cannot be ¼ wave long, yet it should be for proper phase reversal. To assure satisfactory operation under this condition, the inner diameter of the sleeve should be much greater than the outer diam-



eter of the antenna conductor itself.[52]

A vertical colinear array should be so configured that it presents a suitable feedpoint impedance for connection to coaxial line either directly or through a simple matching network. One would not want to attempt to feed the bottom end of a ½ wave section directly, for example, for the impedance would be very high and hard to match. Bottom section lengths of ¼ wave or ⅜ wave, however, are of reasonable feedpoint impedance and can be easily matched. In the Mark III[51] a ¼ wave bottom section was used which was grounded and fed by the "gamma match" method as shown in fig. 46. Thus the antenna should be designed to consist of a number of ½ wave sections, over a bottom section of something less than a ½ wave for ease in feeding. If the antenna is to be self-supporting as was the Mark III, the grounded base design is an excellent idea, for it eliminates the problem of base insulation. With the coaxial sleeve design, other circuits such as lighting lines can be run right up inside the mast itself without worrying about isolation.

As with the Franklin Antenna, the tuned circuit isolation method and the coaxial sleeve method are both frequency sensitive. Since they depend on tuned circuit resonance and shorted stub resonance for phase reversal, a frequency change of more than five percent or so would be expected to degrade performance and cause considerable v.s.w.r. at the feed point.

Five percent would be adequate for coverage of the 7, 14 and 21 mc bands, but it would not be adequate for the entire 28 mc band, nor could one cover from 3.5 to 4 mc without readjustment of tuned phase reversal circuits or stub lengths. To sum it up, the vertical colinear array, since it depends on accurate ½ wave phase reversals, is not a multi-frequency antenna. It is excellent for a narrow band of frequencies, but it is not easy to readjust for frequency changes.

Part VI

The next in this series of articles will deal with broadband vertical antennas of various configurations. We use many of these at our Naval Communication Stations, because our frequency plans must be extremely flexible to allow for variations in propagation and distance to areas of desired coverage. In the past few years we have started using some special types on ships as well.

[*to be continued*]

VERTICAL ANTENNAS

Part VI

BY CAPTAIN PAUL H. LEE,* W3JM

In this part of the series, the author describes several of the broadband typ of vertical antennas which have been used by commercial and military service Design information is given, and practical configurations are shown.

UP TO now the vertical antennas discussed have been designed for specific frequencies or narrow bands of frequencies and the antennas had to be retuned for a QSY of any magnitude. Antennas of this type are usually used by amateurs, whose frequency allocations consist of relatively narrow bands in the spectrum. There has not been much material in amateur literature in the past regarding broadband types of vertical antennas. I shall now describe some broadband verticals and show how they can be applied to amateur requirements and additional types will be discussed later.

First let us examine some of the basic properties which tend to make a radiator broadband. It was described earlier how a structure's bandwidth is affected by its L/D ratio, with a shorter, fatter structure having a wider bandwidth (within certain s.w.r. limits) than a tall, thin one. The concept of a radiator being considered as an open-ended, lossy transmission line, extending into space, was also mentioned. It is well known practice to construct tapered transmission lines[53] to effect a smooth transition of impedance wit out creating standing waves. A tapered (conically shaped) antenna may be consider as an attempt to effect a smooth transition b tween the impedance of a source and the in pedance of space.

The Conical Antenna

A conical antenna may be considered as special case of a horn antenna[54] common used at microwave frequencies. Such devic may be scaled up in size and used at h.f. T reference[54] shows results of model studi made of several conical configurations. Fi ure 48 shows the input impedance plot for typical conical radiator. It will be noted th the cone is fed at its apex against a flat grou plane in this configuration. This type of a tenna is quite easy to build for u.h.f. us where the cone can be made of sheet me and supported on three or more insulato as in fig. 49. The lower frequency limit of th antenna is determined by the length of t side of the cone. As may be seen from fig. 4 it should not be less than ¼ wavelength, f

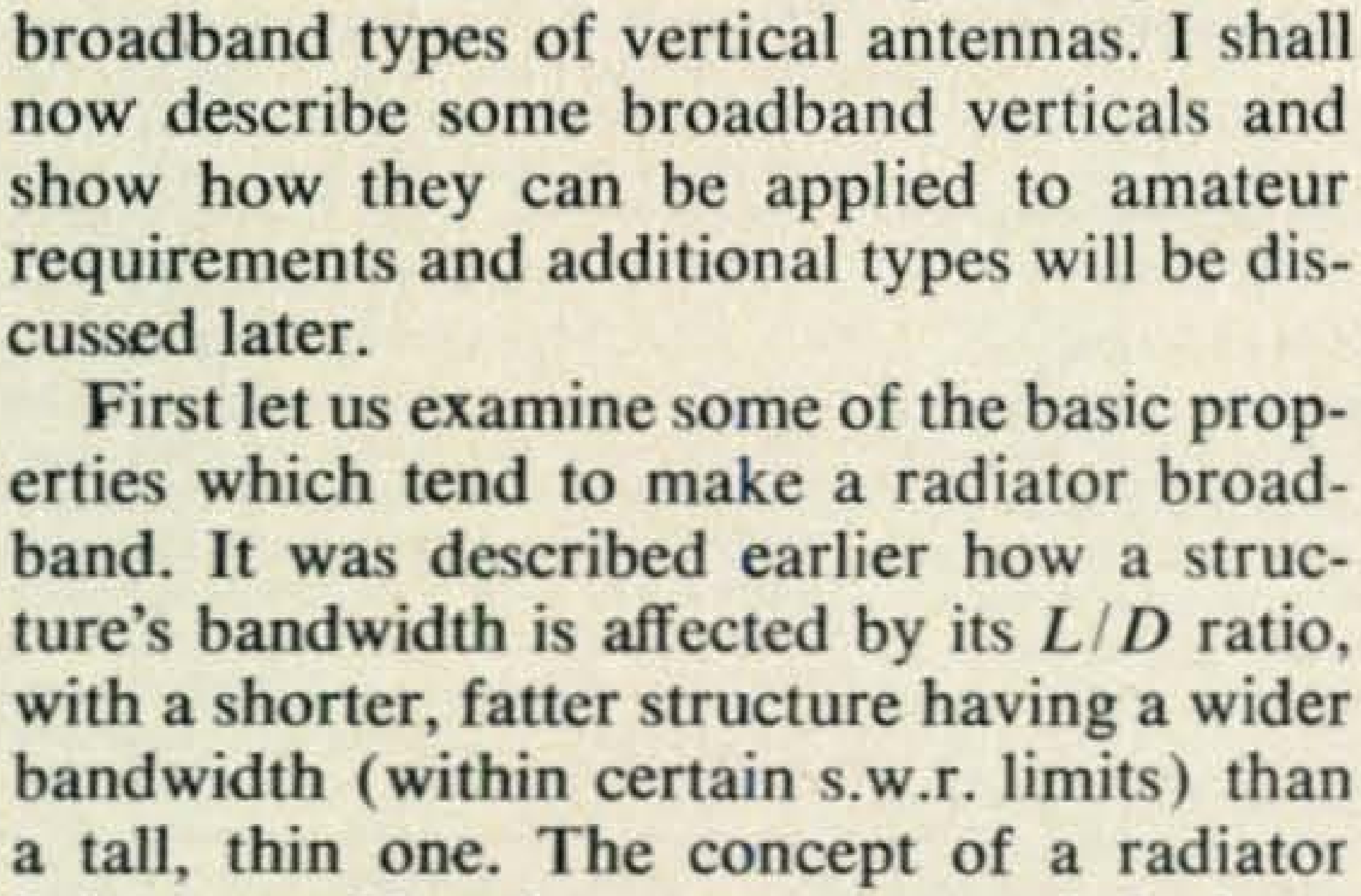


Fig. 48—Configuration and impedance plot of a conical antenna.

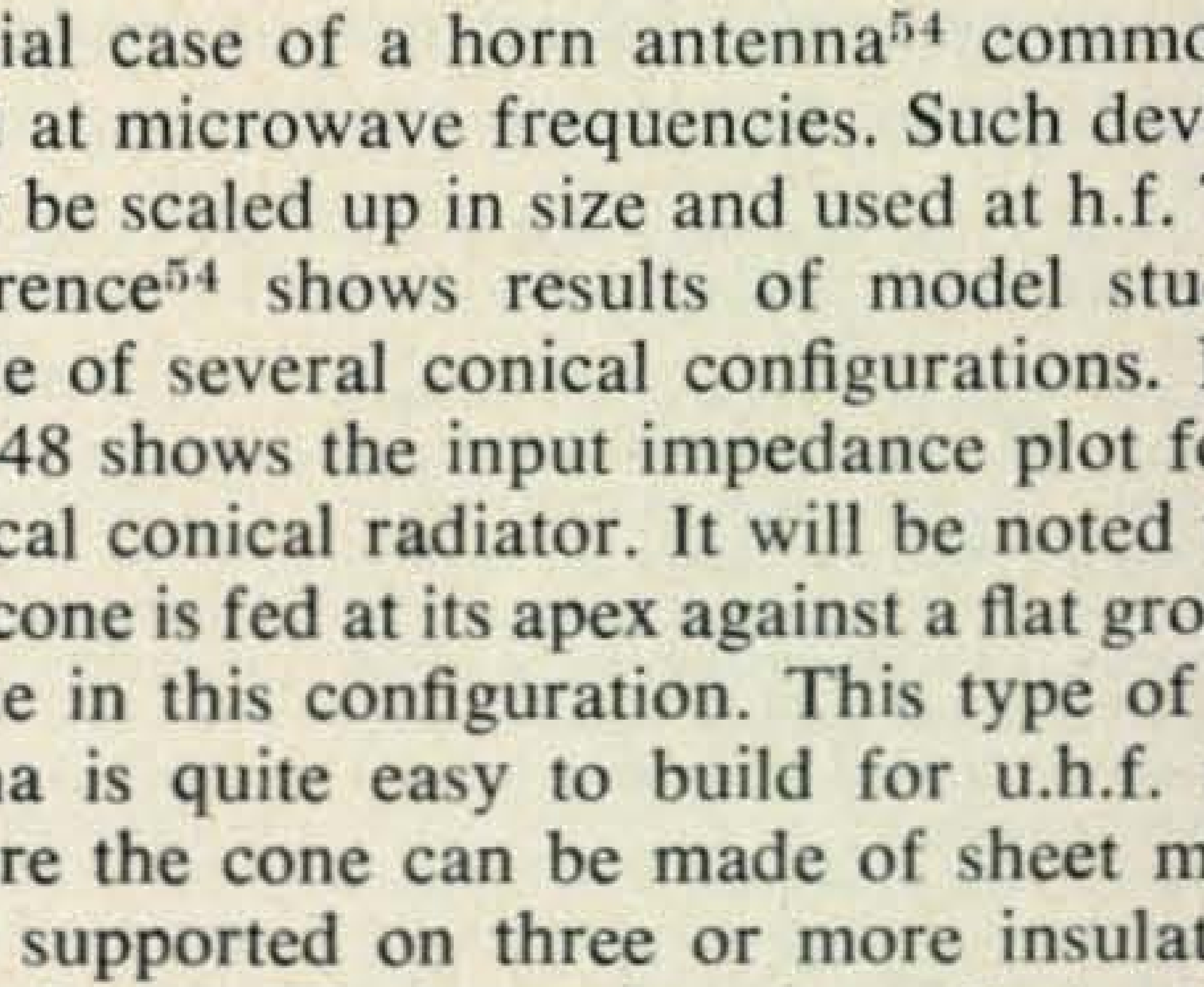


Fig. 49—A practical construction approach for conical antenna at u.h.f.

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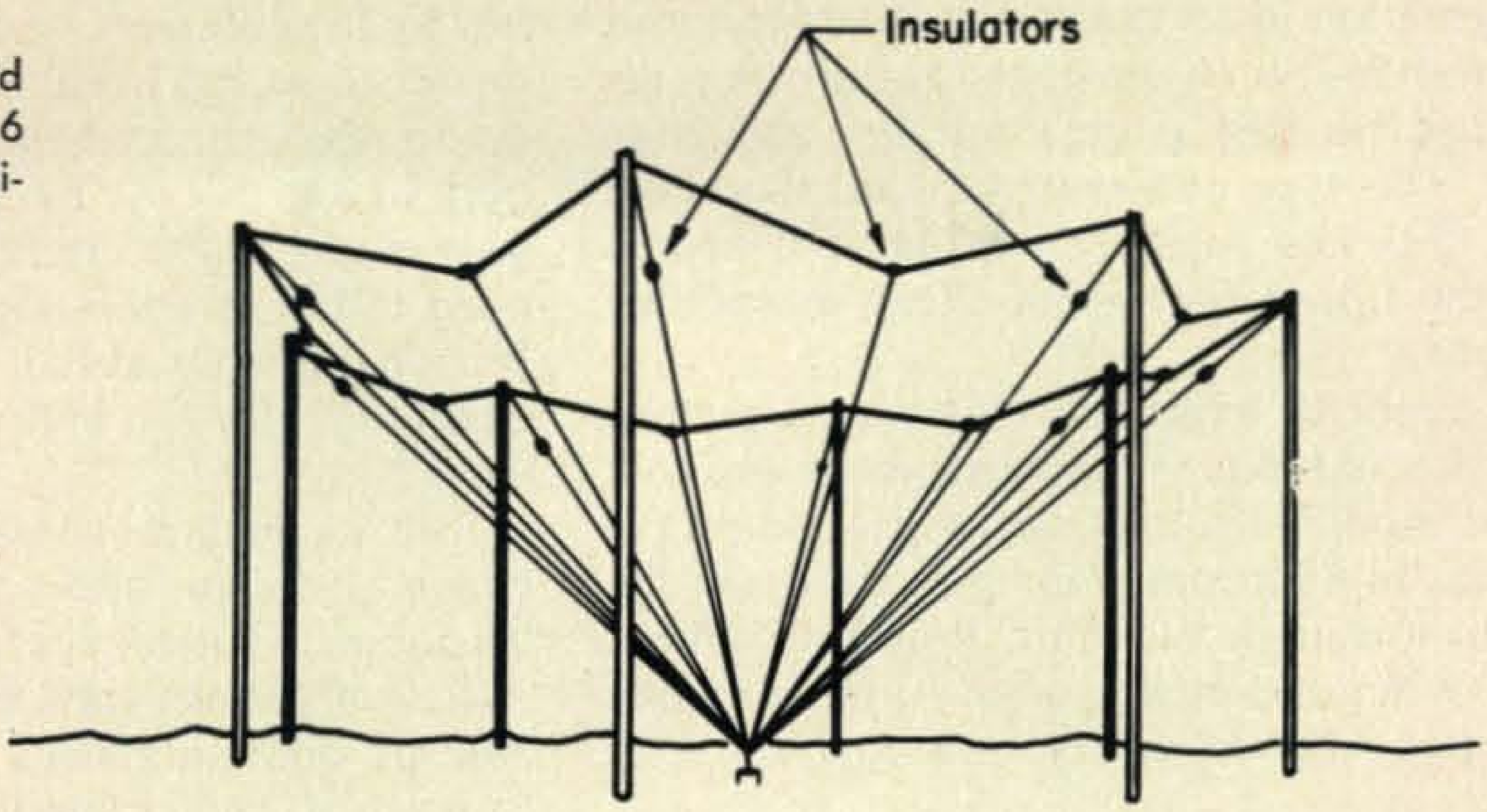
* 5209 Bangor Drive, Kensington, Maryland 20795.

[53] Laport, E. A. *"Radio Antenna Eingineering,"* McGraw-Hill.

[54] Radio Research Lab. Staff, Harvard Universi *"Very High Frequency Techniques,"* McGra Hill.

ig. 50—A h.f. inverted one consisting of 16 ires. The ground radials are not shown.

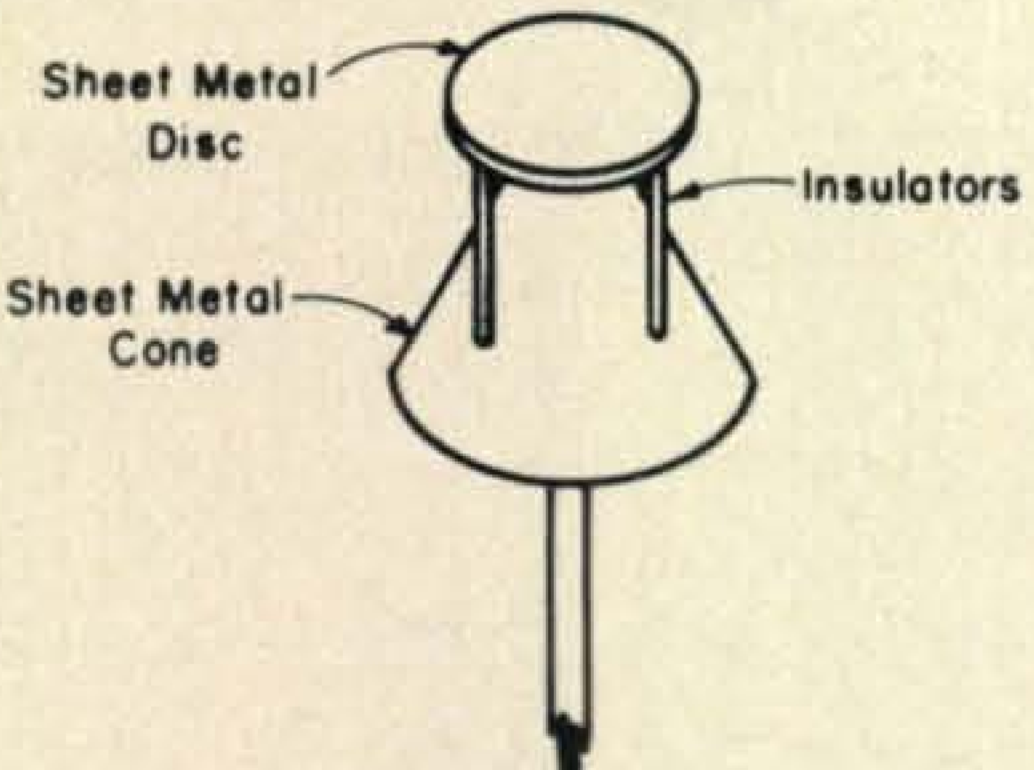


od s.w.r. The high frequency limit is deterined by the practical mechanical consideraons of construction of the feed point. Due its size at h.f., this type of antenna is rather fficult to construct. Some have been built, owever, using closely spaced wires to form e cone, supported by a number of wood oles. Such a configuration is shown in fig. 50. radial ground system is used as the disc.

The Discone

It is quite simple to invert the whole strucre shown in fig. 50. This type of configuraon is called a "discone." It was devised by andoian[55,56] over 25 years ago. Actually e practice of using a cage of wires to form broadband antenna is much older. The disne consists of a disc mounted over a cone hose apex connects to the outer conductor a coaxial feedline. The disc is fed by the ner conductor of the coaxial line. Figure 51 ows the configuration of the discone. As in the case of the inverted cone described in the preceding paragraph, the side of the cone should be ¼ wavelength at the lowest frequency of operation. It has a useful frequency range of at least 10 to 1. For u.h.f. the cone can be made of sheet copper or brass, and the outer conductor of the coaxial line can be soldered directly to it at its apex. The disc can be made of the same material, and supported on three or four fiberglass insulators as shown in fig. 52. The whole antenna can easily be mounted on a pole or other suitable support. Such an antenna would be excellent for use on the 50, 144, and 220 mc amateur bands. In such a case, the side of the cone should be about ¼ wavelength at 50 mc. The diameter of the disc should be 0.7 times the length of the side of the cone.

At h.f., the discone can be built using closely spaced wires to simulate the surface of the cone. The disc can be simulated by a structure consisting of six or eight spreaders, with wires connected between them. As in the case of the u.h.f. type, the h.f. discone can be mounted on a mast or tower. In fact, the



g. 51—The discone antenna. Length D is $\lambda/4$ at e lowest frequency of operation. The inner conuctor of the feedline connects to the disc and the outer conductor connects to the cone.

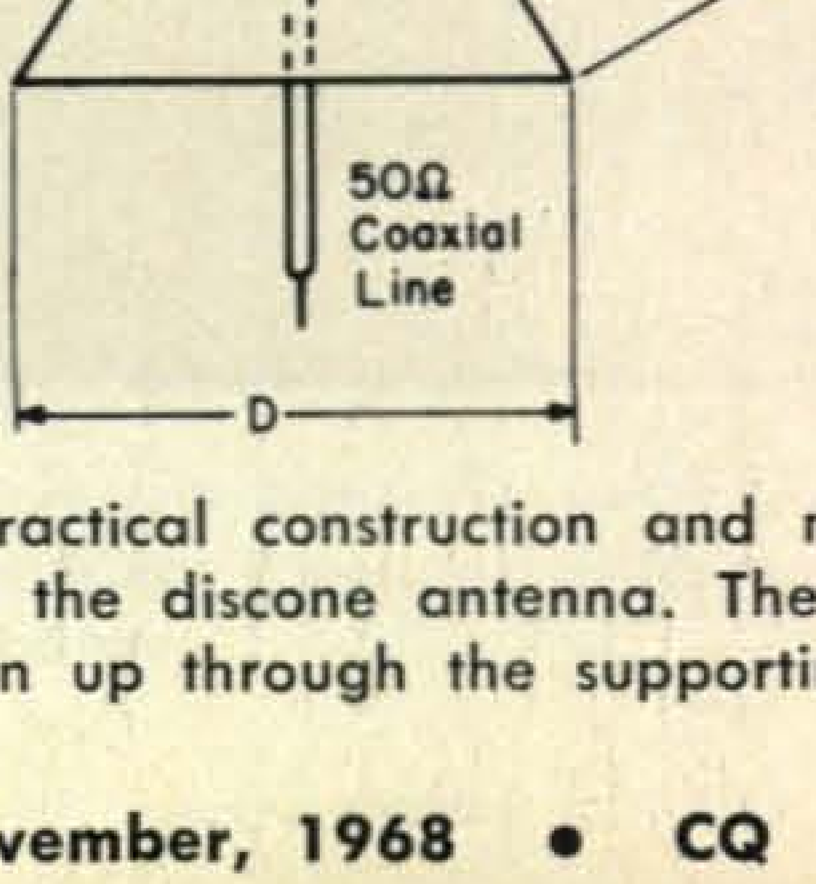


Fig. 52—A practical construction and mounting technique for the discone antenna. The coaxial feedline is run up through the supporting pipe.

Kandoian, A. G., "*Broadband Antenna*," U.S. Patent 2,368,663, 6 Feb. 1945.

Kandoian, A. G., "Three New Antenna Types and Their Application," *Proceedings of I.R.E.*, Feb. 1946, p.70W-77W.

configuration lends itself very nicely to tower use, for the wire elements comprising the cone can be used as guys for the supporting tower. This type of elevated discone is shown in fig. 53. The guys are broken with insulators, the upper portion of them comprising the cone.

As might be expected, the vertical pattern from this antenna, supported above ground, will be modified somewhat by ground reflections, exhibiting some lobing as shown in fig. 54. The low angle radiation, however, is quite good. When elevated as shown, this antenna requires no buried ground plane.

Conical Monopole

There is another type of antenna which has come into wide use by the military services. This is the conical monopole antenna, which is a broadband type useful over a frequency range of about 4 to 1. There have been several articles about this antenna in past amateur magazines.[57,58] This antenna, however, was not developed by either of those authors, nor by the commercial companies with whic one of them has been associated. The conic monopole was developed by Mr. M. L. Le pert of the Naval Research Laboratory, give credit where credit is due. It was deve oped to fill an operational requirement for broadband coaxial-fed antenna of superi characteristics for both shipboard and sho use.

The conical monopole has a simple m chanical design, short vertical height, goo broadband impedance characteristics, goo radiation patterns and efficiency, and is ca able of operating with a grounded mast tower as its center support. The antenna co sists of two truncated cones mounted base base. The upper cone may be considered be a solid, whereas the lower one is hollo The inner surface of the cone and the su porting mast or tower form a short sectio of transmission line which is, in effect, co nected across the terminals of the antenn formed by the outer surfaces of the two cone Electrically it is a stubbed conical antenn with the stub being internally containe

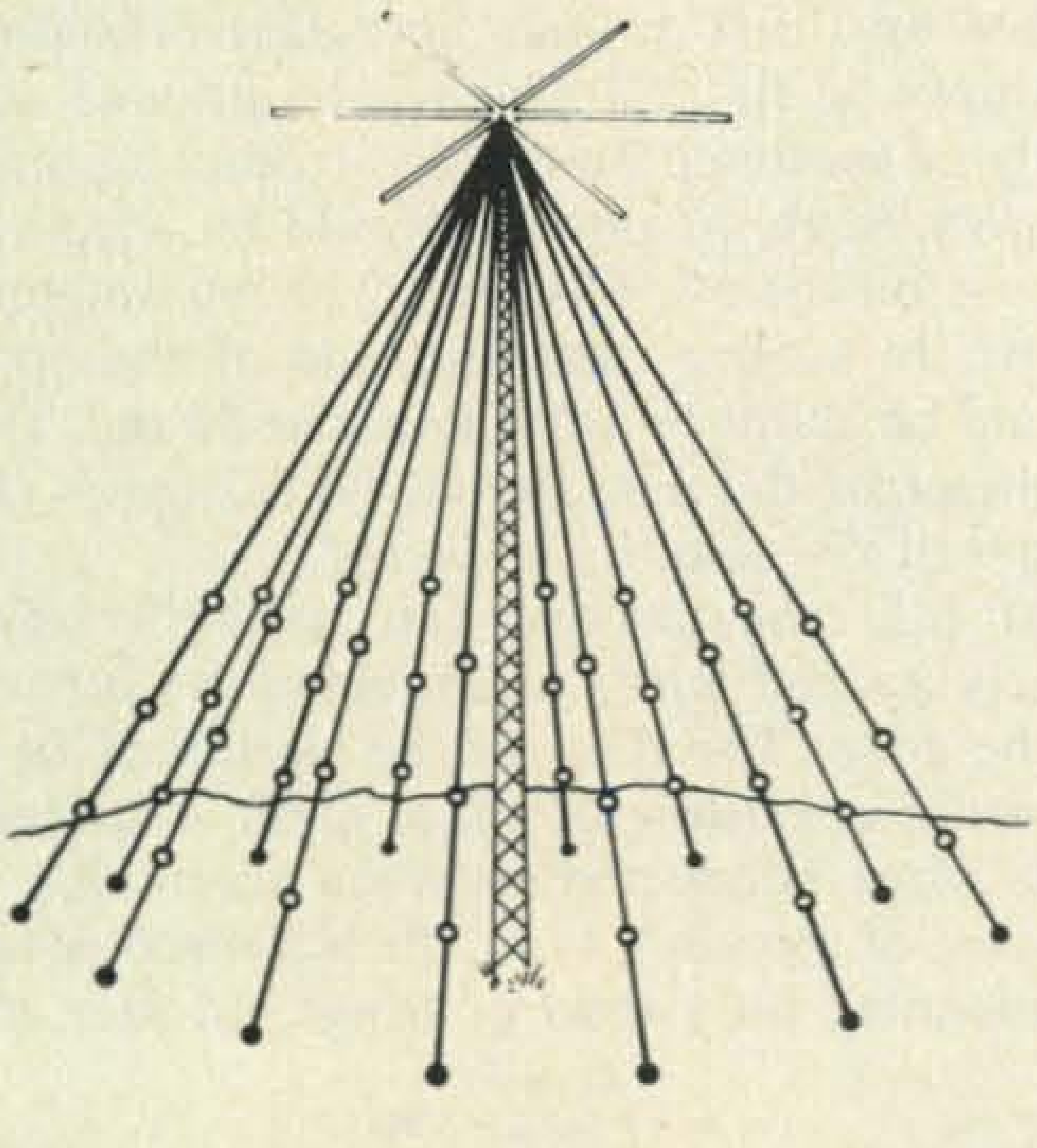


Fig. 53—An elevated discone antenna for h.f. use.

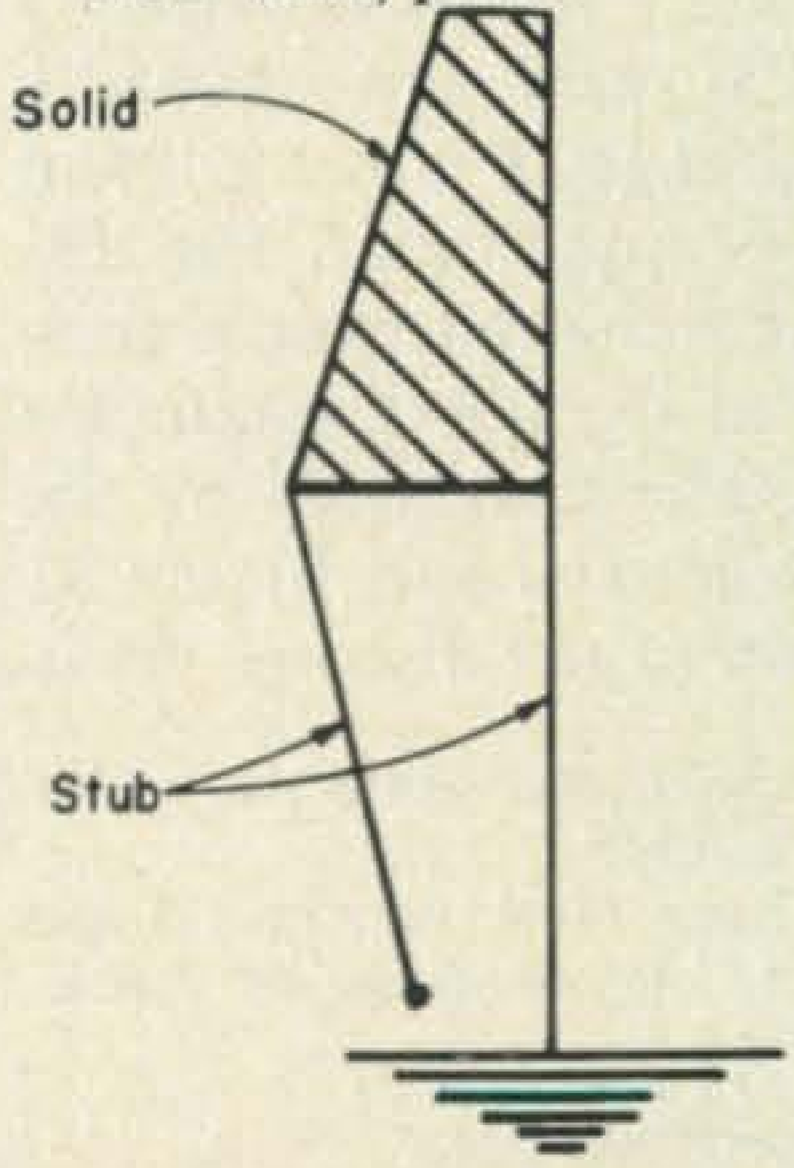


Fig. 55—View of a sli through half of a co cal monopole to sho the concept of a sol top with the bottom h a short section of tran mission line or stub. actuality the structu is simulated by wir and metal spreade

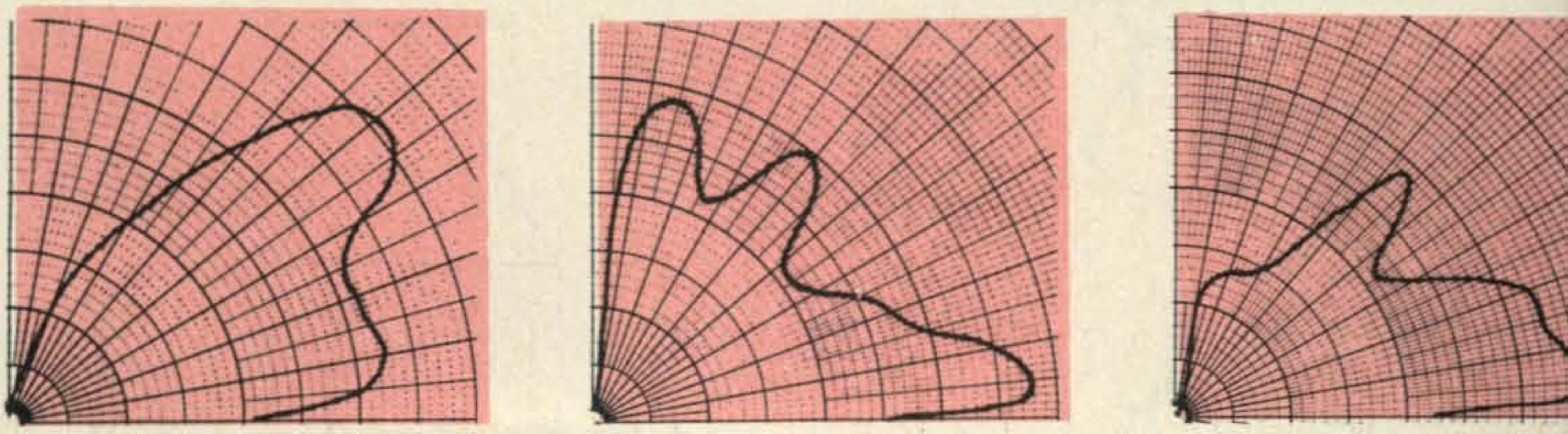


Fig. 54—Typical elevated discone patterns. The exact patterns will depend on the height above ground and the frequency range as well as ground conditions. (A) At lower frequency limit; (B) At midband frequency; (C) At high frequency limit.

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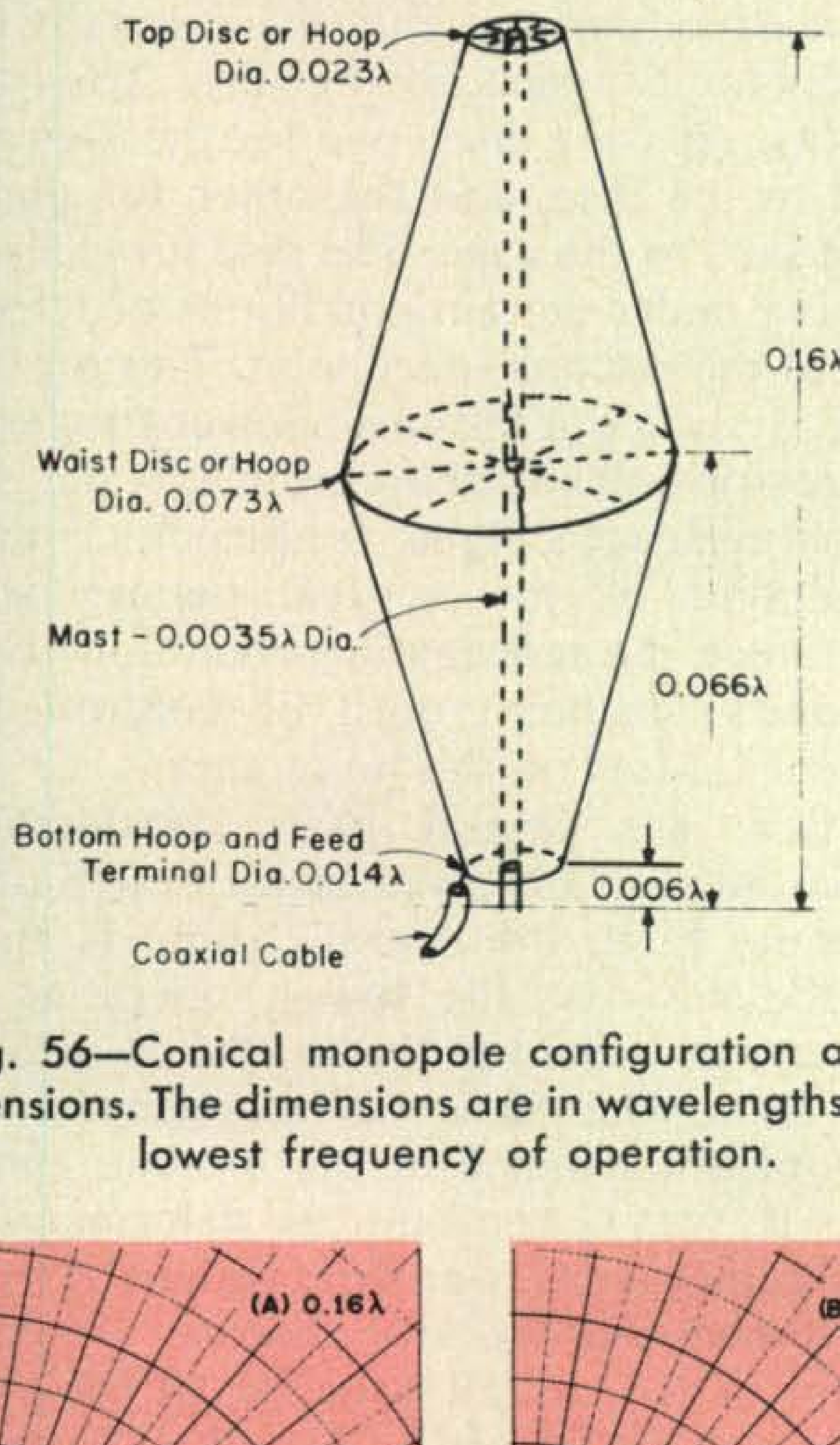
[57] Stroup, L. A., "The Conical Monopole," *CQ*, Ja 1966, p. 59.

[58] Pappenfus, E. W., "The Conical Monopole," *QS* Nov. 1966, p. 21.

vithin the structure. This basic concept is hown in fig. 55.

The dimensions of the antenna developed y Leppert are shown in fig. 56. For practical urposes, the discs or hoops are simulated by neans of metal spreaders, and the outer cone urfaces are simulated by wires, as shown in ig. 57. The references show some mechanical letails of construction of antennas of this ype.[57,58] As with the discone type, this an-enna can be built around a center tower or nast, using portions of the guys as the active ables of the antenna. The bottom hoop or ing is pulled down by means of strain insu-ators.

The vertical patterns for this antenna are shown in fig. 58, for frequencies at which the antenna is 0.16, 0.50, 0.58, 0.64, 0.80 and 0.96 wavelengths tall. As may be seen, the pattern exhibits somewhat the same characteristics as that from a uniform cross-section vertical radiator. It consists of one major low-angle lobe for heights up to about 0.58 wavelength; it then starts to split and the lower lobe shrinks while the upper one grows until, at 0.80 wavelengths, there is only one high lobe. Then, at 0.96 wavelengths, the lower angle lobe appears again. It is for this reason that I stated previously that the antenna is useful over a 4 to 1 frequency range (heights from 0.16 to 0.64 wavelengths). With regard to s.w.r., it is useful over a frequency range



ig. 56—Conical monopole configuration and dinensions. The dimensions are in wavelengths at the lowest frequency of operation.

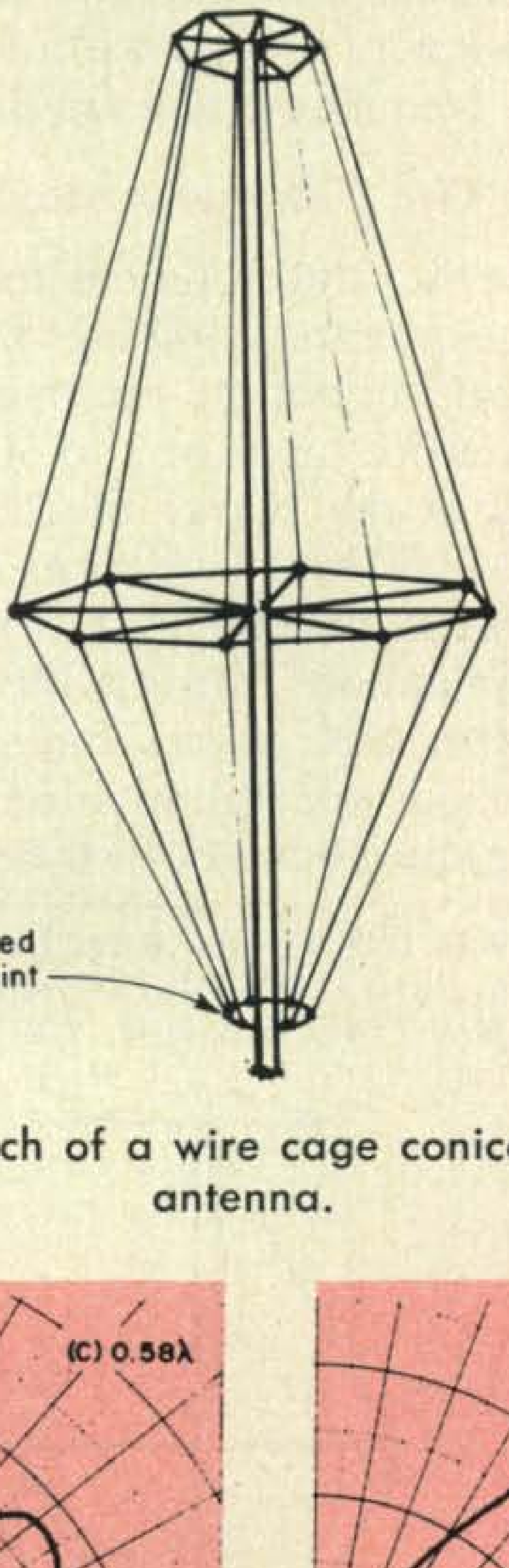


Fig. 57—Sketch of a wire cage conical monopole antenna.

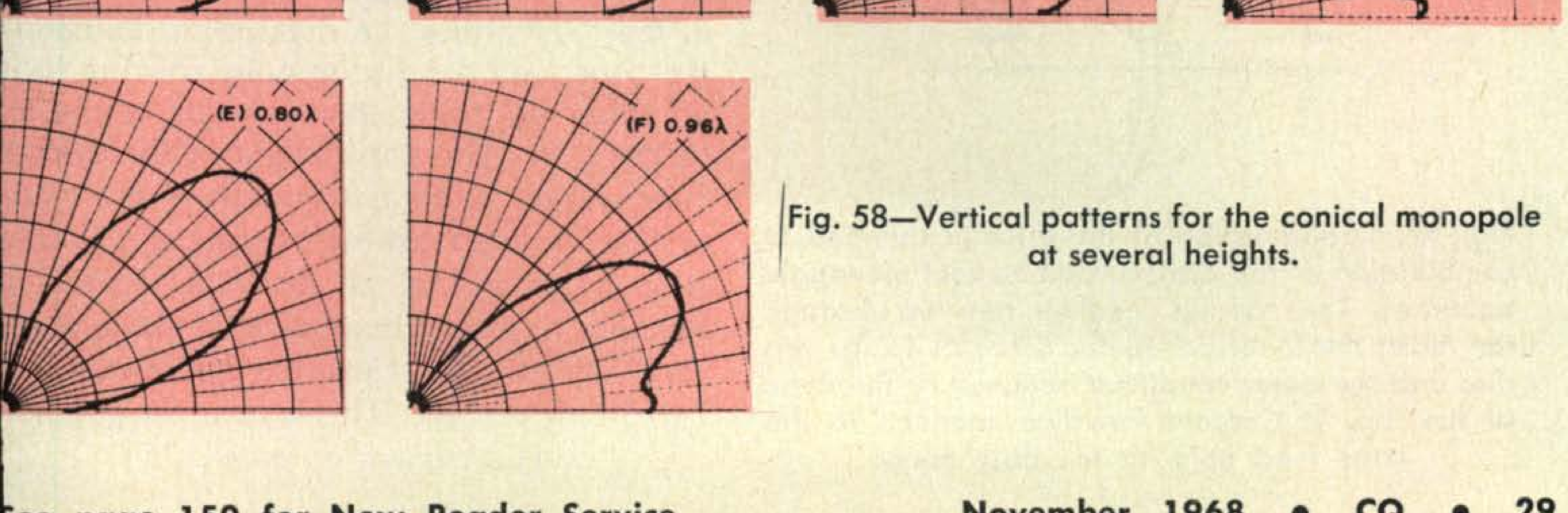


Fig. 58—Vertical patterns for the conical monopole at several heights.

of 6 to 1. Its s.w.r. is better than 2.7 to 1 over this range, relative to 70 ohms.

As with all grounded base antennas, this one must have a radial ground system. At naval shore stations we use ground systems of at least 120 radials a minimum of ½ wavelength long at the lowest frequency of the antenna. Of course, on ships, the metal hull and the sea water serve as the ground plane, a much better one than can ever be found at a shore station. The antenna is fed directly from 70 ohm line. When using 50 ohm line it is necessary to use a transformer section which consists of 0.196 wavelengths (at the antenna's lowest frequency) of 70 ohm line, inserted between the antenna and the 50 ohm feed. The s.w.r. will be within 2.7 to 1 over the 6 to 1 frequency range in this case also.

The Discage Antenna

As a further development for military use, the discage antenna combines the discone and the conical monopole in one structure to cover the entire range of 2 to 30 mc. The idea originated at the Naval Electronics Laboratory in 1954.[59] Many versions of this type of antenna were developed for both ship and shore applications during the past decade. Several sizes and shapes have been used to satisfy various space limitations, and various feed techniques have been used. Antennas of this type with a lower frequency limit o mc are quite practical for shore station u whereas limitations on physical size conf their use to frequencies higher than 6 mc shipboard.

Figure 59 shows the configuration of a to 32 mc discage antenna. This antenna co bines the characteristics of the conical mo pole (top-loaded) and the discone into c compact structure. The cage, like the p viously described conical monopole, is fed its base ring or hoop. The discone, which formed of the top disc and the upper porti of the cage, is fed by a coaxial line which r up through the central mast or tower. T outer conductor of the coaxial line conne to the upper portion of the cage, and the in conductor connects to the disc. Thus th are two separate lines, one for the high ba feed to the disc, and the other for the l band feed to the cage. The disc provides t loading under certain conditions of termi tion of the discone's feedpoint. This top-lo ing is desirable at the cage's lower frequenc for reasons of impedance, but it is not de able at the cage's higher frequencies from standpoint of the vertical pattern sha Therefore the terminating conditions of discone's feedpoint must be controlled, switched. More on this point later.

There are several basic consideratio which must be observed in the design of t antenna. First, the overall height is chos on the basis of the lowest operating f quency, with the top-loading taken into c sideration. The transition frequency betwe the operating bands of the discone and cage is very important. It determines maximum diameter of the cage and the ov all dimensions of the discone. Electri height of the overall structure at the tra tion frequency must be less than ¾ wa length to avoid undue vertical pattern lobi at the cage's high frequency limit. For t discone, the flare angle of the cone should about 60°, the diameter of the disc should at least 0.7 times the maximum diameter the cone, and the disc-to-cone spacing sho be about 0.3 times the diameter of the ap of the cone. The slant height of the discon cone should be approximately ¼ waveleng at the discone's lowest operating frequen It so happens that all these parameters f together to make the choice of about 8 m good one for the transition frequency, fo 2 to 30 mc discage. This is near the geomet

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[59] "Composite Discage Antenna Developed for 2 to 30 mc/s Band," *Naval Electronics Laboratory, Report No. 1504*, 8 August 1967 (Unclassified).

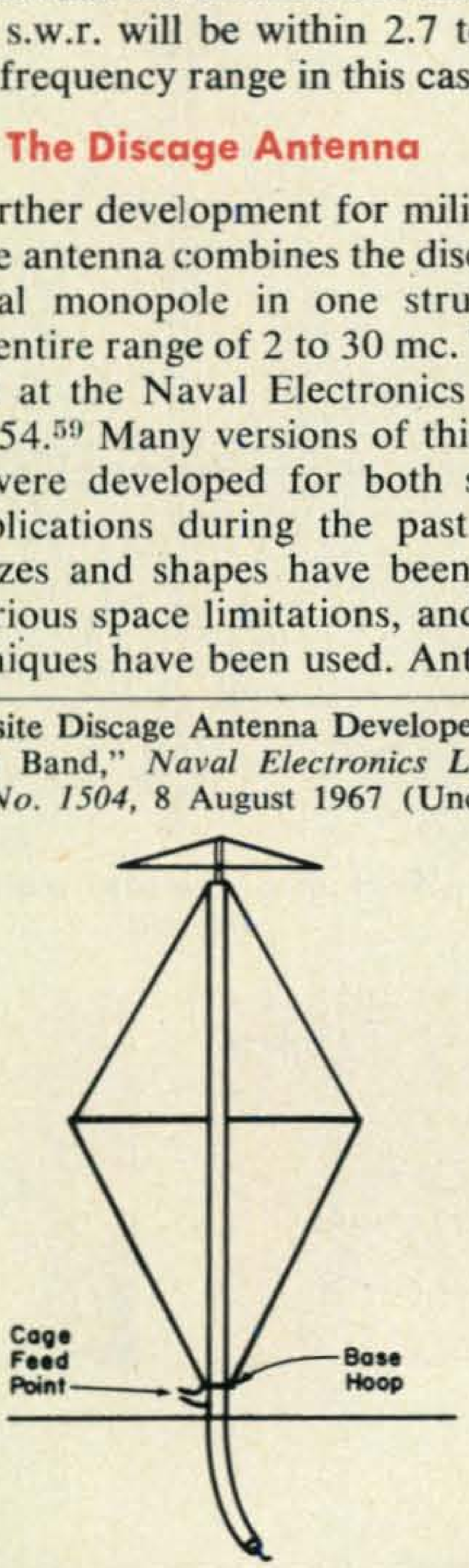

Fig. 59—Configuration of the discage antenna, a combination of the discone and conical monopole antennas. The coaxial feedline runs up through the mast; the inner conductor connects to the top disc and the outer conductor connects to the cage at the top. The second feedline connects to the cage feed point at the base hoop.

Vertical Antennas *[from page 30]*
mean of the limits of the frequency range.

As to the number and size of conductors, the simulation of the solid disc and cage improves as the number and diameter of the conductors is increased. There is, however, a practical limit to this. Experience has shown that a cage made of 12 conductors performs very well. A top disc simulated by 12 spreaders and interconnecting wires is used. Figure 60 shows this configuration. Aluminum pipe, or a small aluminum tower, can be used as the center support. As with the conical monopole, the structure lends itself to being guyed by use of some of the cables as portions of guys, isolated from the remainder of the guys by strain insulators. The disc can be mounted to the top of the mast or tower as shown in fig. 61. A circular plate is used to secure the upper ends of the cone cables. Another circular plate rests on this, supported by four standoff insulators. The disc spreaders are bolted to the plate. A small supporting rod is mounted in the center of the upper plate, to hold the cables which support the far ends of the spreaders. A waterproof relay box is mounted on the side of the mast. Power for the relay is run up through the mast, and, inasmuch as the mast is grounded at its base, the power line can be merely bypassed to ground with a pair of 0.1 mf 600 volt capacitors at the base of the mast.

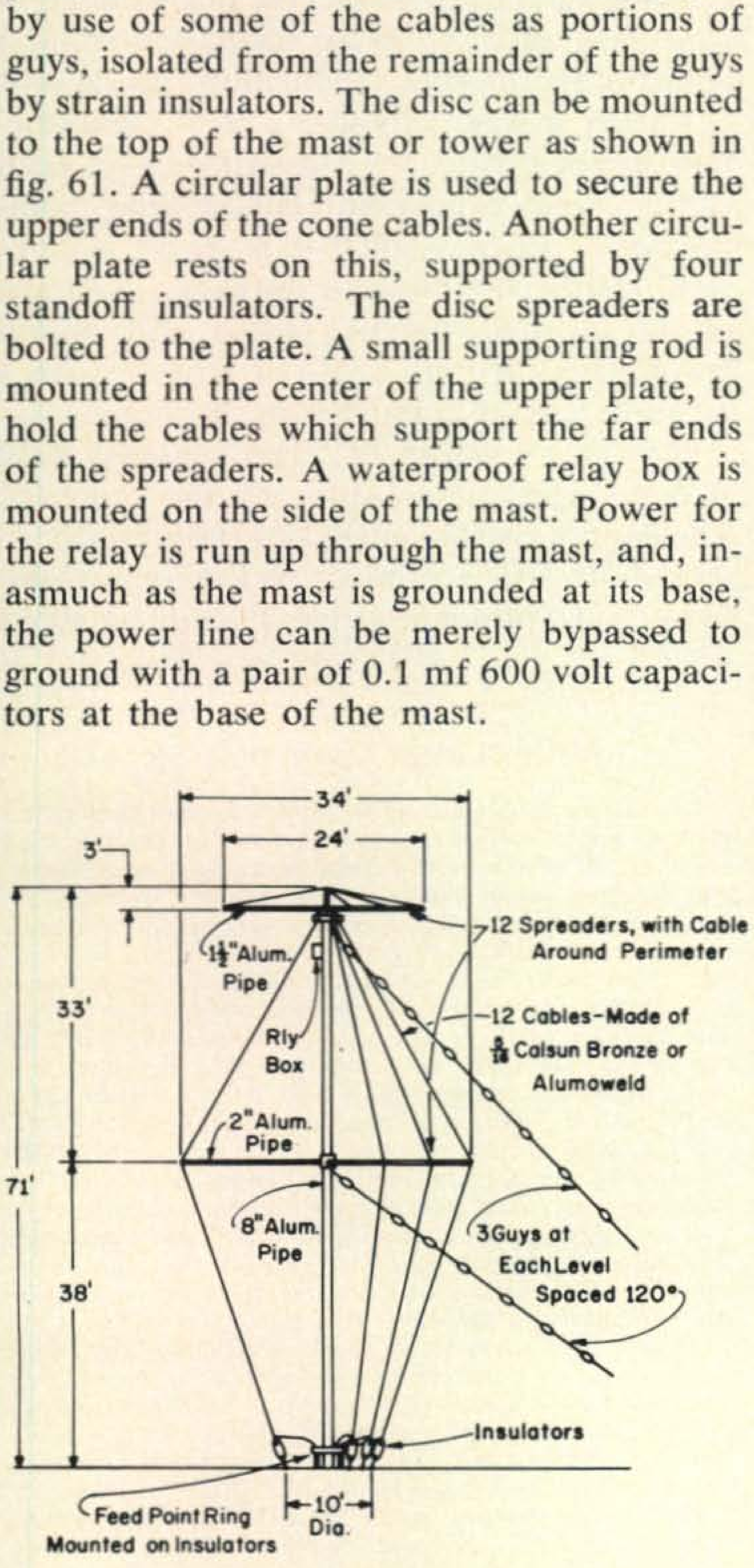

Fig. 60—Dimensions of a 2-32 mc discage antenna. The relay box mounted at the top of the 8" aluminum mast houses a relay which shorts out the disc when the cage is being fed.

It was mentioned previously that the terminating conditions of the discone must be either controlled or switched in order to make use of the top-loading effect of the disc at the cage's low frequency limit. In shipboard applications[60] we often feed this antenna with two or more transmitters, through multicouplers, with several transmitters operating in the high band and several in the low band, all operating simultaneously. In order to do this, and to prevent unwanted interactions between high and low band equipments, it is necessary to use a high pass filter in the coaxial line to the discone, and a low pass filter in the line to the cage. The high pass filter is so designed as to properly terminate the discone so that the disc will act as top-loading at the low frequency limit of the cage. The high pass filter is located up on the mast near the feed point of the discone. However, for amateur applications, where we are not operating transmitters simultaneously, this termination can be switched by means of a relay, mounted on the mast as shown. The relay shorts the disc to the cage, when operating in the low frequency portion of the cage's band.

The dimensions shown in fig. 59 are for a low limit of 2 mc. Throughout the 2 to 8 mc band and the 8 to 32 mc band the s.w.r. will be less than 2.5 to 1, referred to 50 ohms. If it desired to operate this antenna down to 1.8 mc, it size can be increased by a factor of

[Continued on page 138]

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[60] Wilson, K. D., "Communications, A Limiting Factor in Naval Warfare," *Naval Engineers' Journal*, Feb. 1963, p. 51.

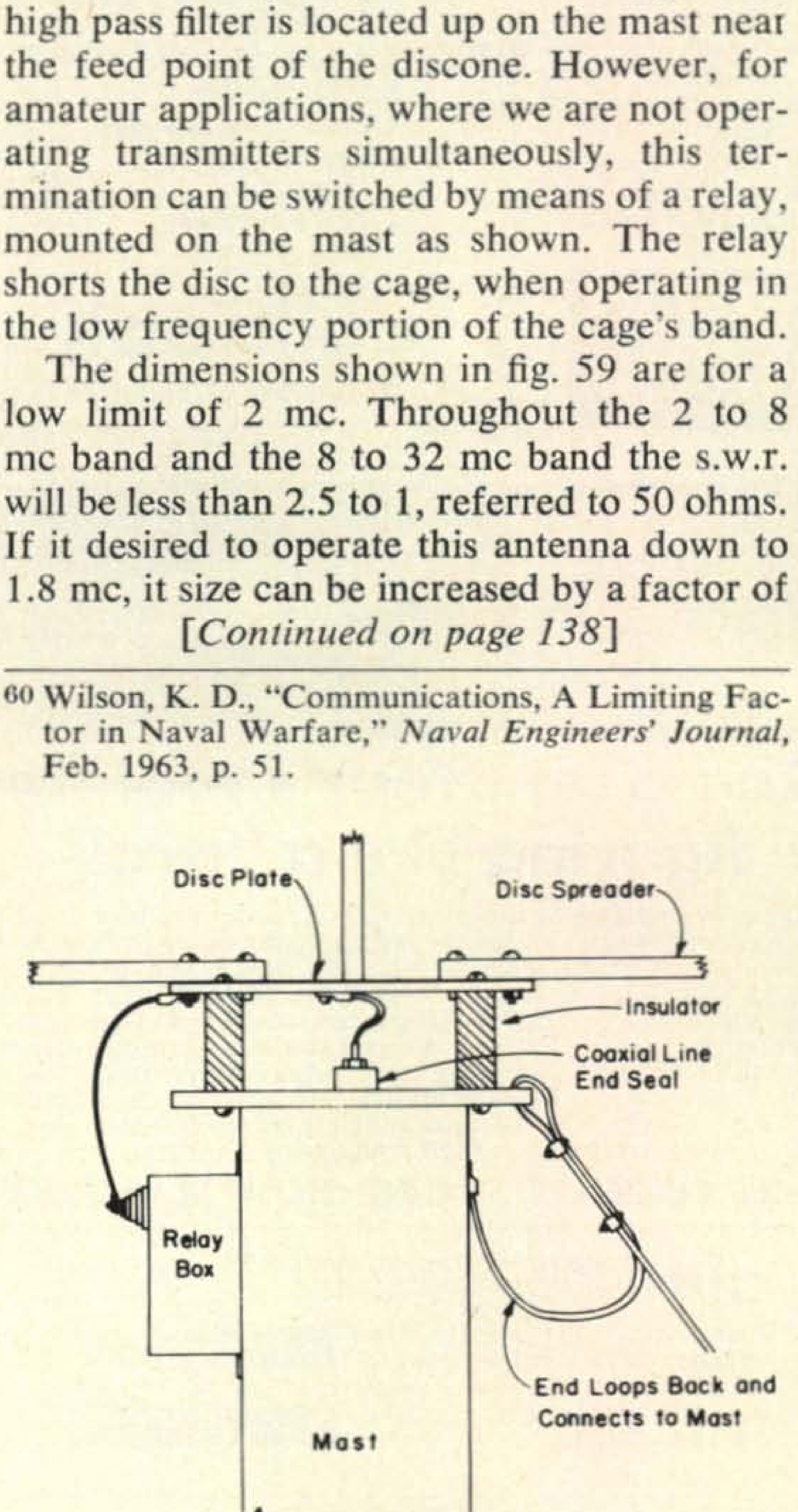

Fig. 61—Detail showing the mounting of the disc plate, disc spreaders and relay box.

Vertical Antennas [*from page 135*]

10%, or one can be content to tolerate an s.w.r. of 3 to 1 in this region. If one wishes to start at a low limit of 3.5 mc, the size can be scaled down by a factor of 0.57, thus giving an antenna which would cover 80, 40, 20, 15, 10 and 6 meters. If one is only interested in 7 mc and up the size can be reduced by a factor of 0.286, and 40, 20, 15, 10, 6 and 2½ meters could be covered. The height of a 3.5 mc version would be 39.7 feet and that of a 7 mc version would be only 19.85 feet.

In the naval service, for shipboard use, we do one other little trick with this antenna, and that is to mount a small u.h.f. unipole antenna on top of it, utilizing the disc as the ground plane for the u.h.f. antenna. One way of carrying the u.h.f. feed line across the h.f. discone feed point would be to coil up the u.h.f. feed line in the form of a choke coil which would have little effect on the h.f. discone feed point. Such a choke could be used to terminate this feed point, instead of using the shorting relay. The choke would thus act as a small loading coil between the cage and the top disc, at the low frequency limit of the cage. This is shown schematically in fig. 62.

As for vertical patterns, fig. 63 shows those for the cage, with the discone feed point shorted, for 2.5, 4.0, 5.5 and 7.5 mc. In fig. 64 we see the vertical patterns of the discone portion, with the cage feed terminated. While the latter show multiple lobes, this antenna is considered to be quite suitable for omnidirectional medium and long distance communications.

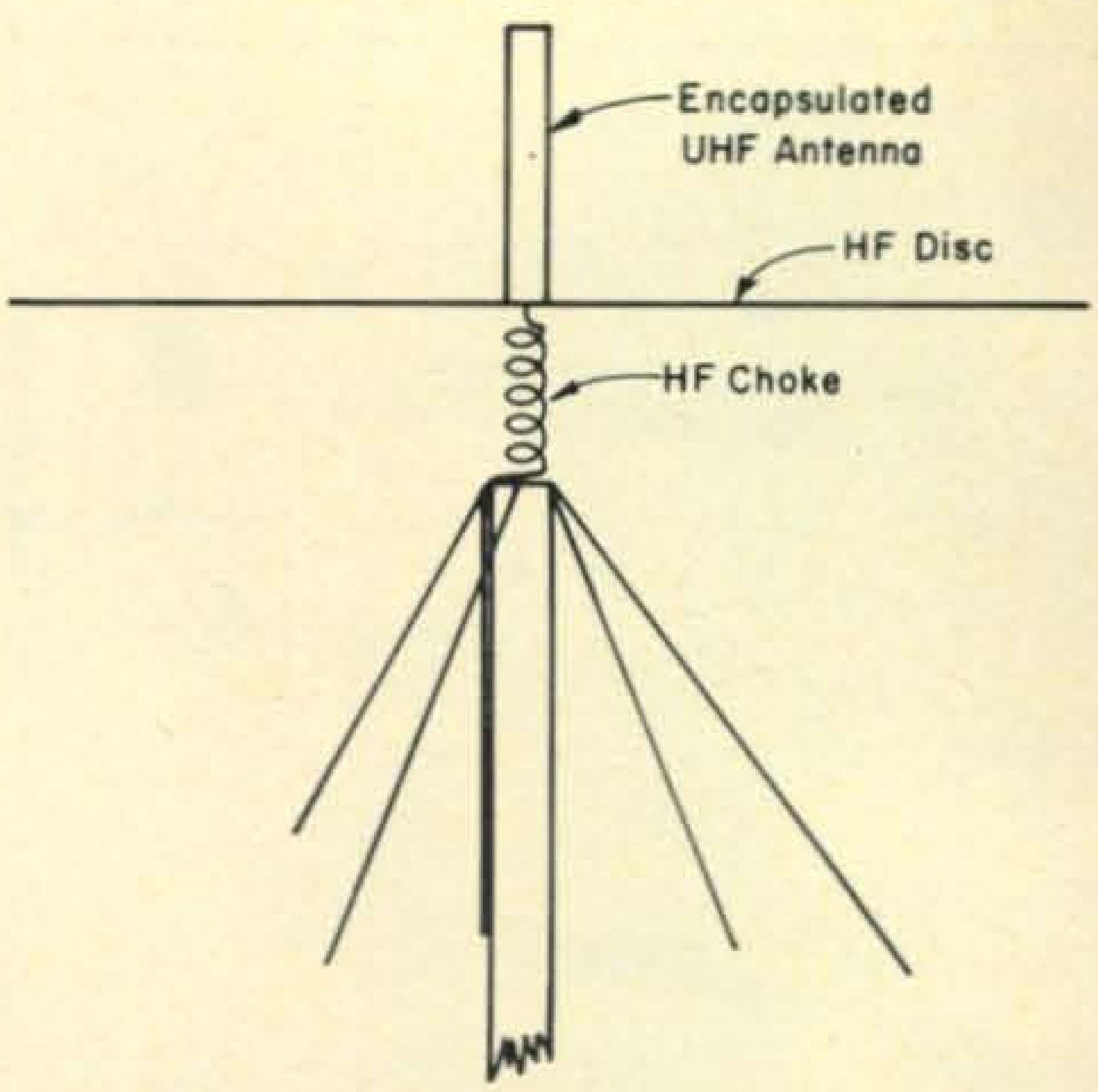

Fig. 62—Configuration of a method of u.h.f. feed across the h.f. discone. The u.h.f coaxial line is wound into an inductance, the h.f. choke. The u.h.f. line then runs down through the h.f. antenna mast.

The discage antenna would be ideal for someone who is limited as to space and who wants one antenna to cover a number of frequencies. While the Mark IV DX Antenna[61] is ideal for amateur band use only, it is not suitable for MARS use, for example, without the addition of more relays and matching networks in the tuning unit. A discage antenna, on the other hand, enables one to operate on *any* frequency without the use of tuning networks or switching. Power at 2 to 8 mc is fed in through one coaxial line, and the other line is used for 8 to 32 mc operation. It is reasonable in size, even for 2 mc.

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[61] Lee, P. H., "Mark IV DX Antenna," *CQ*, Feb. 1967, p. 60.

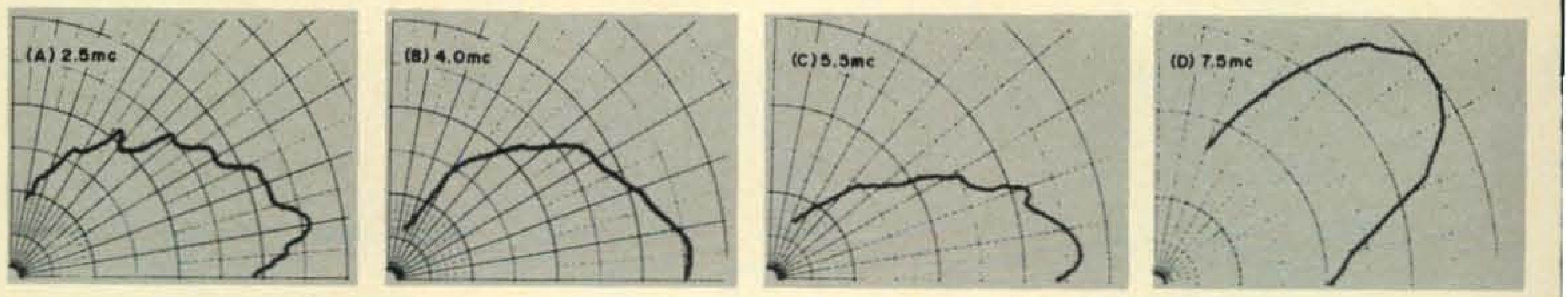

Fig. 63—Vertical patterns of the cage with the discone feed point shorted.

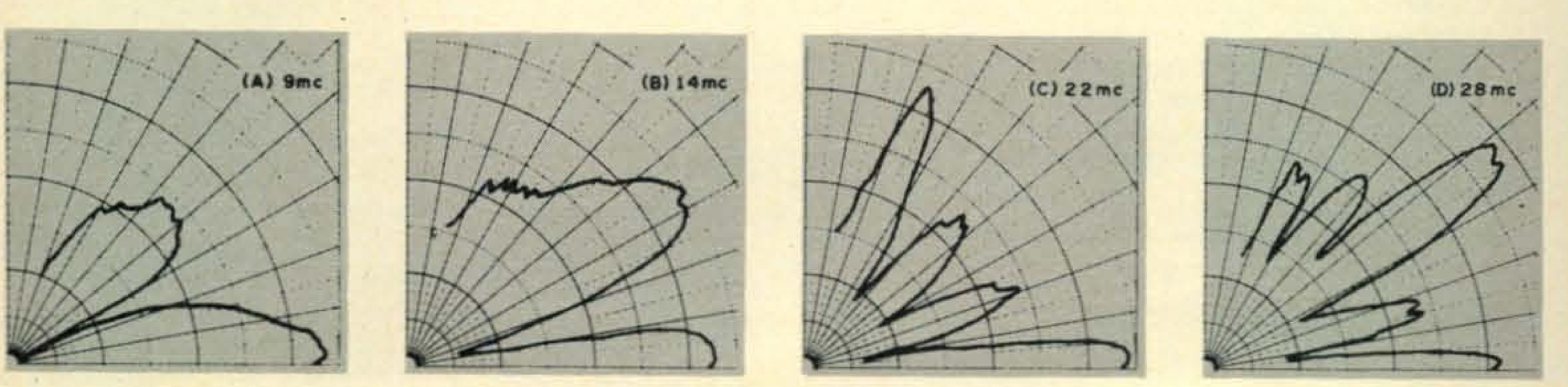

Fig. 64—Vertical patterns of the discone portion with the cage feed terminated.

See page 150 for New Reader Service

In the next part of this series, we shall discuss additional broadband types in current use. Incidentally, the N.E.L. reports which I have referenced in this part[59] and in Part V[44,45,46] are not only "Unclassified," but are marked "For Unlimited Distribution." I have not tried to do so, but it is possible that they may be obtained by purchase from the Clearinghouse for Federal Scientific and Technical Information, U.S. Department of Commerce, by those who are interested. Of course they are obtainable through the Defense Documentation Center.

[*To be continued*]

Puzzle [*from page 68*]

S	Y	S	T	E	M	■	G	R	A	P	H	I	T	E
P	■	T	■	V	■	S	■	O	■	R	■	M	■	R
E	L	E	M	E	N	T	■	C	L	I	P	P	E	R
C	■	P	■	N	■	R	■	K	■	S	■	■	■	O
T	R	U	E	■	V	A	R	I	O	M	E	T	E	R
R	■	P	■	D	■	I	■	N	■	■	■	O	■	S
U	N	■	B	U	R	N	■	G	A	L	E	N	A	■
M	■	M	■	S	■	■	■	■	■	E	■	E	■	D
■	G	E	T	T	E	R	■	W	I	E	N	■	M	Y
S	■	G	■	■	■	A	■	O	■	R	■	H	■	N
T	R	A	N	S	I	S	T	O	R	■	B	E	T	A
A	■	■	■	C	■	T	■	F	■	W	■	A	■	T
T	E	T	R	O	D	E	■	E	M	I	T	T	E	R
I	■	I	■	U	■	R	■	R	■	R	■	E	■	O
C	O	N	T	R	A	S	T	■	L	E	Y	D	E	N

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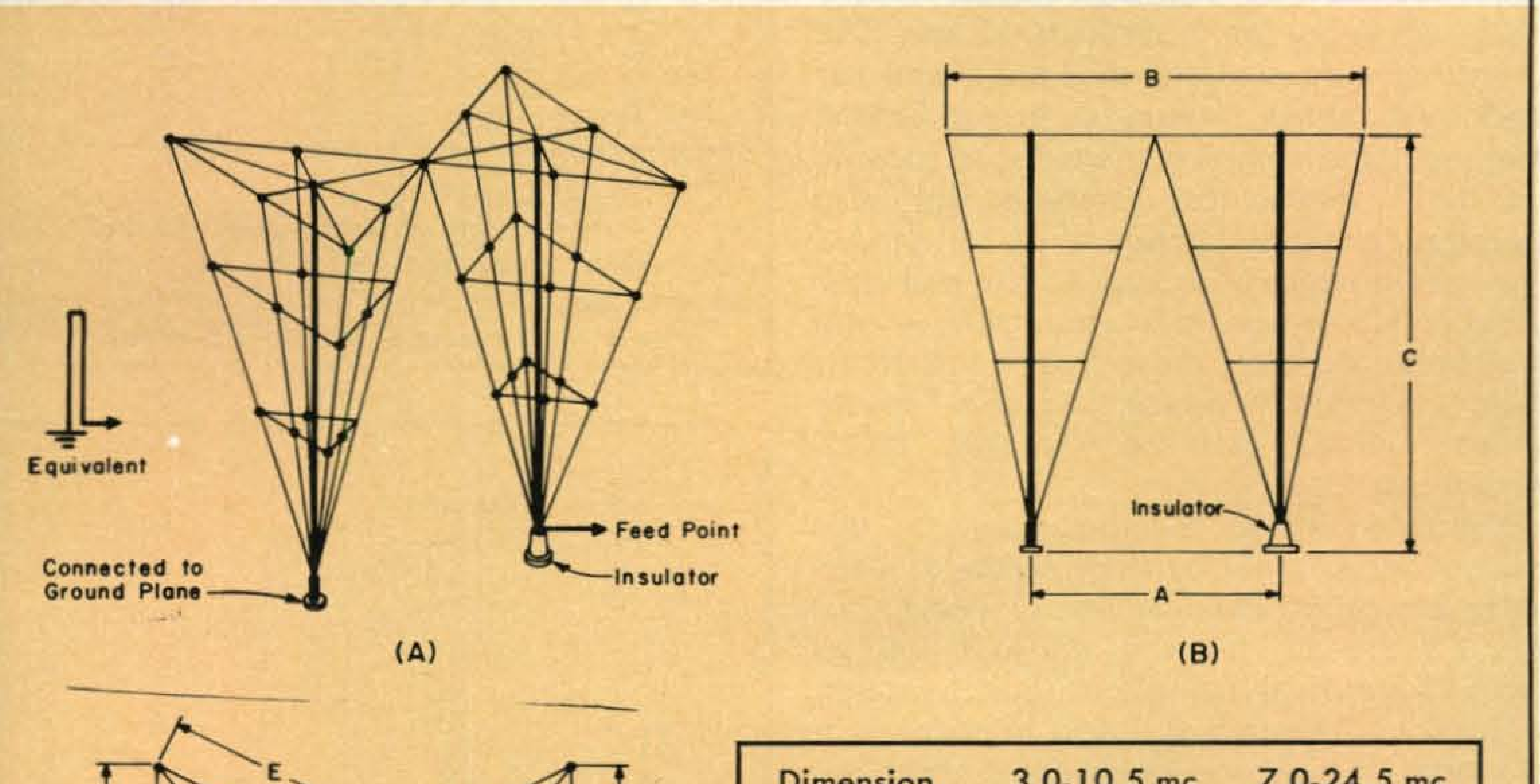
VERTICAL ANTENNAS

Part VII

BY CAPT. PAUL H. LEE*, W3JM

Several additional broadband vertical antennas are described in this article of the series, Part VII. These antenna types can very easily be adapted to amateur use as shown by the author.

IN Part VI it was stated that conical structures make ideal broadband radiators, and their use, both as inverted cones and discones, being fed against a flat planar surface, were shown. This matter can be carried further by stating that the structure does not have to be conical but can be pyramidal in shape. This configuration lends itself to the joining of two structures together to form a folded unipole. Such a configuration is shown in fig. 65 in perspective view. The two pyramids rest on their apexes, with a junction at



Dimension	3.0-10.5 mc	7.0-24.5 mc
A	27′	11.6′
B	45′	19.3′
C	45′	19.3′
D	20′	9.6′
E	25′	10.7′

Fig. 65(A)—Perspective view of a triangular folded unipole and its equivalent circuit. (B) and (C)—Side and top views of the triangular folded unipole and the critical dimensions for two frequency ranges of interest to amateurs.

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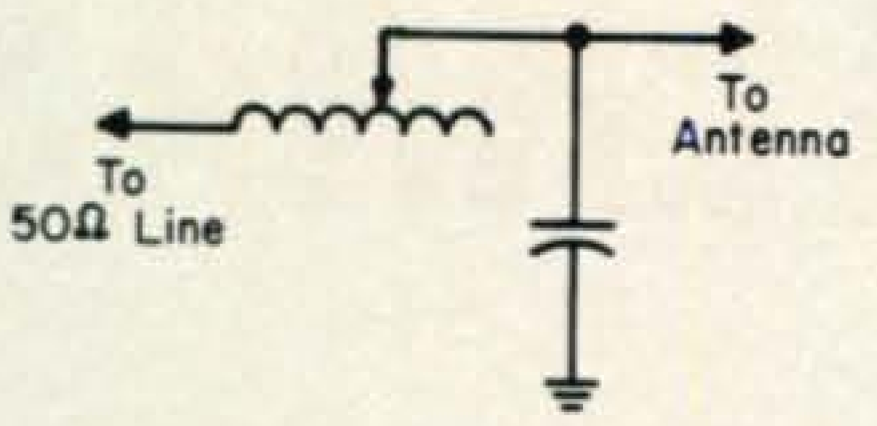


Fig. 66—Circuit of the *L* network used to match the triangular folded unipole's 175 ohm feed impedance to a 50 ohm line.

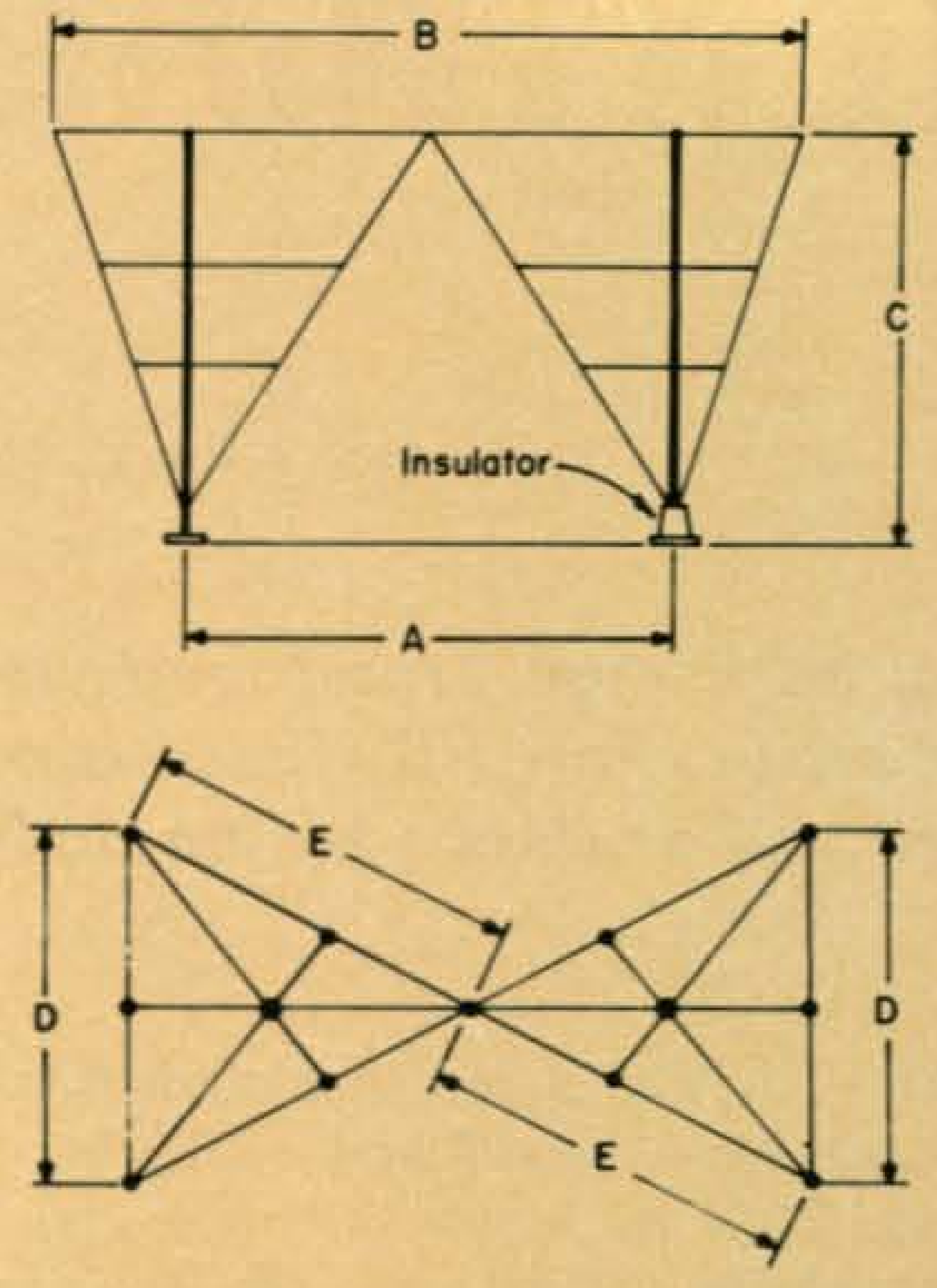
their bases. One apex is grounded, and the other is fed. A ground system is required.

The Folded Unipole

This antenna was used on the "Voice of America" ship USCGC Courier, which for a period of about ten years was moored in the eastern Mediterranean Sea as a short wave and medium wave relay broadcast station. This facility has since been decomissioned and replaced by shore based equipment and antennas, but these broadband structures were very interesting and unusual. There were two of them on the ship. One was for a frequency range of 6 through 11 mc, and the other was used for 9 through 17 mc. The structures were made of steel angle and bar stock, assembled around a strong central steel pipe, and completely welded to provide not only mechanical strength but also thorough electrical bonding of all pieces. This was necessary because of the maritime environment which in a short time would have produced many "rusty bolt" connections in an unwelded structure, and also because of the power involved (35 kw 100% modulated.

Figure 65 shows the dimensions of this antenna for several frequency ranges of interest to amateurs. It is capable of being used over a frequency range of 3.5 to 1 with an s.w.r. of less than 1.5 to 1 at the feed point, referred to the nominal design impedance of 175 ohms which was desired for these antennas. For 50 ohm feed it was necessary to use a simple L network as shown in fig. 66, with shunt capacity and series inductance. Even with the network in use the s.w.r. will still be good over quite a wide frequency range, such as the entire 3.5 to 4.0 mc band for example, without retuning.

The 175 ohm design impedance results from the use of a rather acute angle at the apex of each pyramid. The apex angle of the structures shown in fig. 65 is about 30°. If the apex angle is increased to about 60° (the same value as used in the discone antenna of



Dimension	3.0-10.5 mc	7.0-24.5 mc
A	56'	24'
B	90'	38.6'
C	45'	19.3'
D	51'	21.8'
E	51'	21.8'

Fig. 67—Dimensions of a triangular folded unipole with an apex angle of 60°. This angle, instead of the 30° shown in fig. 65, will provide a feed impedance of 50 to 75 ohms.

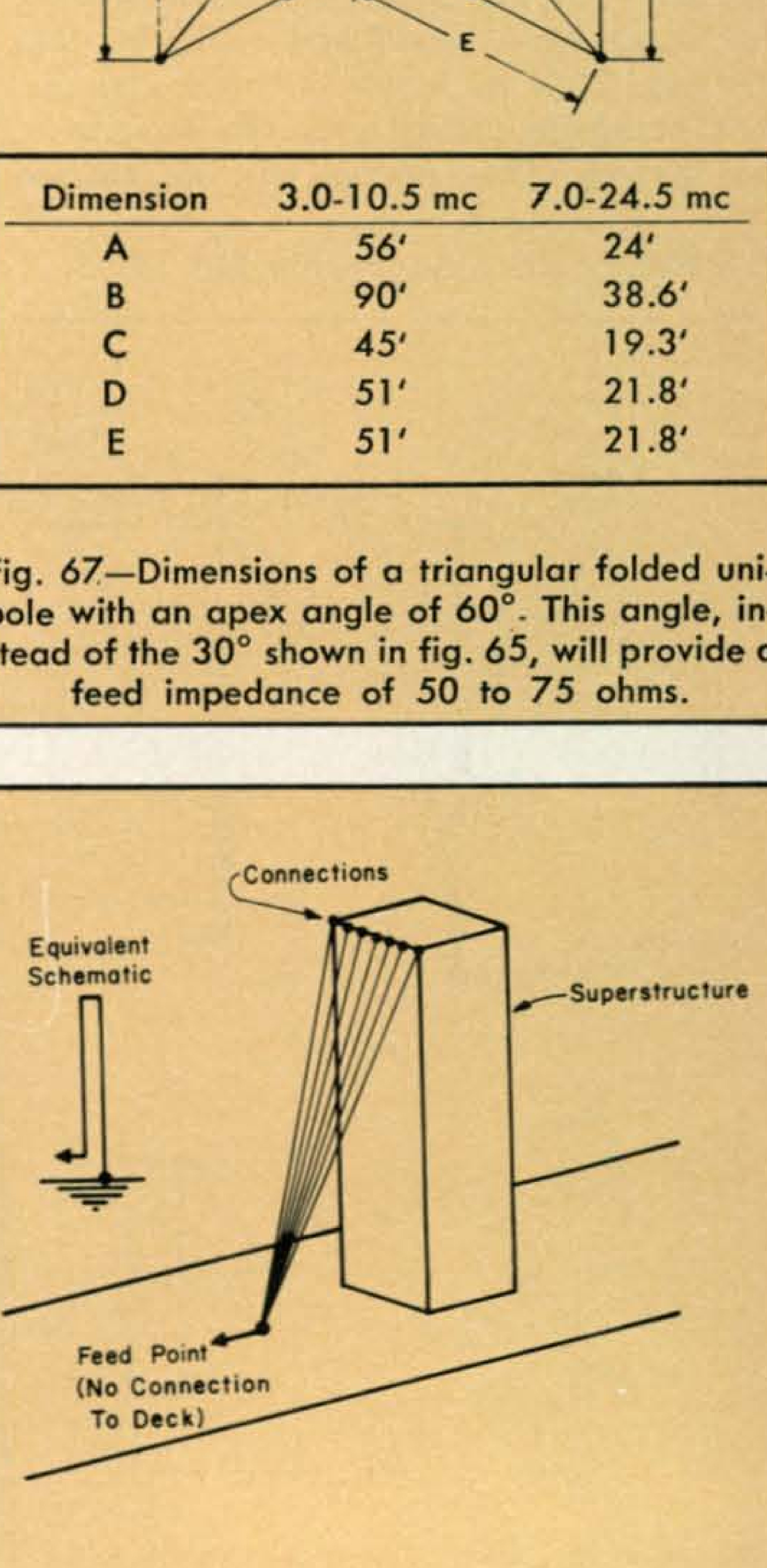


Fig. 68—Folded fan feed of a portion of a ship's superstructure.

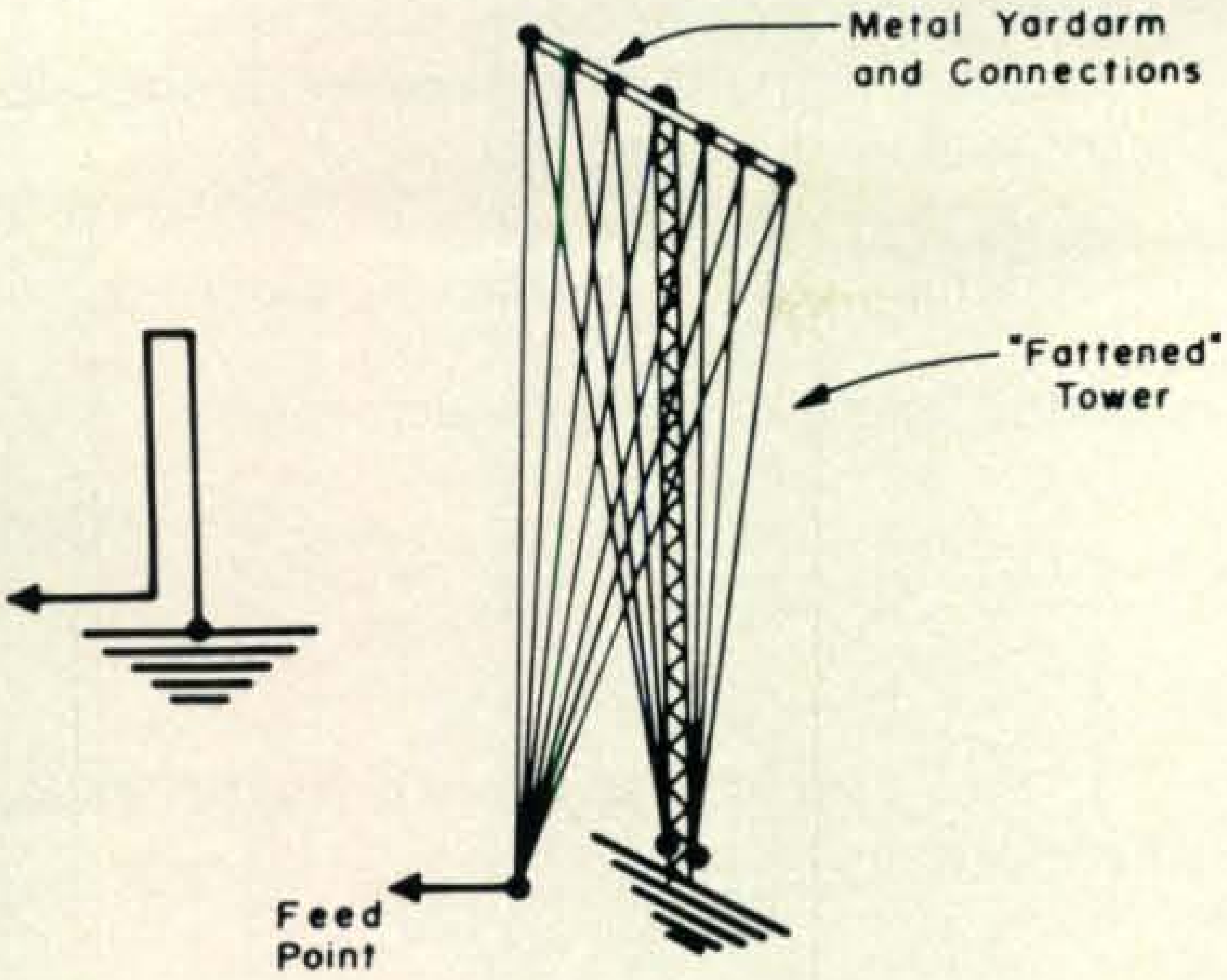


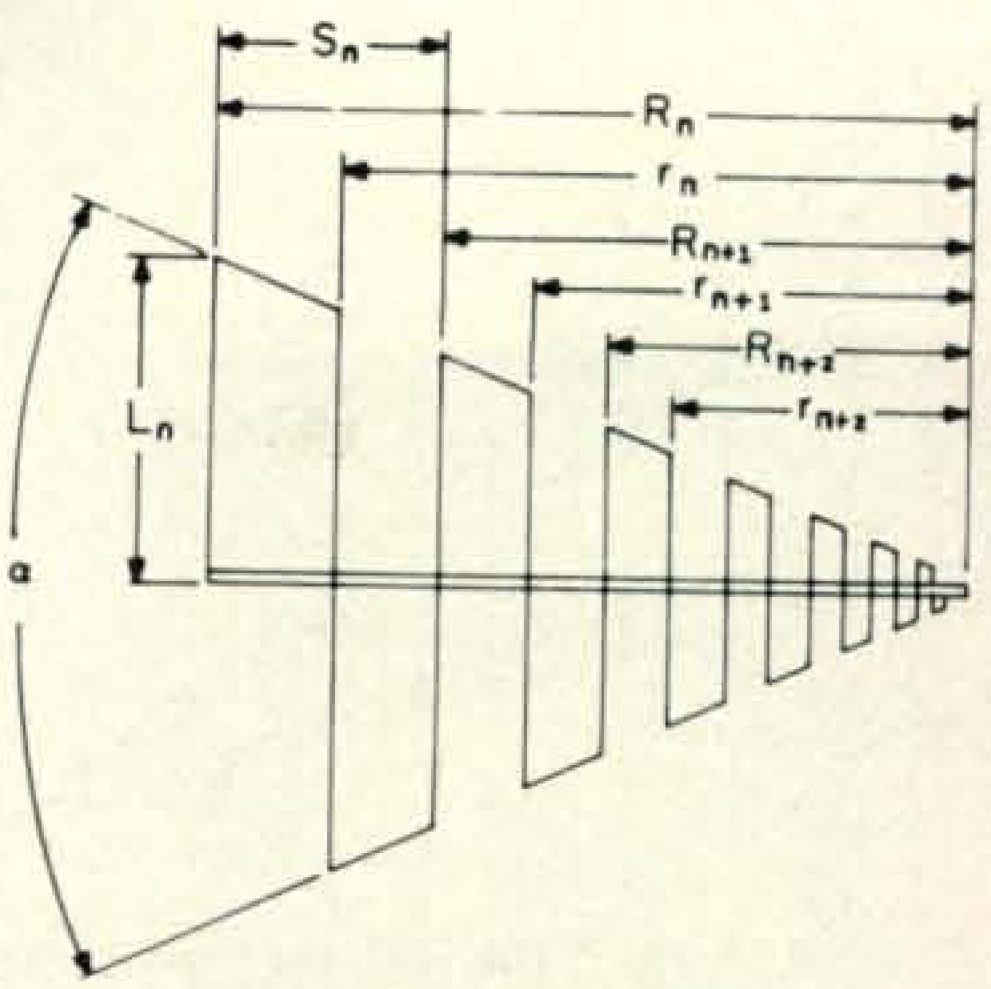
Fig. 69—Broadband folded fan on a tower.

fig. 48), this impedance will come down to a more reasonable value of 50 to 75 ohms, and the excursions of the reactance versus frequency curve will be less pronounced [62] [63] One might assume this to be the case, from what has been said previously about broadband structures, for as the apex angle is reduced in value to 0° we have a linear folded monopole whose input impedance will have extreme variations versus frequency. With the 60° apex angle, the dimensions of fig. 67 will apply. It will be noted that the horizontal area required for the antenna has increased over that needed for the 30° case. This was another factor affecting the shipboard installation, where space was limited.

The amateur could build an antenna of this type using pieces of aluminum tubing flattened on their ends and bolted together. The entire structure would be quite light weight, and would require only four lateral guys and two longitudinal guys.

The Folded Fan

Another arrangement which is somewhat similiar to this is a folded fan type of antenna which is being used on shipboard. An entire portion of a ship's superstructure such as a stack, fire control director or radar tower, *etc.*, is driven as a part of a folded fan type of unipole, as shown in fig. 68. The amateur who has available a tall metal structure such as a chimney or tower can apply this type of feed to it and obtain quite good broadband results. In fact, if the tower is a thin one, it can be "fattened" by the use of a second fan as shown in fig. 69. For matching 50 ohm line to this type of feed, "cut and try" will be required, for I cannot give any absolute values of reactances required. However, if the total height of the folded fan is less than 1/4 wave, the impedance should be quite reasonable (several hundred ohms or less) and easy to match with a simple T or L network.



$$\tau = \frac{R_{n+1}}{R_n} = \frac{r_{n+1}}{r_n}$$

$$\sigma = \frac{r_n}{R_n} = \frac{r_{n+1}}{R_{n+1}}$$

$$\sigma = \sqrt{\tau}$$

Fig. 70—Basic log-periodic antenna structure and some of the design formulas discussed in the text.

The Log Periodic

The types of antennas described above are nominally non-directional, with perhaps 1 to 3 db variation in the horizontal pattern polar plot. Let us now consider a *directional broadband* radiator, the vertical log-periodic antenna. Where in the previous cases we were using simple linear structures and making them broadband by lowering the effective L/D ratio, the log-periodic is of a different breed. This type of structure is composed of thin linear elements, and its geometry is defined so that the radiation pattern and the impedance repeat periodically with the log-

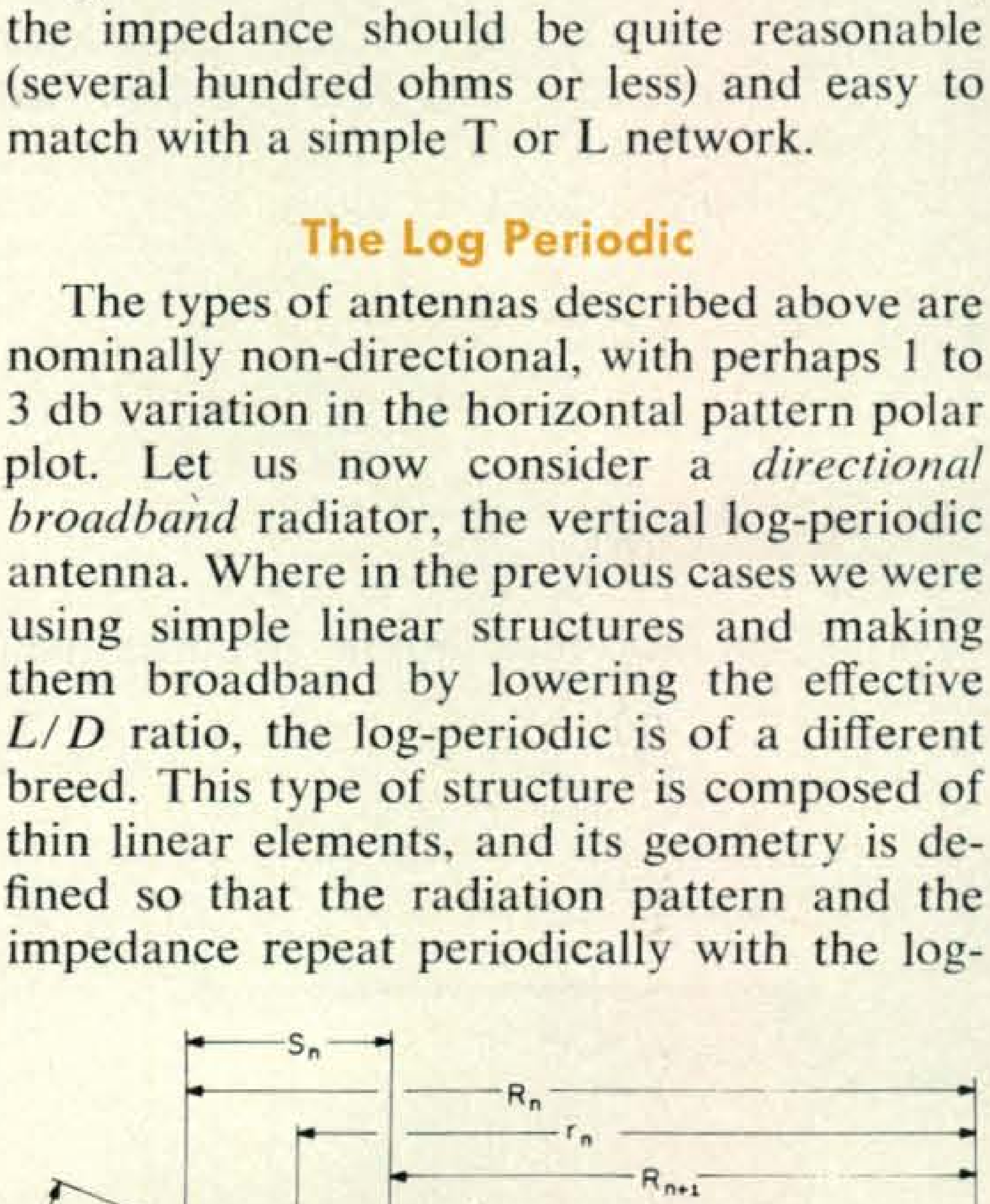


Fig. 71—A vertical log-periodic antenna.

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[62] Jasik, Henry, *"Antenna Engineering Handbook," McGraw-Hill, p. 3-11, 3-12.*

[63] Brown, G. H. and Woodward, O. M., "Experimentally Determined Radiation Characteristics of Conical and Triangular Antennas," *RCA Review,* Dec. 1952.

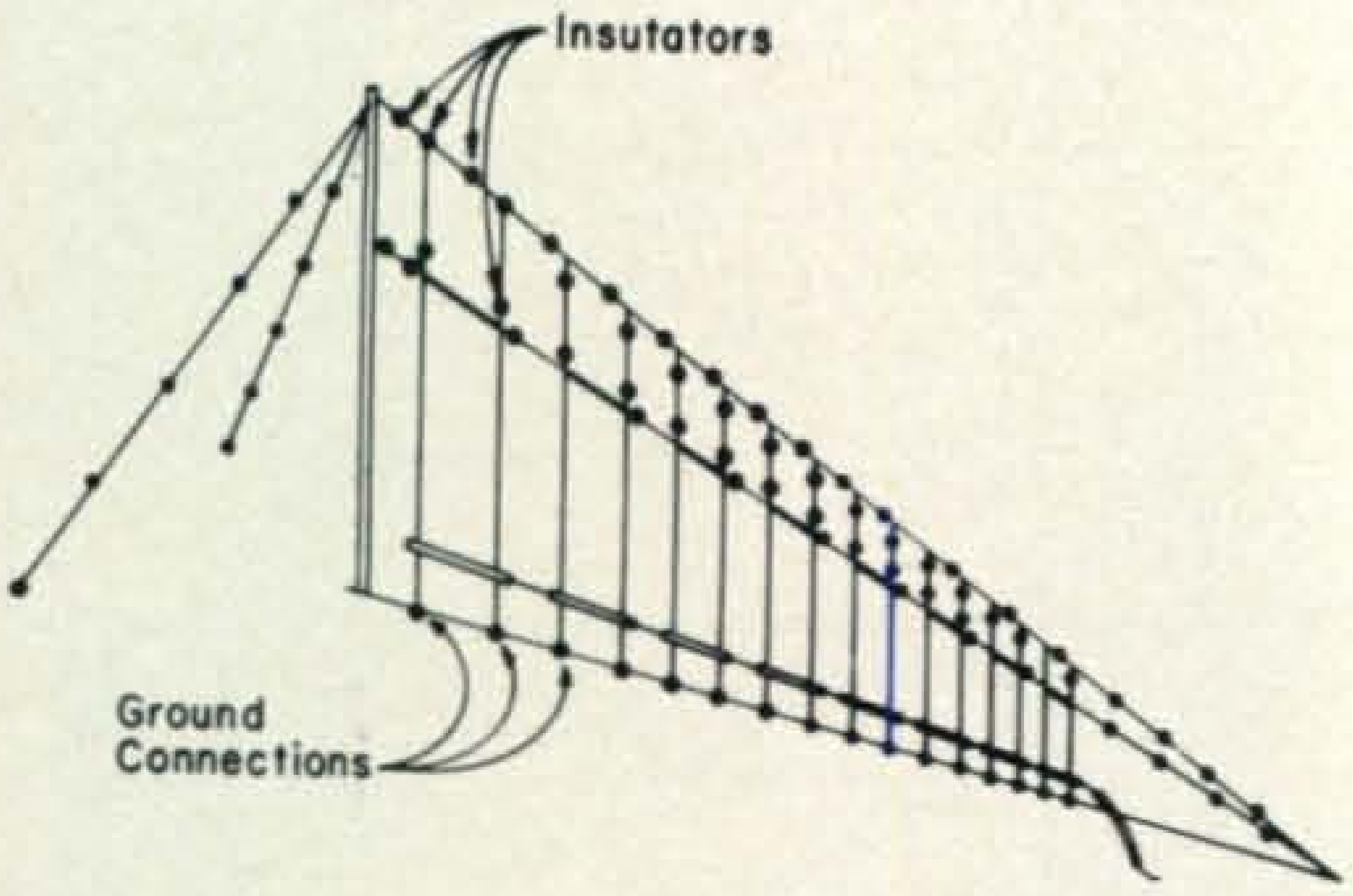

Fig. 72—Sketch of a wire type log periodic constructed by suspending the teeth from a catenary strung from a tower to an anchor block.

arithm of frequency. Some basic design theory of log-periodic antennas is in order here, applying to all types and not only to vertical ones, in order that their operation can be understood.

Figure 70 shows a basic type of log-periodic antenna, used here merely to show the relationships of the various dimensions. (Never mind how it is to be fed at this time.) This antenna is a trapezoidal tooth structure made of wire. One of the basic parameters is the "design ratio," which is called τ. Also related to it is σ, which is equal to: $\sqrt{\tau}$
The following equations apply:

$$\tau = \frac{R_{n+1}}{R_n} = \frac{r_{n+1}}{r_n}$$

$$\sigma = \frac{r_n}{R_n} = \frac{r_{n+1}}{R_{n+1}} = \sqrt{\tau}$$

The design ratio must not be less than about 0.7 for good gain and low back lobes.

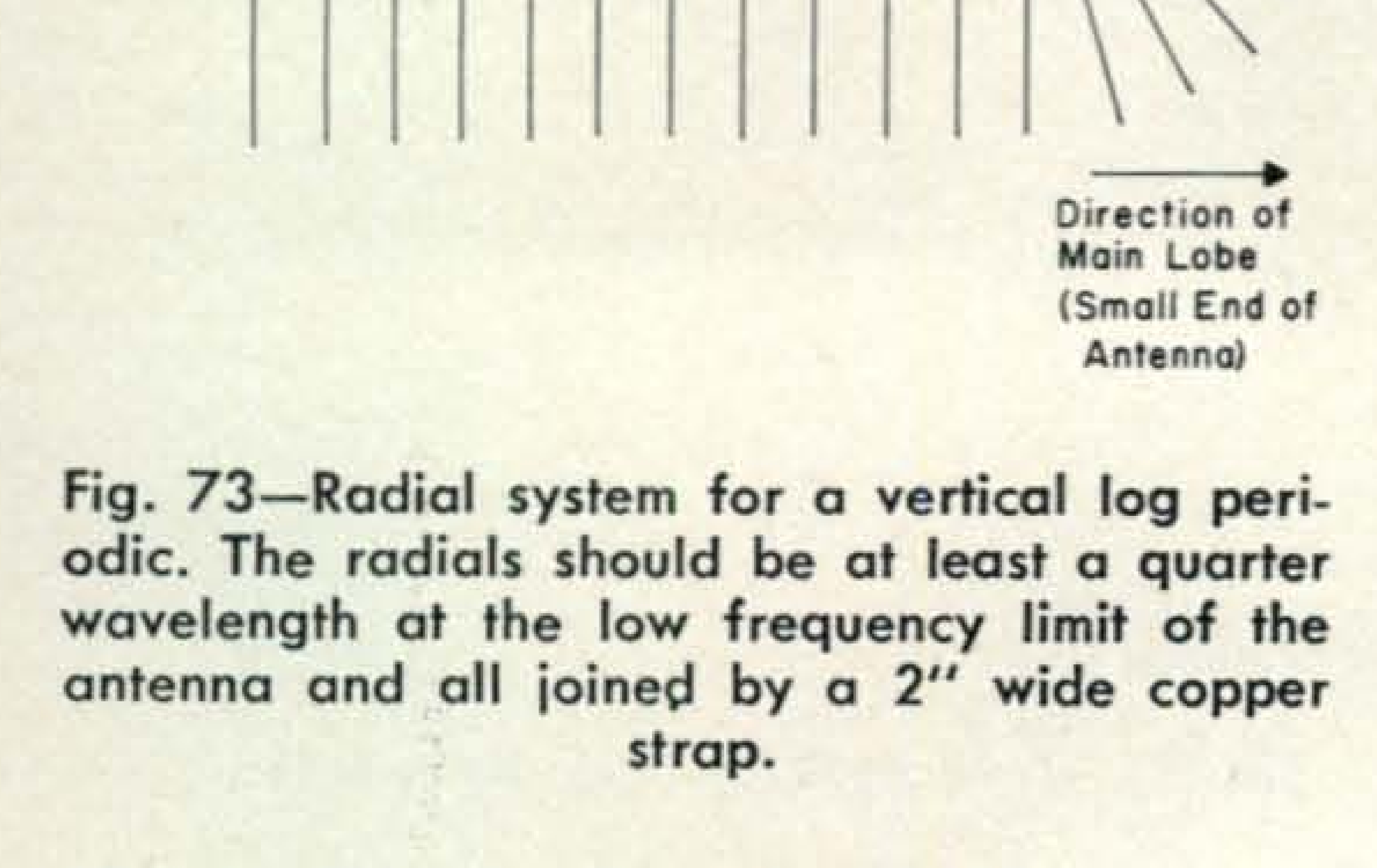

Fig. 73—Radial system for a vertical log periodic. The radials should be at least a quarter wavelength at the low frequency limit of the antenna and all joined by a 2" wide copper strap.

Another important parameter is the element spacing-to-length ratio.

$$\text{Spacing } S_n = R_n - R_{n+2} = R_n\,(1-\tau)$$

and the length of the n-th element is:

$$L_n = R_n \tan\frac{\alpha}{2}$$

and the element spacing-to-length ratio, therefore, is:

$$\frac{S_n}{L_n} = \frac{1-\tau}{\tan\frac{\alpha}{2}}$$

Experimental work has shown that this ratio should not exceed a value of 1.30 for proper operation of the antenna. Thus for a given angle , there is a minimum value of

$$\tau_{\text{min}} = 1 - 1.3 \tan\frac{\alpha}{2}$$

The frequency range of an antenna of this type is determined by the length of the longest and shortest elements, which are 1/2 wavelength at the lowest and highest frequencies, respectively. For all practical purposes, the detail with which the small end can be built determines the high frequency limit.

It can be seen from the above that there are a number of interrelated parameters in the design of a log-periodic antenna. As the antenna is made shorter for a given frequency range, the number of elements decreases, the design ratio decreases, and the front-to-back ratio and gain decrease. On the other hand, a longer antenna is more expensive to construct, and requires more real estate.

The configuration shown in fig. 70 is a balanced one. There are several ways of constructing and feeding this one, and antennas of this type are usually used in the horizontal mode, with a rotary mounting for directional operation, with the direction of the main lobe off the small end of the antenna. Since we are dealing with vertical antennas in this series, consider fig. 71, which is one half of the above antenna, with the lower half replaced by a ground system. A practical configuration which will give good results is shown. The front-to-back ratio at the lower frequencies will be about 14 db, while at the higher frequencies it will be about 20 db, with the value of $\alpha/2$ shown.

This antenna is fed by means of a capacitive coupling arrangement. The outer conductor of the coaxial feedline is broken between the trapezoidal teeth, as shown, and each piece is connected to one of the teeth forming one plate of a capacitor. The inner conductor is the other part of the capacitor, and is common to all teeth. The bottom end of each tooth is connected to the ground system. Angle $\in$ is about 3°. If the s.w.r. is to be optimized, the angle $\in$ should be varied somewhat, while input impedance is plotted on a Smith Chart, over the antenna's frequency range. With 50 ohm line, it is possible to obtain an s.w.r. below 3 to 1 over the frequency range of such an antenna. A frequency range of 10 or 15 to 1 is easily possible, and the horizontal and vertical patterns hold shape remarkably well over the entire range. This type of antenna is an excellent one for those who wish to cover a wide range of frequencies, with transmission and reception in a particular direction. Again I repeat that the longer the antenna, the greater the number of teeth, and the larger the design ratio τ, the higher will be the gain and the front-to-back ratio. For the one shown in fig. 71 I have not shown any dimensions. Dimensions will depend on the frequency range to be covered. Obviously an antenna for a range of 2 to 30 mc will be longer and have more teeth than one for a range of 7 to 30 mc. The parameters will be the same, however.

The actual construction is quite simple. The teeth, made of wire, can be supported on a catenary suspended from one tall pole or tower to an anchor block in the earth, as shown in the sketch of fig. 72. The ground system can be a buried wire mat of the type shown in fig. 73, with a center buss of two inch wide copper strap, to which the bottom ends of the teeth must be bonded.

The teeth of the log-periodic do not have to be of trapezoidal shape. They can also be triangular in shape, as shown in fig. 74. In this case, the following equations apply:

$$\tau = \frac{R_n + 2}{R_n} \text{ and}$$

$$\sigma = \frac{R_n + 1}{R_n} = \sqrt{\tau}$$

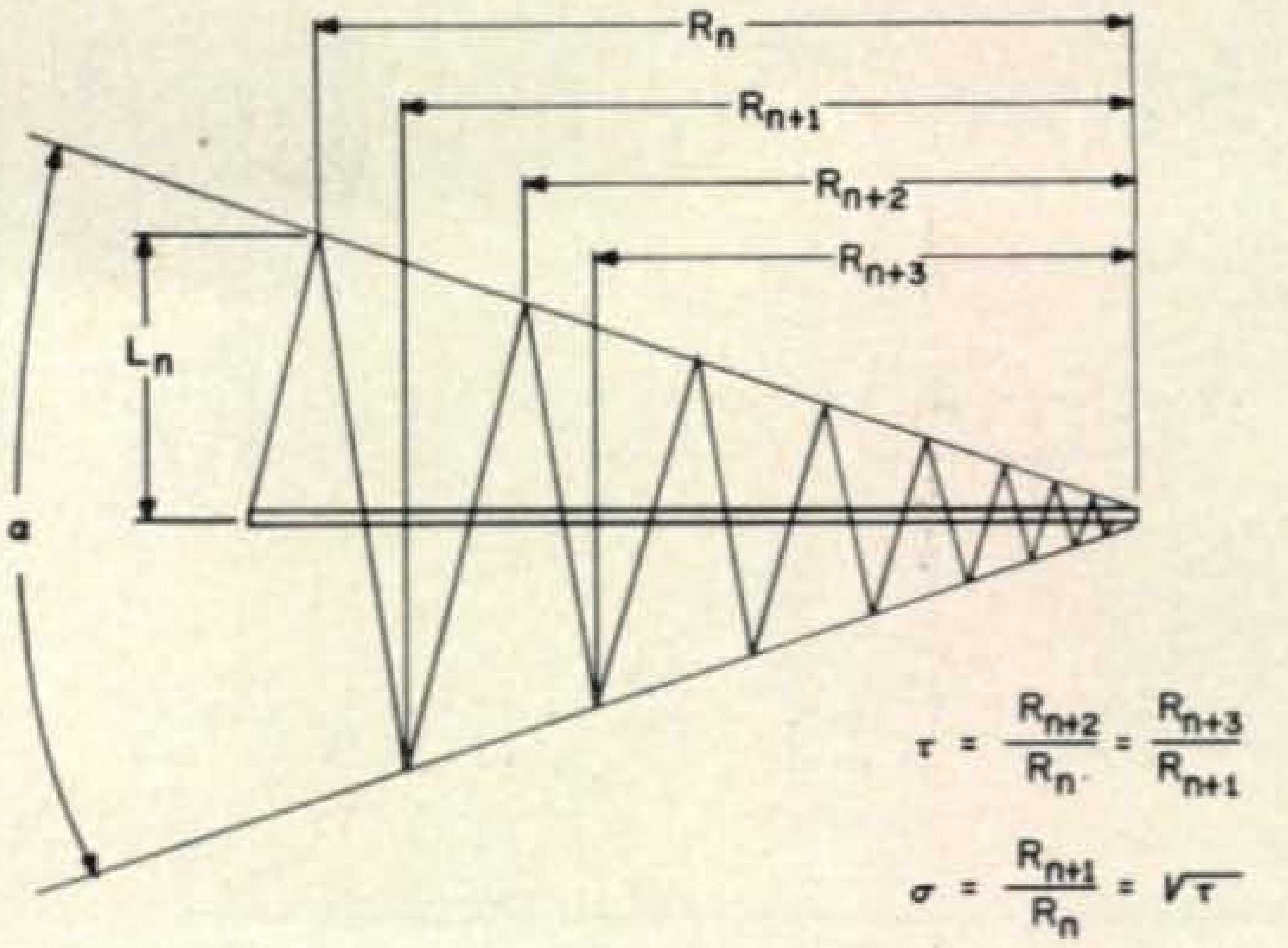

Fig. 74—Log periodic with triangular teeth.

As in the case of the trapezoidal teeth, the design ratio τ must not be less than about 0.7 for good gain and low back lobes.

$$\textit{Spacing } S_n = R_n - R_{n+1} = R_n (1 - \tau),$$

and the length of the n-th element is:

$$L_n = R_n \tan \frac{\alpha}{2},$$

and the element spacing-to-length ratio; therefore, is:

$$\frac{S_n}{L_n} = \frac{1 - \tau}{\tan \frac{\alpha}{2}}.$$

As in the previous case, this should not exceed a value of 1.30 for proper operation of the antenna. And as in the previous case,

$$\tau_{\min} = 1 - 1.3 \tan \frac{\alpha}{2}$$

For the case of the triangular tooth structure working against ground, one must actually design the structure of fig. 74, and

[*Continued on page 118*]

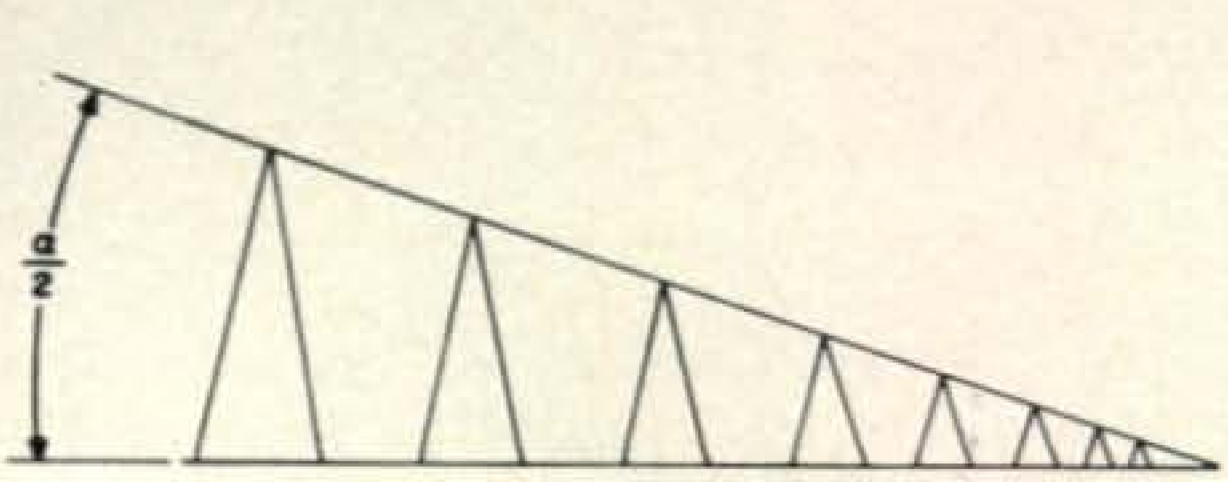

Fig. 75—Log periodic with triangular teeth for operation against ground.

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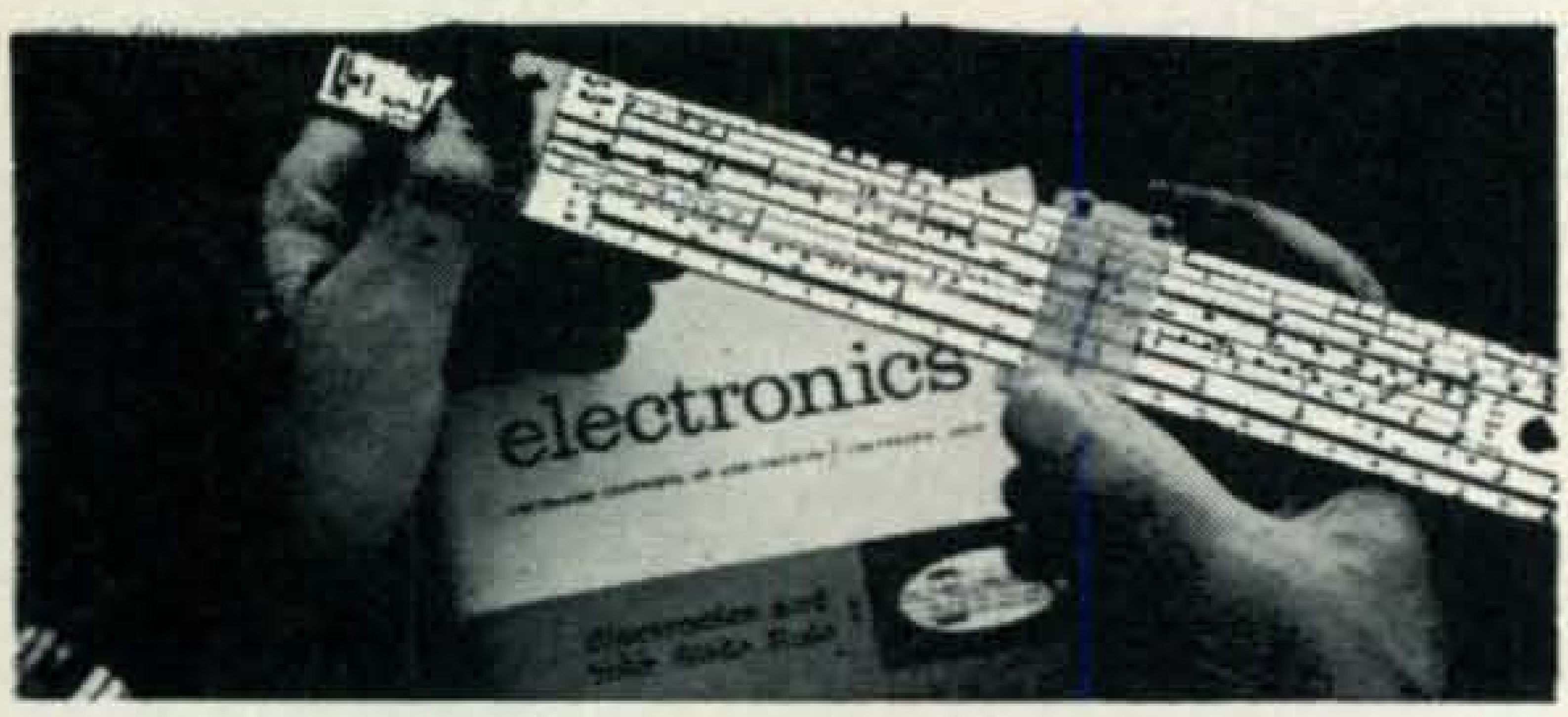

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is given by Eq. (1) in Part I. The proper viewing distance is 750 times the average center-to-center spacing between elements. If this is combined with Eq. (1), we find that the proper viewing distance is approximately given by:

$$Viewing\ Distance = 375D\sqrt{\frac{F}{W}} \qquad (2)$$

where D is the picture diagonal (in the same units as the viewing distance), F is the frame frequency, and W is the bandwidth. ■

Vertical Antennas [*from page 63*]

then cover up one half of it with a plain sheet of paper, leaving only the configuration shown in Fig. 75. The teeth of this one can be supported by a catenary, with single point suspension for each tooth. This triangular tooth model is perhaps somewhat easier to rig than the one with trapezoidal teeth. It can be fed in the same manner as shown in fig. 71, with coaxial line with broken outer conductor acting as sections of a capacitor.

It is possible to build an array of antennas of this type by using one common center supporting pole for the catenaries, and extending the catenary cables for two, three or four of these antennas out in the desired directions of transmissions. Each one would have its own feed cable, and thus the station operator would have a choice of directions by switching antennas. In a case of this kind, the ground systems should be connected together where they intersect.

In addition to the references listed [64, 65], there are many others in the technical literature. Jasik [62] is an excellent source of reference listings on antennas of all types, including the log-periodics.

[*to be continued*]

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[64] DuHamel, R. H. and Ore, F. R., "Logarithmically Periodic Antenna Designs," 1958 *IRE National Convention Record,* Part 1, p. 139-151.

[65] DuHamel, R. H. and Berry, D. G., "Logarithmically Periodic Antenna Arrays," 1958 *IRE WESCON Convention Record,* Part 1, p. 161-174.

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VERTICAL ANTENNAS

Part VIII

BY CAPTAIN PAUL H. LEE,* W3JM

Part IV, dealing with directional arrays, aroused considerable interest. In this part the author discusses the design of a specific array and its feed system. This array is easily adaptable to multi-element switchable configurations for changing direction of transmission.

SINCE the publication of Part IV[66], there has been considerable reader correspondence concerning the detailed design of directional arrays and their feed systems. Most of the inquiries have concerned the two-element array with 90° spacing and 90° phasing, and ways of switching three or four elements in pairs in order to use this two-element array for transmission in several selectable directions. Examples of this are three elements in an equilateral triangle, or four elements in a square, with 90° sides, with means of switching to any pair of them at one time.

Outlined below are the complete details of the design of a two-element array with 90° spacing and 90° phasing, and the design of its feed system and antenna matching units. This configuration will give only 3 db gain over the radiation from a single element, in spite of some claims of 6 db made by others.

A	B	C	D	E	F	G	H
ϕ	Cos A	S x B	$C+\psi$	Cos D	1+E	$\sqrt{F}$	KxG
0°	1.000	90.0	180.0	-1.00	0	0	0
10°	.985	88.7	178.7	- .99	.01	.1	13.8
20°	.940	84.6	174.6	- .99	.01	.1	13.8
30°	.866	77.9	167.9	- .98	.02	.14	19.3
40°	.766	68.9	158.9	- .93	.07	.26	35.9
50°	.643	57.9	147.9	- .85	.15	.39	53.8
60°	.500	45.0	135.0	- .71	.29	.54	74.5
70°	.342	30.8	120.8	- .51	.49	.70	96.5
80°	.174	15.7	105.7	- .27	.73	.85	117.3
90°	0	0	90.0	0	1.00	1.00	138.0
100°	- .174	-15.7	74.3	.27	1.27	1.12	154.6
110°	- .342	-30.8	59.2	.51	1.51	1.23	169.7
120°	- .500	-45.0	45.0	.71	1.71	1.31	180.7
130°	- .643	-57.9	32.1	.85	1.85	1.36	187.7
140°	- .766	-68.9	21.1	.93	1.93	1.39	191.8
150°	- .866	-77.9	12.1	.98	1.98	1.40	194.6
160°	- .940	-84.6	5.6	.99	1.99	1.41	195.6
170°	- .985	-88.7	1.3	.99	1.99	1.41	195.6
180°	-1.000	-90.0	0	1.00	2.00	1.41	195.6

Table I—Data for the computation of antenna radiation pattern.

It is impossible to obtain 6 db gain from two elements in any configuration. Three elements are required. Maximum in-line gain from two elements is 4.74 db, and this is with 30° spacing and 165° phasing. Readers are refered to references 39, 40 and 41 of Part IV for complete details of directional designs and patterns, and gains obtainable.

Pattern Computation

The first step in the design of any array is the pattern computation. This is a rather laborious process if one does not have a digital computer handy. It requires use of a slide rule and trigonometric tables, and a quick ability to visualize angles of more than 90° and their sines and consines. For pattern computation for ground wave only, and where the two tower currents are equal, the equation; $E = K\sqrt{1 + \cos(S \cos\phi + \psi)}$ is an easy one to use, where S is the spacing in degrees, ϕ is the azimuth angle, ψ is the phase angle, and K is a constant which depends on the r.m.s. of the mathematical plot.

For the array in question, S is 90°, ψ is 90°, ϕ is taken every 10° from 0° through 180°, and the computations are tabulated as shown here. For simplicity in labelling the columns, each is given a capital letter designation in Table I.

Columns A through G can be computed directly from the equation and the given values of S, ϕ and ψ. The next step is the determination of K, in order to produce column H which is a tabulation of unattenuated field intensity at one mile in millivolts per meter, for 500 watts radiated power using

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*5209 Bangor Drive, Kensington, Md. 20795

[66] Lee, P. H., "Vertical Antennas–Part IV", *CQ*, Sept. 1968, p. 37.

See page 110 for New Reader Service

two quarter wave elements. The first thing to be done is to find the r.m.s. of the pattern. This is done by adding up Column *F*, multiplying it by 2 (to get the whole pattern from 0° through 350°), then subtracting one set of values for 0° and 180° (so that they are not added in twice), dividing by 36, then taking the square root of what remains, thus:

$$\begin{array}{r} \text{Sum of column } F = 19.00 \\ \times 2 \\ \hline 38.00 \\ -0.00 \\ \hline 38.00 \\ -2.00 \\ \hline 36.00 \end{array}$$

$$\frac{36.00}{36} = 1.00$$

$$\sqrt{1.00} = 1.00 \text{ r.m.s. of pattern.}$$

$$1.00 = 138 \text{ mv/m for } \lambda/4 \text{ elements.}$$

$$K = 138$$

The pattern can be plotted in mv/m, in which case Column *H* is plotted, or it can be plotted normalized to its r.m.s. When one is discussing array theory and design, the plot is usually normalized to an r.m.s. of 1.00 so that the plot shows the gain or loss at any particular azimuth angle ϕ. The plot of the above computations is shown on this basis in fig. 76, which is the same as fig. 27 in Part IV. It will be seen that the voltage (field intensity) gain at 180° is 1.41. The power gain is therefore 2, and this equals 3 db.

In the event that you are a bit confused by the mathematics above, let's say that in the case of an in-line array the pattern will be the same on both sides of the line of towers. Hence the tabulation stopped at 180°. There is no need to carry it on to 360°, for the values will be identical to those already tabulated. However, in computing the r.m.s., one must include 36 items, and only 36. Hence the doubling of the sum of Column *F*, and the subtraction of one set of 0° and 180° items which would otherwise appear twice in the summation. It is purely happenstance that the sum of Column *F* comes out as it does, and that the r.m.s. of the pattern is 1.00, in the above case. It does so because of the 90°

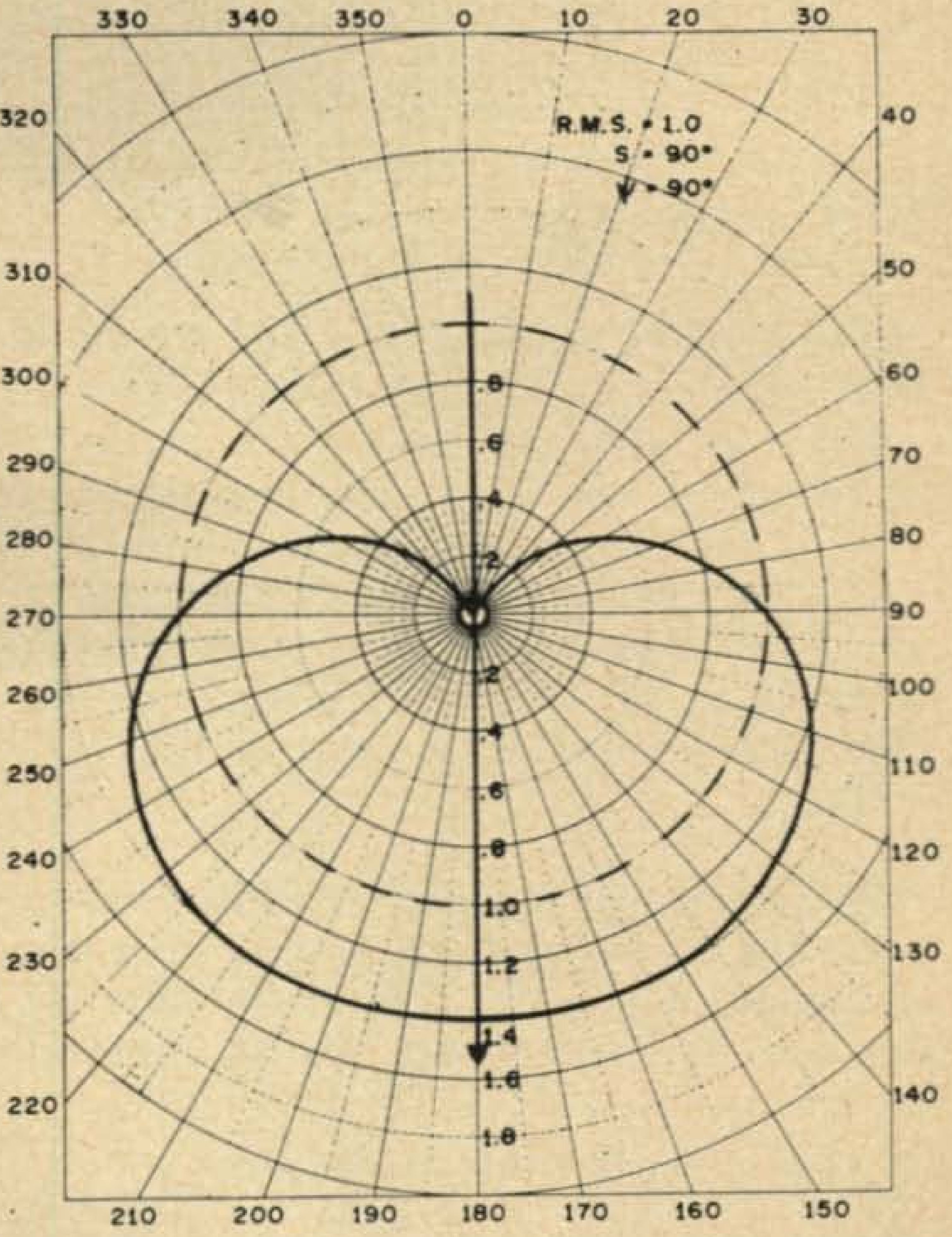

Fig. 76—Polar pattern for the design problem illustrated in the text.

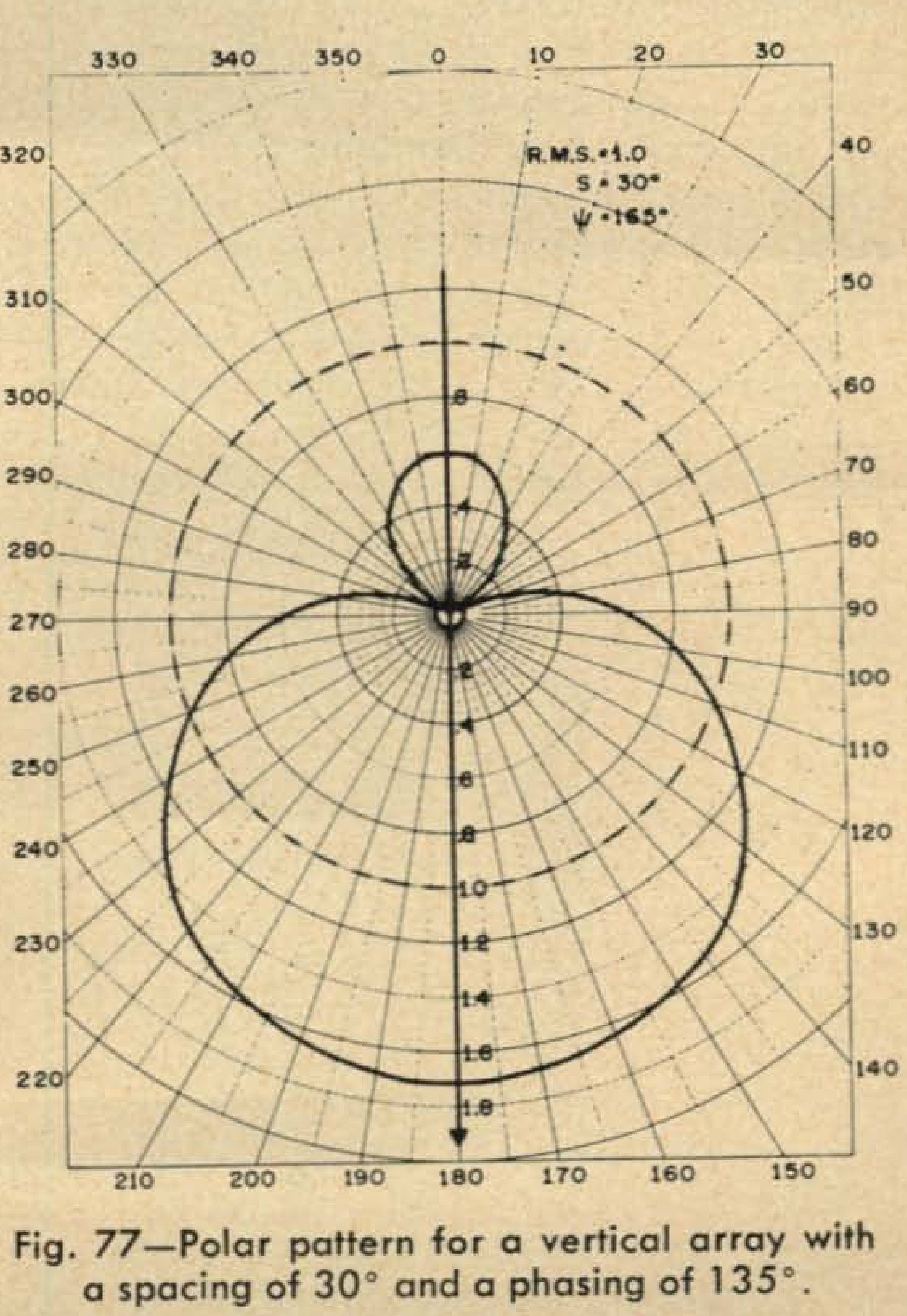

Fig. 77—Polar pattern for a vertical array with a spacing of 30° and a phasing of 135°.

A	B	C	D	E	F	G	H	I	J
φ	CosA	.985B	S×C	D+ψ	CosE	1+F	√G	.965H	K×I

Table II—Headings needed for tabulation of data for vertical pattern computation.

phasing and 90° spacing. It would not do so with other values. For example, if I were to tabulate the computations for the case of S = 30° and ψ = 165° (maximum in-line gain of 4.74 db), the sum of Column *F* would be 1.871, and when the r.m.s. is computed it would be 0.308. For an r.m.s. of 138 mv/m, *K* would be 448. Figure 77 is a plot of this pattern, normalized to an r.m.s. of 1.00.

Vertical Pattern

In commercial practice we often need to know the vertical pattern as well. This can be computed in a like manner, by inserting the vertical angle θ into the formula, as shown here:

$$E = K\,f(\theta)\sqrt{1 + \cos\,(S \cos\phi \cos\theta + \psi)}$$

The vertical shape factor $f(\theta)$ was discussed in Part IV, and it depends on the tower height *G* in degrees. For the case of quarter wave towers used here, $f(\theta)$ is 0.965 when θ is 10°. Cos θ is 0.985 when θ is 10°. The table of computations would thus look like Table II as a start. There is no point in finishing it as it would not accomplish very much except to use up space. A similar table would be required for each value of θ, every 10 degrees. In broadcast consulting work, this is required by the FCC for directional arrays. Let me summarize by saying that for in-line arrays, the vertical pattern of the main lobe in the line of towers is generally a bit more flat than that from one tower alone, the vertical pattern broadside to the line of towers is the shape of that of one tower alone, and the vertical pattern at other angles has to be computed to be known accurately. But in our case, let's not worry about the exact vertical pattern of this array, and get on with the design of the system.

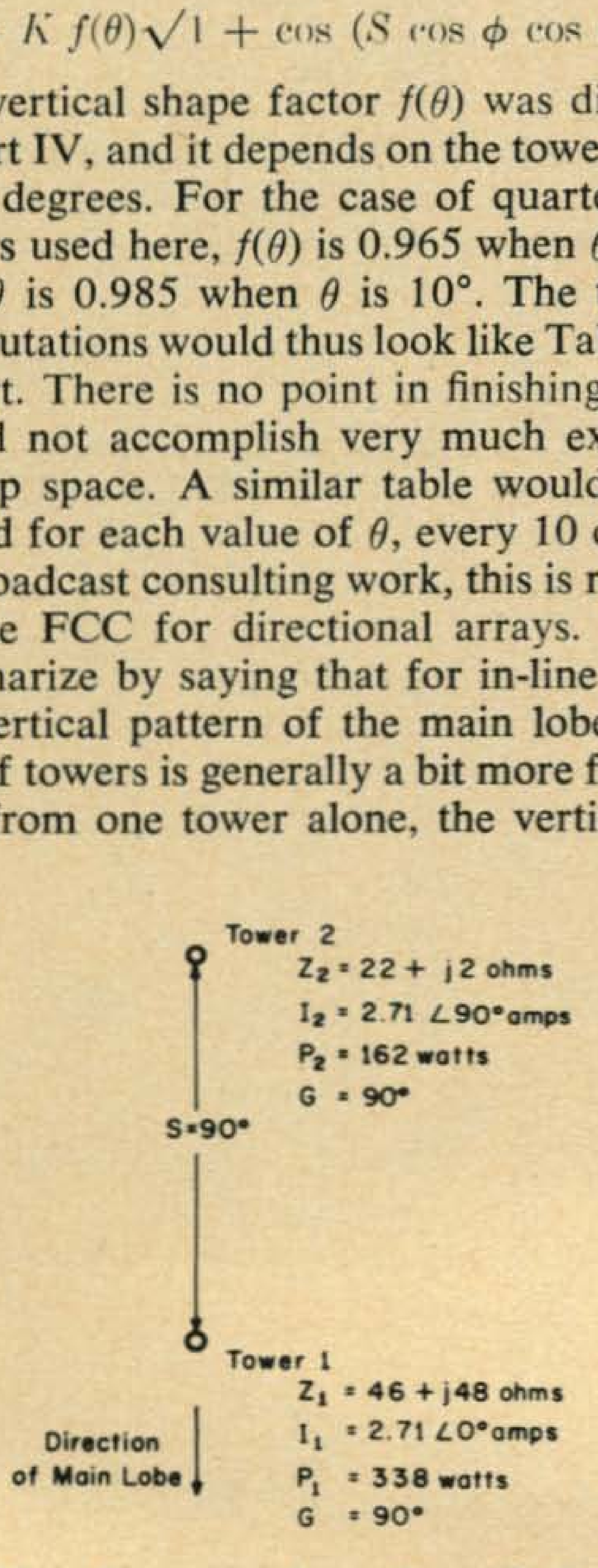

Fig. 78 — Array configuration of the design example discussed in the text.

Element Self-Impedance

Now that we have the array parameters, how do we feed it? The first step is a determination of the self-impedance of the elements (which are called towers). The array designer has to start somewhere, and that place is with published plots of *R* and *jX* versus tower height in wavelengths. Let's assume that this array is to be designed for 3.9 mc. A tower height of 60 feet would be about right for a quarter wavelength. An effective diameter of 7 inches would be reasonable. L/D would therefore be about 100. Referring back to Part II[67] it will be found that K_a for this value of L/D is 599. Or K_a can be computed from the equation:

$$K_a = 120 \log \frac{L}{D} - 120$$

Again referring to Part II, figure 13, for a tower height of a quarter wave and K_a of 600, R = 34 ohms and $X = +j25$. The next step is the computation of the effect of the mutual impedance between the towers, and the actual operating impedances of each tower. Again refering to Part IV, fig. 32, we find that the mutual impedance between towers 1 and 2 equals 23–j12 ohms, for the 90° spacing of two quarter wave elements.

The equations for the operating impedances of the two towers when connected in the array are:

$$Z_1 = Z_{11} + \frac{I_2}{I_1} Z_{21} \text{ and}$$

$$Z_2 = Z_{22} + \frac{I_1}{I_2} Z_{12}$$

where Z_{11} is the self-impedance of tower 1 by itself,

Z_{22} is the self-impedance of tower 2 by itself,

I_1 is the base current (loop current) of tower 1,

I_2 is the base current (loop current) of tower 2,

Z_1 is the actual operating impedance of tower 1 in the array, and

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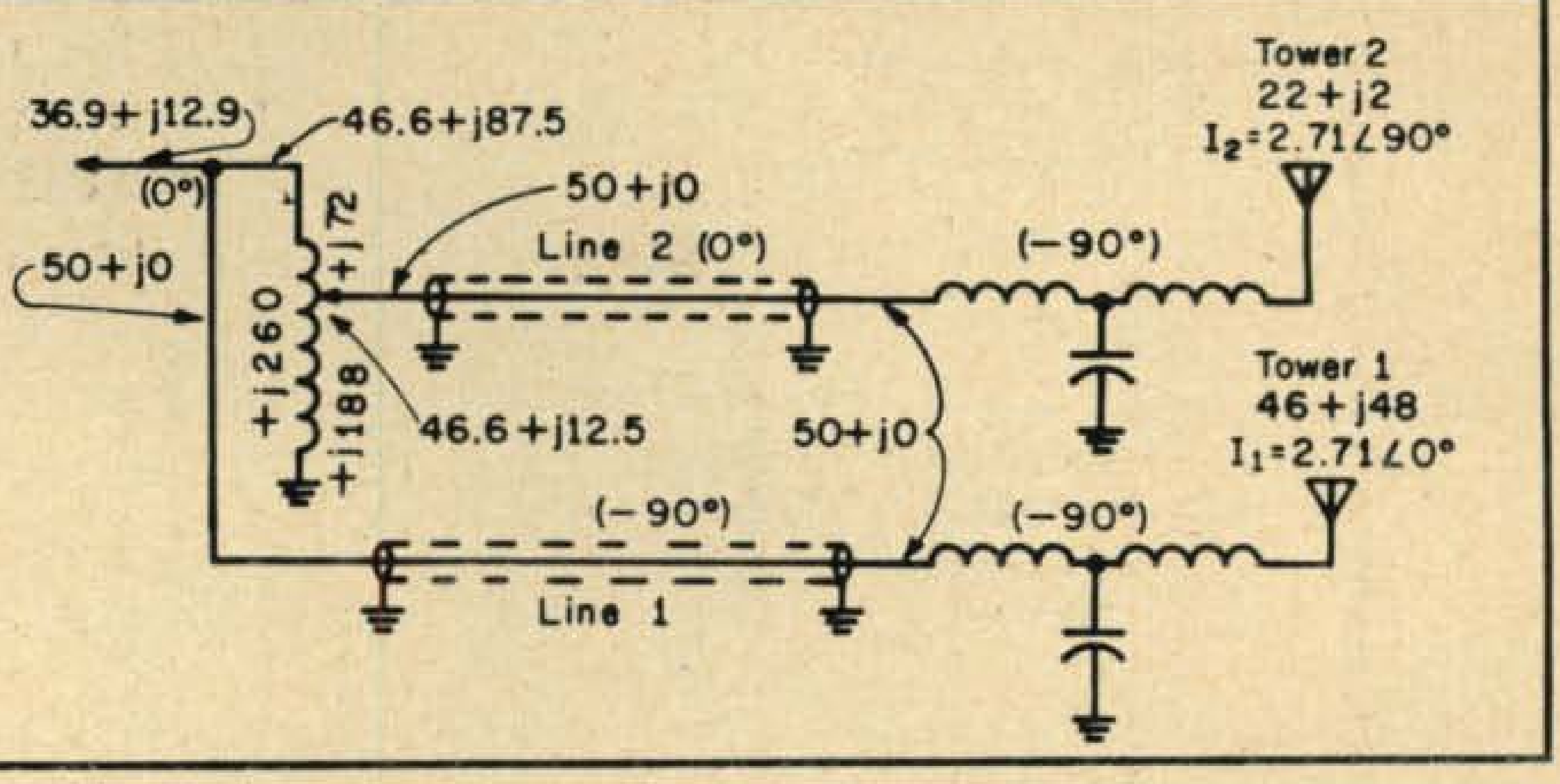
[67] Lee, P. H., "Vertical Antennas–Part II", *CQ*, July 1968, p. 25.

Fig. 79—Power dividing circuit for the array design of fig. 78. Phase shifts and impedances at various points are noted. Line 1 is 90° longer than line 2 and the relative phase shifts are 90° and 0°.



Z_2 is the actual operating impedance of tower 2 in the array.

We just found Z_{11} and Z_{22} from fig. 13 of Part II, and they are $34 + j25$. Since we don't know the currents yet, and we are only interested in their ratio and phase angle at this time, let $I_1 = 1.0/\,0^\circ$ and $I_2 = 1.0/\,90^\circ$. Mutual impedance $Z_{21} = Z_{12} = 23 - j12$.

Solving for Z_1:

$$\begin{aligned} Z_1 &= (34 + j25) + \left(\frac{1.0\ \underline{/90^\circ}}{1.0\ \underline{/\,0^\circ}}\right)(23 \times j12) \\ &= (34 + j25) + (1.0\ \underline{/90^\circ})\ (26\ \overline{\diagdown 27.5^\circ}) \\ &= (34 + j25) + (26\ \underline{/62.5^\circ}) \\ &= (34 + j25) + (12 + j23) \\ &= 46 + j48 \text{ ohms} \end{aligned}$$

Solving for Z_2:

$$\begin{aligned} Z_2 &= (34 + j25) + \left(\frac{1.0\ \underline{/\,0^\circ}}{1.0\ \underline{/90^\circ}}\right)(23 - j12) \\ &= (34 + j25) + (1.0\ \overline{\diagdown 90^\circ})\ (26\ \overline{\diagdown 27.50}) \\ &= (34 + j25) + (26\ \overline{\diagdown 117.5^\circ}) \\ &= (34 + j25) + (-12 - j23) \\ &= 22 + j2 \text{ ohms} \end{aligned}$$

Note the difference between these values and the self-impedance of the towers! The mutual impedance and the currents flowing cause quite an effect!

Now that we have the actual operating impedances of the two towers, we can find the currents.

$$\begin{aligned} P_1 &= I_1^2\, R_1 \\ P_2 &= I_2^2\, R_2 \\ P_1 + P_2 &= 500 \text{ watts} \\ I_1 &= I_2 \\ I_1^2\, R_1 + I_1^2\, R_2 &= 500 \\ I_1^2\,(R_1 + R_2) &= 500 \\ I_1^2\,(46 + 22) &= 500 \\ I_1 &= 2.71 \text{ amps.} \end{aligned}$$

As a check:

$$\begin{aligned} P_1 &= (2.71)^2\, 46 = 338 \\ P_2 &= (2.71)^2\, 22 = 162 \\ P_{\text{Total}} &= 162 + 338 \\ &= 500 \text{ watts} \end{aligned}$$

The array configuration is shown in fig. 78. This brings up one point to be remembered, which is that in the case of an in-line array, the main lobe is always in the direction of the tower with the lagging phase (in this case I_1 legs I_2 by 90°).

Power Divider

Now that we have the tower operating impedances, it is possible to design the power dividing circuit and the antenna tuning units. Again referring to Part IV, we shall use the Ohms Law network. Since we have only two towers, and one of them is taking 2.1 times the power taken by the other, it is quite simple. We can feed tower 1 directly from the branching point, and tap down on a power divider coil for the feed to tower 2. See fig. 79 for the complete network.

How do we arrive at the various values of reactance shown? First, since the array is to work on 3.9 mc, we assume a 10 micro henry power divider coil will be used. This is a reasonable value. Since the power ratio between the towers is 2.1, tower 2 feed is tapped down on the coil at a 72.5% point. The total coil reactance at 3.9 mc is $+j260$ ohms. The tap is at $+j188$ ohms, leaving $+j72$ ohms above the tap. Considering the feedline to be a pure 50 ohms resistive load, the parallel combination of 50 and $+j188$ is computed:

$$\frac{(50\ \underline{/\,0^\circ}\ )\ (188\ \underline{/90^\circ})}{50 + j188} =$$

$$\frac{9400\ \underline{/90^\circ}}{195\ \underline{/75^\circ}} =$$

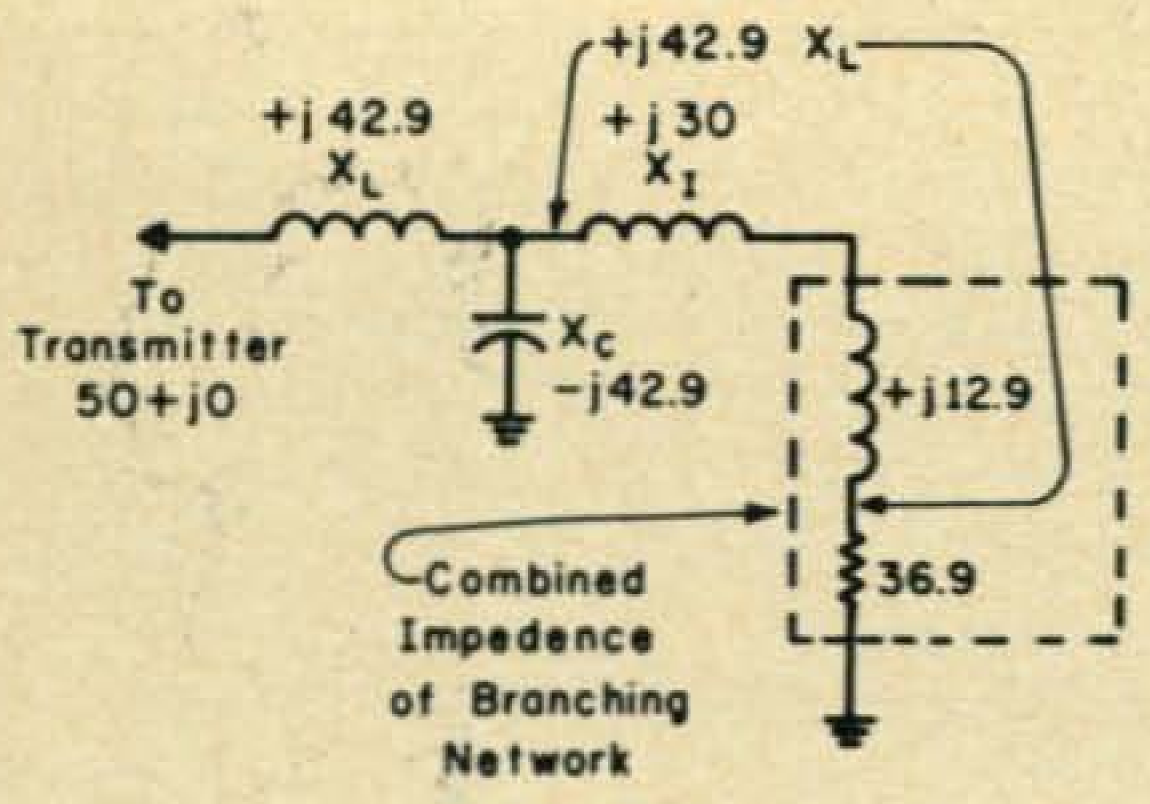


Fig. 80—Input T network.

$$48.2\ \angle 15^\circ = 46.6 + j12.5$$

Add the upper portion of the coil to this, to find the total impedance of the tower 2 feed which is presented to the branching point:

$$46.6 + j12.5 + j72 = 46.6 + j87.5 \text{ ohms}$$

Next, add in parallel the 50 ohm pure resistance of tower 1 line and the above combined value for tower 2 feed:

$$\frac{(46.6 + j87.5)\ (50\ \angle 0^\circ)}{50 + 46.6 + j87.5} =$$

$$\frac{(99.1\ \angle 67^\circ)\ (50\ \angle 0^\circ)}{96.6 + j87.5} =$$

$$\frac{4960\ \angle 62^\circ}{130\ \angle 42.2^\circ} =$$

$$38.1\ \angle 19.8^\circ = 36.9 + j12.9 \text{ ohms}$$

This is the parallel combination of the tower 1 and tower 2 feeds at the common point. As may be seen, it is quite a long way from being a pure 50+j0 ohms which a transmitter would like to see. Since we have only two towers, and this impedance value is so close to 50 ohms, we can dispense with the tuned tank arrangement shown in fig. 35 of Part IV and transform this 36.9 + j12.9 ohms to 50 + j0 with a simple T network. (Another reason for the tuned tank in broadcast applications is that it enables the operator to maintain the common input impedance to licensed value quite easily. In this application we are not concerned with this.)

Another very helpful trick which one soon learns in this business is the usefulness of a 90° network. It is so easy to compute and to use, where the 90° phase shift is of no consequence! In a 90° network, where R_1 and R_2 are the input and output terminating resistances, the values of X_C and X_L in the network are determined very easily from the formula:

$$X = \sqrt{R_1 R_2}$$

The T network for the input of this branching system is shown in fig. 80. In this case:

$$X = \sqrt{36.9 \times 50}$$
$$= 42.9$$

$X_C = -j42.9$ or 950 mmf at 3.9 mc.
$X_L = +j42.9$ or 01.85 mh at 3.9 mc.
$X_1 = +j42.9 - j12.9 = +j30$ or
0.14 mh at 3.9 mc.

Tuning Units

Now we must turn our attention to the antenna tuning units. Working our way outward from the branching circuit, tower line 1 must have 90° more electrical length in it than tower line 2. If it does not, a T phase shift network would be necessary. A 90° T for 50 ohms would consist of series X_L = +j50 elements, and shunt $X_C = -j^{50}$ elements, which would have to be variable to take care of strays. It is much easier to make the lines 90° different in length, and take care of any strays by slight adjustment of the antenna tuning units (ATUs).

As in the case of the input T, we again make use of the easy design of the 90° T in the ATUs. For tower 1, the ATU is shown in fig. 81.

$$X = \sqrt{46 \times 50}$$
$$X = 47.9$$

$X_C = -j47.9$ or 850 mmf at 3.9 mc.
$X_L = +j47.9$ or 1.85 mh at 3.9 mc.
$X_1 = +j47.9 - j48 = -j0.1$

In this case it would be necessary to put a series capacitor in, because X_1 is so close to zero, it could go a bit either way in actual adjustment. Series 50 ohms is 800 mmf at 3.9 mc. X_1 should then be made about +j75, adjustable.

ATU number 2 is done in the same way. It is shown in fig. 82.

$$X = \sqrt{22 \times 50} = 33.2$$

$X_C = -j33.2$ or 1230 mmf at 3.9 mc.
$X_L = +j33.2$ or 1.35 mh at 3.9 mc.
$X_1 = +j33.2 - j2 = +j31.2$ or
1.27 mh at 3.9 mc.

This, then, is how we design a directional antenna system with its phasing and branching networks and antenna tuning units. In actual practice the values of reactance required are given about a 50% increase in tolerance to take care of differences between measured and computed antenna impedances and mutual impedances. The first step is the design shown here. The next step is construction of the array and its ground system, and actual r.f. bridge measurement of tower and mutual impedances. These should be fairly close to the predicted values. Using the *measured* values, the professional engineer then runs through the phasing and branching network calculations *again,* to determine as closely as possible the values to which all reactances should be set. Coils are variable, either with movable taps or of the rotary variety. Fixed capacitors are used, in series with adjustable coils, to obtain the $-jX$c values required. (Capacitive reactance is made too large, and a portion is cancelled out by a variable coil.) The engineer then uses the r.f. bridge to set all components to their final *computed* values. Power is then applied (low power at first), and tower currents and phases are read. Field intensity readings are taken in the nulls in the pattern. Final adjustments are made, sometimes over a period of many night (midnight to 6 A.M.), to bring the array in to its design values and the nulls down to FCC required values of field intensity.

For the amateur, the proof of successful operation would be the reading of tower currents, and a check of the forward gain, or the depth and azimuth of the designed nulls. This can be done more easily and with less hard work than in the broadcast case where tolerances must be very close. If a good check on the operation of the above array is desired, it can be obtained by first operating one tower alone, with the other one floating or detuned, and measuring field intensity around it at various azimuths. If it is in the clear, with no other objects to absorb or distort the field, a fairly circular pattern should be obtained. With a known power input, the radiation efficiency can be obtained by plotting field intensity versus distance as described in Part I.[68] The array an then be connected, and with the same input power, its field intensity should be measured *at the same points* as with the single tower. This pattern can then be plotted. The ratio of the directional to non-directional field intensity at a particular point or along a particular radial is the gain (or loss) of the array at that azimuth. Unless there are unpredictable things such as houses, power line, other antennas, *etc.*, distorting the field, the plot should be close to the original design plot. In no case will the two-element array shown, with 90° spacing and 90° phasing, produce more than approximately 3 db in the main lobe.

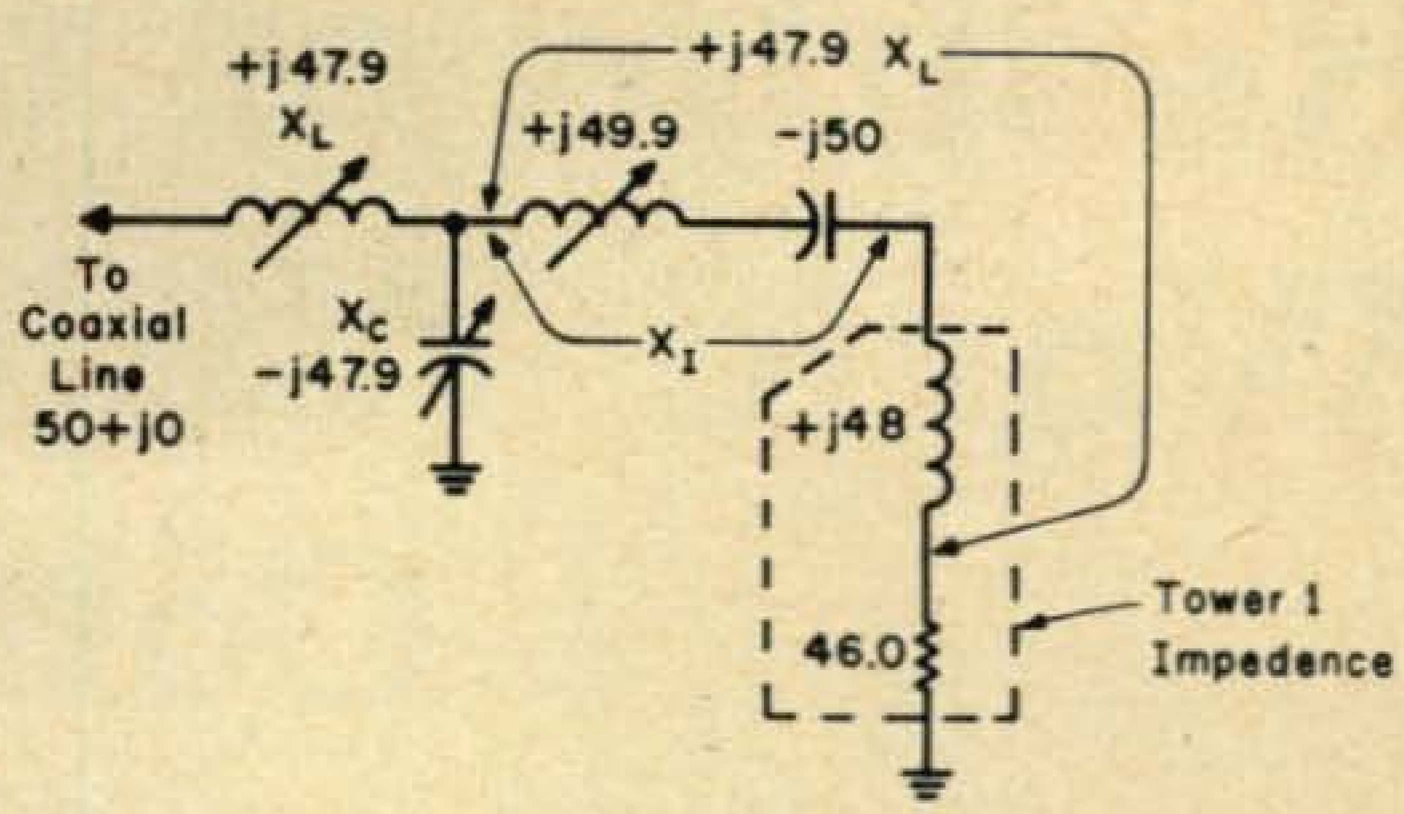


Fig. 81—Antenna tuning unit (ATU) for tower 1.

One additional check which is useful is that the r.m.s. value of the directional pattern should approach very closely the value of the field of the circular non-directional pattern, with the same input power. It may be slightly lower due to added losses in the second tower and coupling systems.

Arrays of this configuration have been built without ATUs or branching circuits, feeding power to the towers by merely connecting coaxial lines to them and paralleling them, with one 90° longer than the other. These do

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[68] Lee, P. H., "Vertical Antennas—Part I", *CQ,* June 1968. p.

[*Continued on page 100*]

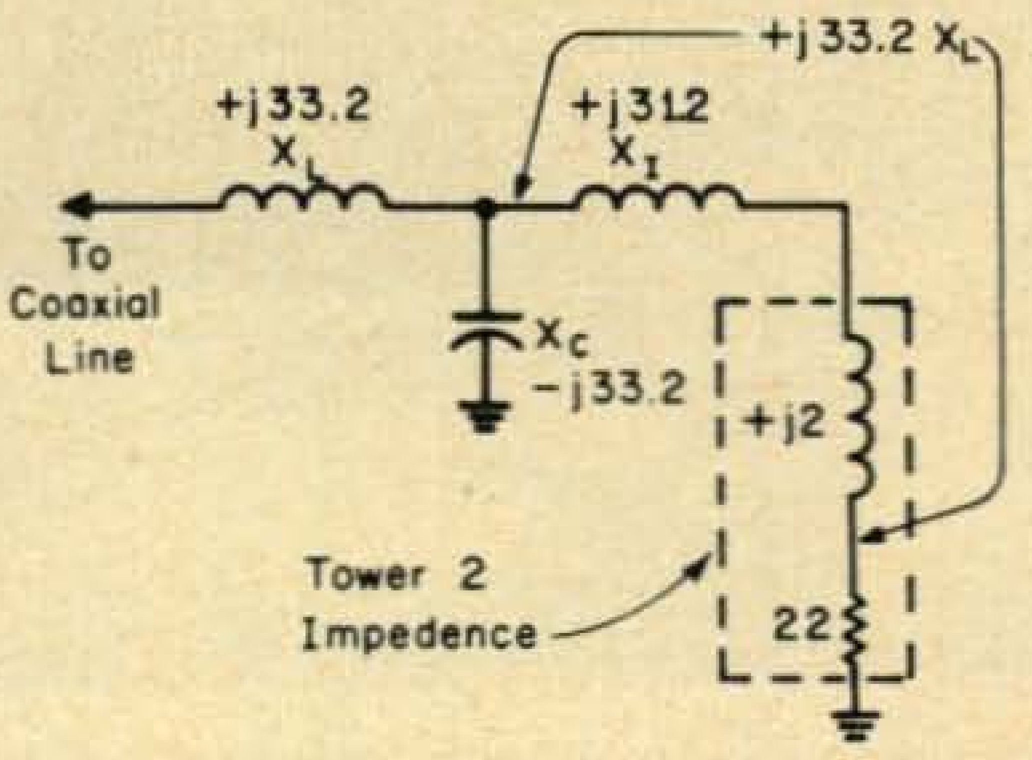

Fig. 82—Antenna tuning unit for tower 2.

section of the higher and most interesting early scores, so don't panic if you don't see yours listed.

All certificates for the 1967 contest have been mailed. Some have already been returned marked "unknown" or "insufficient" address. So if you have not received yours you might forward us your correct mailing address.

A report on the c.w. weekend next month.

73 for now, Frank, W1WY

Vertical Antennas [*from page 57*]

work after a fashion, but the adjustment can hardly be optimum without some means of assuring proper power division and equal tower currents.

There have been inquiries about the broadside case, where $S=210°$ and $\psi=0°$. This one produces a figure eight pattern with a gain of 5.2 db in each lobe. This one should be very popular, for the fact that all ATUs are the same (with 0° phasing) makes it very easy to erect three towers in an equilateral triangle and switch pairs of towers, thus covering six directions. I plan to discuss this one in the next installment.

Erratum

It is regretted that figs. 42 and 43 were inadvertently reversed in Part V.[69]

For those who write, please enclose a self-addressed stamped envelope if you wish a reply. The mail from this series is quite heavy.

[To be continued]

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[69] Lee, P. H., "Vertical Antennas–Part V", *CQ*, Oct. 1968, p. 43.

Z-Bridge [*from page 35*]

odd dollars the apparatus cost. Aluminum tubing and U-bolts are much cheaper than pre-built arrays, and the home-brew jobs work just as well as their commercial counterparts provided they are tuned and matched correctly.

To tune a parasitic array whose front-to-back ratio is 18 db or more, actual height operating conditions may be closely simulated by pointing the beam straight up in the air, provided the back reflector is about nine feet off the ground. Using the bridge to adjust feed-point impedance and a field strength meter to adjust back cut-off, one man may tune a beam very close to optimum in a very short time. ■

VERTICAL ANTENNAS

Part IX

BY CAPT. PAUL H. LEE,* W3JM

The author, in this installment, Part IX, discusses a very simple directional array which can be built in an equilateral triangle configuration. Using any two elements at a time world wide coverage can be obtained at a gain of 5.2 db.

As previously stated in Part IV[70], the maximum gain obtainable with two vertical elements in any configuration is 5.2 db. This occurs with an element spacing of 210°, and with equal in-phase currents. Readers should refer to references 39, 40 and 41 of Part IV for details of this and other directional configurations, and gains obtainable. I should also reiterate here that when talking about gain of an array of equal height elements, the reference is the non-directional field which would be radiated from one single element of the same height when the total power fed to the array is fed to it. The field from a single element radiating 500 watts would be 138 mv/m at one mile, for example. This field, minus any losses due to the directional array's phasing and branching system (usually less than 2% for a two element array), will be equal to the r.m.s. of the directional pattern. Thus, when plotting a directional pattern, we can use the ratio of the pattern's field in any direction to its r.m.s. as the pattern's voltage gain in that particular direction. Knowing the voltage gain, we can find the gain in db easily.

Equlateral Triangle

The case of two elements spaced 210° with equal in-phase currents lends itself very nicely to an equilateral triangle configuration, with the elements fed two at a time by means of a switching arrangement. This case is also a very easy one to compute. Inasmuch as the currents in the equal height elements are equal and in phase, the elements' operating impedances will be equal, they will be fed equal amounts of power, and their antenna tuning units will be identical. This makes the switching arrangement very simple, for the triangular configuration.

First, let's run through the pattern computation for this one, as done in Part VIII[71]

A	B	C	D	E	F	G	H	J
ϕ	Cos A	S x B	$C+\psi$	Cos D	1+E	$\sqrt{F}$	K x G	1.29xG
0°	1.000	210.0	210.0	-.866	.134	.366	65.1	.472
10°	.985	206.7	206.7	-.894	.106	.326	48.2	.421
20°	.940	197.3	197.3	-.954	.046	.214	38.1	.276
30°	.866	182.0	182.0	-.999	.001	.031	5.5	.040
40°	.766	160.9	160.9	-.945	.055	.234	41.7	.302
50°	.643	135.0	135.0	-.707	.293	.542	96.4	.699
60°	.500	105.0	105.0	-.259	.741	.861	153.2	1.110
70°	.342	71.8	71.8	+.313	1.313	1.143	203.5	1.474
80°	.174	36.5	36.5	+.804	1.804	1.342	239.0	1.731
90°	0	0	0	1.000	2.000	1.414	252.0	1.825
100°	-.174	-36.5	-36.5	+.804	1.804	1.342	239.0	1.731
110°	-.342	-71.8	-71.8	+.313	1.313	1.143	203.5	1.474
120°	-.500	-105.0	-105.0	-.259	.741	.861	153.2	1.110
130°	-.643	-135.0	-135.0	-.707	.293	.542	96.4	.699
140°	-.766	-160.9	-160.9	-.945	.055	.234	41.7	.302
150°	-.866	-182.0	-182.0	-.999	.001	.031	5.5	.040
160°	-.940	-197.3	-197.3	-.954	.046	.214	38.1	.276
170°	-.985	-206.7	-206.7	-.894	.106	.326	48.2	.421
180°	-1.000	-210.0	-210.0	-.866	.134	.366	65.1	.472

Table III — Data for the computation of the antenna radiation pattern shown in fig. 83.

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*5209 Bangor Drive, Kensington, Md. 20795.

[70] Lee, P. H., "Vertical Antennas–Part IV", *CQ,* Sept. 1968.

[71] Lee, P. H., "Vertical Antennas–Part VIII", *CQ,* Jan. 1969.

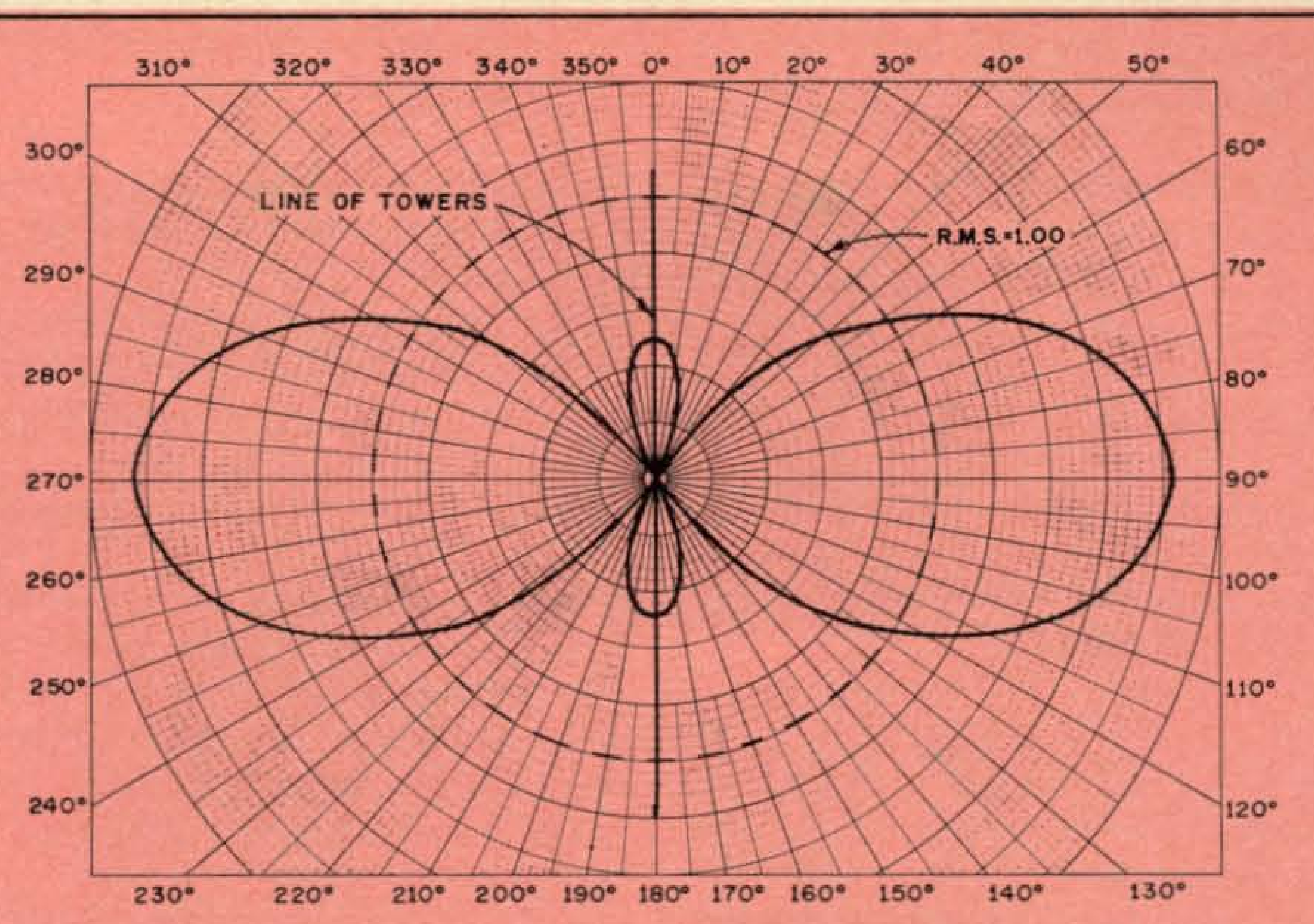

Fig. 83—Antenna radiation pattern, plotted from Column J of Table III for the two elements 210° apart with equal, in phase, currents.

for the case of 90° spacing and 90° phasing. For ground wave pattern computation, and where the two tower currents are equal, the equation used is:

$$E = K\sqrt{1 + \cos\,(S \cos \phi + \psi)}$$

where S = spacing in degrees
ϕ = azimuth angle
ψ = phase angle
K = constant depending on r.m.s. of the pattern's mathematical plot.

For the array being discussed here, S is 210°, ψ is 0°, and ϕ is taken every 10° from 0° through 180°. The tabulation of computations is shown in Table III. Each column is given a capital letter designation for simplicity in labelling the columns in the heading of the table. The computation follows through very logically, step by step, column by column.

The pattern will be symetrical about the line of towers, so it is necessary to compute only from 0° through 180° the values for columns A through G. The r.m.s. of the pattern is determined by adding column *F*, multiplying it by 2 (to get the whole pattern from 0° through 350°, then subtracting one set of values for 0° and 180° (so that they are not included twice in the summation), dividing by 36, then taking the square root of what remains:

$$\begin{array}{rr} \text{Sum of column } F = & 10.986 \\ & \times\ \ 2 \\ \hline & 21.972 \\ & -.134 \\ \hline & 21.838 \\ & -.134 \\ \hline & 21.704 \end{array}$$

$$\frac{21.704}{36} = 0.603$$

$$\sqrt{0.63} = 0.776 \text{ r.m.s.}$$

$$K = \frac{138}{0.776} = 178$$

Column *H* shows the value of the radiated field at the various values of ϕ, in mv/m at one mile. Column *J* shows the pattern normalized to a value of 1.00 for its r.m.s., for purposes of determining voltage gain. The values in column *J* are plotted in fig. 83. The gain in the direction of the maximum lobes (broadside to line of towers) is 1.825, which is a power gain of 3.33 or 5.23 db. There are two minor lobes, with two pairs of nulls at 31°, 149°, 211°, and 329°. I might state here that if the spacing were 180° instead of 210°, with equal in-phase currents, the two minor lobes would not be present. There would be only two nulls, at 0° and 180°, but the gain at 90° and 270° would be reduced to 4.56 db. Any reader who wishes to run through the pattern computation for this latter case is welcome to do so, and find out this answer for himself.

If one wishes to compute the vertical pattern in the case of this 210° spacing, 0° phasing array, it may be done by use of the expanded formula:

$$E = K f(\theta) \sqrt{1 + \cos (S \cos \phi \cos \theta + \psi)}$$

Factor $f(\theta)$ was discussed in Part IV, and it depends on the tower height G in degrees. θ is the vertical angle for which the value of radiation is to be computed.

Feed Design

With the array parameters decided, we must now determine how to feed it. The first step is the determination of the self-impedance of each tower. Assuming a design frequency of 3.9 mc, a tower height of 60 feet is about right for a quarter wavelength. Assuming an effective diameter of 7 inches, the L/D of the tower would be about 100. Referring back to Part II[72] it will be found that K_a for this value of L/D is 599. Or K_a can be computed from the equation:

$$K_a = 120 \log \frac{L}{D} - 120.$$

From fig. 13 of Part II, for a tower height of a quarter wave and a K_a of 600, $R = 34$ ohms and $X = +j25$ ohms. Next comes the computation of the effects of mutual impedance between the towers, and the actual operating impedance of each tower. Again referring to Part IV, fig. 32, we see that the mutual impedance between the towers spaced 210° is $-9 -j11$ ohms. Yes, -9 ohms! Don't let the minus sign in front of the R term frighten you. It is perfectly "legal."

The equations for finding the actual operating impedances of each tower are:

$$Z_1 = Z_{11} + \frac{I_2}{I_1} Z_{21} \text{ and,}$$

$$Z_2 = Z_{22} + \frac{I_1}{I_2} Z_{12}.$$

where Z_{11} is the self-impedance of tower 1 by itself,

Z_{22} is the self-impedance of tower 2 by itself,

I_1 is the base current (loop current) of tower 1,

I_2 is the base current (loop current) of tower 2,

Z_1 is the actual operating impedance of tower 1 in the array, and

Z_2 is the actual operating impedance of tower 2 in the array.

This is the same set of equations used in Part VIII.

Having found Z_{11} and Z_{22} from fig. 13 of Part II, we know them to be $34 + j25$ ohms. The mutual impedances Z_{21} and Z_{12} equal $-9 -j11$ ohms. We do not know the magnitude of I_1 and I_2 yet, but they are equal and in phase, and can be represented as $I_1 = I_2 = 1.0 \underline{/ 0°}$.

Solving for Z_1:

$$Z_1 = (34 + j25) + \left(\frac{1.0 \underline{/ 0°}}{1.0 \underline{/ 0°}}\right) (-9 -j11)$$
$$Z_1 = (34 + j25) + (1)(-9 -j11)$$
$$Z_1 = 25 + j14 \text{ ohms}$$

Solving for Z_2:

$$Z_2 = (34 + j25) + \left(\frac{1.0 \underline{/ 0°}}{1.0 \underline{/ 0°}}\right) (-9 -j11)$$
$$Z_2 = (34 + j25) + (1)(-9 -j11)$$
$$Z_2 = 25 + j14 \text{ ohms}$$

Note that we get the same result. This means that the operating impedances of the two towers are identical. Note, however, how different they are from the tower self-impedances. The effect of the mutual impedance and the currents flowing is quite pronounced.

Tower Currents

Now that we know the actual operating impedances we can find the tower currents:

$$P_1 = I_1^2 R_1$$
$$P_2 = I_2^2 R_2 \text{ and}$$
$$P_1 + P_2 = 500 \text{ watts}$$

$$I_1 = I_2 \text{ and, in this case,}$$
$$R_1 = R_2$$

Therefor:

$$2 (I_1^2 R_1) = 500$$
$$2 (I_1^2 25) = 500$$

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[72] Lee, P. H., "Vertical Antennas—Part II", *CQ*, July 1968.

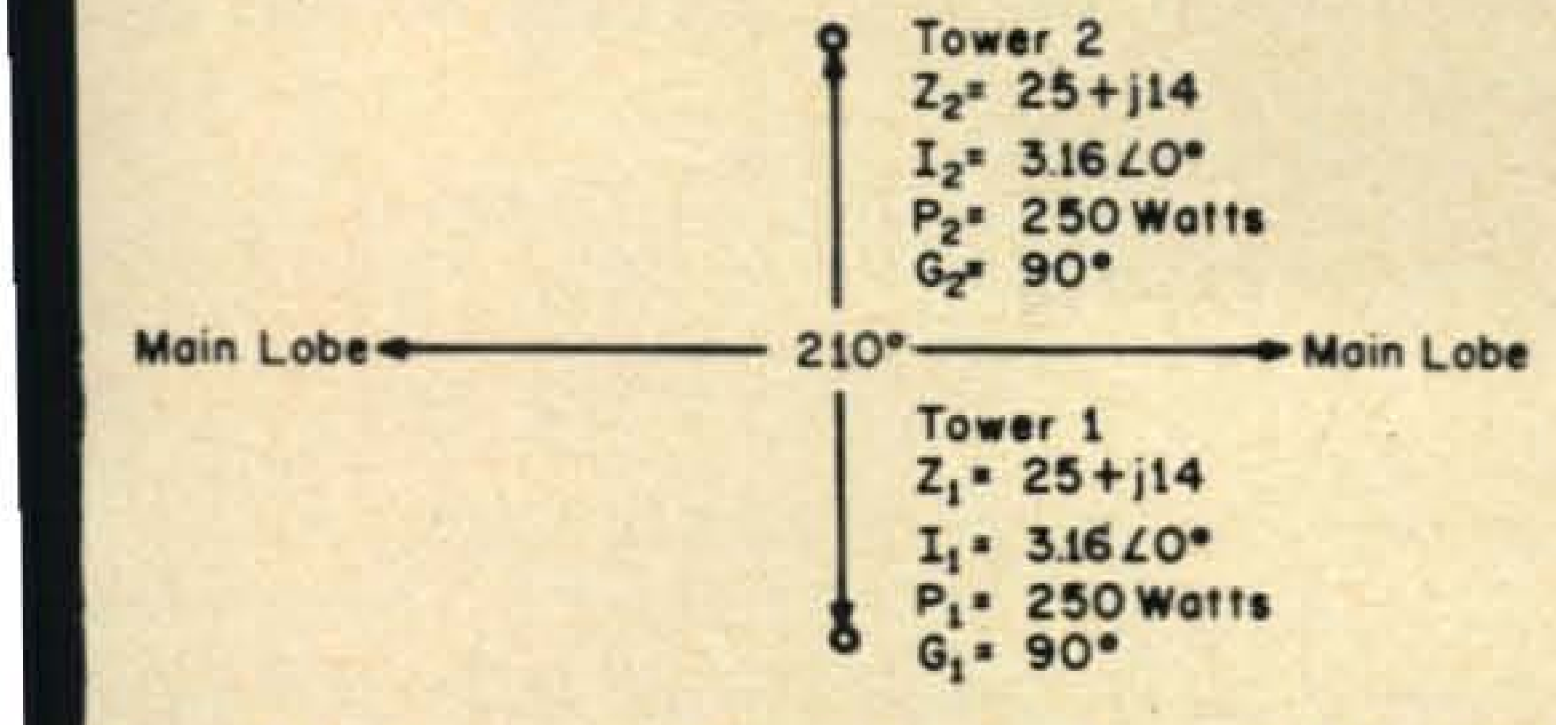


Fig. 84—Array configuration discussed in text.

$$I_1^2 = 10$$
$$I_1 = 3.16 \text{ amps} = I_2$$

As a check:

$$P_1 = (3.16)^2\,25 = 250$$
$$P_2 = (3.16)^2\,25 = 250$$
$$P_T = 250 + 250 = 500 \text{ watts}$$

The array configuration is shown in fig. 84.

ATU's

Now that we know the tower operating impedances, it is possible to design the power dividing circuit and the antenna tuning units. It would be possible to do without any tuning units and simply connect 50 ohm line to the owers, and parallel the two equal length lines at the feed point. However, quite a large s.w.r. will result, and this is undesirable. The circuit of fig. 85 is recommended. An Ohm's Law network is used to give exact control over power division. Since the array is to work on 3.9 mc, 10 microhenry power dividing coils are assumed. Each of these has a reactance of $+j260$ ohms at 3.9 mc. The aps are at equal distances above ground, and are placed at the $+j188$ ohm points, to make he computation simple. This leaves $+j72$ ohms above each tap. Considering each feedine to be pure 50 ohms resistance load, the parallel combination of 50 and $+j188$ is computed:

$$\frac{(50\,\underline{/\,0^\circ})\,(188\,\underline{/\,90^\circ})}{50 + j188} = \frac{9400\,\underline{/\,90^\circ}}{195\,\underline{/\,75^\circ}} =$$
$$48.2\,\underline{/15^\circ} = 46.6 + j12.5$$

Adding the upper portion of the coil to this, he total impedance of each tower's feed which is presented to the common branching point is:

$$46.6 + j12.5 + j72 = 46.6 + j87.5$$

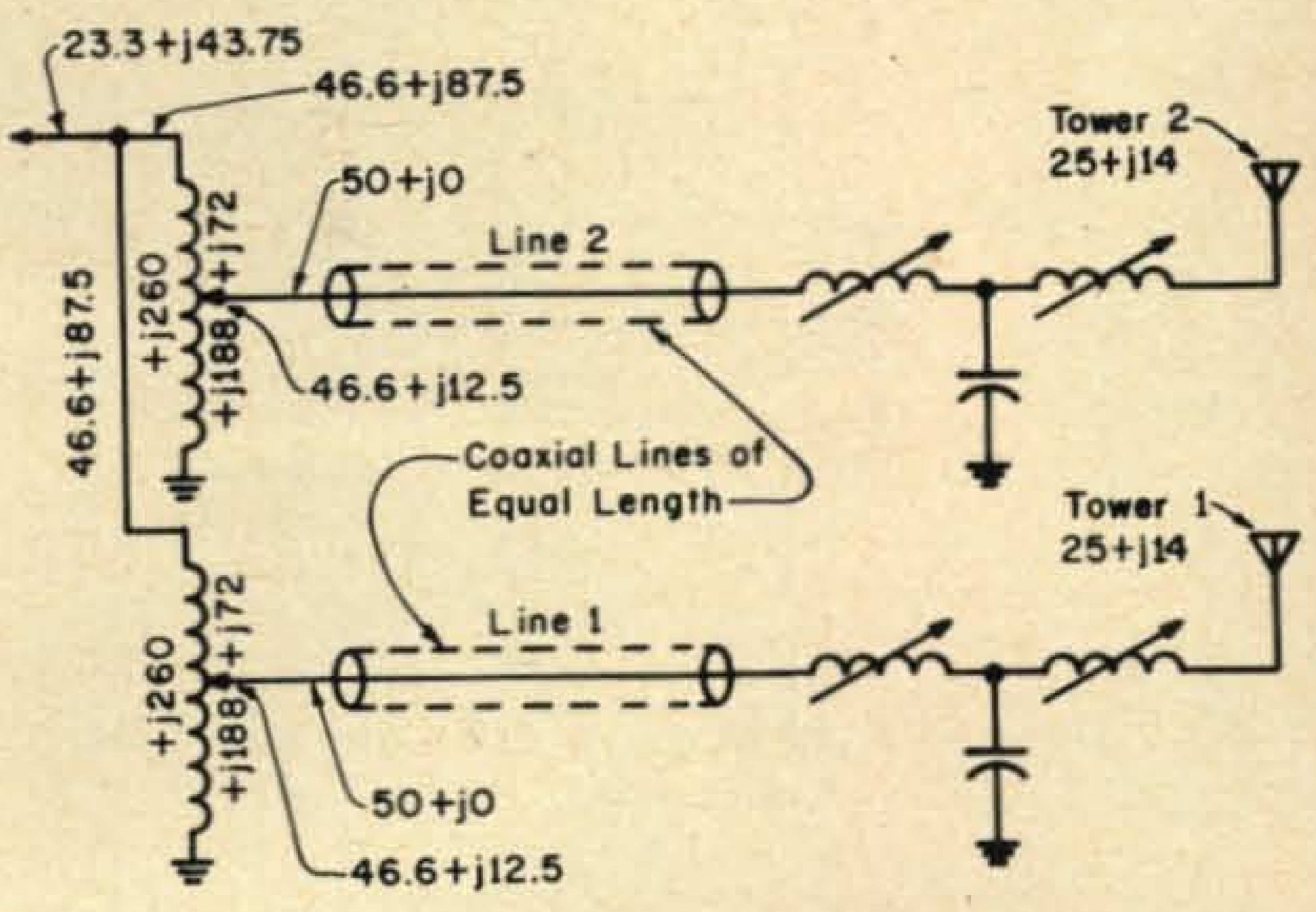


Fig. 85—Branching circuit and the various impedances and reactances.

Inasmuch as the two tower feeds are equal, adding them in parallel can be accomplished by dividing one of them by 2:

$$\frac{46.6 + j87.5}{2} = 23.3 + j43.75$$

These several impedances and reactances are shown at appropriate places in fig. 85.

A matching network will be required to transform this value of 23.6 + j43.75 to 50 + j0 ohms. Again, as in Part VIII, we use our old friend the 90° network, so easy to compute. It is shown in fig. 86. The values of X_C and X_L are easily computed from the equation:

$$x = \sqrt{R_1\,R_2}$$

In this case:

$$x = \sqrt{23.3 \times 50}$$
$$= 35.8$$
$$x_C = -j35.8 \quad \text{or} \quad 1120 \text{ mmf at } 3.9 \text{ mc.}$$
$$x_L = +j35.8 \quad \text{or} \quad 1.45\ \mu\text{h at } 3.9 \text{ mc.}$$

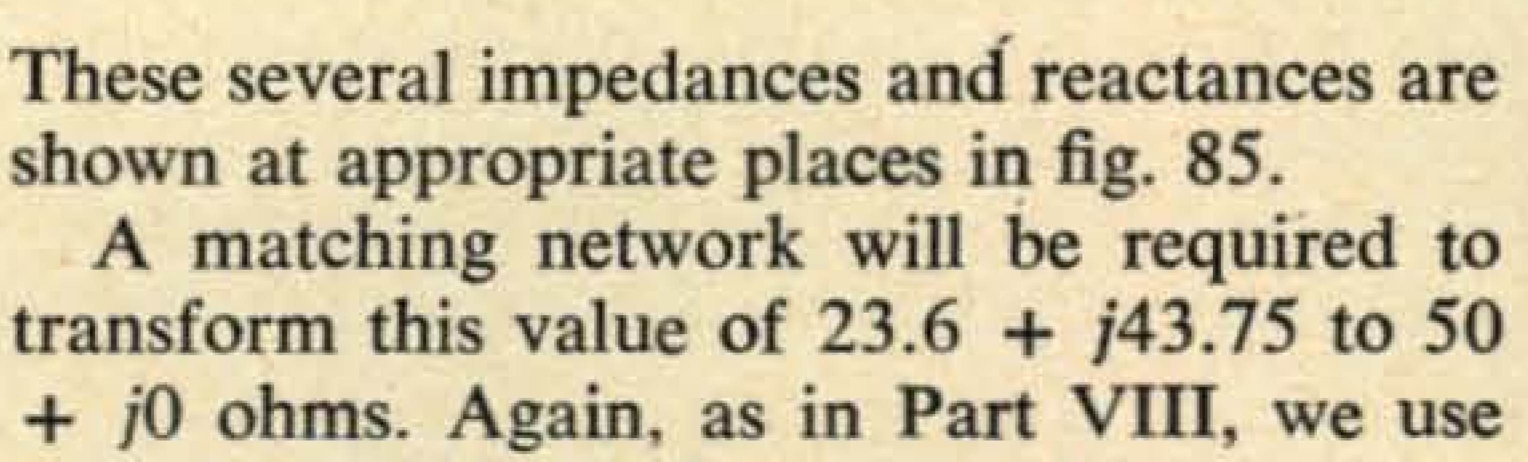


Fig. 86—Input T network, a 90° network that is easy to compute, is used to match branching network to transmitter.

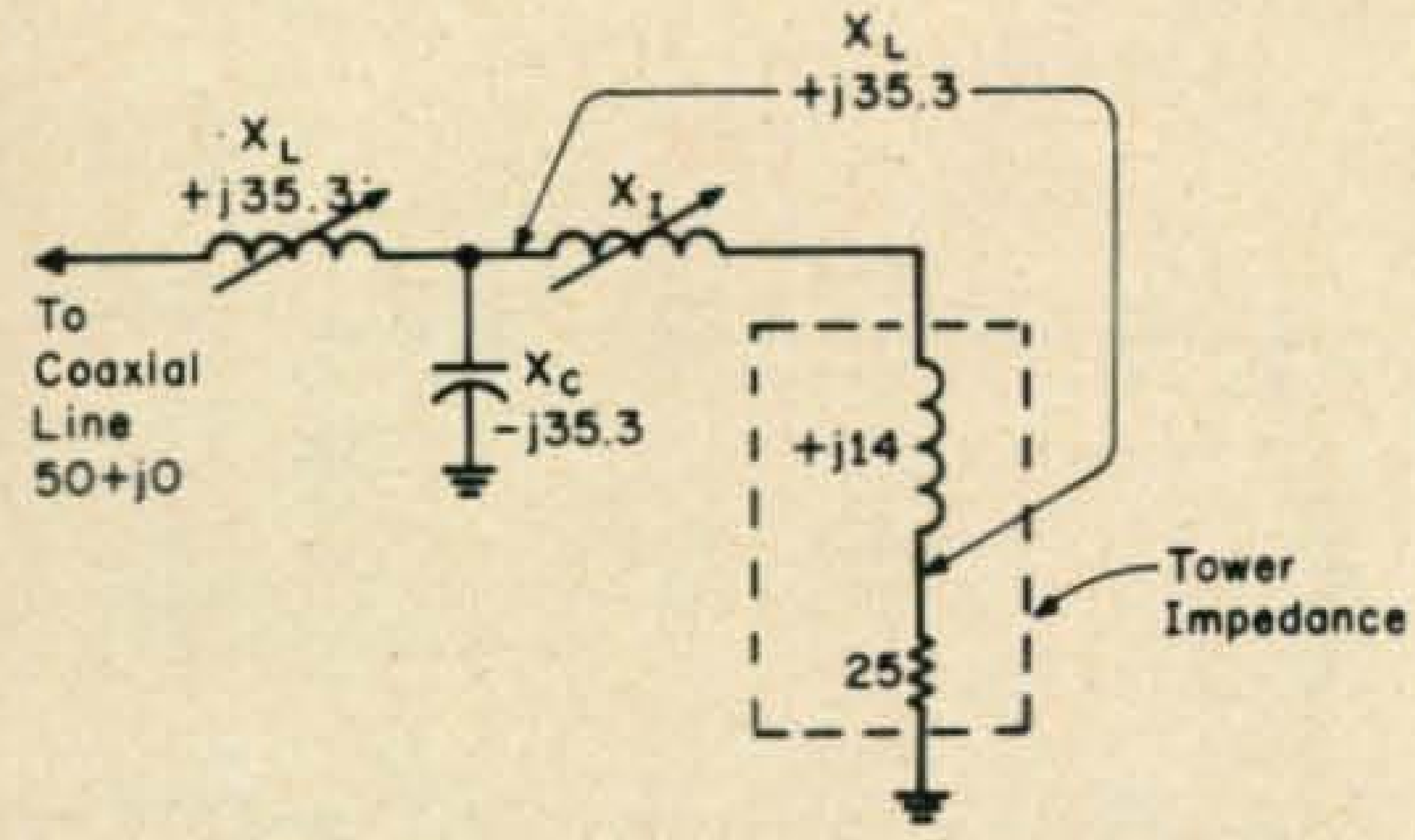


Fig. 87 — ATU employs a 90° network for matching.

Inasmuch as X_L is less than the reactance of the input to the branching network, it is most expedient to insert some negative reactance X_2 in series and to cancel some of it out with an adjustable positive X_1. Why not simply insert a negative reactance equal to the difference between $+j43.75$ and $+j35.8$ ohms? This would be equal to about $-j8$ ohms, which would be 5000 mmf at 3.9 mc. It would be a bit impractical to make this variable. It is much easier to make the inductance variable. In this case a 1000 mmf fixed capacitor is chosen for X_2, with a reactance of $-j41$ ohms. Thus X_1 can be found as follows:

$$x_1 = +j35.8 - (+j43.75 - j41)$$
$$x_1 = +j33.05 \quad \text{or} \quad 1.35\ \mu\text{h at } 3.9\text{ mc.}$$

Now, turning our attention to the antenna tuning units and noting that the tower operating impedances are identical, the ATUs will be identical. (Figs. 85 and 87.) Again using our old friend the 90° T network, so easy to handle,

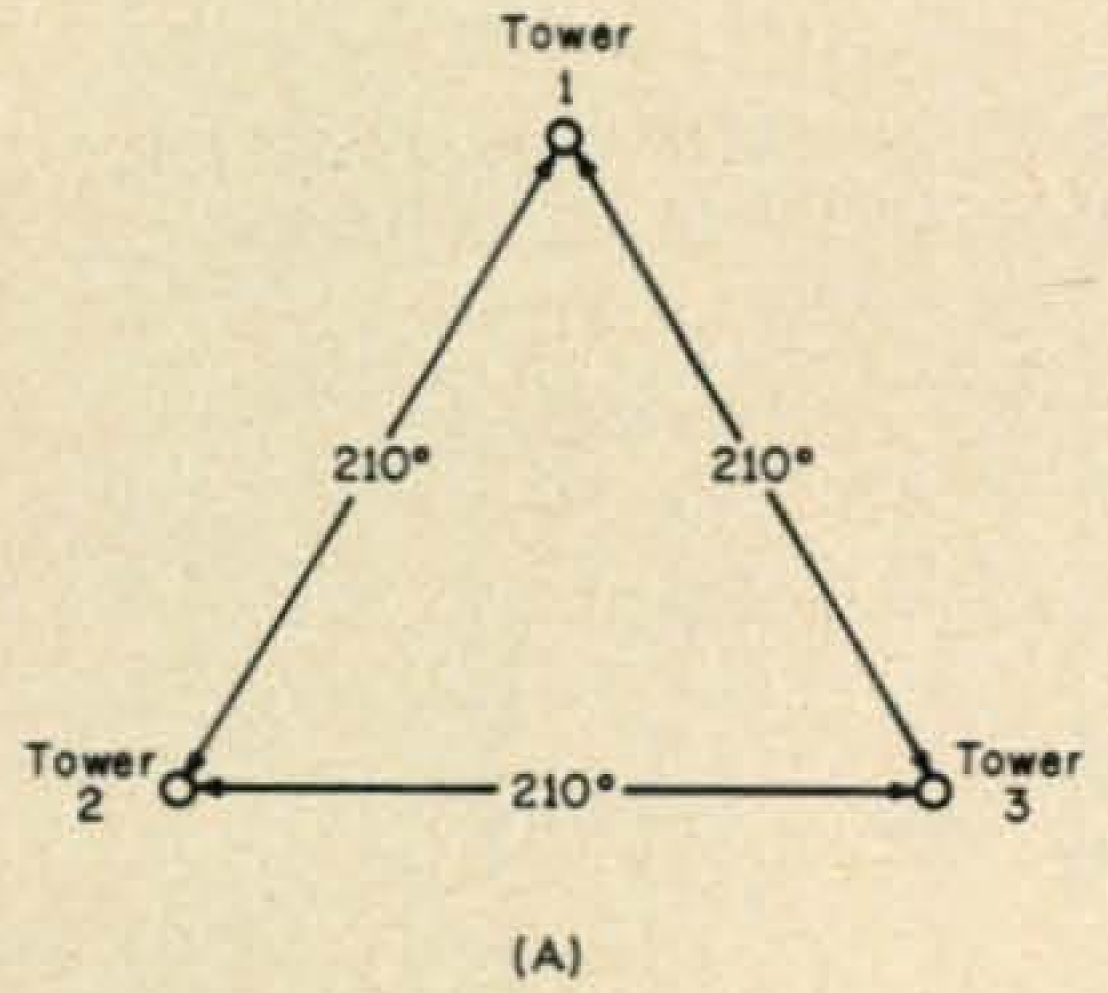
$$x = \sqrt{25 \times 50}$$
$$= 35.3$$

$$x_C = -j35.3 \quad \text{or} \quad 1106\text{ mmf at } 3.9\text{ mc.}$$
$$x_L = +j35.3 \quad \text{or} \quad 1.47\ \mu\text{h at } 3.9\text{ mc.}$$
$$x_1 = +j21.3 \quad \text{or} \quad 0.886\ \mu\text{h at } 3.9\text{ mc.}$$

It must be emphasized that this is the *computed* design. In actual field practice the professional engineer will measure the tower self-impedances and the mutual impedance with his r.f. bridge, and will then run through the phasing and branching network calculations again using the actual *measured* values. The results should be fairly close to the computed values. In actual practice, the equipment designer will make all reactances with a 50% increase in tolerance to allow for the differences which may occur between computed and measured values. To obtain odd values of $-jX_C$, it is standard practice to use a fixed capacitor in series with a variable coil.

Three Element Array

Now that we have the array and feed system designed, it is quite simple to use it in an equilateral triangle configuration, with three elements, driving any pair of them at a time. Such a system is shown in schematic form in fig. 88. A three position rotary switch is needed, with provision for open-circuiting



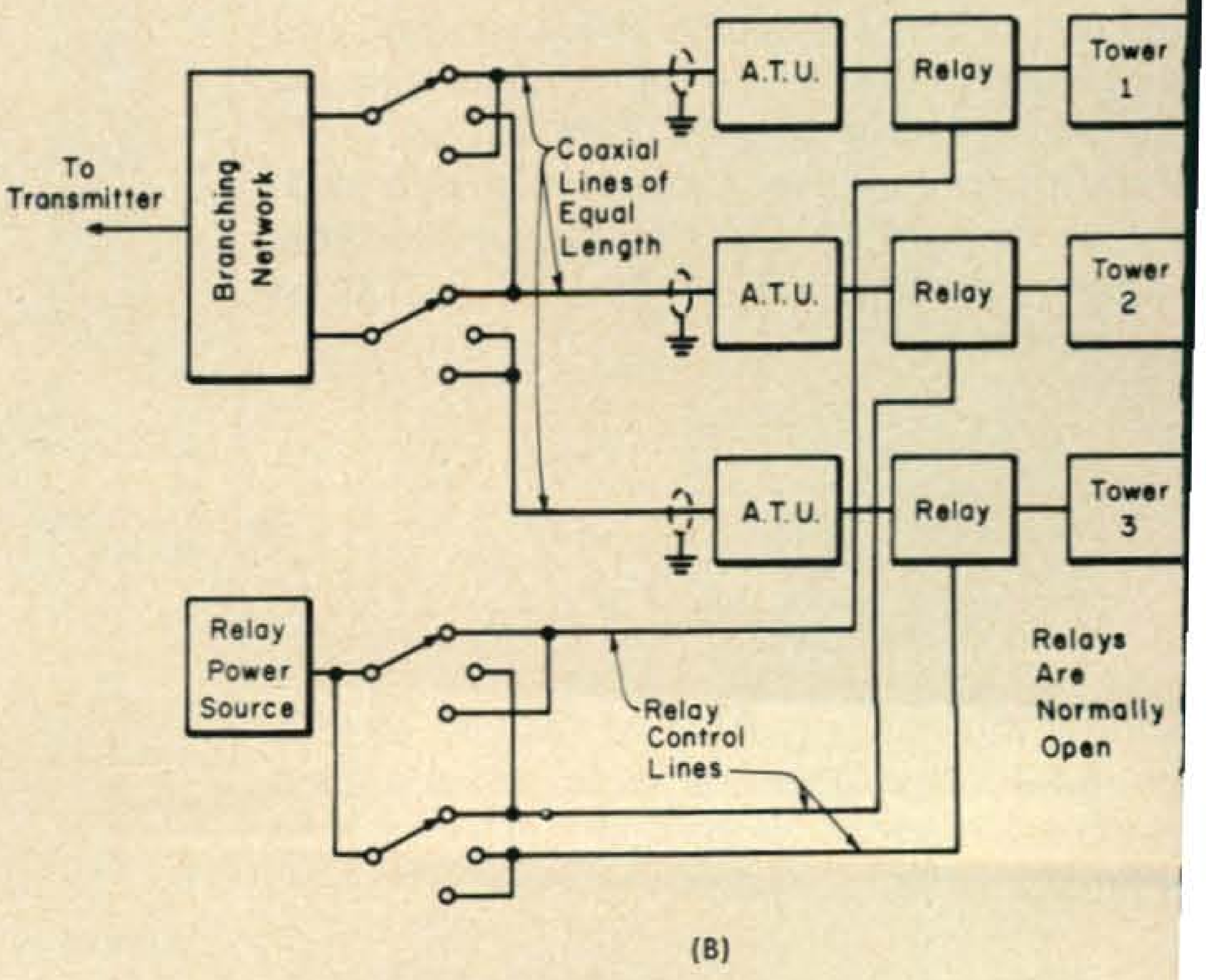


Fig. 88(A)—Configuration of the towers. (B) Switching arrangement for triangular configuration.

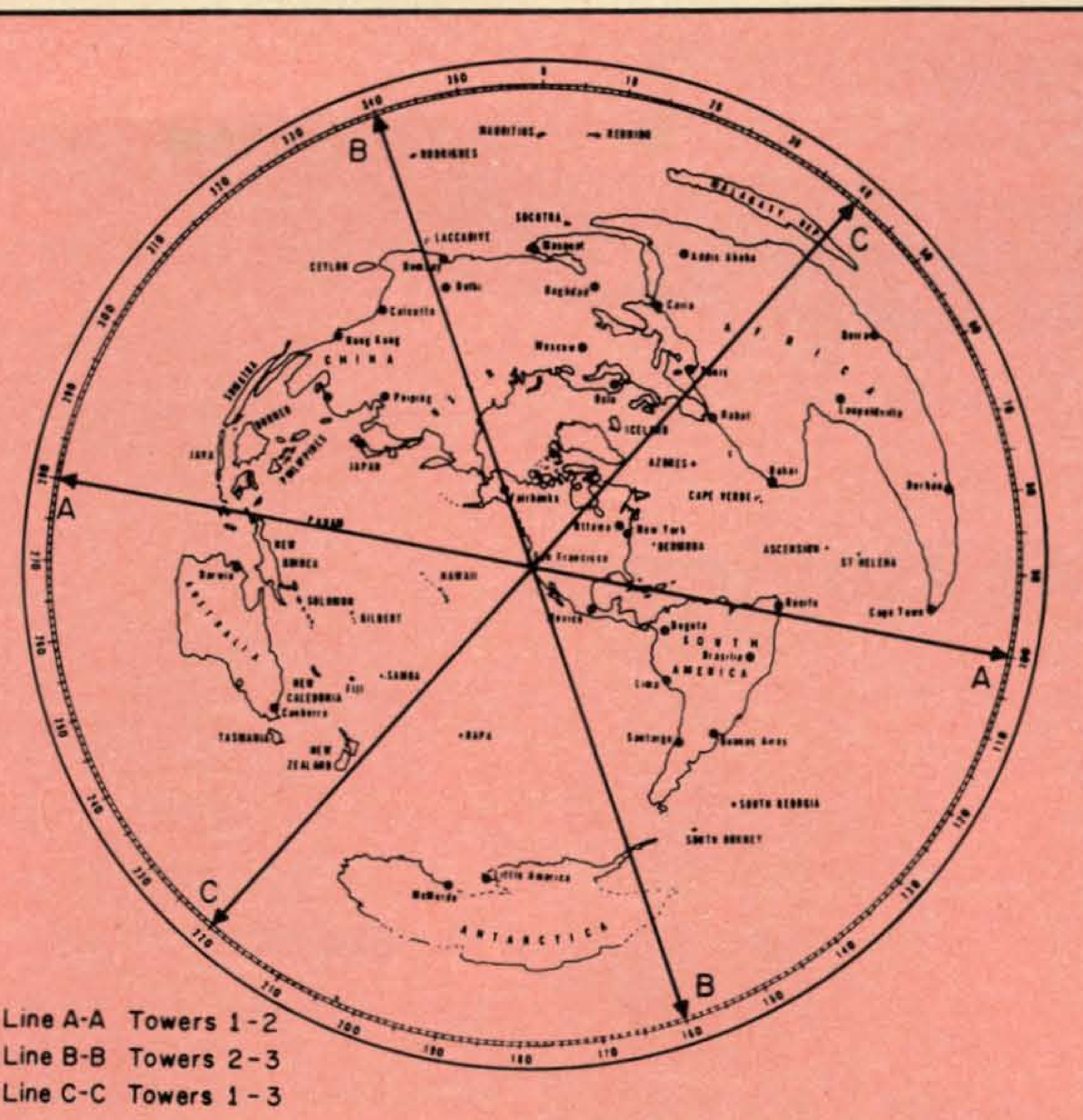


Fig. 89—Directions of the main lobes as shown on an azimuthal projection centered on Los Angeles Line A-A is the direction of the main lobes from towers 1 and 2, B-B from towers 2 and 3 and C-C from towers 1 and 3. The tower orientation for this pattern is discussed in the text.

the unused tower in each position. This is most easily done by means of a relay in each tower.

The triangle can be oriented so that the bidirectional beam from each pair of elements falls on a desired azimuth, for global coverage, as shown in fig. 89. This is an example of the directions which can be obtained from a west coast site. A similar map can be used for any other site in the United States. Azimuthal maps such as this often appear in the front pages of the *Radio Amateur Call Book,* and they may be obtained also from the U. S. Navy Hydrographic Office, Washington, D. C., and the U. S. Coast and Geodetic Survey, Washington, D. C.

In fig. 89, Line *A-A* is the direction of the main lobes from towers 1 and 2, Line *B-B* is the direction of the main lobes from towers 2 and 3, and Line *C-C* is the direction of the main lobes from towers 1 and 3. To produce the main lobes oriented on the azimuths shown, the triangular configuration of towers shown in fig. 88(A) is oriented as follows:

Line of towers 2 and 1—bearing 10°
Line of towers 2 and 3—bearing 70°
Line of towers 1 and 3—bearing 130°

The next Part of this series will cover the theory and design of the folded unipole antenna. There have been several requests for more information on this type.

[*To Be Continued*]

Back issues of *CQ* containing earlier installments of "Vertical Antennas" by Capt. Paul H. Lee, W3JM, are available from the *CQ* Circulation Department, 14 Vanderventer Ave., Port Washington, N.Y. 11050. Price per copy is $1.00, with the exception of January 1969, which is 75¢. The entire series is planned to run twelve consecutive installments.

VERTICAL ANTENNAS

Part X

BY CAPTAIN PAUL H. LEE,* W3JM

A folded unipole antenna less than a quarter wave long can be used to transform the low input resistance of a short vertical antenna to a resistance which is more reasonable to match and drive. The author discusses the operation and design of the folded unipole antenna in this installment.

VERY low input resistance is often present in antennas. This is due to the antenna being very short electrically or to the mutual impedance present from another nearby antenna. The coupling network required to match a low resistance (of the order of one or two ohms, or less) to a 50 ohm line is not difficult to compute, but it may include some rather impractical values of reactance. A short series fed antenna looks capacitive, and its capacitive reactance is usually quite high; the shorter the antenna the higher the reactance. The series coil necessary to resonate it (called a "helix" in low frequency or very low frequency work) usually contributes considerable loss in itself, and it is therefore desireable to get rid of it if possible and use some other method of matching and feeding power to the antenna. The Type UG and the NORD antennas described in Part III[73] are designs which accomplish this. It will be noted that each of these uses a folded unipole type of feed. Folded antennas as a class or type provide a means of securing the desired impedance transformation within the antenna itself, thus simplifying the required matching network.

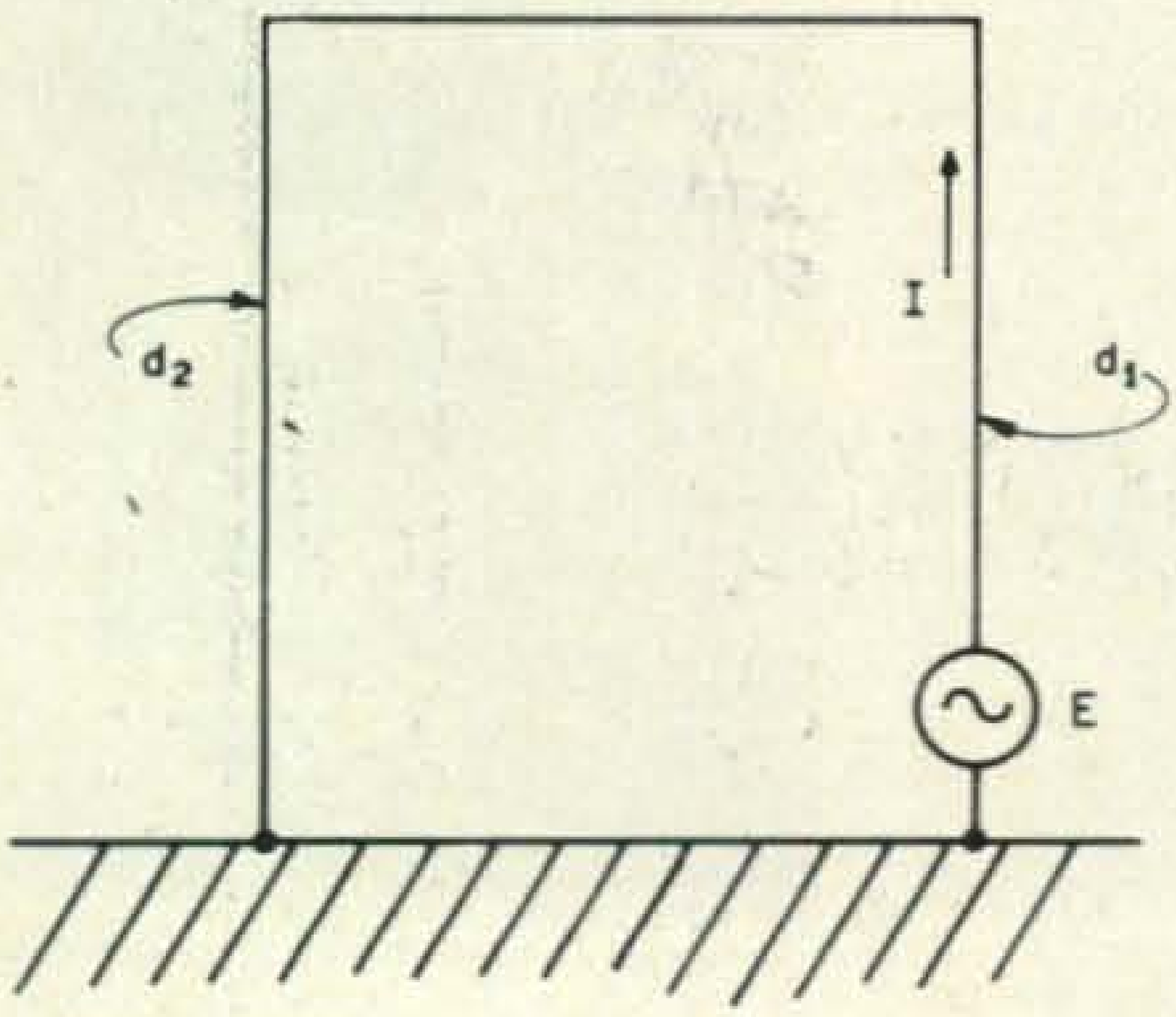


Fig. 90 — Basic circuit of the folded unipole antenna.

Folded Dipole

It is likely that all readers are familiar with the folded dipole. Some may be using one for transmitting, but it is much more probable that one is being used for TV reception, as the folded dipole is the "driven element" of most such v.h.f. Yagi arrays. The reason for its use in that application is the very one mentioned previously, to present a more favorable impedance match to the 300 ohm transmission line than would be possible if an ordinary linear dipole were used.

The folded unipole is nothing but a half of a folded dipole, with ground replacing the other half. It is represented in fig. 90, which shows a simple single fold unipole antenna. To analyze this antenna and its operation, let us assume a generator voltage, E_1, and proceed to determine the current, I, flowing in the lower end of part d_1, of the antenna. Roberts[74] has shown an analysis of this type of antenna. Figure 91 is the equivalent circuit of fig. 90, for purposes of the analysis. Also assume that the antenna is 90 electrical degrees tall.

By use of three generators shown in fig. 91, we can by the principle of superposition

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*5209 Bangor Drive, Kensington, Maryland 20795.

[73] Lee, P. H., "Vertical Antennas—Part III," *CQ*, August 1968, p. 52.

[74] Roberts, W. V., "Input Impedance of a Folded Dipole," *RCA Review*, Vol. 8, No. 2, June 1947, p. 289.

add the currents produced by each generator to find the current in the lower end of part d_1. The polarities of the generators are shown by the arrows. Since each generator is producing the voltage E_1, and generators 2 and 3 are opposed, the lower end of part d_2 is at ground potential. Generators 1 and 3 produce a voltage $2E_1$ which is impressed on the lower end of part d_1. In view of these facts· fig. 91 is in fact equivalent to fig. 90.

As the next step in the analysis, assume for a moment that generator 3 is shut down, and as a result there is only a voltage $2E_1$ developed by generators 1 and 2 between the lower ends of parts d_1 and d_2. It was stated previously that the antenna is 90° tall. Thus, inasmuch as parts d_1 and d_2 form a transmission line of 90° length which is shorted at its upper end, the input resistance between d_1 and d_2 for this transmission line case is very high, and only a very small transmission line current will flow through generators 1 and 2, and into the lower end of part d_1.

Next, assume for a moment that only generator 3 is producing any voltage, and that generators 1 and 2 are shut down. In this case, the lower ends of parts d_1 and d_2 are effectively connected together at the same potential, as far as generator 3 is concerned, assuming zero internal impedance in the generators. Thus parts d_1 and d_2 act merely as a 90° vertical radiator (in parallel). Assume that the radiation resistance of this vertical radiator is R, and that it is being driven by generator 3, which is supplying a current equal to E_1/R to this parallel combination of conductors d_1 and d_2. But since there are two conductors the current, $I = E_1/R$, divides between them. If the conductors d_1 and d_2 are of the same diameter, the current will divide equally between them. Thus I_1, the current in part d_1 is equal to $1/2 \times E_1/R$, and I_2, the current in part d_2, is the same.

Now if all three generators, 1, 2 and 3, are working at the same time, the voltage impressed at the bottom end of part d_1 is $2E_1$ and the current in it is $1/2 \times E_1/R$ plus a very small amount of transmission line current produced by generators 1 and 2 in series as described above. Since Ohm's Law applies, and resistance equals voltage divided by current, the input resistance at the lower end of part d_1 is:

$$R_{IN} = \frac{2\,E_1}{\frac{1}{2} \times \frac{E_1}{R}}$$

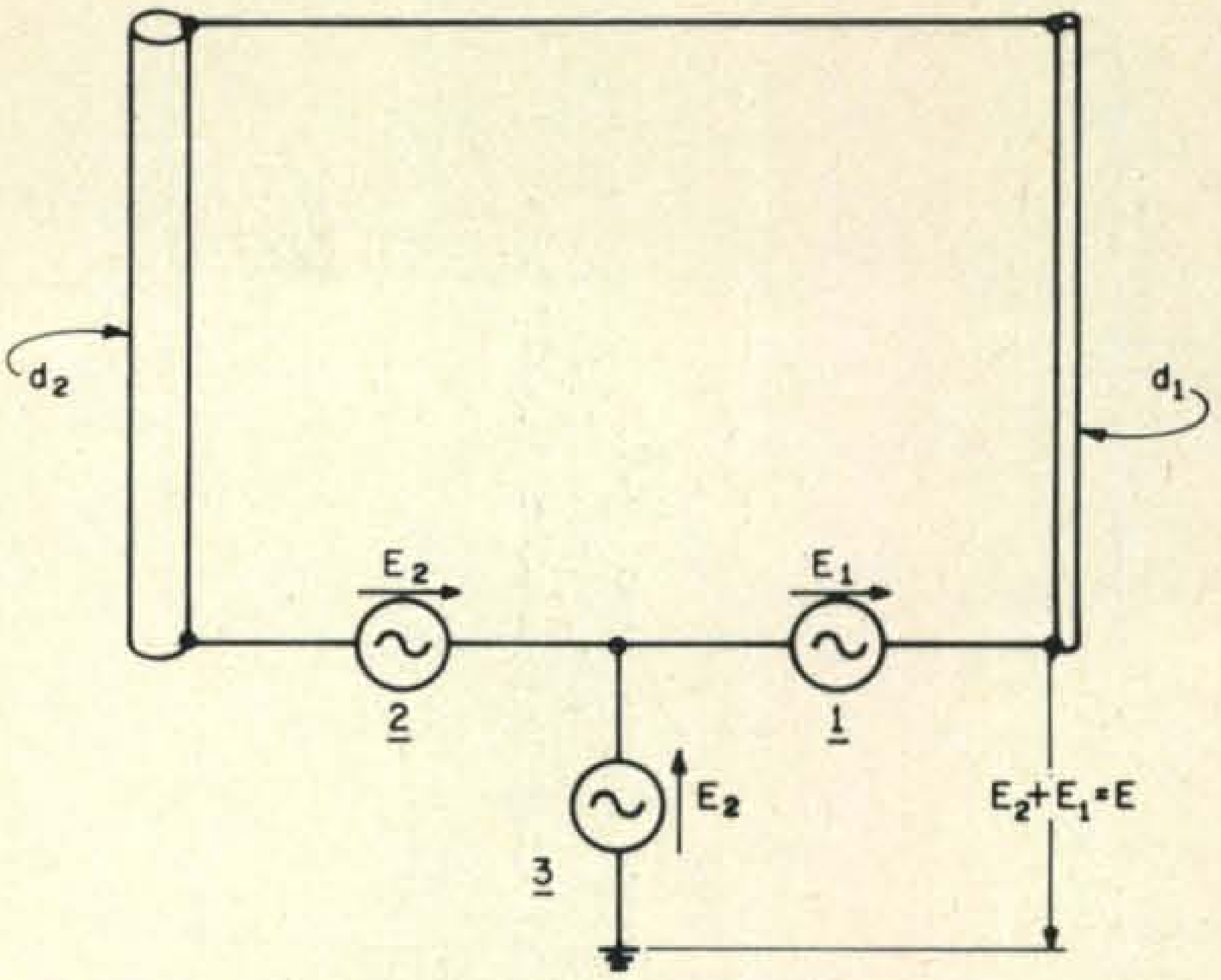

Fig. 91—Equivalent circuit of the folded unipole that can be used for analysis.

which is equal to approximately $4R$. This is true provided that parts d_1 and d_2 are close together. The impedance transformation (for equal size conductors d_1 and d_2) is approximately 4.

This transformation ratio can be expressed in the form of an equation:

$$\rho = \frac{Z_1}{Z_0} = (1 + n)^2$$

where Z_1 = input impedance of the folded unipole antenna.
Z_0 = input impedance of a single element depole.
n = input current ratio I_2/I_1 (For equal size conductors this equals 1.)

Unequal Conductors

So far in this analysis the case of equal size conductors has been discussed. Now, however, with the transformation ratio expressed in terms of the current ratio (which depends on conductor size), we can consider the case of unequal size conductors, which is shown in fig. 92. As in the previous case, generators 2 and 3 are alike and produce equal and opposing voltages E_2, which place the bottom end of part d_2 at ground potential. However, generator 1 must now be producing a voltage E_1 of such value that no current will flow through generator 3 when generator 3 is not providing any voltage. In this case E_1 is not equal to E_2, and its determination is one essential part of the problem. The division of the antenna current between parts d_1 and d_2 (when generators 1 and 2 are not generating

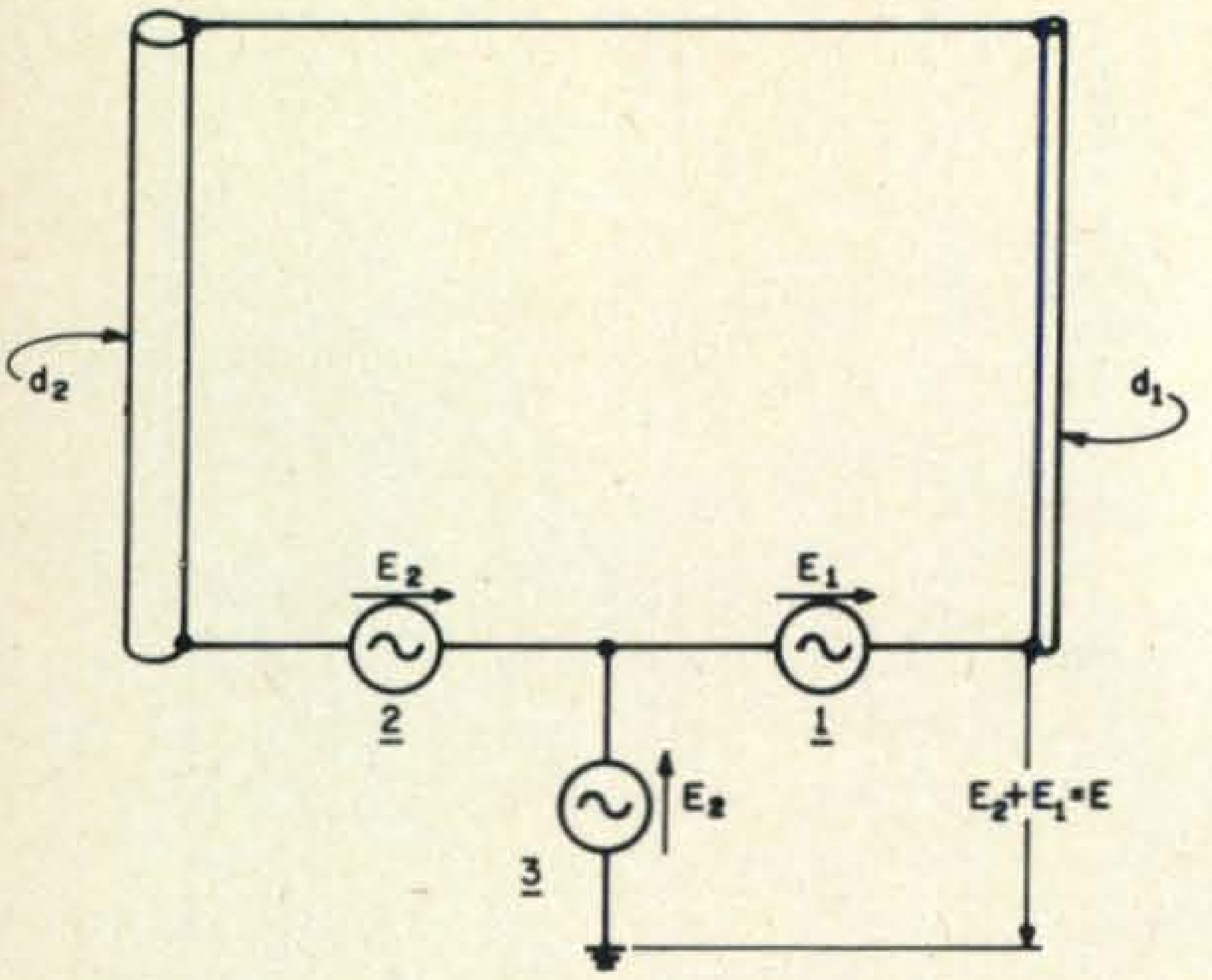

Fig. 92—Equivalent circuit, for analysis, with unequal diameter elements.

and generator 3 is generating) is the other part of the problem. Roberts uses an electrostatic or capacitive method of analysis[74]. whereas Guertler uses another more complicated method.[75] The former described here. Simply stated, the currents will divide directly in proportion to the ratio of the capacities to ground of the two elements, whereas the voltage ratio will be the inverse of this. Thus, in the analysis we can assign capacities C_1 and C_2 to parts d_1 and d_2. Refering to fig. 92, then:

$$\frac{E_2}{E_1} = \frac{C_1}{C_2} \quad or \quad E_2 = E_1\left(\frac{C_1}{C_2}\right)$$

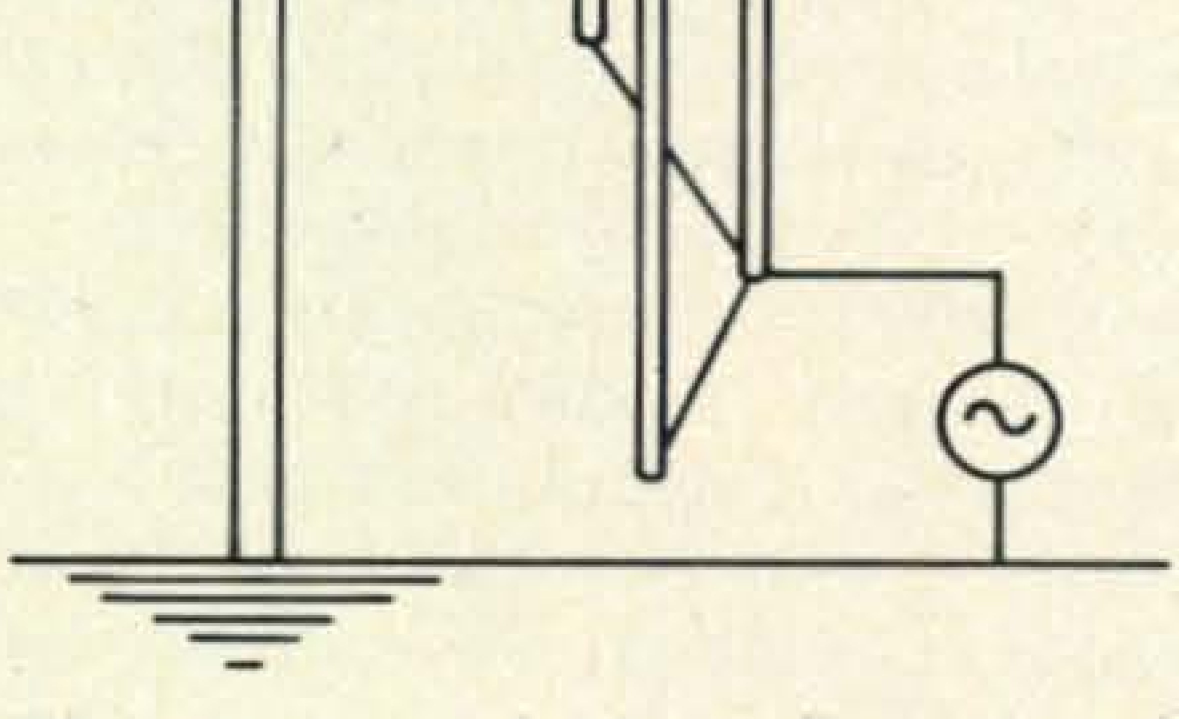

Fig. 93 — Multiple fold configuration for increased bandwith.

Considering the whole thing as a vertical antenna of parallel conductors, the current I_1 at the bottom end of part d_1 will be:

$$I_1 = I \times \frac{C_1}{C_1 + C_2}$$

where I is the total antenna current due to generator 3.

Inasmuch as parts d_1 and d_2 are a 90° shorted section, the transmission line current, which is very small, can be neglected for practical purposes, and the total current due to generator 3, which we called I, is equal to E_2/R, where R is the radiation resistance of the two parts connected in parallel. The input resistance at the lower end of part d_1 (the driving point resistance of the folded unipole) is:

$$R_1 = \frac{E_2 + E_1}{I_1}$$

From this we can derive:

$$R_1 = R\left(1 + \frac{C_2}{C_1}\right)^2 \quad or \quad \rho = \left(1 + \frac{C_2}{C_1}\right)^2$$

This last equation says that the resistance (or impedance) step-up ratio is proportional to the ratio of the conductors' diameters. (Their capacities are proportional to their diameters.) The step-up ratio is inversely proportional to the diameter of the driven fold or element, and directly proportional to the diameter of the grounded element or tower. The spacing between fold and tower enters into the picture slightly also, but it is not critical.

This antenna has fairly good bandwidth, but the best way to increase the bandwidth is by increasing the number of folds, as in fig. 93.

It can also be shown that the transformation ratio is:

$$\rho = \left(1 + \frac{Z_1}{Z_2}\right)$$

where Z_1 is the characteristic impedance of a two-conductor transmission line made up of conductors of the smaller diameter, and Z_2 is the characteristic impedance of a two-conductor transmission line made up of conductors of the larger diameter, with the spacing of each of these two lines equal to

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[75] Guertler, R. "Impedance Transformation in Folded Dipoles," *Proceedings of IRE*, Sept. 1950, p. 1042.

the center-to-center distance of the two conductors of the antenna.

It is assumed in the above equation that the tower is grounded, and the smaller conductor (or fold) is fed. The impedance step-up will always be greater than four in this case.

Short Unipole

Thus far a folded unipole 90° tall has been discussed. Now we must turn to the case of the short folded unipole, something much less than 90°, which is the case where the method of feed gives us the greatest advantage of impedance step-up, enabling us to get rid of the helix with its inherent losses. Some assume that the transformation in the short case is the same as that in the 90° case but this is not correct, because in the short case the transmission line currents present become of appreciable magnitude and can no longer be neglected.[76] In this case, fig. 94 applies. Reactances have been arbitrarily added to the two branches of the circuit of fig. 92 for the sake of the analysis. As in the previous case, we can consider the whole thing as an antenna consisting of parallel conductors fed by generator 3, and also we must consider the transmission line case where generators 1 and 2 are in series feeding the short section of transmission line. The circuit of fig. 94 can be replaced by an equivalent circuit as shown in fig. 95. The sections of the unipole have been replaced by boxes containing certain impedances. Z_1 and Z_2 are the impedances to ground of the two parts of the unipole, and Z_{12} is a complex impedance representing a mutual impedance between the two parts (or elements).

As the first step in this analysis, consider the antenna mode, where generators 1 and 2 are not producing voltage, and the configuration is being excited by generator 3. The current, I, will divide into two parts, I_1 and I_2, in accordance with the transformation ratio as previously explained, for $Z_1/Z_2 = \rho$. If the currents I_2 and I_1 are to be in phase and of the ratio $\rho = I_2/I_1$, which they must be in the antenna case, then jX_1 must equal $\rho \times jX_2$. As far as Z_{12} is concerned, no current flows in it, since points 1 and 2 (lower ends of parts d_1 and d_2) are at the same potential and parts d_1 and d_2 are effectively in parallel.

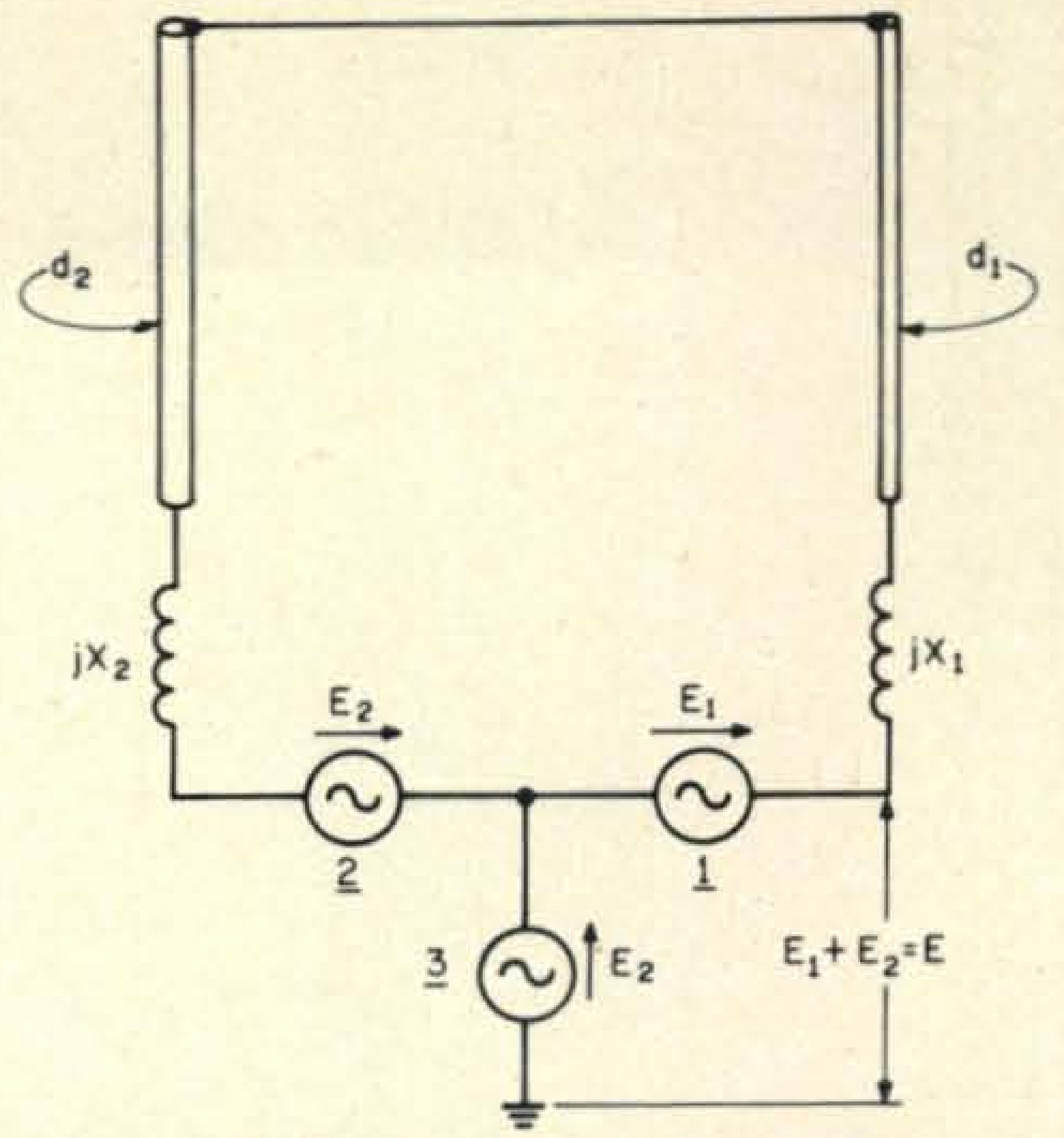

Fig. 94—Equivalent circuit, for analysis, of the short folded unipole.

Now to consider the transmission line mode, we assume generator 3 is not producing. In order for the currents in Z_1 and Z_2 to be equal and opposite, which they must be in this case, E_1 must equal ρ times E_2. Since E_1 plus E_2 equals E (refer back to fig. 90). E_2 is equal to $E/(1+\rho)$, and E_1 is equal to $E\rho/(1+\rho)$. This is shown in fig. 96.

We are now ready to examine the input impedance of the unipole, at feed point F, fig. 96. The total current flowing at F is the sum of the antenna mode current and the transmission line mode current. Let the former be designated by I_A and the latter by I_T. By shorting out the lower generator 3 we have the sum of generators 1 and 2 driving the unipole as a section of transmission line. I_T is therefor determined from the following equation:

$$I_T = \frac{\left[E\left(\frac{\rho}{1+\rho}\right) + \frac{E}{1+\rho}\right]}{j\,(X_2 + \rho X_2 + X_L)} =$$

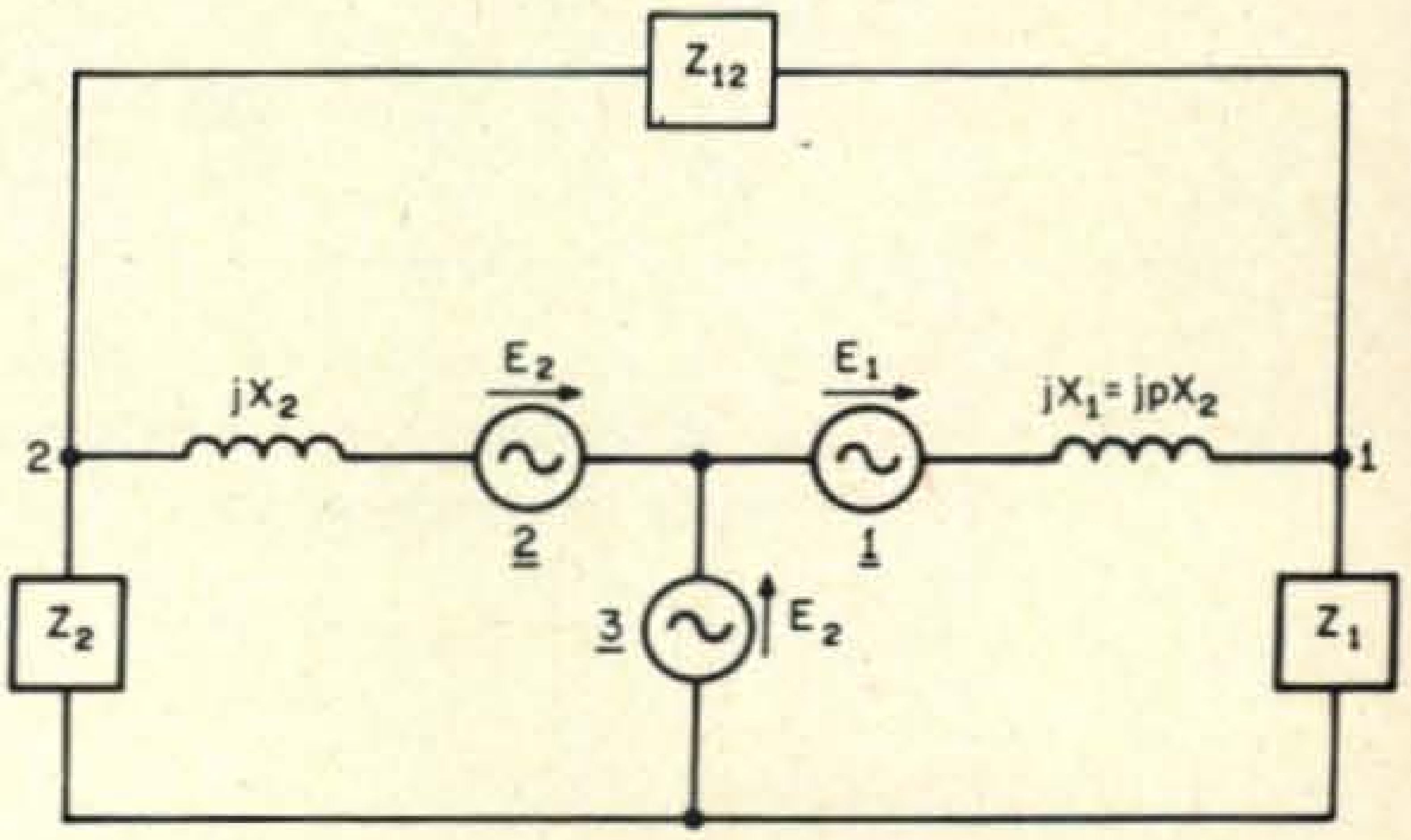

Fig. 95—Equivalent schematic of fig. 94.

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[76] Leonhard, J. *et. al.*, "Folded Unipole Antennas," *IRE Transactions on Antennas and Propagation*. Vol. AP-3, No. 3, July 1955, p. 111.

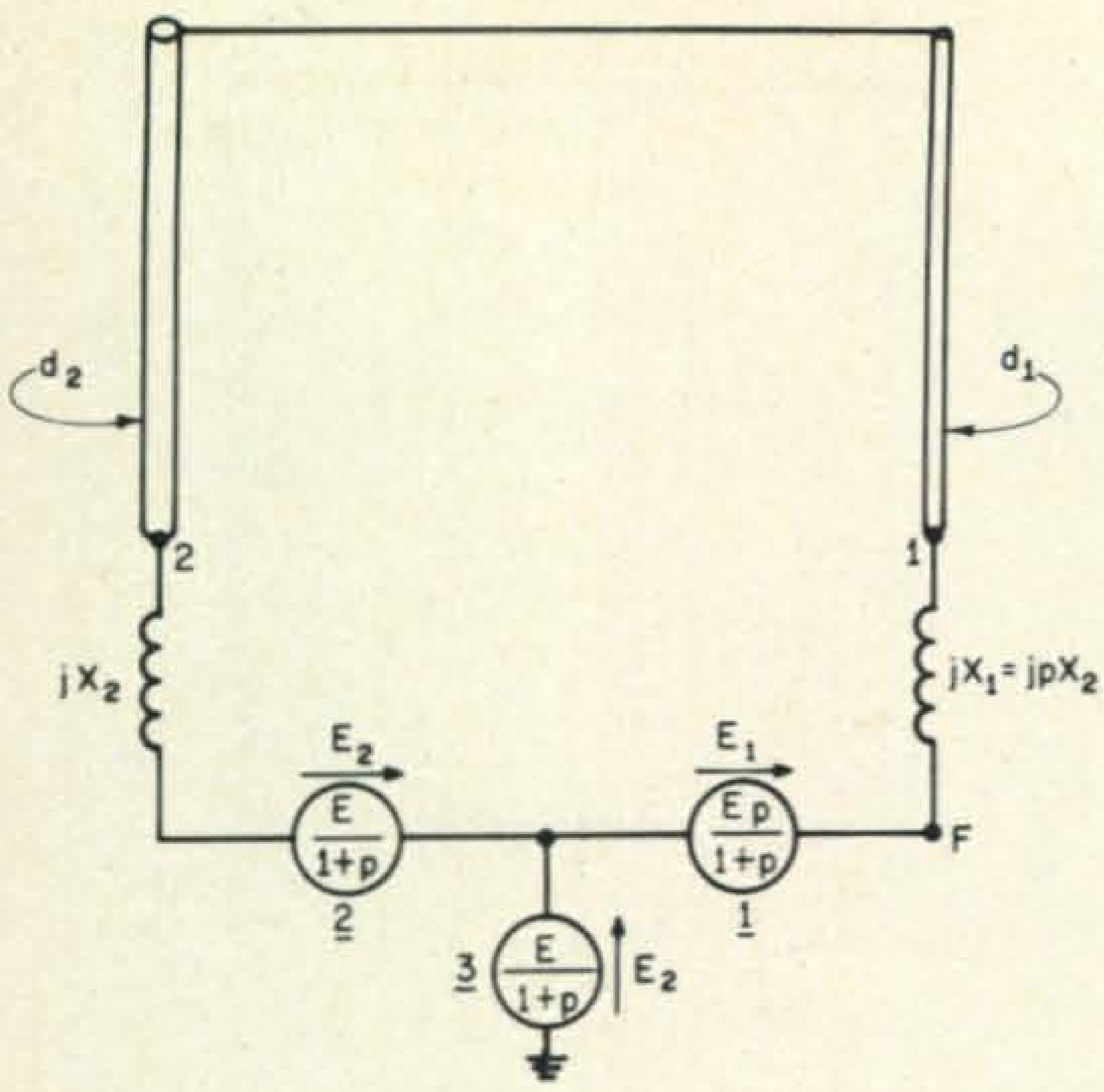

Fig. 96—Equivalent circuit of the folded unipole showing the generators in terms of E and P.

$$\frac{E}{j\,[X_2\,(1+\rho)+X_L]}$$

where X_L is the transmission line inductance of the shorted section.

The antenna current is found by shorting out the two upper generators 1 and 2. Since points 1 and 2 are then at the same potential, the two conductors of the unipole are considered to be combined into a single vertical radiator, whose input impedance we shall designate by $R_a - jX_a$. The reactance will be negative because the radiator is shorter than 90°. The values of R_a and X_a can be determined by consideration of the radiator's L/D ratio and its electrical length, and by consulting fig. 13A and 13B of Part II of this series.[77] We also have X_2 and ρX_2 in parallel in this antenna mode, in series with $R_a - jX_a$. The parallel combination of X_2 and ρX_2 equals $[\,\rho/(1+\rho)\,]X_2$, and the driving voltage for the antenna mode is $E/(1+\rho)$.

The total antenna mode current is, therefore:

$$I_{A\,(TOTAL)} = \frac{\left(\frac{E}{1+\rho}\right)}{\left[R_a - jX_a + j\left(\frac{\rho}{1+\rho}\right)X_2\right]}$$

Only a fraction of this, however, flows in part d_1 of the unipole. That fraction is:

$$I_A = \left(\frac{1}{1+\rho}\right) I_{A\ TOT}$$

or:

$$I_A = \frac{E}{[R_a(1+\rho)^2 - jX_a(1+\rho)^2 + j\rho(1+\rho)X_2]}$$

From feedpoint F of the unipole to ground, the input impedance is:

$$Z = \frac{E}{I_A + I_T}$$

From this let us now subtract the value of jX_1 (equals $j\rho X_2$) to obtain the true input impedance:

$$Z_{IN} = \frac{E}{I_A + I_T} - j\rho X_2$$

By substituting the values of I_A and I_T in this equation, we can find the input impedance as a function of X_2 as shown in the equation at the bottom of the page.

The equivalent circuit of the short folded unipole is shown in fig. 97. In the case of the 90° folded unipole, the circuit of fig. 97 and the preceding equation can be used, and since in that case X_a is zero (the antenna is self-resonant), X_2 is zero and X_L is infinite (shorted quarter wave line), the resultant $Z_{IN} = R\,(1+\rho)^2$, which would be expected.

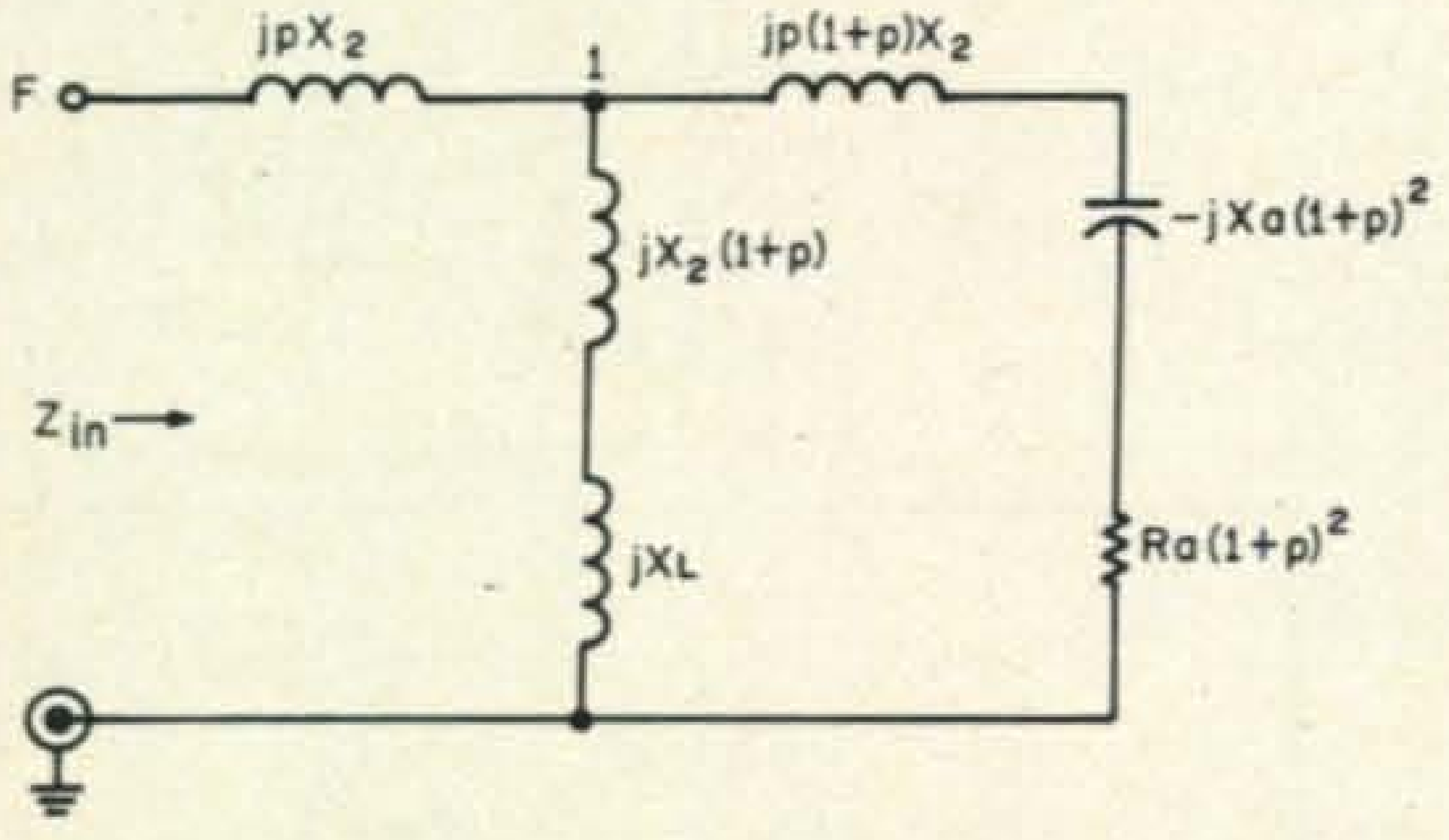

Fig. 97—Schematic diagram of the equivalent circuit for input impedance, Zin.

$$Z_{in} = \frac{1}{\frac{1}{[R_a(1+\rho)^2 - jX_a(1+\rho)^2 + j\rho(1+\rho)X_2]} + \frac{1}{j\,[X_2(1+\rho)+X_L]}} - j\rho X_2$$

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[77] Lee, P. H., "Vertical Antennas—Part II," *CQ*, July 1968, p. 25.

Thus the general case does fit the 90° special case.

From all of this we observe that the unipole multiplies the input resistance and reactance of the antenna by the factor $(1+\rho)^2$, and it also transforms these new values of R_a and X_a through an equivalent circuit T-network action due to its inherent transmission line mode. The final result is dependent on the value assigned to X_2. In the case of the grounded base short tower, which is quite common, X_2 is of course absent from the circuit. However, use of X_2 can be quite beneficial if optimum efficiency and bandwidth are desired.

Summary

To summarize, the input impedance of the short folded unipole is influenced by a number of factors. First, it depends on the division of currents between the fed and unfed conductors, on the presence of considerable transmission line currents in the fed and unfed conductors, and on the value of an impedance which can be connected between the unfed conductor (or tower) and ground. The reactance of a short vertical antenna can be reduced by increasing the diameter/length ratio of the antenna. This is done by dropping wires down from outrigger arms connected to the top of the tower, and connecting them in parallel with the tower. This is in effect a "fattening" or broadbanding action, as described in Part VII of this series.[78]. Such a structure can be easily modified to the folded unipole method of feed by driving one or more of the drop wires, while the rest are either left connected to the tower or grounded through a reactance X_2. Such a configuration is shown in fig. 98.

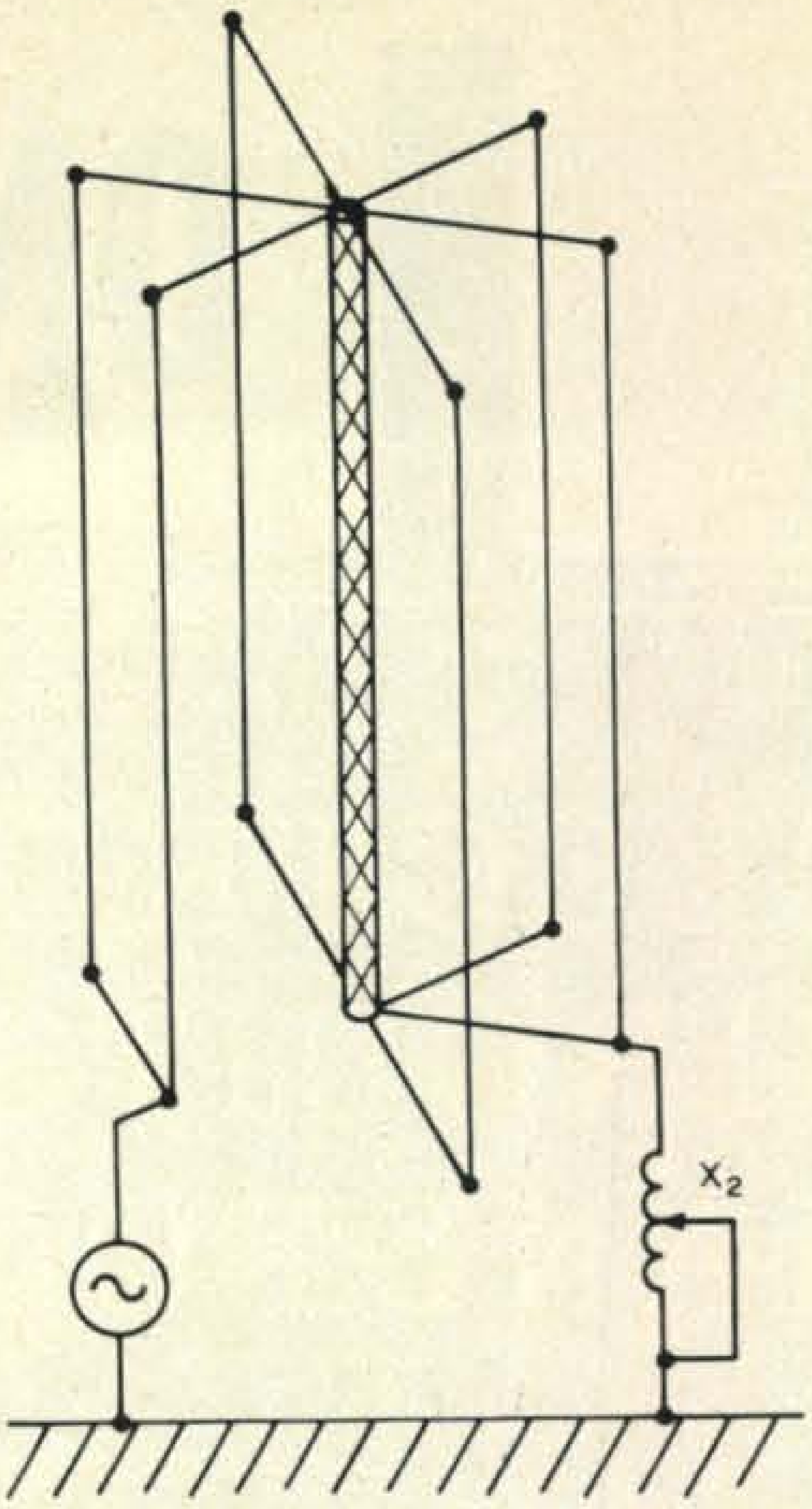

Fig. 98—"Fattened" or broadbanded tower fed as a folded unipole with multiple folds.

An additional advantage of the folded unipole is that the antenna structure is at d.c. ground potential, and no static discharge devices are required. If X_2 is not employed the tower is actually grounded, and lighting circuits, transmission lines to other antennas such as u.h.f. and v.h.f. arrays, and rotator control circuits can be run right up the tower without any isolation.

In this Part, both the general and the special cases of folded unipole antennas have been summarized. In Part XI I am going to discuss the effects of ground on the efficiency and vertical patterns of antennas, and the necessity (or lack thereof) for a ground system at the base of a vertical antenna.

Errata

We regret that there are several typographical errors in Part VII in the December 1968 issue. On page 62, at the top of the right hand column, the equation should read:

$$\textit{Spacing}\ S_n = R_n - R_{n+1} = R_n\,(1-\tau)$$

The second sentence in the second paragraph on that side of the page should read:

Thus for a given angle α, there is a minimum value of τ:

On page 63, in the first paragraph below fig. 74, the equation should read:

$$\textit{Spacing}\ S_n = R_n - R_{n+2} = R_n\,(1-\tau)$$

[*To Be Continued*]

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[78] Lee, P. H., "Vertical Antennas—Part VII," *CQ*, Dec. 1968, p. 59.

VERTICAL ANTENNAS

Part XI

BY CAPTAIN PAUL H. LEE,* W3JM

The effects of earth on the efficiency of radiation and the vertical pattern to be expected from a vertical antenna are often misunderstood or are no understood or are not understood at all. In this installment, the autho discusses these effects in two phases. The first deals with the earth near th antenna and the need for a good ground system. The second is the effec of the earth in the reflection zone on the shape of the vertical pattern

THESE articles have brought much mail, most of which has been from readers interested in using vertical antennas on 75 or 160 meters. The recent power increases authorized on 160 meters, plus the increased availability of s.s.b. equipment for that band, have just about doubled its "population" during the past six months. Because of space restrictions, most of the stations on that band are using verticals of one form or another. There has also been some mail from amateurs on 10, 15, 20 and 40 meters for DX contacts. One of these amateurs announced that he had made the discovery that the could tune and operate a half wave vertical without a ground system, driving it either by a parallel tuned tank or an "L" network whose lower end is grounded. He claimed that since a thermocouple ammeter in the ground lead showed no current, he cou dispense with the ground system and its losse He stated that although this series had so f covered the current fed antennas very we I should now "discover the new world of t half wave vertical with no ground system Actually, he was voicing a popular misco ception about ground systems and the ne for them. This moved me to write this pa of the series, to present a rather complicat subject in as clear and simple a fashion possible.

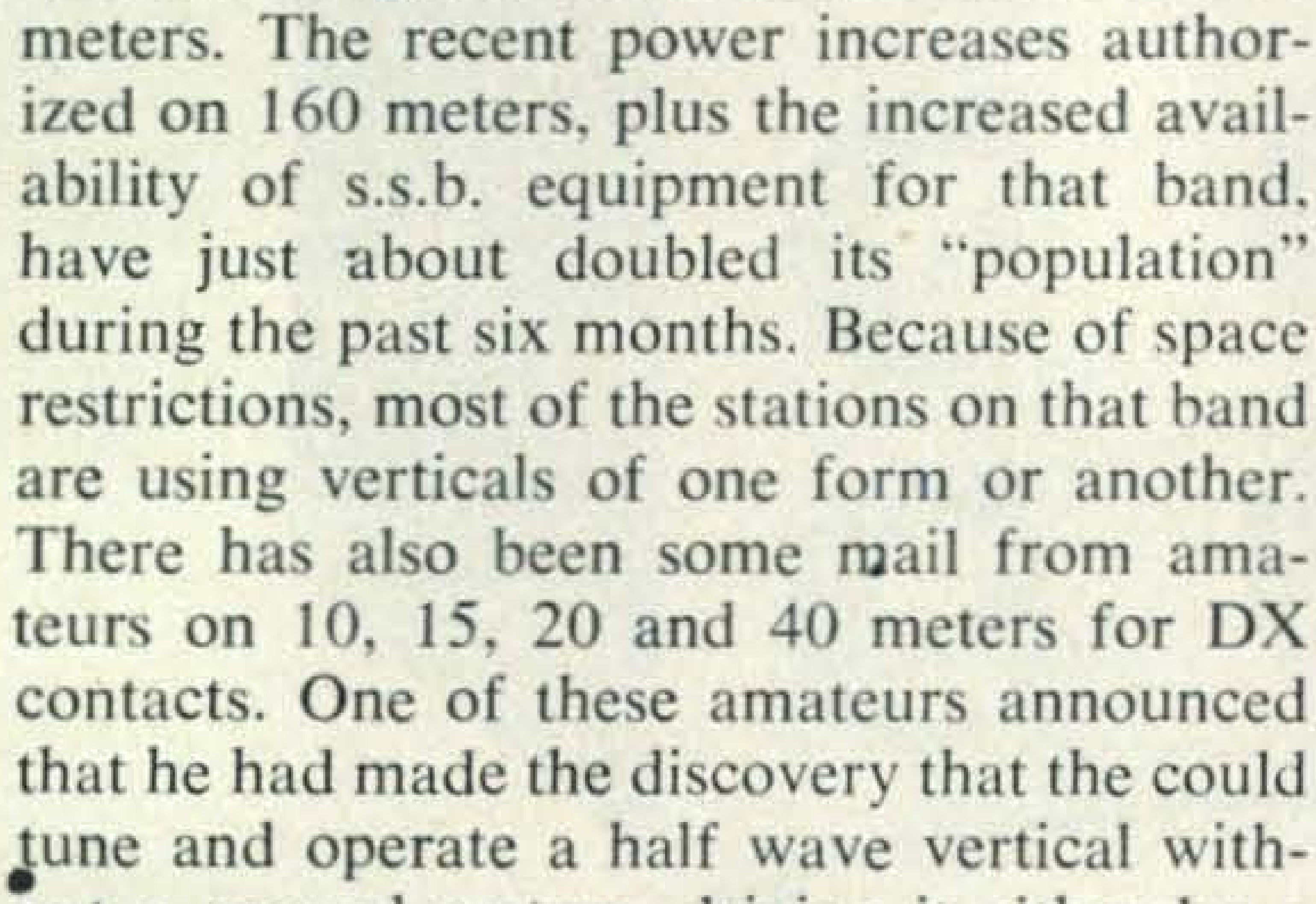

Fig. 99 — Current distribution along a quarter wave vertical and flow of r.f. currents into the ground.

There are two areas of interest when o studies the effect of the earth on radiati from vertical antennas. One of these is t area immediately beneath and surroundi the antenna, and the losses which occ therein which make a ground system nec sary. The other area is that of the reflecti zone, or as it is called by those of us in t business, "the Fresnel Zone." I shall discu the close-in area and ground systems first.

Earth Conductivity

There have been many studies made a many papers written on the subject of ear currents and ground systems and their effe on antenna radiation efficiency. G.H. Brow whom we have met before in this series, pe formed an excellent analysis and confirmed by practical experiments.[79,80] R. C. Hil

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*5209 Bangor Dr., Kensington, Maryland 20795.

[79] Brown, G. H., "The Phase and Magnitude Earth Currents Near Radio Transmitting A tennas", *Proc. of IRE,* Feb. 1935, p. 168.

[80] Brown, G. H. et al, "Ground Systems as Factor in Antenna Efficiency", *Proc. of IR* June 1937, p. 753.

See page 110 for New Reader Servi

3HRH, a well known radio engineer in his vn country, wrote a very fine paper on the bject covered by this Part.[81] The matter is so covered quite thoroughly in technical ɔcuments of the International Radio Con- ltative Committee (C.C.I.R.) of the Inter- tional Telecommunications Union (I.T.U.), eneva, Switzerland.[82]

All materials are conductors of electricity. ɔme are very much better than others, and me are very much poorer than others. The tter are sometimes called insulators. The rth is a conductor, and one may find fferent levels of ability to conduct for the rious geological types of earth surface. hen current flows in the earth's surface, the ell-known "skin effect" occurs.

Radio engineers who deal in h.f. and v.h.f. ork have to take this "skin effect" into nsideration in the design of conductors d inductors. Simply stated, the current tends concentrate near the conductor's surface, th the depth of penetration being less at gher frequencies. Usually, conductors are a homogeneous nature. However, the rth is not homogeneous, being made up of rious geological layers. It has been found, r example, that v.l.f. and e.l.f. waves pro- gate very well through certain types of ological formations, while they are rapidly enuated by others. At frequencies of 2 mc more of the current will flow in the upper yer of soil of good conductivity, rather an through underleyins strata.

Depth of penetration is a function of the nductivity, and it is greater for poorer con- ctivities. The following table shows depth penetration.[82]

requency (kc)	Depth (meters)		
	$\sigma = 5\times10^{-11}$ $\varepsilon = 81$	$\sigma = 1\times10^{-13}$ $\varepsilon = 10$	$\sigma = 1\times10^{-14}$ $\varepsilon = 5$
10	2	50	150
100	0.67	15	50
3000	0.20	5	17
10000		2	[illegible]

[illegible]

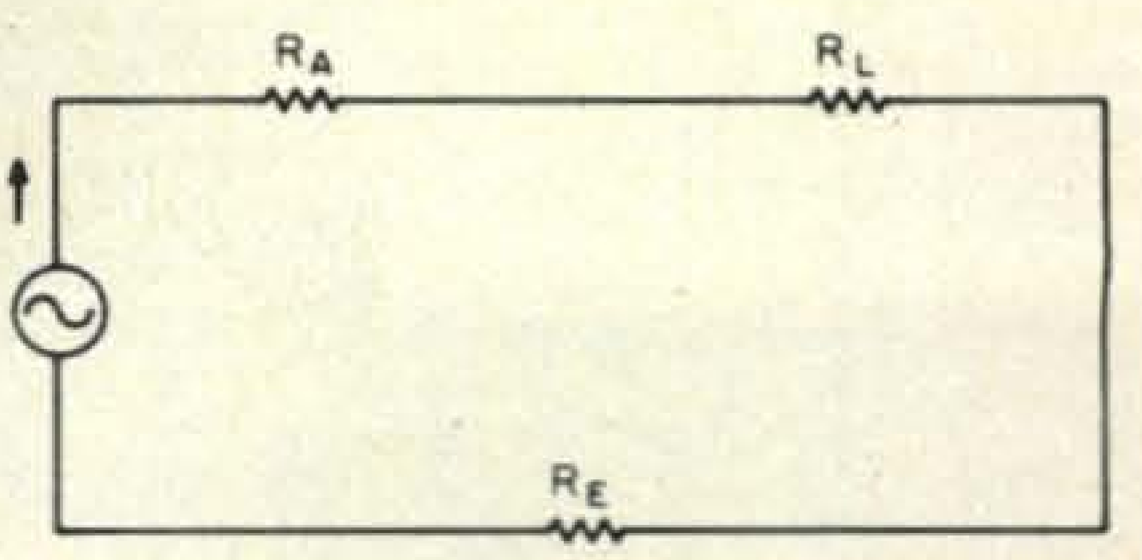
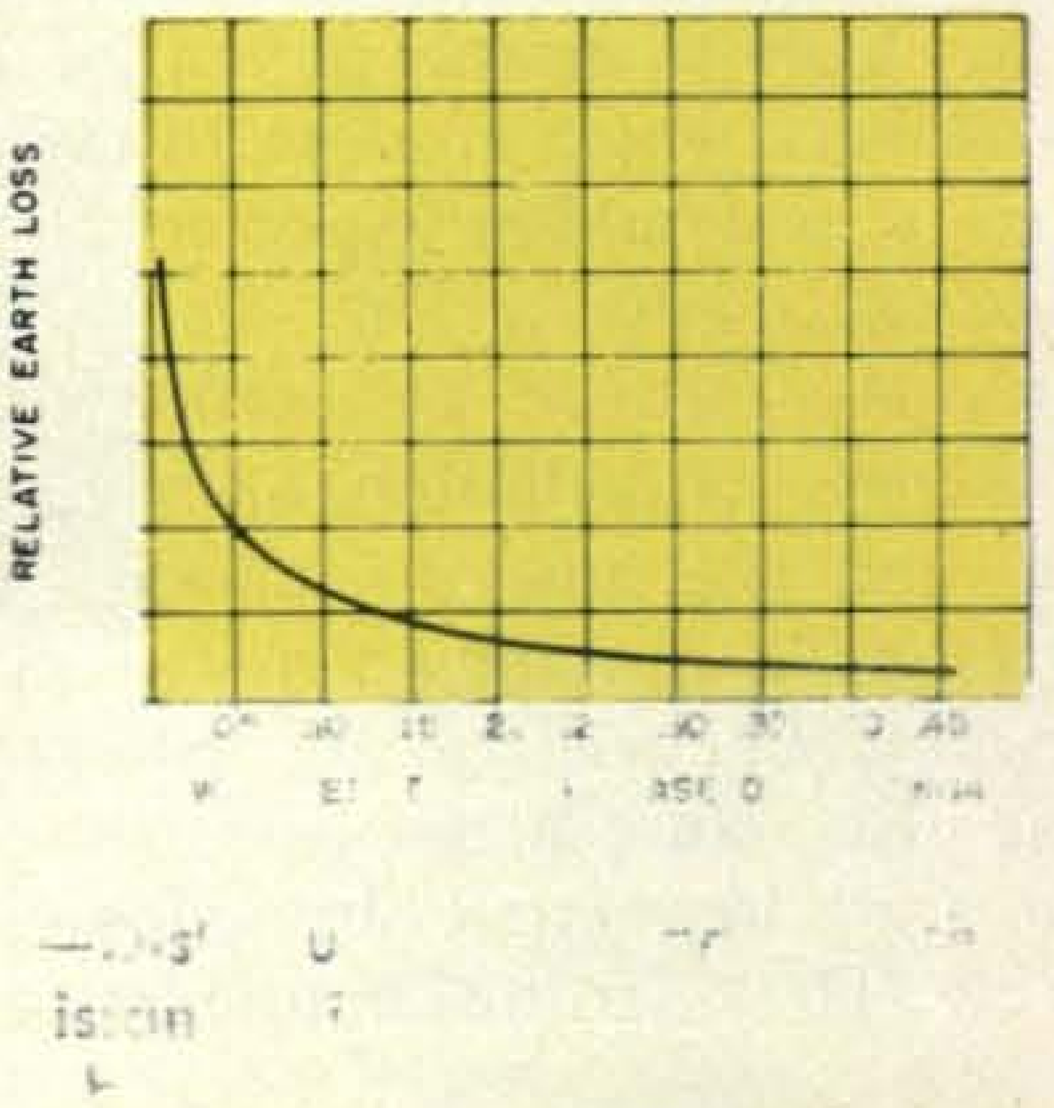


Fig. 100—Equivalent circuit of fig. 99. The radiation resistance is RA, conductor losses RL, and the effective ground resistance is RE.

It may be seen that depth of penetration is also inversely dependent on frequency.

The permittivity[83] of the earth as a dielectric also has an effect. Below about 2 mc it is not important, but at the higher frequencies it becomes increasingly important in considering the earth's role as a reflector. Generally, higher permittivity is associated with higher conductivity, and therefor the effect of earth is usually spoken of as depending on its conductivity.

In the first area of interest, that near the vertical antenna, the earth acts as a return path for the flow of r.f. currents. Let us consider first the case of the quarter wave vertical antenna, current fed at its base. Figure 99 shows the current distribution along the antenna, and the flow of r.f. currents into the ground. The current in the antenna induces charges in the earth surrounding it, which give rise to the circulating current which flows back to the generator. This flow of current is at a depth of penetration which, as mentioned above, depends on frequency and on ground conductivity· decreasing as both in-



[illegible]

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[81] Hills, R. C. "The Ground Beneath Us", *RSGB lletin,* June 1966, p. 375.

[82] Determination of the Electrical Characteris- s of the Surface of the Earth", Documents of IXth Plenary Assembly, Los Angeles, 1959, l. III–Reports, Report No. 139, p. 267.

[83] Permittivity it the property possessed by a material to permit an electric force field to be set up in it with greater or lesser effectiveness. If a material has a high permittivity an electric field will produce more effect in it than it would in a material of low permittivity.

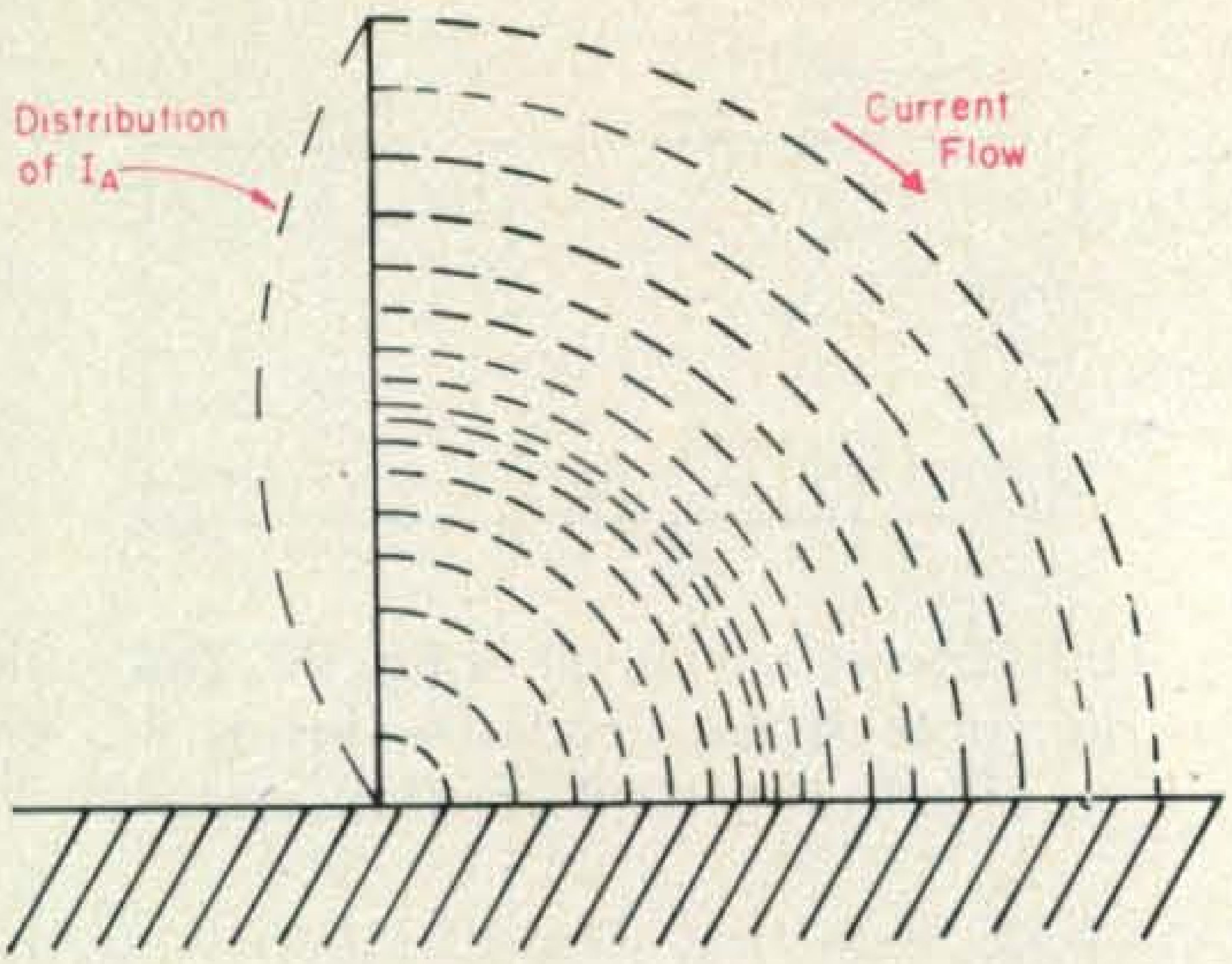

Fig. 102—Current distribution along a half wave vertical antenna and the flow of r.f. currents to ground of a halfwave antenna.

crease. The effect of this can be represented schematically by the series circuit of fig. 100, which shows r.f. power being dissipated in the several resistive elements of the circuit, which are the radiation resistance, R_A, the ohmic conductor losses, R_L, and the effective earth or ground resistance, R_E.

The standard practice is to make the radiation resistance as high as possible while making losses as low as possible, thus giving the highest efficiency. Ohmic losses can be kept low by proper design of inductances and use of low loss capacitors. Earth resistance, on the other hand, is something which is inherent to one's location, and unless one wishes to move the home and family to a new location, chosen on the basis of earth resistance, one has to live with it as it happens to be and make the best of it.

There is something one can do to make the best of it· and that is to reduce the earth losses by the use of a ground system. Brown determined the distribution of earth currents and earth losses both analytically and experimentally.[80,81] The distribution around a quarter wave vertical antenna is shown in fig. 101. It may be seen that the current and the losses are highest in the region of greatest current density which is close to the base of the antenna, as would be expected.

Half Wave Antennas

The current distribution on a half wave antenna, and the flow of currents into the ground from it, are shown in fig. 102. The series circuit schematic of fig. 100 applies in this case also. Here again it is necessary to keep the earth losses and ohmic losses as low as possible. The distribution of earth currents and losses around a half wave vertical a tenna whose base is close to earth is shown fig. 103. Brown determined experimentally that the region of maximum current and lo occurs at a distance of about 0.35 wavelengt from the base of the antenna. There is ze loss at the base of the antenna itself, ina much as there is no base current because t antenna is fed at a current node. A therm couple ammeter in the ground lead at th point will read *zero*. However, don't be d ceived by this phenomenon, because a the mocouple ammeter in the antenna lead w also read zero.

Efficiency Versus Earth

Figure 104 shows the variations in a tenna radiation efficiency over earth, for se eral values of effective earth resistance ar various antenna heights (lengths of vertic radiator). It may be seen from this figure th with low effective earth resistance provid by a good ground system, the short vertic radiator (one eighth wave or so), can be qui efficient. It may also be seen that for a giv effective earth resistance the efficiency d pends on the antenna's radiation resistanc which for a short antenna is less than that a tall antenna. There is not too much diffe ence between a half wave and a quart wave antenna provided that the effecti earth resistance is low. There is considerab difference between antennas ·of vario heights when effective earth resistance high. This set of curves very effectively sho that low effective earth resistance provid by a good ground system is an *absolu necessity* for vertical antennas of *any* heigh if good radiation efficiency is desired.

The correspondent's claim that one do not need a ground system under a half wa vertical radiator is true *only if he is conte to throw away from 40 to 80 per cent of h radiated power in the form of earth loss* He stated, "The ZL's *call me,* when I use m half wave vertical!" This is not surprising, view of the fact that the half wave's vertic pattern has a lower main lobe angle than quarter wave would have, and lower th that of the usual horizontal Yagi array. Ho ever, he would hit the ZL's even harder if h would put in a ground system. Of course, th half wave vertical antenna is not depende on a ground plane, however lossy or efficien for the condition of *resonance,* since it *resonant in itself* because of its half wa length. However, *it is dependent on a groun* *ne for its efficiency of radiation,* as is any tical antenna. Actually, the 5/8 λ vertical etter than the half wave vertical from the ndpoints of low angle radiation and feed nt impedance.

The Ground Plane

How does the ground plane function? at should be its configuration? To answer se questions, one should look back at fig. and 102, which show the necessity for a urn path to the base of the antenna, and at 100, which shows the effective series cuit. Since the currents have to flow from points in the earth surface to a common tral point (base of the antenna), it natuy follows that a *radial* configuration of ductors is required. Remembering what s previously said about the depth of penetion of earth currents being inversly prortional to frequency, and recalling that ses in the earth increase with frequency, it lows that the radial wires should be buried se to the surface, for h.f. work. In case of awn or other sodded area, let them be just ow the level of the sod, at two or three hes depth. One of the half-round lawn ger blades, with a long handle, is ideal for king a slot in sod. By moving the handle erally as one steps on the blade, the slot may opened and the sod pushed aside for an h or so, and the wire dropped or pushed init with a narrow stick of wood. The wire ould be at least number 16 in size. Belden . 8012, #16 tinned copper, in 1000 foot ls, makes excellent ground radial wire. This antity will make 25 radials of average gth of 40 feet.

How many radials are required? Reference ould be made to fig. 9 & 10 of Part I[84] to te the effect of varying the number and gth of radials. Refering to fig. 104, a ound system of at least 120 radials a half ve long would be required to give an effece earth resistance of from 2 to 5 ohms. In e case of a short radiator, it is more impornt to have a large number close in, as own in fig. 105. If the configuration of e's property limits the length of radials in particular direction, a larger number of dials should be laid down where they have be short than where they can be nger, to improve the return path for the rth currents in the "short" sector, to keep the losses down. In the case of the half wave radiator, however, there need be no larger number close-in, because the current density in that region is low. Instead, there should be a large number *as long as possible,* preferably a half wave long, for lowest losses and greatest efficiency, bearing in mind that the region of greatest current density occurs from about 0.35 wavelengths from the antenna on out to further distances.

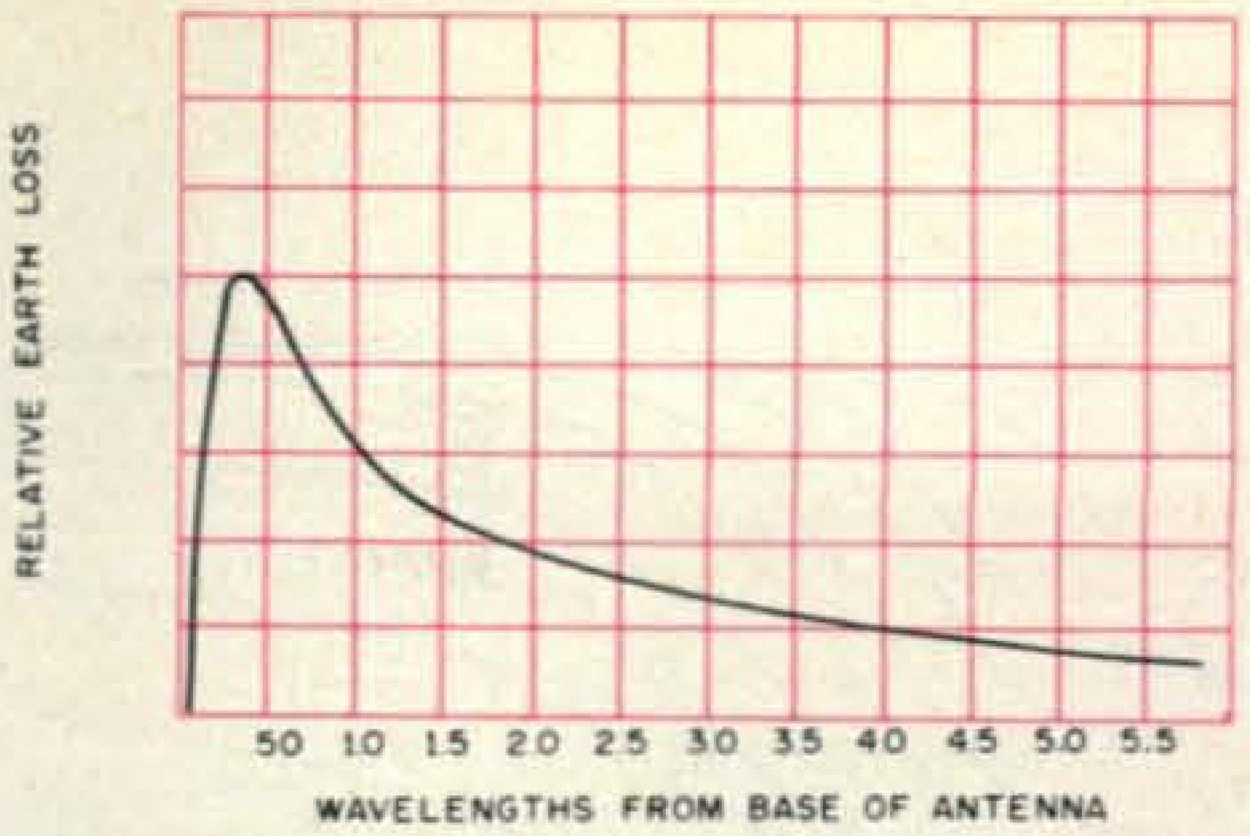

Fig. 103—Distribution of earth losses plotted against distance, in wavelengths, from the antenna base.

Since not everyone has enough property for such long radials, it could actually turn out that a quarter wave antenna with a large number of short radials might be more efficient, although its angle of main lobe radiation would be higher. If one were fortunate enough to be located on a body of water, with its inherent high conductivity, one would indeed have a very fine site for an antenna of any height, with a low loss ground plane.

Fresnel Zone

The second area of earth influence is that of the reflection zone, or "Fresnel Zone." Here again the earth conductivity plays a part, although not such a great one as it does in the launching of the wave in the immediate area of the antenna. In practice, all antennas must be installed at some finite distance above ground, or with base on the ground. Therefor their vertical radiation patterns are always influenced by the earth, and never, never conform to the patterns for "free space" conditions. The signal radiated at any angle is the vector sum of the direct ray and the reflected ray. Consider fig. 106, wherein a dipole is located at a distance *h* above ground. For horizontal polarization:

$$E'_\theta = 2\,E_\theta \left(\sin \frac{2\pi\, h}{\lambda}\right) \sin \theta$$

where: $E\theta$ is the resultant field at a distant point,
$E\theta$ is the field at the same point, in free space,

Lee, P. H., "Vertical Antennas–Part I", *CQ,* ne 1968, p. 16.

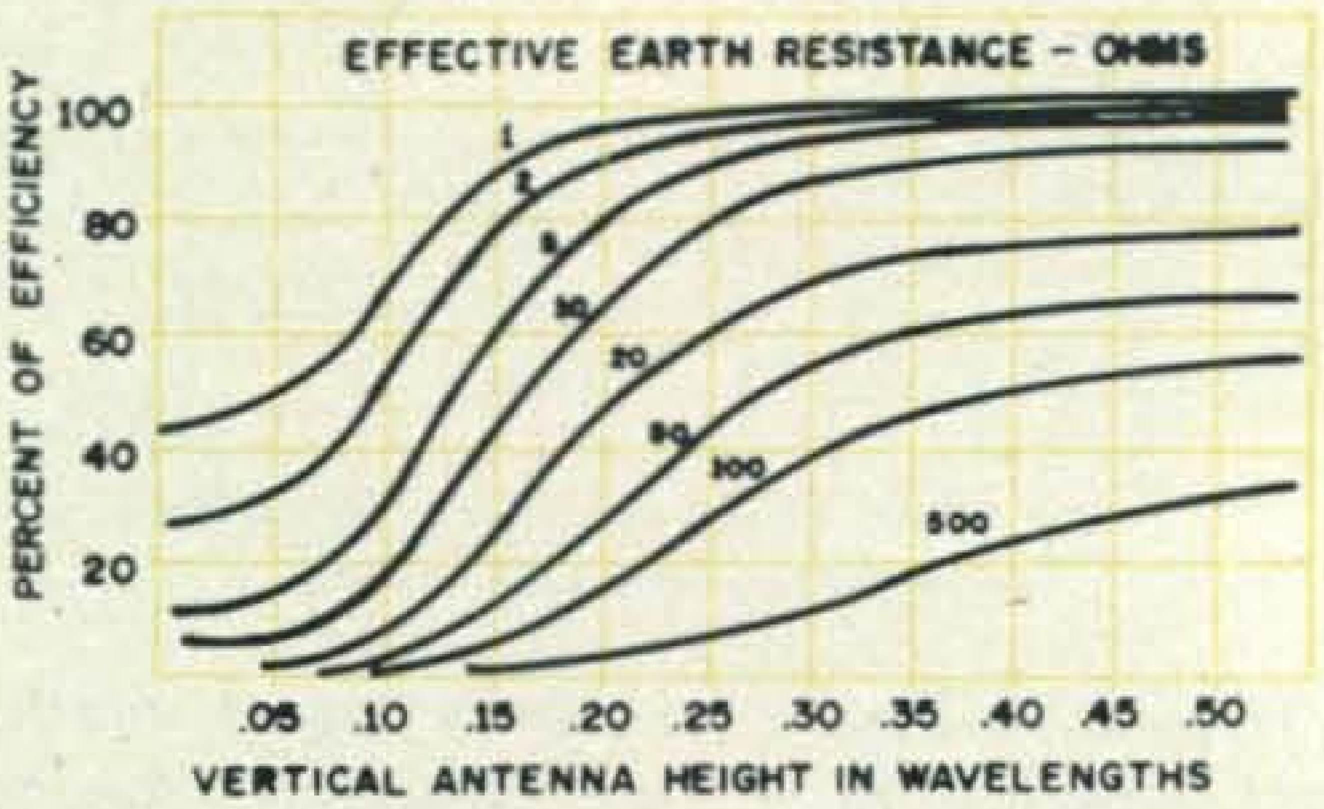

Fig. 104—Efficiency of radiation for antennas of different heights over various values of earth resistance.

θ is the angle of elevation of the point, and

h is the height of the center of the dipole above ground in wavelengths.

$$E'_\theta = 2\,E_\theta \left(\cos \frac{2\pi\,h}{\lambda}\right) \sin\theta$$

These two equations are of the same basic form, the difference between them being that in the case of horizontal polarization the wave is reflected with a phase shift of 180° at the reflection point, and with vertical polarization there is zero phase shift. *This is only with a perfectly conducting reflecting plane,* which is never the case in actual practice, although sea water approaches it.

In the "real life" case, with an imperfectly conducting earth, there is an effect called the "Brewster Effect," named after an English physicist, Sir David Brewster, who investigated certain optical properties of reflecting planes as related to polarization of incident light waves. Using non-polarized light, Brewster found that it was partially reflected and partially refracted at a plane surface, such as the surface between air and glass. (You snorkel fisherman may be aware of this effect as you look upward from below the surface of the water.) He discovered that there is a critical angle at which the reflect wave is totally plane polarized. In the ca of radio waves and the earth's surface, it the horizontal component which is reflect at the critical angle, and the vertical cor ponent which is reflected or suppressed. S fig. 107. If the earth were a perfect diele tric, the critical angle would be 15° above t horizontal. However, it is not a perfe dielectric nor is it a perfect reflector, a energy will be lost at the reflection point in the earth. The ground reflection coefficie and the Brewster Angle will therefore va with ground conductivity.

Figure 108 shows the phase and amplitu of the ground reflection coefficient for varyi angles of incidence of a vertically polariz wave. The curves for higher frequencies m be taken to represent the trend for poor conductivity at the lower frequencies. Figu 109 shows the same thing for a horizonta polarized wave. The following relationsh applies:

$$\textit{Reflection Coefficient} = \frac{\textit{Reflected Wave}}{\textit{Incident Wave}} \angle \phi$$

What do these curves show us? We c easily see that there is a "suck-in" or atte uation of the low angle radiation from vertical antenna, plus a large phase shift the reflection point for very low angles incidence. On the other hand, with the ho izontal antenna there is very low attenuati at the reflection point, but there is almo 180° phase shift at all angles of inciden This tells us then that the horizontal anten to have any good low angle radiation, mu be located at considerable height above t earth (at least a half wavelength and pref ably higher) to equal the low angle perfo mance of the vertical. This fact, coupled w mechanical and structural consideratio plus those of available space, make the ve tical an ideal choice for the three low band 40, 75 and 160 meters. There is anoth benefit to be gained, also, and that is the fa that with a good ground plane and a quart wave antenna whose maximum current is the base of the antenna, the rays that accou for most of the radiation from the anten emanate from its lower portion of hi current and their reflection points will [illegible] hereby incurring less loss than if they were o fall at some distant points beyond the conrol of the station owner. In fact, if one were o assume that the center of radiation of the uarter wave vertical is at a very small disance above ground, for the sake of the formlas and curves above, the results would not e very far from reality as far as the vertical attern shape is concerned. There would be ome suck-in at low angles, which would epend to a great extent on the excellence of he ground plane itself. With a computer one an actually compute the vertical plane paterns from antennas of various heights, taking nto account the various ground conductvities which exist in different areas of the ountry.

This might all be summed up by saying hat *ground systems are very important,* and hat the conductivity of the earth itself is also vital factor in antenna efficiency. The folowing points should be observed, when intalling a vertical radiator:

a. Install as many radials as possible, as ong as possible, in your ground system.

b. A short radiator can be quite efficient f ground radials are of sufficient number and ength to keep earth losses low.

c. If you use a halfwave or 5/8 wave adiator, use radials of at least one half wave ength, if possible, to keep earth losses low nd to enable you to realize the full benefit f the added height and its increased low ngle radiated field.[80, 82, 85]

d. Radials should be at least #16 copper vire, and should be brazed or soldered to a opper strap of 2" by 1/16" size around the ase of the antenna. If the antenna can be ocated on top of a sheet of copper or exanded copper screen, about two or three eet square, this is ideal as a tie point for the adials.

e. Soft or hard solder may be used. If it is sed, all soldered joints should be coated vith an asphalt paint or compound to prevent them from corroding when buried. Asphalt roofing cement or tile cement, when eated to make it more fluid, is ideal for this. A soldering torch should be used for solderng. Do not rely on the limited heat from a oldering iron. Brazing or silver solder is est.

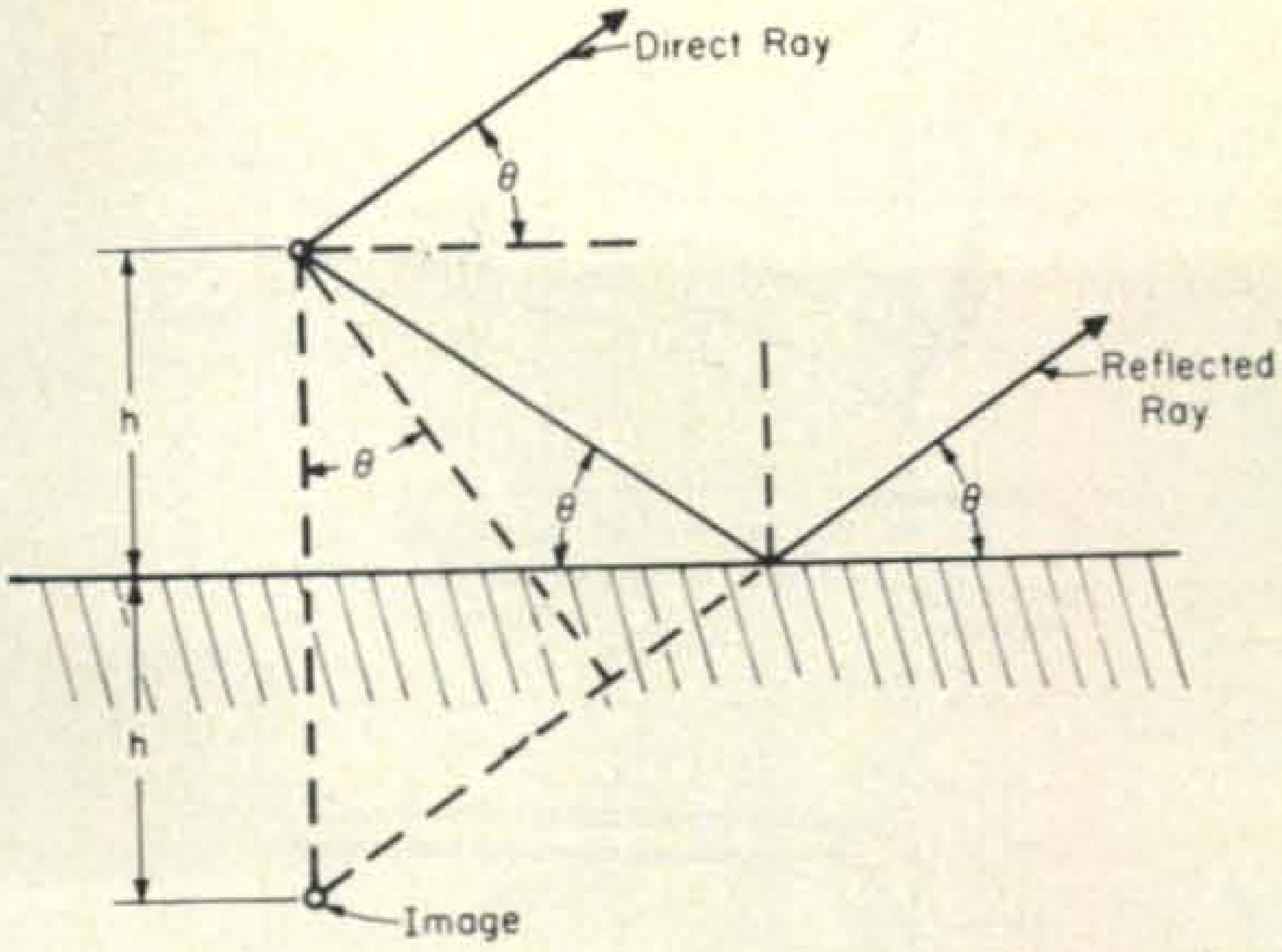

Fig. 106—Relationship between the direct and reflected wave from a dipole located a finite distance above ground.

f. Do not cross radials or tie their distant ends together. This avoids circulating currents which could cause loss.

g. If a Gamma Match type of feed is used with a grounded tower, the connection between tuning unit and tower should be heavy because it will have to carry considerable current if the feed point resistance is low.

h. Radials should be buried about 2 or 3 inches, just enough to get them under the sod for protection.

Summary

In closing, let me relate some personal experience. When I started operation at this location in 1959, I installed 8 radials of #9 aluminum wire, and several years later added 8 more. In the intervening years the aluminum has gradually corroded and been eaten away, and recently I was not sure how much

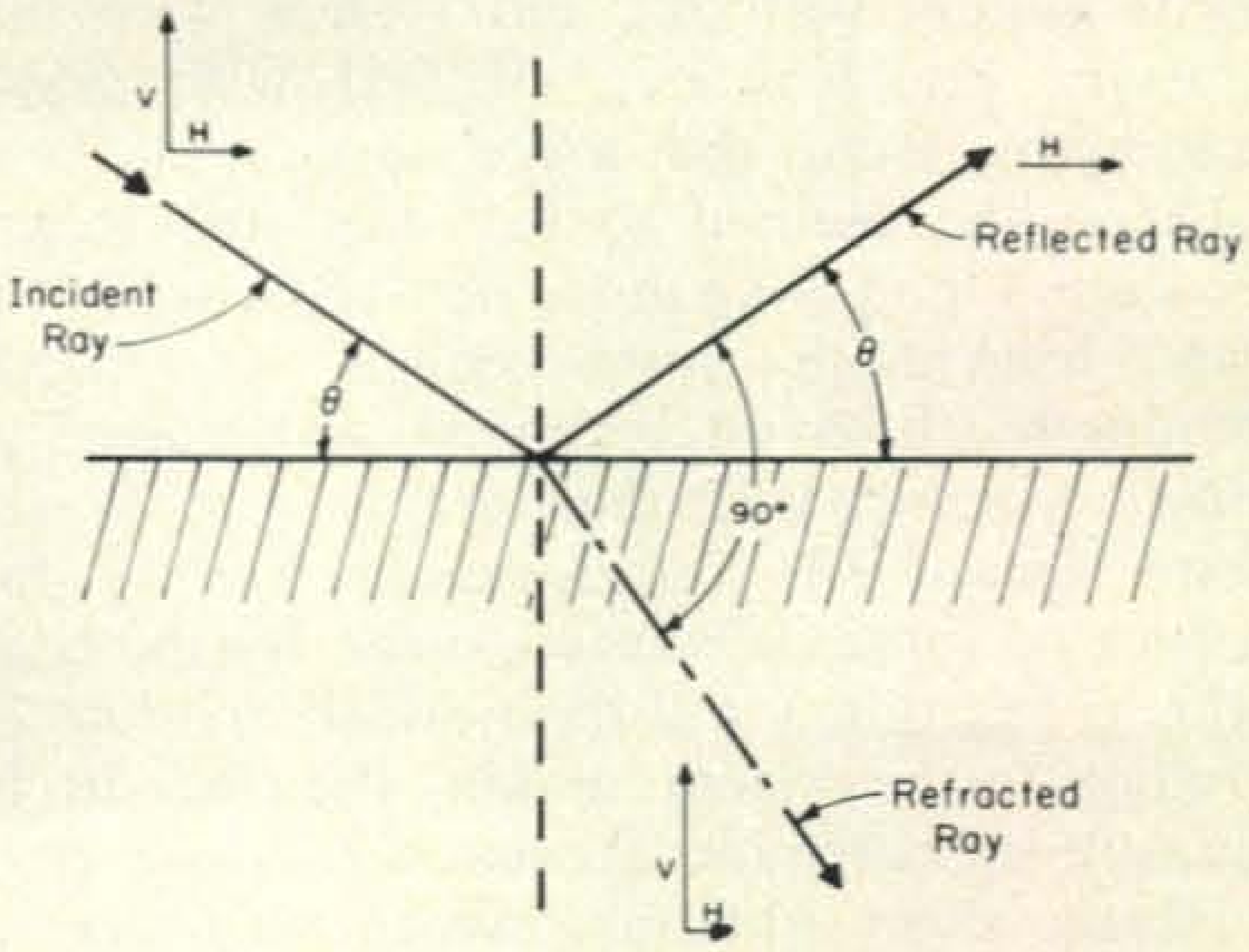

Fig. 107—Relationship between the reflected and refracted rays. The polarizations are shown for each ray.

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[85] "HF Vertical Plane Patterns of Monopoles and Elevated Vertical Dipoles With and Without Extended Ground Systems", *Naval Electronics Laboratory Center Report* 1567, 25 June 1968.

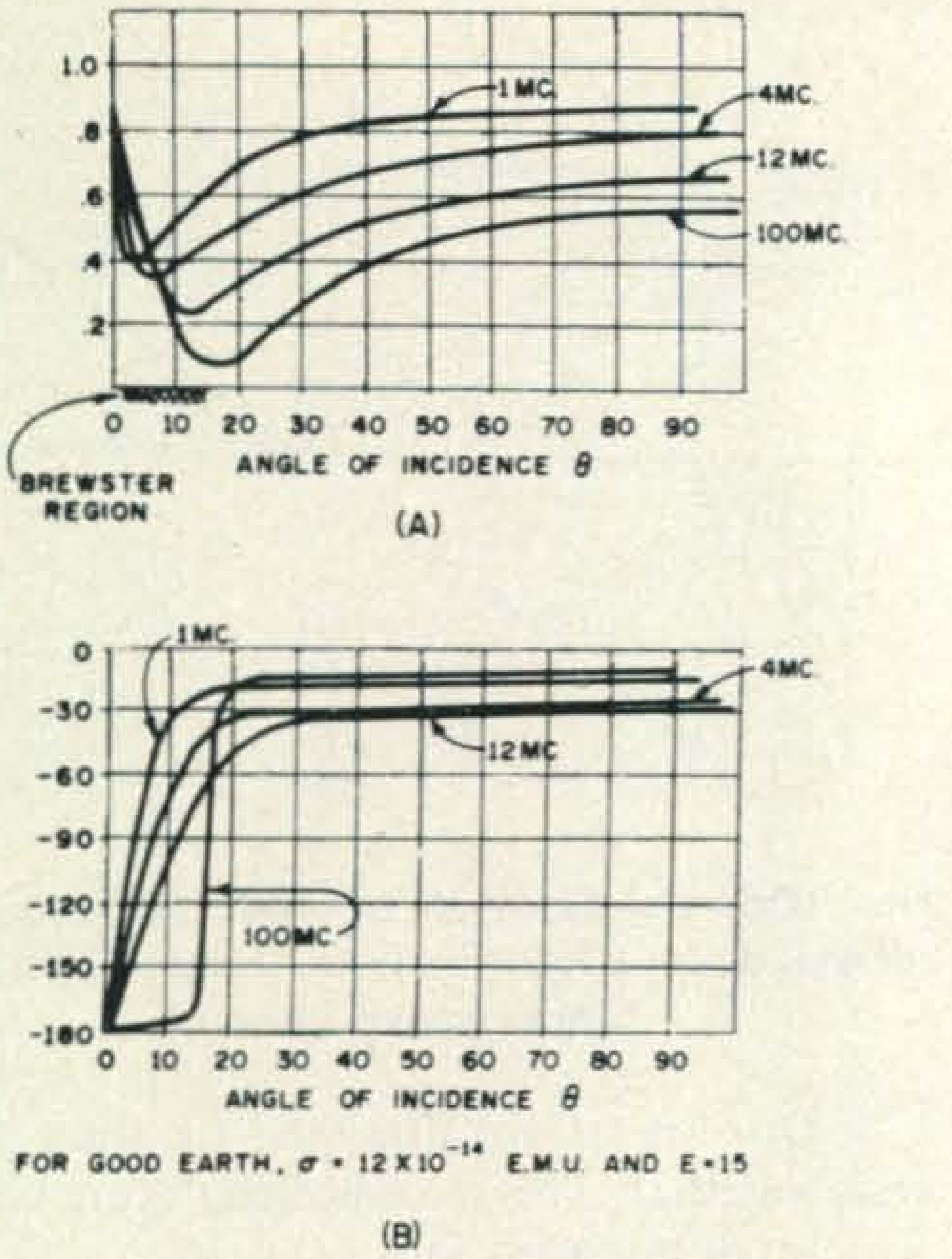

Fig. 108(A)—Amplitude of the ground reflection coefficient for various angles of incidence at different frequencies, (B) Phase angle for various angles of incidence at different frequencies. Both plots are for a vertically polarized wave. For good earth conductivity:

$$\sigma = 12 \times 10^{-14} \text{ e.m.u.}$$
$$\text{and } \varepsilon = 15.$$

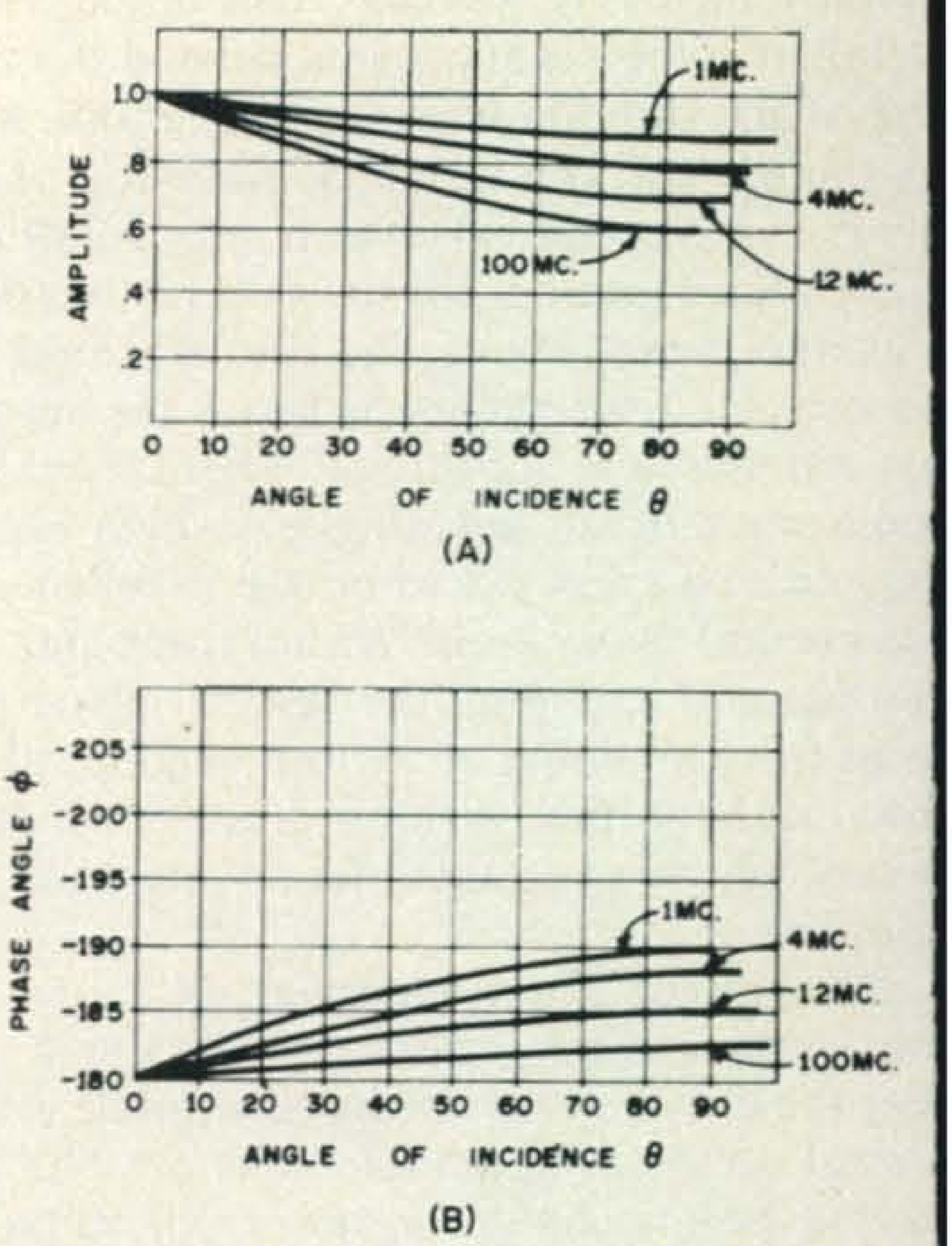

Fig. 109(A)—Amplitude of the ground reflectio coefficient for various angles of incidence at dif ferent frequencies for horizontally polarize waves. (B) Phase angle for various angles o incidence at different frequencies for horizon tally polarized waves for good earth conductivity

ground system I actually had left. Not wishing to dig it up to find out, I bought 1000 feet of #16 copper and proceeded to install 50 new radials, of varying lengths from 35 to 80 feet, at intervals of about 7° around the Mark IV Antenna.[86] I had been working on 160 meters with the old system with fair results, but was not satisfied with signal strengths from the more distant stations. There had seemed to be some loss in the system. Upon tying in the new radials I noted an immediate improvement in signal strengths, both on receiving and transmitting, especially with the stations in more distant areas. The improvement was of the order of three or four S-points. By the time this is in print, I will have added another 24 radials to the system, making the total 50, to reduce the earth losses even further. An electrically short antenna, which this one is (about 0.16 wavelengths tall on 160 meters), can be quite efficient when earth losses ar kept low.

Correction

We regret an error in Part IV of this series in the September 1968 issue. In Figure 32 page 42, the designations of the two curve (resistance and reactance) were inadvertentl reversed. However, this does *not* make th numerical values for mutual impedance use in Parts VIII and IX incorrect. The value used in the examples were taken from correctly labelled original.

(To be continued)

ANNOUNCEMENT

Next month we conclude this twelve part series, "Vertical Antennas," by Captain Paul H. Lee. If you have missed any part of this series and wish to obtain earlier installments, write to: *CQ* Circulation Department, 14 Vanderventer Avenue, Port Washington, New York 11050. Issues published during 1968 are priced at $1.00 each and 75¢ for those published in 1969. These prices include postage.

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[86] Lee, P. H., "Mark IV DX Antenna", *CQ*, Feb. 1967, p. 60.

VERTICAL ANTENNAS

Part XII (Conclusion)

BY CAPT. PAUL H. LEE,* W3JM

In this, the final part of the series, the author, in summary, lists and answers some of the questions he has received from readers during the series.

ONE of the things that goes with writing articles for amateur magazines is the large amount of correspondence from readers seeking advice and assistance. I have always tried to answer all letters received, albeit not as promptly as I would like to have done it, due to the pressure of other things. One thing that any author appreciates is the enclosure of a stamped, self-addressed envelope. This is only common courtesy, and it usually brings a more prompt and complete answer. The mail from this series on vertical antennas has been considerable. In fact, it has been greater than that from anything else I have ever written, which shows that readers are interested in learning about antennas. This has been especially true of those who want to use verticals on 75 or 160 meters. The recent power increases on 160 meters and the increasing availability of s.s.b. equipment for 160 meters have led to considerable interest in antennas for that band, shown both in the correspondence and in my on-the-air contacts.

In thinking of what to say in this final installment of the series, I decided that it would be appropriate to give some practical information on problems which confront our readers, and what better way to do it can there be than to quote actual questions received, and the answers I have given? I am aware that this may lead to a flood of additional correspondence with questions, but I am sure that I can make some provision for handling it, and perhaps publishing the answers for the information of all. Incidentally, it is the plan of this publisher to put the twelve parts of this series together in small handbook form, together with other articles I have written in the past on verticle antennas. This has been something I have wanted to do for a long time, to get out a small book on verticals, a subject which, until this series, has not been covered in any depth in print.

Questions and Answers

1. Q. *I am new in amateur radio, and don't know much about antennas. What do you recommend for 80 meter c.w?*

A. The answer to this will depend on several factors which I do not know, such as the space you have available, and what areas and distances you expect to work. If you have the space, and a pair of tall poles or other supports, you can put up a dipole cut for about 3650 kc, feeding it in the center with a balun and coaxial line. The height above ground will determine the vertical angle of maximum radiation, in general the greater heights giving lower angles. If it is only 30 to 40 feet above ground, for example (less than 1/4 wavelength), most of your radiation will be at high angles, which will give you good local area coverage within 200 or 300 miles. A vertical antenna of 1/4 wave height or less, with a good ground system, will give you a lower angle of radiation, which will extend your coverage out well beyond 1000 miles reliably. The vertical will take less space than the horizontal dipole, but it does require a ground system if it is to work efficiently.

2. Q. *What would be the result of turning my three element tri-band beam on end and operating it as a rotary vertical array? Could I still mount it on my 50 foot tower and pipe mount?*

A. This would be very nice if you could mount it somehow without any steel pole, tower, or supporting structure. However, the presence of such items will distort the beam pattern and one cannot predict the results. Also, there is the matter of feeding it. Unless

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*5209 Bangor Drive, Kensington, Md. 20795 you could devise some means of carrying the feedline out horizontally from the center of the driven element for considerable distance, you would have an unbalanced situation which would give you antenna currents on the outside of the feedline. (This would be the case if you were to bring the feedline down vertically, parallel to the elements.) It is impossible to predict what you would get from this installation without building a small model (v.h.f. or u.h.f. range) and actually measuring the patterns on a model range. I once considered using a 5/8 wave grounded base, gamma fed vertical as a driven element, mounting the rotor right in it at the proper distance above ground, mounting a crossboom above the rotor, and hanging vertical reflector and director from the crossboom. By this means one could solve the feed problem and the support problem in one stroke. However, such a thing would be a single band affair. I may yet do it as an experiment, on 10 or 15 meters, where the size would be reasonable and easy to work with.

3. Q. *Will a ground system under my horizontal beam give me improved performance? What should be its configuration?*

A. A ground system under a Yagi array is a waste of money and effort. The radiation from the array is horizontally polarized, and is mainly horizontal in direction. Therefor a ground system beneath it will not affect it. The ground (earth) which does affect it is that in the Fresnel Zone (first reflection zone) which is many yards away from your antenna. Of course this area is not usually under your control, and you are unable to do anything about its character. If you live on a body of water you will have an excellent, low loss reflecting surface in the Fresnel Zone, and you can consider yourself fortunate indeed.

4. Q. *I have a 40 foot cabin cruiser, and wish to operate mobile with my KWM-2 in it. What do you recommend for an antenna? How can I get a ground connection inasmuch as the boat has a wooden hull?*

A. I recommend you use one of the several good mobile whips now on the market, if your operation is going to be on the amateur bands only. One with traps or replaceable coils would be very good. Make sure it is one with the loading coil in the whip rather than at its base, inasmuch as his will bring your current maximum up into the antenna instead of having it appear in the loading coil where it contributes nothing to the radiation. If you wish to operate in the ship-shore bands between 2 and 3 mc, I would suggest one of the wound whips for this service which you will find advertised in such sources as the Radio Master, *etc.* A ground connection can be obtained by installing a bronze plate about 2 by 4 feet on the bottom of the boat, and bringing several bronze bolts through the hull (approximately caulked, of course), for connections inside the boat. The motor, fuel tank, and other associated metal parts should be connected to this ground plate. You may have to install an ignition noise suppression system also, as you would do in an automobile. By the way, don't install the plate near the bow. Put it back near the stern, so that if you go fast in your boat it will not lift out of the water and unground you!

5. Q. *I have a Hy-Tower vertical, and for a ground connection I have connected to a well casing which goes down 40 feet. The water table is at about 25 feet. Is this sufficient, or do I need some radials? If the latter, how many?*

A. You have a good d.c. and lightning protection ground, but practically none for h.f. radio. If you will read Part XI, you will see that at h.f. the depth of penetration of the earth currents is very small, so what you have down there at 25 feet makes no difference. You need ground radials just below the surface to provide you with a low loss return path for the earth currents. Put in about 25 to 50 radials of number 16 wire, about 2 or three inches deep. This can be done with a powered lawn edger to make a slot in the sod, or by one of those half-round edger blades powered by your foot stepping on it. I did 50 radials (2000 feet of wire) in two Saturdays. When you get this ground system down and connected, you will be surprised at the increased performance of your vertical antenna.

6. Q. *I am in a house which is surrounded on three sides by other houses very close, and there is not much yard space. If I put a quarter wave vertical for 40 meters on top of the house, will it work? I can't put down any ground system.*

A. Yes, you can put a vertical on top of the house. For a ground plane of sorts, you can lay some radials on the roof of the house. I would lay down at least 16 of them, to assure a reasonable efficiency. They should be as long as possible. If necessary, run them over

See page 110 for New Reader Service

the edge of the roof and down the sides a bit. You could even connect each one to a copper ground rod driven into the earth at ground level. Make sure that you do not have any unbonded contacts to gutter pipes, *etc.*, for non-linear joints which develop at such places will give you plenty of TVI problems. Of course, you will not get the classic patterns out of this antenna, but it will work reasonably well. Feed it with coaxial line run up to its base.

7. Q. *Doesn't a vertical cause more TVI and BCI than a horizontal antenna?*

A. I don't believe it does. I have used one ever since I moved to my present location in 1959. I have had several TVI complaints which have been solved in accordance with the FCC's established program, by having the set owner get from his set manufacturer, at no charge, the necessary filter, and I have installed them as a courtesy. I found that with my Mark IV Antenna, which uses the tri-band beam on 10, 15 and 20, and the tower (ladder) as a top-loaded vertical on 40, 75 and 160, I had more complaints from the high band operation on the beam than I did with the low band operation on the vertical. This is probably due to several factors. First, at the higher frequencies, house wiring, TV antennas, speaker leads, *etc.*, are a larger fraction of a wavelength than they are at the lower frequencies, and thus they tend to pick up more h.f. energy. Also, the beam concentrates its signal, and when it was pointed at certain neighbors they really got it! On the other hand, those with outdoor antennas (unnecessary in this area) had lower frequency energy picked up by the long downleads. This caused a beat between the TV sound carrier and the h.f. transmitter signal, which caused a spurious signal to appear in the TV set's picture passband. The filters solved this problem also. As I recall it, when I used a simple vertical on 15 and 20 meters, before putting up the beam, the TVI problems were less severe, and I feel this difference is due to the beam's present concentration of the energy in one direction. BCI, in the little transistor sets, is impossible to eliminate, and I don't see any difference between the beam and the vertical in this respect. If there is any difference, it is probably due to frequency more than to polarization.

8. Q. *I have a crank-up tower for my beam. How can I use it as a folded unipole? Where should I tap onto it?*

A. You have a problem! You can either choose to crank it up and down, or to feed it as a folded unipole, but not both. In the first place, you will have to bond the joints between sections of tower to assure a good connection, first from the standpoint of a good r.f. joint, and second, from the standpoint of preventing any non-linear joints which would generate TVI. When you have done this you will not be able to crank it up and down. Also, if you do not bond it, each time you crank it up and down it is probable that the tower sections will not make connection with the same exact path length, and the tuning will change a bit. Where should you tap it? That depends on what bands you want to work. I suggest you see my article in February 1967 *CQ* on the Mark IV DX Antenna. I would go to the top of the tower with the 160 meter fold, and this could also be used for 75 meters if the tower is less than about 50 feet. If more, tap down at about the 30 foot level. For 40 meters, tap it at about 20 or 25 feet. Matching can be done with simple L networks consisting of two capacitors. See the Mark IV article for details.

9. Q. *I tried feeding my 50 foot tower on 160 meters by tapping onto it at about 20 feet above ground with the coaxial line, but it would not match, so I gave up the idea. Now, with your articles you make me think it can be done. Where should I tap on it and how should I feed it?*

A. Well, you tried, but forgot the fact that you have an impedance matching network in the circuit. As in the previous answer, take the fold wire all the way to the top of the tower and connect it there. Even though it is a 50 footer, the impedance looking into the fold on 160 meters will be of quite low resistance and rather high inductive reactance. This means that you have to use two capacitors in an L network to match it to RG-8/U line. Refer to the Mark IV article in February 1967 *CQ* for an example of this feed on 160 meters, and for typical capacitor sizes. I should mention one thing, though, and that is that your area is now allowed 500 watts daytime on 160 meters, and the voltage ratings of the capacitors will have to be increased over those used in the Mark IV. Those had only 0.1″ spacing, and when I tried 500 watts they arced over due to the currents and voltages involved. I had a couple of vacuum variables which I put in, and now all is well. I also had to increase the contact spacing on the relay that lifted the coax braid off ground. But perhaps you will not have that problem. If you are going to run only 100 watts or so, you won't have this arcing problem with 0.1" spacing capacitors.

10. Q. *I saw sometime ago in one of the magazines an article about verticals in an array which were grounded at their bases and fed at their tops. Why have you not covered this in your series? Where can I get information on this feed method?*

A. You have a good memory. That item appeared in QST for April 1959 in an article by R. W. Johnson, W6MUR, entitled, "The Groundpole Antenna." I did not cover it in my series because the configuration is not purely vertical, but also has horizontal elements which radiate. Basically, the idea is as follows. Take two 1/4 wave verticals, for example, separate them 1/2 wavelength, ground their bases and feed them by means of a center-fed half wave dipole whose ends are connected to the tops of the vertical elements. The radiation pattern from this combination will be complex, and would require computer analysis, or actual scale modelling for its determination. There are other configurations which may be used also, involving more than two elements. I should emphasize even more than W6MUR did that a good ground system is necessary for this type to work efficiently. In fact, inasmuch as maximum current occurs at the grounded ends of the vertical elements, ground currents will be quite high, because the whole thing can be considered as a closed loop with earth forming one part of the loop. It follows that this return path should be as low loss as possible, and even if many radials can not be put down, it is essential that there be a low resistance ground bus between the bottom ends of all vertical elements. This can be made of copper strap or several number 16 or number 12 wires run together in parallel. You might consider this type of antenna this way: normally, vertical arrays are fed from the base of the elements by a non-radiating system of transmission lines. In this case, the vertical elements are fed from the top with single wire tranmission lines that are allowed to radiate and contribute to the pattern, which then becomes complex and requires considerable mathematical analysis for its determination. My congratulations to W6MUR for his fine article.

11. Q. *Will my Quad work as top loading on my tower for 75 and 160 meters, as your tri-band beam does on your Mark IV DX antenna.*

A. I see no reason why not. The Quad element wires would constitute a considerable added top capacity on the tower, and it should work fine. I don't have a Quad but common sense tells me that it will work.

12. Q. *In your Mark IV DX antenna I notice that you have your CDR rotor motor physically and electrically in series with the vertical element of the antenna, with no bonding across it. Doesn't the motor winding burn up? Are you sure of the r.f. path through the motor housing? How do you protect it?*

A. Before making this installation I asked several CDR representatives whom I met at a local electronics show whether they had any reservations about the idea. They felt that the large number of ball bearings in the raceway would provide a good multiple contact between upper and lower portions of the housing. They did recommend that the rotor control cable conductors be bypassed to ground at the base of the antenna, inasmuch as the control cable is in effect in parallel with the tower itself r.f.-wise and will carry some r.f. current. I did this. Each of the seven conductors is bypassed to ground at the base of the tower with a 0.01 mf disc ceramic capacitor. These capacitors are housed in an aluminum beer can (empty), entrance to which is through the bottom end to keep water out. The can is mounted on one of the 4 × 4 tower supports. I do notice a very slight upward swing of the rotor indicator needle on 75 meters when I talk, but it is less than 1/4", and I attribute it to r.f. getting into the cable somewhere in the basement or the shack itself. Incidiently, there *is* an r.f. path across the rotor motor housing, and this is through the outer conductor of the coaxial line and through the balun coil. Obviously this is also a d.c. path for static discharges.

13. Q. *In finding the gain of a directional array, shouldn't you take the r.m.s. of the whole pattern through the vertical angles, instead of just the r.m.s. of the horizontal pattern?*

A. As I have said before, *gain is meaningful only when referred to a specific direction (horizontal and vertical angle).* It is standard practice among consulting engineers to use the horizontal pattern (vertical angle zero degrees) because that is the easiest one to

[*Continued on page 96*]

Verticals [*from page 62*]

measure by walking or driving to measuring points. Also, consultants are interested in ground wave coverage, usually. In some cases it is necessary to know the skywave pattern at a particular horizonal azimuth angle. The FCC insists on knowing the predicted vertical patterns, taken every 10° vertically, for all horizontal azimuth angles. If one wishes to know the gain of an array at a particular vertical angle, he can compute it by putting the vertical angle into the pattern equation, computing the pattern at that vertical angle, finding its r.m.s., and computing the gain, as I did for the horizontal plots in Parts VIII and IX. I did not do it for the vertical angles because I felt it would add too much complication to the articles for the average reader to follow. However, it can be done by anyone so deeply inerested. (This item came from a college professor who had worked out a computer program for deriving the whole three-dimensional pattern of an array, and he felt that to know the gain of the array one should base it on the r.m.s. of the three-dimensional pattern. It is very commendable that he has worked this out. I wish I had such facilities at my disposal. However, I reiterate that gain is meaningful to the communication sysem user only when referred to his specific direction of interest. The gain at other directions is nice to know because he can then tell whether his antenna is wasting power in spurious lobes, but it is not essential to the basic question of gain in the desired direction. And in my case I chose the horizontal plane for ease in measurement.)

14. Q. *In your directional computations you show only the horizontal patterns. What about the verical angles? These anennas can't be as perfect as you have shown them. Isn't there power lost in high angle skywave lobes?*

A. Yes, there is power in skywave lobes, but in the case of the simple two and three tower patterns shown, the skywave lobes are small, relatively. In the case of in-line arrays, one can generalize and say that in each null of the horizontal (groundwave) pattern there will be a small skywave lobe. Its angle above the horizontal will depend on several parameters of the array, the most important of which is the factor f (θ) for the tower heights involved. In the case of arrays of other configurations and more elements, such as parallelograms or "dog-legs," the skywave lobes can be found only by computation. A computer does indeed come in handy for this. I know of one consultant who designed a multi-element array of irregular configuration for a client some years ago, who did not compute the whole pattern at 10° vertical angle increments (before it was required). When the array was built, he could not make his horizontal r.m.s. come up to the value required by the FCC. In other words, he was losing too much power in skywave lobes and in circulating power within the array. It was a "losser." The array had to be torn down and redesigned. Naturally the client became quite irate, instituted a law suit, *etc.* This was quite embarrassing as well as costly to all concerned. So, the answer is, "Yes, there are skywave lobes, but in the simple patterns they are minimal."

15. Q. *My radio room is on the third floor of our house. I would like to use a vertical on the roof, but how do I make a ground connection from this height?*

A. Obviously you cannot make a good r.f. ground connection to earth from this height, because your ground lead will be a part of the radiating system and will place your entire installation at some r.f. potential above ground, besides introducing possible losses from coupling to house wiring, plumbing, *etc.* I suggest you install a ground plane antenna on your roof, feeding it with coaxial line, in the same manner as I suggested to the writer of question 6.

Conclusion

This concludes the present series on vertica antennas. I want to thank those who have written, and to those who have expressed your interest over the air. Your number ha been considerable, and it is very gratifying t an author to know that his works are rea and appreciated. It is also pleasing to th publisher, who wants you to know that bac issues containing these articles which bega in June 1968 are available. Please do no write to me for reprints. I cannot furnis them. Write to *CQ*. The handbook containin all of the articles will be published as soo as possible. I have enjoyed writing for yo and thank you for your interest.

Erratum

In Part IV, fig. 32, the labels "reactance and "resistance" on the curves were inadve tently interchanged. Please correct them.

See page 110 for New Reader Servi