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THEORY AND PRACTICAL ATTAINMENTS IN THE DESIGN AND USE OF RADIO DIRECTION FINDING APPARATUS USING CLOSED COIL ANTENNAS.*

BY

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INTRODUCTION.

It is a common enough experience in radio stations to be able to hear signals on a sensitive receiving set when the antenna is disconnected entirely from the apparatus. In such cases the tuning coils of the receiver pick up energy directly and the signal produced depends upon the electromotive force induced in the coils by the alternating magnetic flux component of the passing wave which threads through the windings. Another familiar example of coil reception is afforded by the ordinary wavemeter. Such small coils as these are, of course, extremely poor receivers; but the fact that they do receive enough energy at all over distances of the order of a number of wave-lengths at once leads to speculation as to the possibility of using larger coils especially designed for the efficient reception of signals.

In considering this problem the average engineer would at once conclude that the coils should be given large area, many turns and low resistance. The questions that he would probably not be able to answer, however, would be—How large shall the

* Communicated by Maj.-Gen. George Owen Squier.

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area be, and how many turns. As a matter of fact, his first conclusions would only be partly correct, for while it is, of course, desirable to keep the resistance down to the lowest possible value, it has been found that the size of the coil and the number of turns cannot be illimitably increased without seriously reducing the efficiency. Actually, there exists for every wave-length a certain set of optimum dimensions giving maximum response at the detector. These facts have not been generally recognized heretofore, and although closed coil or loop receivers have been in practical use for the reception of signals over long distances for several years, they have not, up to the present time, been built according to completely rational designs. The proper size of the loop, the number of turns, the size and kind of wire and the spacing of same has been largely a matter of good technical judgment.

In addition to the use of the coil or loop for ordinary receiving purposes to replace the antenna, one of its most important practical applications comes from its directional qualities. It requires but little thought to realize that a coil placed with its winding plane perpendicular to the direction of travel of passing electromagnetic waves will have induced in it no voltage at all, while if it is turned around through 90 degrees so as to be in line with the wave propagation it will be threaded by maximum flux and develop its maximum *e.m.f.* This at once presents the possibility of locating the direction of any transmitting station that may be heard, and it has been found possible by correct design to build apparatus capable of locating such directions with an error not exceeding plus or minus $\frac{1}{2}$ degree. Actually, a great many factors affect the accuracy of the device as a direction finder and the best results can only be obtained by properly taking all of them into account. Theoretical analysis of the effects involved has led to the development of methods for greatly improving the accuracy of the loop for direction finding and also to the important invention of a method for determining, by means of a single isolated loop structure, not only the *line* of a distant transmitting station but also its *sense* or *absolute* direction.

It is the purpose of the present paper to summarize an investigation that has been carried out in the U. S. Signal Corps Radio Laboratories during the latter part of 1917 and 1918 of all of these factors that enter into the efficient design of direction find-

ing apparatus using the loop antenna. No loop receiver can ever be made to be as efficient a collector of radio energy as a well-designed elevated antenna system and recourse is usually had, therefore, to the use of very sensitive detecting apparatus involving vacuum tube detectors and vacuum tube amplifiers in order to get the desired strength of signal. There are other reasons, also, of a more involved nature which make it necessary to employ specially designed amplifying apparatus in connection with the loop direction finder, so that while the main points to be discussed in this paper are those dealing with the efficiency of the loop as a receiver, its proper design, and with its directional properties, a few paragraphs are also devoted to investigations that have been made on the subject of amplification for this particular class of work. The experimental data presented with reference to the design of the loop for high efficiency is reasonably complete and would appear to be sufficient to allow fairly exact mathematical formulation. This phase of the problem has not been developed, however, in the present report.

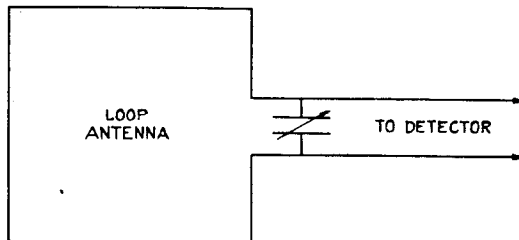
PART I.

DESIGN OF THE LOOP RECEIVER.

GENERAL THEORY.

THERE are several ways in which the loop receiver may be connected to the detecting apparatus, but the one most commonly used and the one that is considered in this paper is that

FIG. 1.



shown in Fig. 1, where it will be seen that a variable air condenser is connected directly across the loop terminals for tuning and the voltage developed across this condenser is impressed upon the detector.

The engineering problem presented is that of proportioning the loop so that this voltage will be as high as possible. The points involved, as will appear shortly, are:

1. Determination of best size of loop and number of turns for given wave-length,
 2. Effect of spacing the turns of the winding,
 3. Effect of size and kind of wire,
 4. Effect of insulation and coloring matter in same,
 5. Proper size of tuning condenser,
 6. Effect of proximity of loop to walls of rooms,
 7. Effect of the presence of dead or unused turns on coil;
- and in order to come to practical conclusions of value to the engineer in building such coils it was necessary to study several other points, such as the effects of obtaining a given flux linkage or a given inductance through the use of large area and few turns or with smaller area and a large number of turns. Thus, in the following pages, sections are also devoted to the cases of:

1. Constant flux linkages with variable turns and area.
2. Constant inductance with variable turns and area.

This part of the investigation is then completed by working out from the data accumulated a design chart which enables all of the principal dimensions of a loop to be quickly determined when the working wave-length is given.

Let

- h = Instantaneous value of field intensity at the loop.
 H_o = Max. instantaneous value of h .
 λ = Wave-length.
 N = Number of turns on loop.
 A = Area of a turn.
 L = True self-inductance of loop.
 R = Total effective resistance of loop.
 C = Capacity of tuning condenser.

The instantaneous value of *e.m.f.* induced in the loop is

$$\begin{aligned} e &= N \frac{d\phi}{dt} \cdot 10^{-8} \\ &= NA \frac{dh}{dt} \cdot 10^{-8} \dots \dots \dots (1)^1 \end{aligned}$$

If the field varies harmonically,

$$h = H_o \sin \omega t \dots \dots \dots (2)$$

¹ If the loop is of the flat pancake type the value of NA to use is the summation of the individual areas of all the turns, i.e., $\sum_{N,A}$

and (1) becomes

$$e = NAH_o \omega \cos \omega t \times 10^{-8}$$

Therefore, the instantaneous current in the loop and through the tuning capacity, C , is, at resonance,

$$i = \frac{E}{R} = \frac{NAH_o \omega \cos \omega t \times 10^{-8}}{R}$$

and the effective value of this current is

$$I_{eff} = \frac{NAIH_o \omega \times 10^{-8}}{R \sqrt{2}}$$

The voltage across the tuning condenser due to this current is, as has been stated above, used to actuate the detector and its value will be a measure of receiving efficiency. This voltage is (approximately)²

$$\begin{aligned} E_c &= I_{eff} / \omega C \\ &= \frac{NAIH_o \times 10^{-8}}{\sqrt{2} RC} \\ &= \frac{4 \pi^2 V^2 H_o}{\sqrt{2}} \cdot \frac{NAL \times 10^{-8}}{\lambda^2 R} \\ &= K \left(\frac{NAL}{\lambda^2 R} \right) \dots \dots \dots (3) \end{aligned}$$

From this it appears that we have in general to deal with the problem of making the factor NAL/λ^2 as large as possible. This factor has been termed the "reception factor" in what follows.

At first sight, it would seem that a given loop would become increasingly more effective as the wave-length was shortened. In practice, however, such is not the case and audibility measurements have indicated that there is a certain best wave-length for a given loop above and below which the reception falls off.

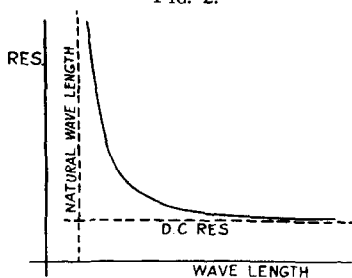
The reason for this can be directly traced to the fact that the loop resistance is not constant but changes with the wave-length. At very long wave-lengths the resistance approaches its *d.c.* value. As the wave-length is shortened, however, the resistance increases, slowly at first, up to a point 2 or 3 times the natural period of the coil when it rises almost asymptotically (see Fig. 2), and it is this inverse variation of effective resistance with wave-length

² This expression is not exact because part of the capacity is that of the loop itself which is distributed and does not all carry the total current I .

that produces the maximum value in the reception at a particular wave-length already mentioned. The reception factor curve drawn as function of wave-length has the form shown in Fig. 3.

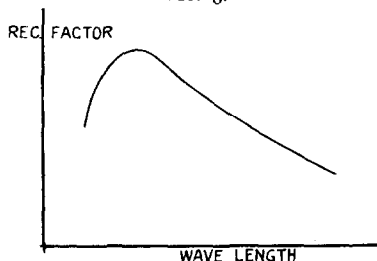
The variation of resistance just described is due to a combination of several effects, being chiefly caused by the capacity between

FIG. 2.



turns of the winding, but involving also the effects due to eddy current loss, skin effect, electromagnetic radiation, and losses in nearby imperfect dielectrics. It is very greatly affected by the number of turns, the size of the loop, and the spacing of the wires. It is also influenced, though to a lesser extent, by the actual *d.c.*

FIG. 3.



value of resistance, the diameter and shape of the wire and whether stranded or solid.

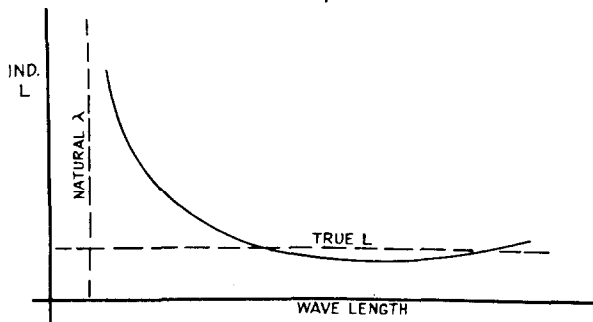
It is to be noted that the apparent inductance of the loop varies with the wave-length (Fig. 4) in a manner similar to the resistance but less abruptly. The increase in apparent inductance at short wave-lengths is due to the effective shunted capacity of the loop. The slight rise at long wave-lengths is due to the disappearance of skin effect.

For a given wave-length the equation (3) would indicate the

use of many turns, large self-induction and a large loop. These factors cannot be changed, however, without at the same time raising the natural wave-length of the loop and its effective resistance; and there actually comes a time when increasing the size of the loop and the number of turns is detrimental. There is, in fact, a certain best value of turns, area, spacing, etc., for any given wave-length. For short wave-lengths only a few turns can be used and the proper combination is quite critical, while for long waves where a large number of turns are employed, deviation from exactly best proportions is less serious.

No loop may be efficiently used at wave-lengths less than 1.5 to 2 times its fundamental.³

FIG. 4.



METHOD OF MEASURING LOOP EFFICIENCY.

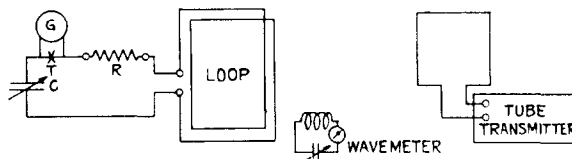
The method used in studying the various factors that enter into the design of loops was very simple. For each different set of conditions the effective resistance was measured at different wave-lengths, and from the physical dimensions of the loop and the data on its resistance thus obtained the reception factor $NAL/\lambda^2 r$ was calculated. This procedure was particularly well adapted to manipulation in the laboratory, and was justified by the results of a number of special tests made over considerable distances in which the audibility of received signals was measured directly at different wave-lengths. A description of these tests

³ The above discussion neglects entirely the reaction of the induced loop oscillation on the wave. The effect is very small, however, with this type of antenna.

is given later. They check the performance of the loop as calculated from measurements of its resistance.⁴

The "Resistance Variation Method" was used in determining loop resistance (see Fig. 5). The loop to be measured was inserted in a series circuit containing a variable air condenser known to be free from losses, and a low resistance thermoelement, T , and galvanometer, G . The galvanometer chosen was one which gave, accurately, deflections proportional to the square of the current in the thermoelement *throughout its entire range*. The thermoelements used were made up at the National Bureau of Standards and had resistances somewhat less than one ohm. The galvanometer was a single pivot Paul instrument, giving full scale deflection with about 80 milliamperes. Various known resistances could be inserted at R . These resistances consisted

FIG. 5.



of fine manganin wires a centimeter or so in length enclosed in glass tubing and fixed to heavy copper wire terminals which dipped into small mercury cups.

The loop to be measured was coupled directly with and carefully turned to a vacuum tube generating circuit, the wave-length measured, and several resistances inserted successively at R , the galvanometer deflection being read for each resistance. The resistance of the loop was then calculated from the formula

⁴ Attention should be called to the fact that the value of resistance in the expression for the reception factor is the total effective resistance of the oscillatory circuit which limits the flow of current therein, and this comprises not only the resistance of the loop alone, but also the resistance of the tuning condenser and an effective resistance introduced into the circuit by the attached detector. If a well designed air condenser is used for tuning, the resistance of this element can be neglected. The resistance introduced by the attached detector when this is a vacuum tube is also very small and need not be considered in any but exceptional cases. It can be calculated or determined experimentally by the methods given in Appendix A.

$$R = \frac{R_2 - R_1 \sqrt{\frac{\delta_1}{\delta_2}}}{\sqrt{\frac{\delta_1}{\delta_2}} - 1} - R_T$$

R_1 and R_2 = different values of inserted resistance.

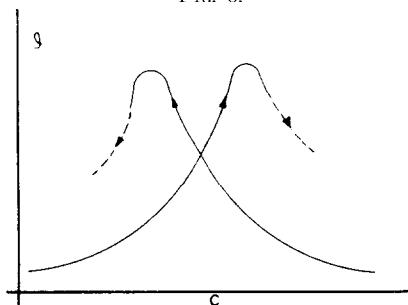
δ_1 and δ_2 = galvanometer deflections corresponding to R_1 and R_2 .

R_T = resistance of thermoelement.

The average of several values determined in this way for any given set of conditions gives all the accuracy desired.

Precautions to be Observed.—In making measurements of this kind it is necessary to arrange the set-up in a large room or out-of-doors and well away from possible absorbing resonators.

FIG. 6.



Proximity of the loop to the walls of a room may result in high effective resistance due to dielectric losses in same. The effect may be considerable, as is shown by one of the tests, when the loop is one of large size and many turns so that there is considerable condenser effect to the walls of the room.

Very loose coupling should be used between the generating and measuring circuits. This point must be carefully watched, for two reasons. First, when the coupling is tight the voltage induced in the loop will change with different inserted resistances.⁵ In the second place, there will be two coupling waves, either of which may be tuned to and the results will be inaccurate, due to the impurity of the tuning. Fig. 6 shows the nature of this effect. The coupling should always be made loose enough so that only one hump is present, as in Fig. 7. When the adjustments

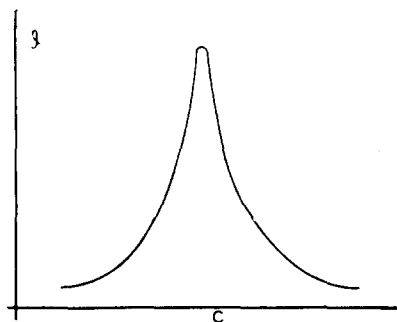
⁵ Due to reaction on the exciting circuit.

are properly made an ammeter in the generating circuit will drop only very slightly at resonance. When the coupling is too tight, the reading falls abruptly when the test circuit is brought in tune. The coupling must not be changed during one series of observations on a given wave-length.

The resistance of the thermoelement should be checked occasionally to see that it does not change.

The leads of the loop should be as short as possible, especially for the smaller loops, for in such cases the capacity of the leads may be a large part of the total coil capacity and the resistance will be seriously affected.⁶

FIG. 7.



RESULTS OF LOOP RESISTANCE MEASUREMENTS.

The results of the present experiments are here recorded graphically and in general in two parts.

⁶ It might be supposed that the above method would not give entirely accurate results, especially at the shorter wave-lengths, due to the fact that in such cases the current distribution varies through the circuit and is greater near the centre of the loop than at the ends. To test this point a number of resistance measurements were made by another method for verification. In this method the various known resistances were inserted in the circuit to be measured at its electrical centre and the galvanometer with its thermoelement was connected to an auxiliary coil coupled inductively with the loop. With this arrangement the deflections of the galvanometer are practically independent of the current distribution in the loop. When all the proper precautions had been taken it was found that the results obtained by this method checked those obtained by the method described in the text practically exactly.

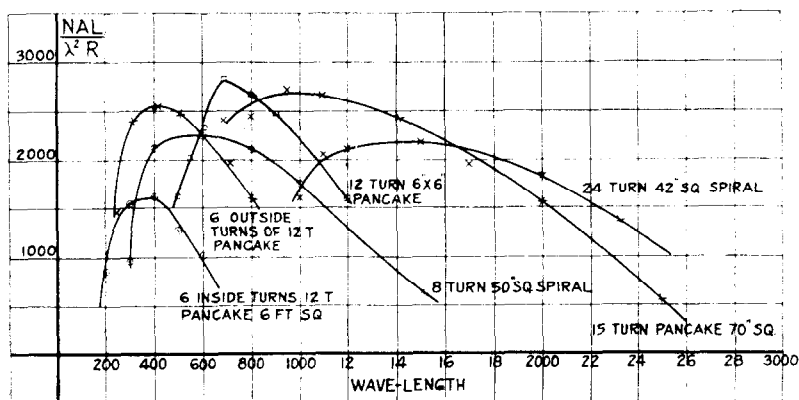
1. The resistance of the loop as function of wave-length.
2. The reception factor as function of wave-length.

The true inductance was estimated from the curve of apparent inductance.

I.

The first set of curves (Fig. 8) show the reception factors

FIG. 8.



of a miscellaneous lot of loops taken at random from loops that had been in use on direction finding experiments. It is interesting to compare these curves with those of some of the later loops in which the best proportions of spacing, diameter, number of turns, etc., were realized. These early loops were relatively inefficient.

The following data are descriptive of this lot of loops:

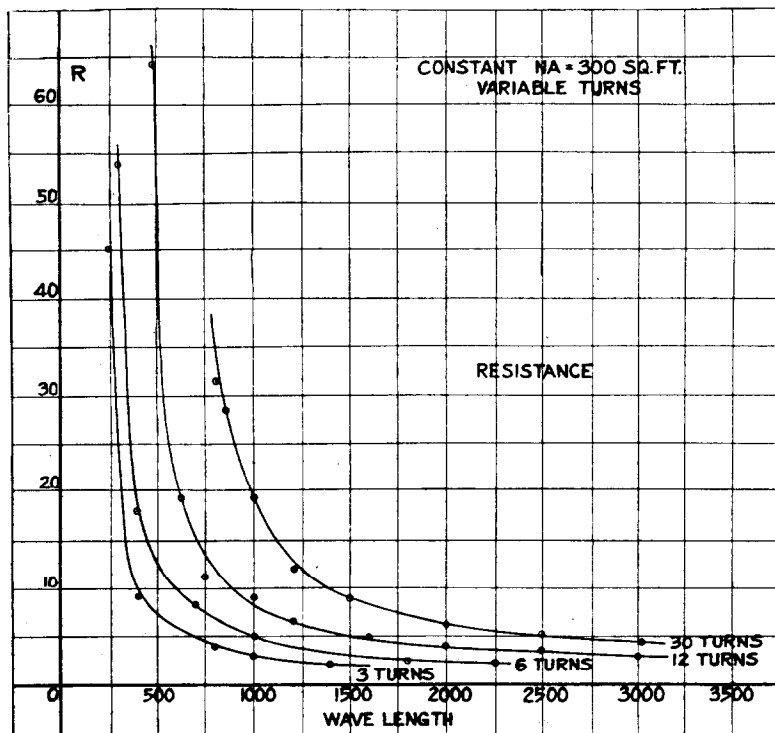
Loop	L cms.	Description
1	580,000	2 crossed loops at right angles 6 ft. sq. 2" spacing No. 16 lampcord.
2	70,000	4 turns bronze antenna wire on 50" sq., solenoid spacing $\frac{1}{2}$ "
3	230,000	8 turns same as No. 2.
4	94,000	Inside 6 turns of 12 turn pancake 6 ft. sq., spacing $1\frac{3}{4}$ " stranded No. 18.
5	155,000	Outside 6 of same.
6	340,000	All 12 turns of same.
7	800,000	15 turn pancake 70" X 70" outside spaced $\frac{3}{8}$ " No. 20 wire.
8	2,100,000	24 turn 42" sq. solenoid closely wound litz. 32 No. 38 enameled wires.

II.

CONSTANT FLUX LINKAGES.

As has been shown, the *c.m.f.* induced in a loop depends, among other things, upon the total flux linkages; that is, upon the

FIG. 9.

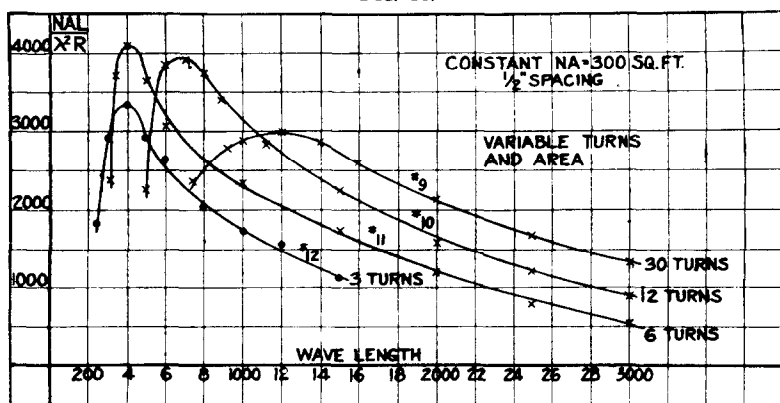


value of the product NA . Now it is not immaterial how a given value of this product be obtained. Either a large loop of few turns or a smaller loop of more turns may be used, but the characteristics of the two loops are widely different.

This is well shown by the curves of Figs. 9 and 10, which give the resistance and reception factor for 4 different loops whose size and number of turns were varied in such a way as to keep the product NA constant.

It will be seen from Fig. 10 that for short wave-lengths it is better to use large loops of a few turns, while for long waves smaller loops having more turns are preferable. This general conclusion is important and should never be lost sight of, although, as will be seen later, there finally comes a time at very long wave-

FIG. 10.



lengths when it is again better to decrease the turns and increase the size.

The 4 loops just mentioned have the following constants :

Loop	Turns	Area, sq. ft.	Spacing	Type	L cms.
9	30	10	$\frac{1}{2}$ "	Solenoidal	1,250,000
10	12	25	$\frac{1}{2}$ "	Solenoidal	582,000
11	6	50	$\frac{1}{2}$ "	Solenoidal	280,000
12	3	100	$\frac{1}{2}$ "	Solenoidal	120,000

III.

CONSTANT INDUCTANCE.

In proportioning a receiver for given wave-length, it is always best to use small tuning condensers, because this offers the possibility of large loop inductance (turns and area). A given inductance may be obtained either by few turns on a large frame or many turns on a small frame. There is a difference, however, as regards the relative effectiveness in the two cases.

Figs. 11 and 12 show the results of a comparison of several

FIG. 11.

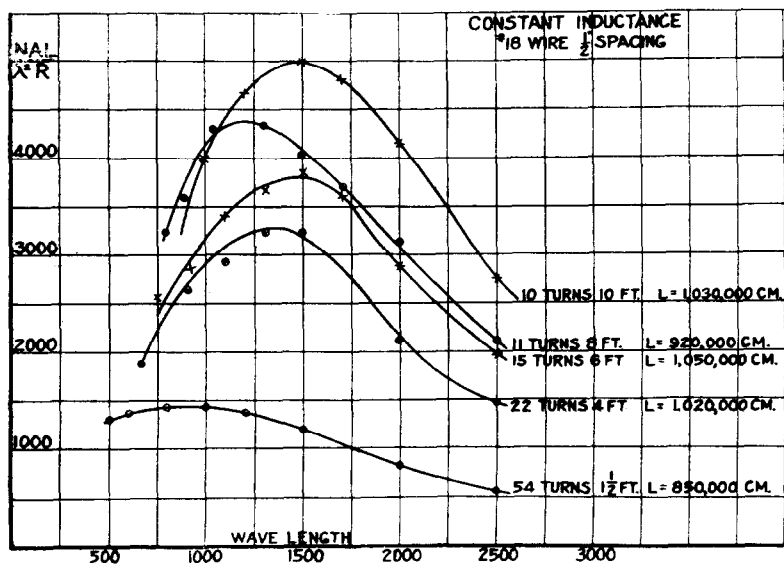
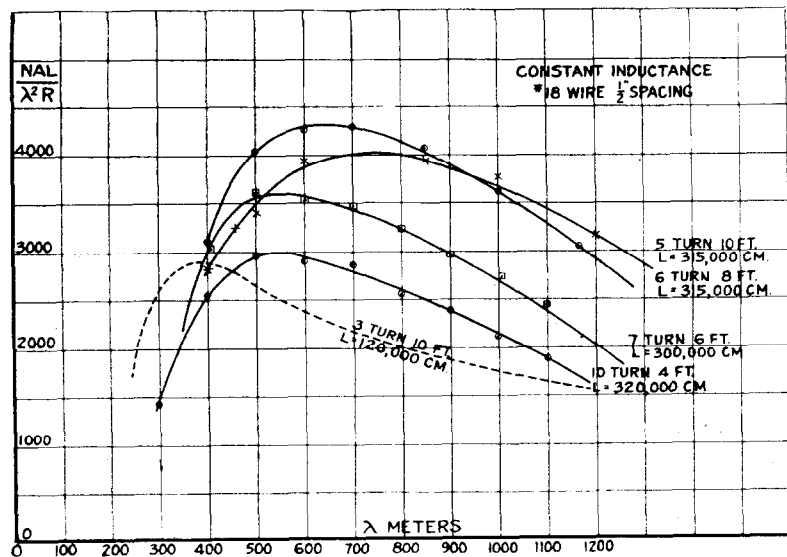


FIG. 12.



coils in which the number of turns and the area of the loops were varied, but in such a way as to maintain the inductance approximately constant. It will be seen that in this case the maximum reception factor always occurs at approximately the same wave-length, regardless of whether the given inductance is obtained by few turns and large area or the reverse. The curves become flatter as the number of turns increases, which means that a coil of many turns responds efficiently over a wider range of wave-lengths than does one of a few turns.

This last statement has direct application to small tuning coils as well; for example, the secondary of the ordinary loose-coupler. The general theory outlined above holds exactly for this case, and the same type of characteristics may be obtained for such coils.

While the data of this test does not cover very large loops of only one or two turns and so cannot be interpreted for such extreme cases, it does show that within the range used it is better for given inductance to use large loops with few turns. It would appear that for given inductance a single turn very large loop would be best, as the total flux (NA) would then be maximum.

IV.

DETERMINATION OF BEST SPACING.

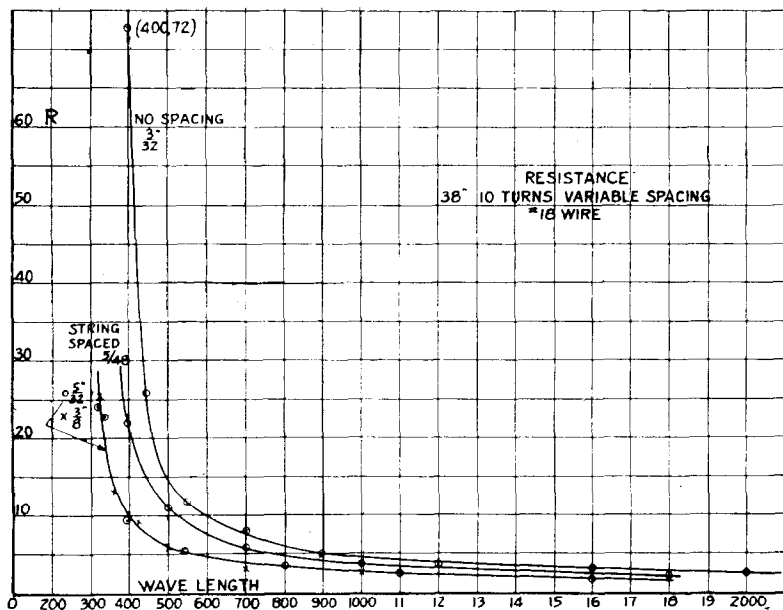
The spacing of the turns is a most important factor. Except at very long wave-lengths a closely wound coil has much higher resistance than one on which the turns are spaced. It is, therefore, better to space the winding unless the coil is to be used for extremely long wave-lengths. It is actually better in this case not to separate the wires very much because of the sacrifice in inductance.

For a given size of loop and given number of turns, *i.e.*, constant flux linkages, we have two opposing effects resulting from an increase in spacing, the decrease in self-inductance *vs.* the decrease in resistance. At first, the resistance decreases more rapidly than the inductance, so that increasing the spacing is for a time advantageous. A point is soon reached, however, where further increase in spacing affects the resistance very little, and this point should not be exceeded; for the inductance still falls off and the reception factor is therefore lowered.

If the inductance is kept constant by adding turns as the spacing increases, the best value of spacing is, of course, not so sharply defined, but still exists and corresponds to the point where the resistance ceases to be appreciably affected. It coincides very closely with the best value as determined for constant turns.

The nature of the several effects just mentioned is shown in Figs. 13, 14, 15, 16, 17, 18, 19, 20. Figs. 13, 15, 17, 19 show the resistance as function of wave-length for various sizes of coils

FIG. 13.



(3, 6, 10, 15 ft.) wound with 10 turns of No. 18 wire and spacing systematically varied. Figs. 14, 16, 18, 20 show the corresponding reception factor curves. A best value of spacing is clearly evidenced in each case. Figs. 13-A and 15-A are given to show the effect of spacing on inductance and should be studied in conjunction with the resistance curves for the same loops (Figs. 13 and 15).

It will be noticed that in general the closer the spacing the greater is the useful range of wave-lengths of the loop. Wide spacings make the reception factor curve peaked. It is, therefore,

FIG. 13A.

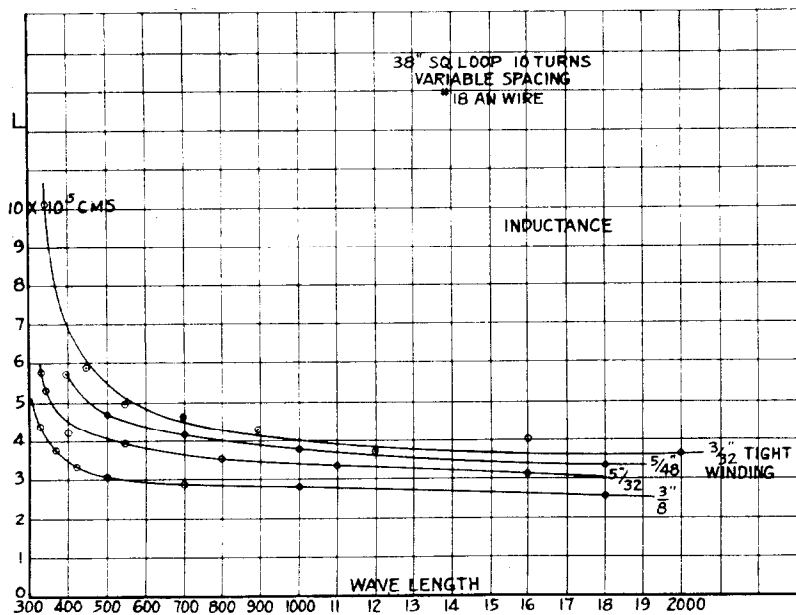


FIG. 14.

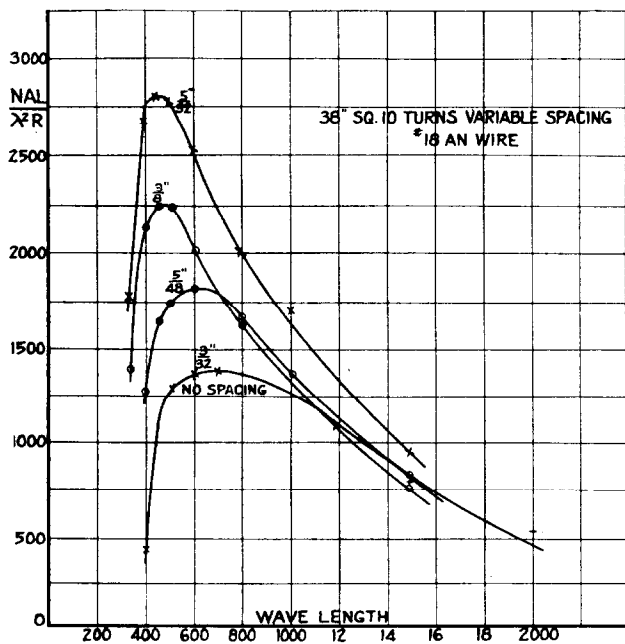


FIG. 15.

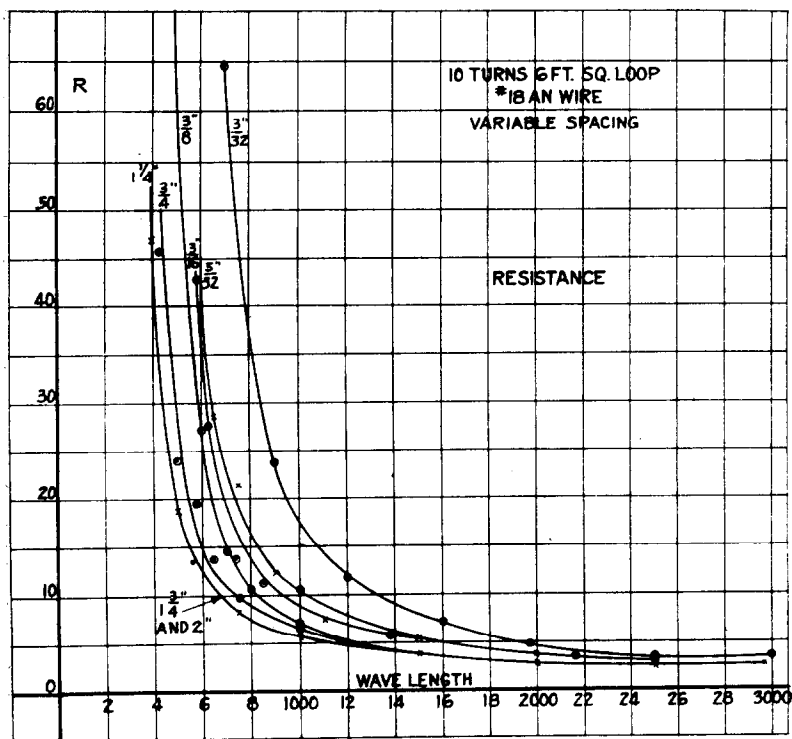


FIG. 15A.

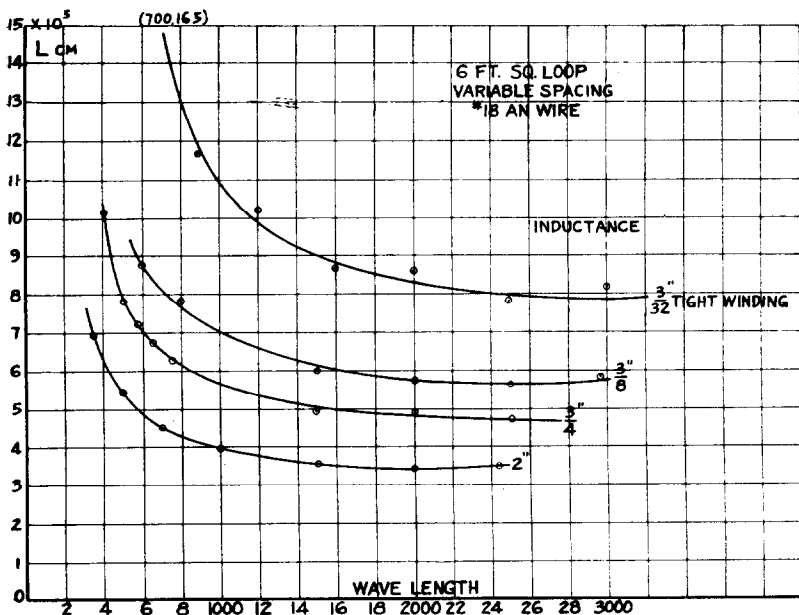


FIG. 16.

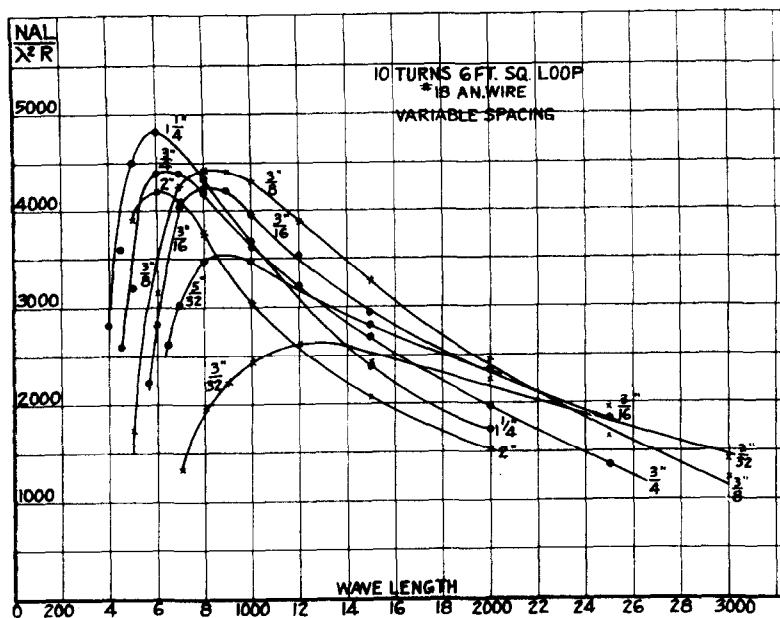


FIG. 17.

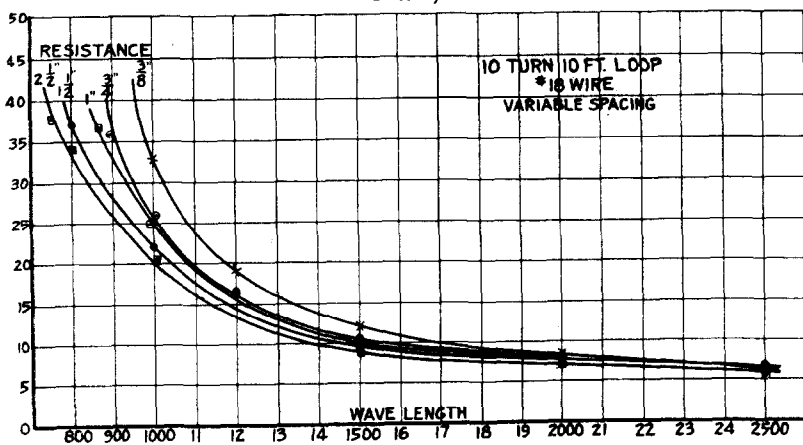


FIG. 18.

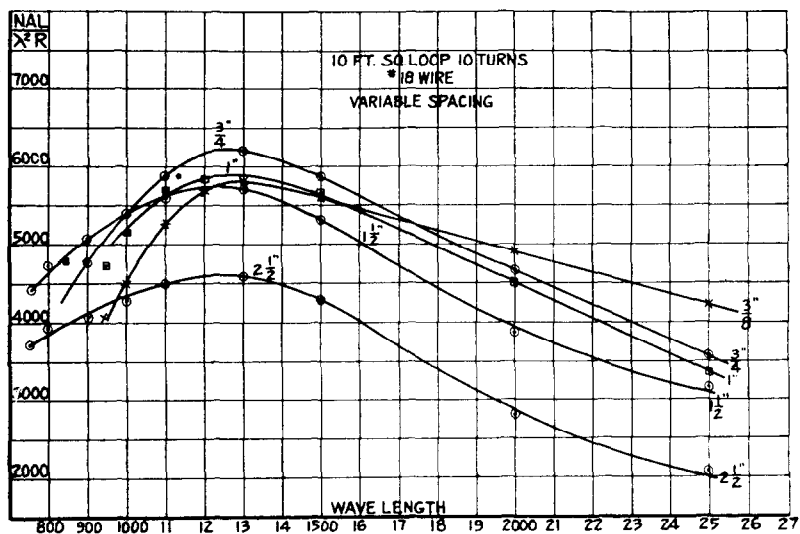


FIG. 19.

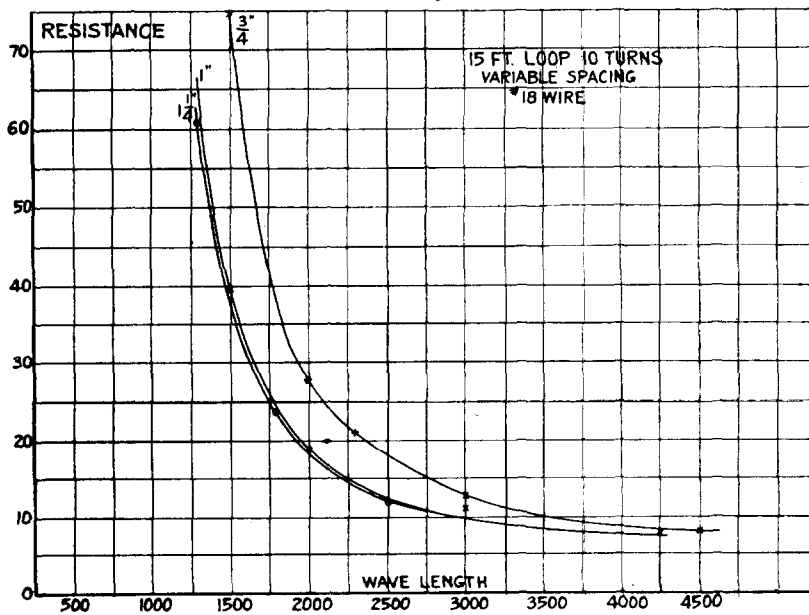


FIG. 20.

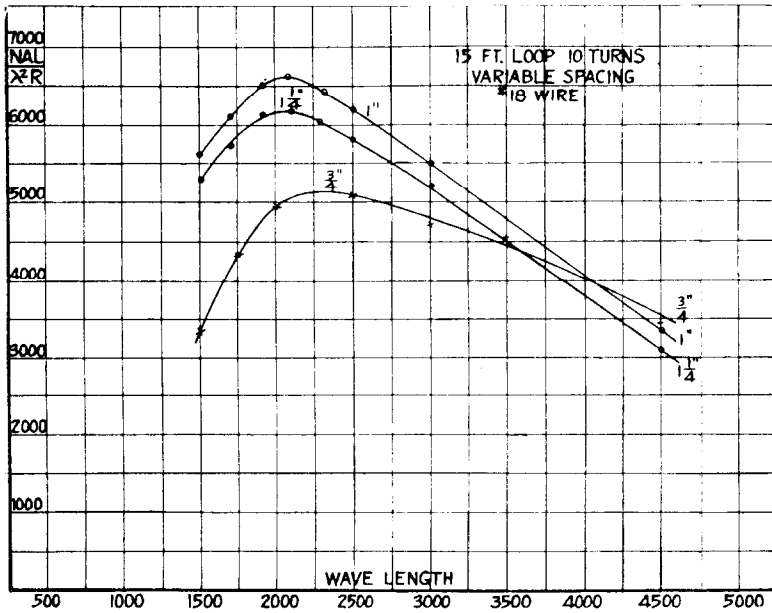
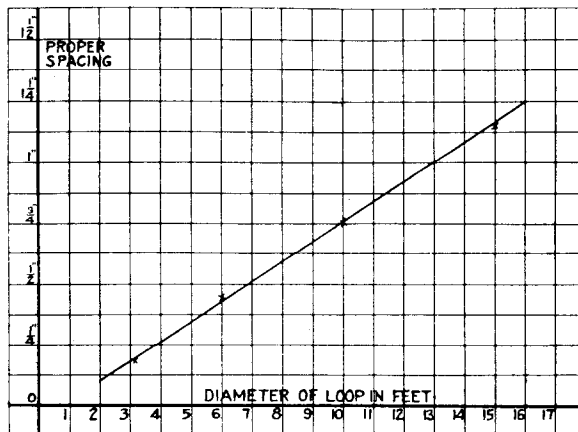


FIG. 21.



necessary to choose the best spacing not simply as that which gives the highest maximum in the reception factor curve but the sharpness of this curve should also be considered. The effectiveness of the loop ought not to fall away too quickly as the wave-length changes from the best value.

The curves show that the natural period of the coil and correspondingly the best wave-length is lowered by increased spacing. This effect is most pronounced for changes in the spacing when the latter is small.

The best spacing has been determined for four different sizes of loop, *viz.*, 3 ft., 6 ft., 10 ft., 15 ft. (Figs. 14, 16, 18, 20), and there appears to be a direct proportionality between size of loop and best spacing. Thus, when the best spacing is plotted against size of loop the straight line relation of Fig. 21 is obtained. It would seem that the capacity between turns is a most important factor, since this also increases directly with the linear dimensions of the loop. The data of Fig. 21 are very useful in designing loops.

V.

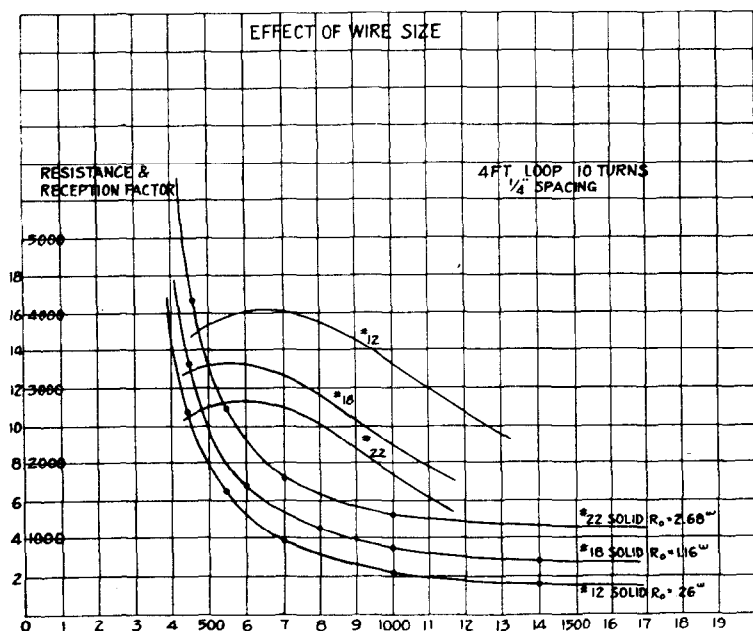
EFFECT OF SIZE AND KIND OF WIRE.

For the wires ordinarily used, that is, from say No. 22 to No. 14 B. & S. gauge, the size of the wire has little influence on the best spacing as determined above. In general, large wires should be spaced farther apart than small ones, but this effect is only pronounced when the spacing is so small as to be comparable with the diameter of the wire itself. For given spacing under these conditions it may actually be better to use smaller wire so as to make the ratio of wire diameter to spacing less. This is particularly true for short or moderate wave-lengths. For very long waves the resistance approaches its *d.c.* value and the smaller wire in that case offers no advantage.

Fig. 22 gives the resistance curves for three 10 turn coils wound on a 4 ft. frame with $\frac{1}{4}$ " spacing, using three different sizes of wire, No. 22, No. 18, No. 12. It will be noticed that at short wave-lengths the resistance depends very little on the size of the wire, while for longer wave-lengths the curves separate more and more and are controlled by the *d.c.* resistance in each case. This figure also shows the reception factor curves for the three coils just mentioned, and it is seen that the best wave-length for a given coil is independent of the size of wire with which it is wound.

There is some advantage, of course, in the matter of efficiency if the size of wire is greatly increased. This is not so great as might be at first imagined, however; for in the first place, the effect of *d.c.* resistance on the total effective resistance in the neighborhood of best working wave-length is of rather secondary order, and in the second place, the inductance of the large wire coil is less than that of a coil using fine wire so that the reception

FIG. 22.



factor NAL/λ_{2r} is prevented from increasing as rapidly as would be indicated by variation in resistance alone.

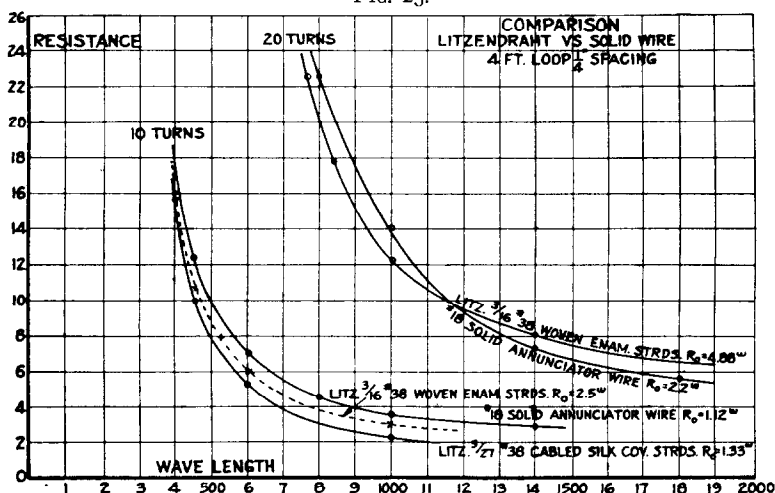
Litzendraht.—In order to compare the relative efficiency of solid wire with that of litzendraht and stranded wire the curves of Fig. 23 were taken. Two different size coils were compared, one of 10 turns and one of 20 turns. Both were on frames 4 ft. square and the spacing was $\frac{1}{4}$ ". For the 20 turn loop No. 18 solid wire was compared with litzendraht having about 45 per cent. of the equivalent cross-section and composed of three bundles of sixteen No. 38 enameled wires each. The separate strands

were woven criss-cross, in and out, in such a way as to form a sort of tubular conductor.

For the 10 turn loop the same wire was compared with the No. 18 solid, and in addition a stranded conductor having approximately the same cross-section as the No. 18 was also used. This latter consisted of three bundles of twenty-seven No. 38 silk-covered strands each; but instead of being woven the separate strands were simply cabled together in a long spiral.

The curves show that the asymptotic rise in resistance at short

FIG. 23.



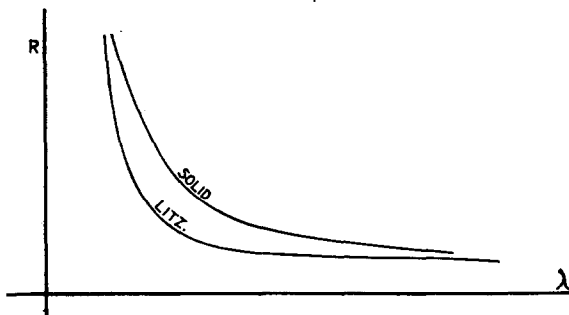
wave-lengths is much more abrupt with stranded wire and litzendraht than with solid wire. At short waves there is very little advantage in the use of litzendraht over solid wire for a given total cross-section; and the same is true for very long waves, because the resistance for both wires is approaching the same *d.c.* value. But for intermediate wave-lengths the stranded wire or litzendraht is better. Fig. 24 shows the nature of the effect on an exaggerated scale.

If the litzendraht has less cross-section than the solid wire, then the two curves will cross (see Fig. 23) and we then have the interesting conclusion that for wave-lengths above a certain value the solid wire has less resistance than the litzendraht and is therefore better, while below this wave-length the litzendraht

should be used. Or it may result that the two curves practically coincide for a portion of their length and thus the use of litzendraht or solid wire is immaterial.

Effect of Insulation Covering.—When the wires are wound tightly together there are losses in the dielectric between turns, that is, in the insulation, which raises the effective resistance of the coil. When the wires are spaced several diameters, however, it is immaterial whether they be insulated or bare. Thus, the resistance curve of a 10 turn coil of No. 18 bare wire spaced $\frac{1}{4}$ " on a 4 ft. frame was compared with those of similar coils of No. 18 d.c.c. white and No. 18 d.c.c. paraffined blue wires. The three curves coincided perfectly.

FIG. 24.



The reason for comparing the blue insulated wire was that an analysis of the insulation showed the coloring matter to contain iron salt (ferro-ferri-cyanide) which it was thought might be magnetic and therefore affect the overall resistance. It must be concluded that coloring matter has little or no effect on the resistance, at least for the spacings used.

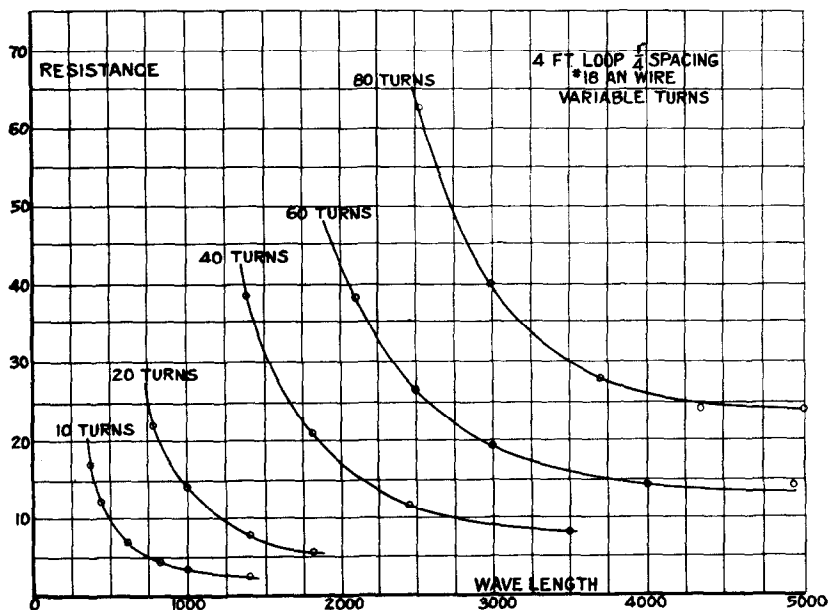
VI.

DETERMINATION OF BEST SIZE OF LOOP AND NUMBER OF TURNS FOR GIVEN WAVE-LENGTH DESIGN CHART.

The results of Sections 2 and 3 above show that for given inductance it is best to use for N the minimum and for A the maximum, while for given flux linkages the best values of N and A depend on the wave-length. Combining these conclusions we

can see that there are certain best proportionings of flux linkages and inductance. The problem is somewhat as follows: Given a certain wave-length, a small value of tuning capacity may be assumed and the required inductance calculated. This may be obtained by the use of a few turns on a large frame or many turns on a small frame. Now, at first sight it would seem as though the combination using few turns and large diameter would be best because this gives highest flux linkages⁷ (Sect. 3). But, as

FIG. 25.



shown in Sect. 2, such disposition lowers the natural wave-length of the coil and hence the best working wave-length. For given wave-length, therefore, there are certain proportions of inductance and total area NA which give best results.

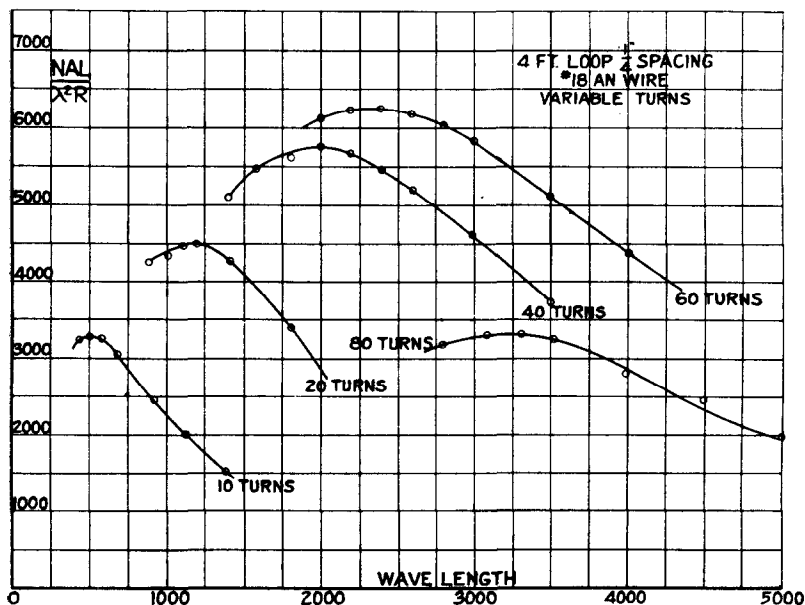
In order to work out these relations, resistance curves were taken and reception factor curves calculated therefrom for different sizes of loops and different numbers of turns. The spacing

⁷ L varies as square of turns but only directly as the area. Flux linkages are proportional to NA . Hence for constant L large area and few turns give larger flux linkages than many turns and small area.

in each case was that best value, as read from Fig. 21 of Sect. 4, corresponding to the size of the loop used. The wire was No. 18 d.c.c. annunciator (solid).

Figs. 25 and 26 refer to 4 ft. loops, $\frac{1}{4}$ " spacing with turns varied from 10 to 80; Figs. 27 and 28 to 6 ft. loops $\frac{7}{16}$ " spacing; Figs. 29 and 30 to 10 ft. loops $\frac{3}{4}$ " spacing; and Figs. 31 and 32

FIG. 26.



to 15 ft. loops with $1\frac{1}{8}$ " spacing. For this series the 4 ft., 6 ft., and 10 ft. loops were mounted horizontally in a large room, so that the edges of the loop were as far from the walls as possible. The minimum clearance in the case of the 10 ft. loop was 6 ft. The 15 ft. loop was built out-of-doors and the lower edge was 5 ft. from the earth.

Two important facts are shown by these curves. The first is that as the number of turns is increased the maximum in the reception factor curves becomes less sharply defined and the loop receives efficiently over a comparatively greater wave-length range. The second important feature is that as the number of turns on a given frame is continuously increased the maximum

FIG. 27.

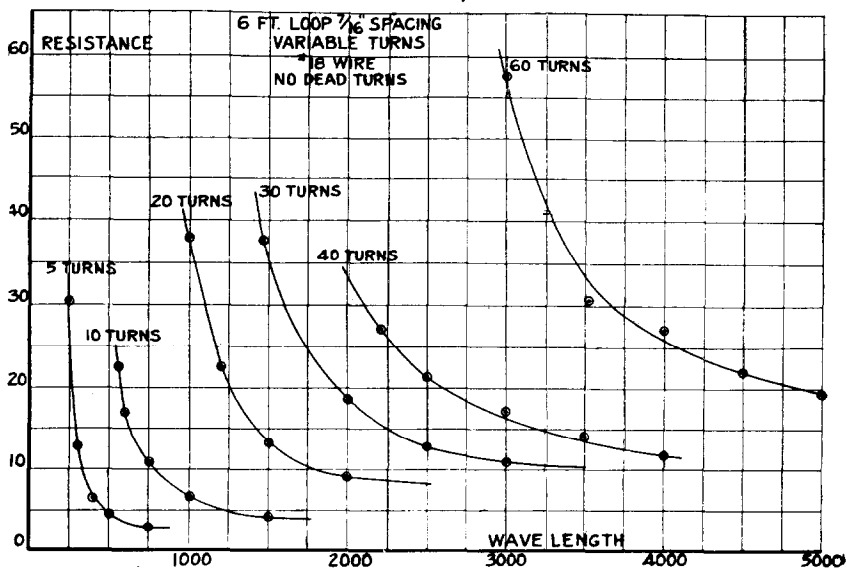


FIG. 28.

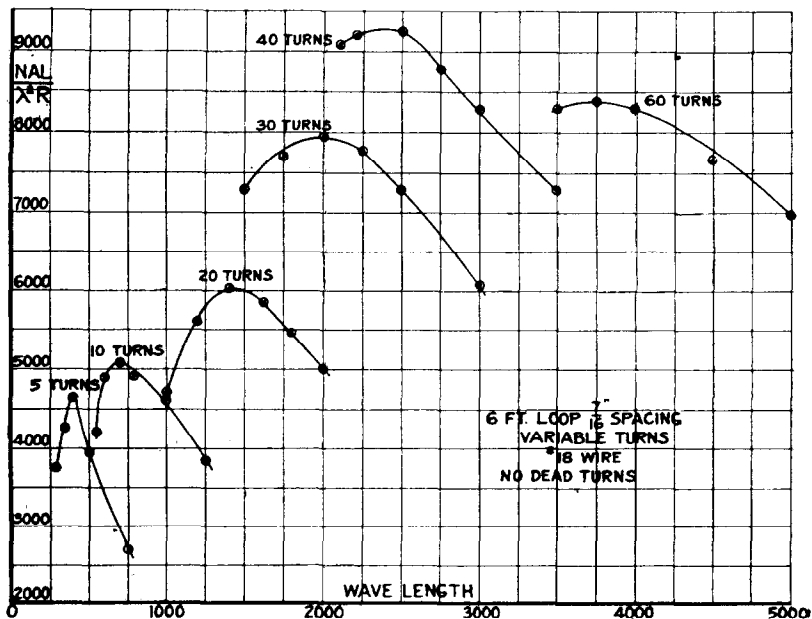


FIG. 29.

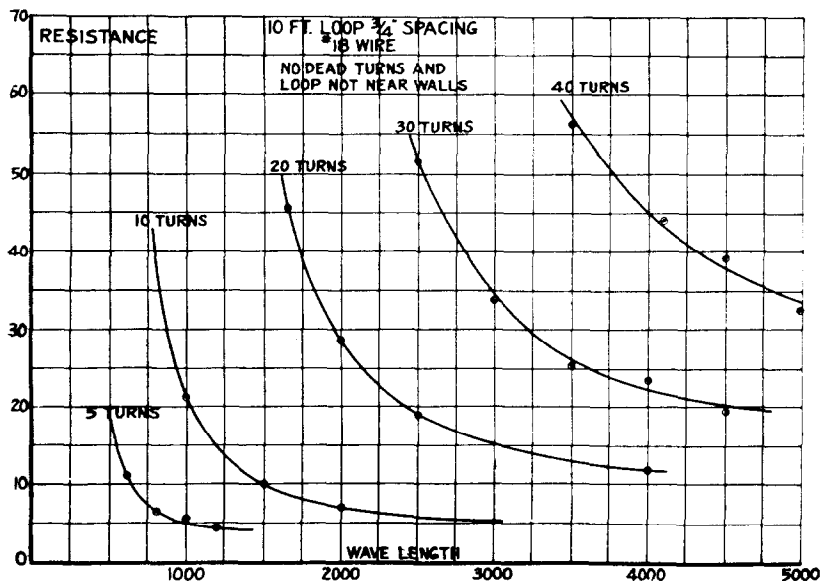
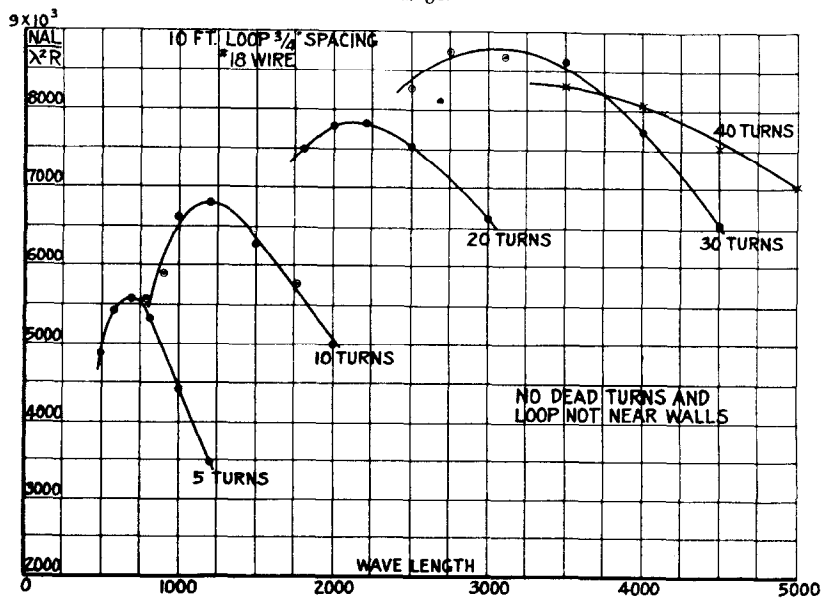


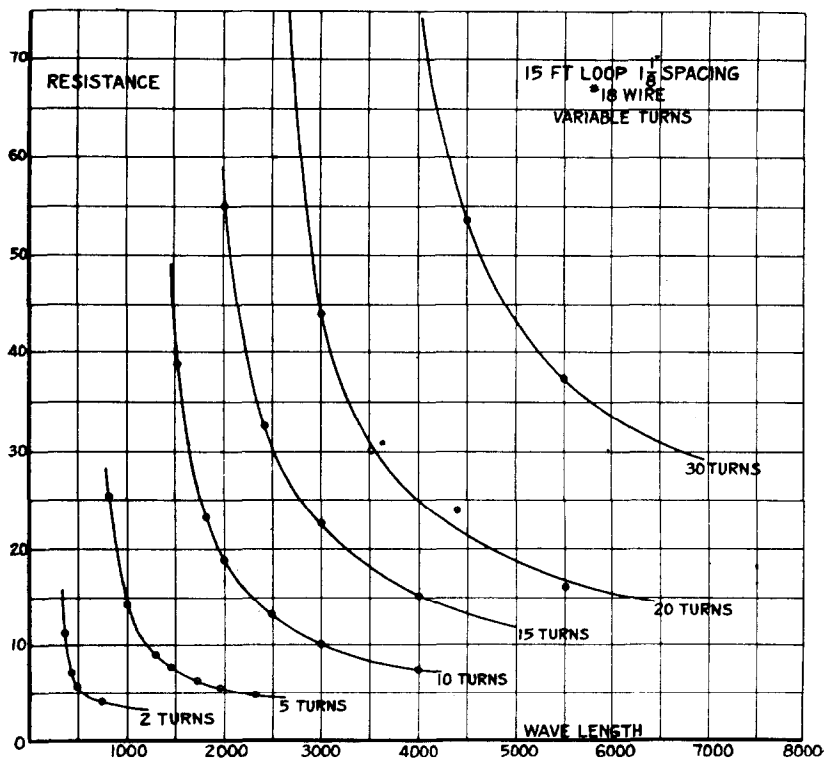
FIG. 30.



reception factor increases, reaches a maximum, and then falls off. The highest efficiency for a 4 ft. loop occurs with about 50 turns, while for 6 ft., 10 ft., and 15 ft. loops it is less, and about as shown in the following table.

Size of loop	No. turns for best possible reception
4 feet.....	52
6 feet.....	45
10 feet.....	30
15 feet.....	25

FIG. 31.

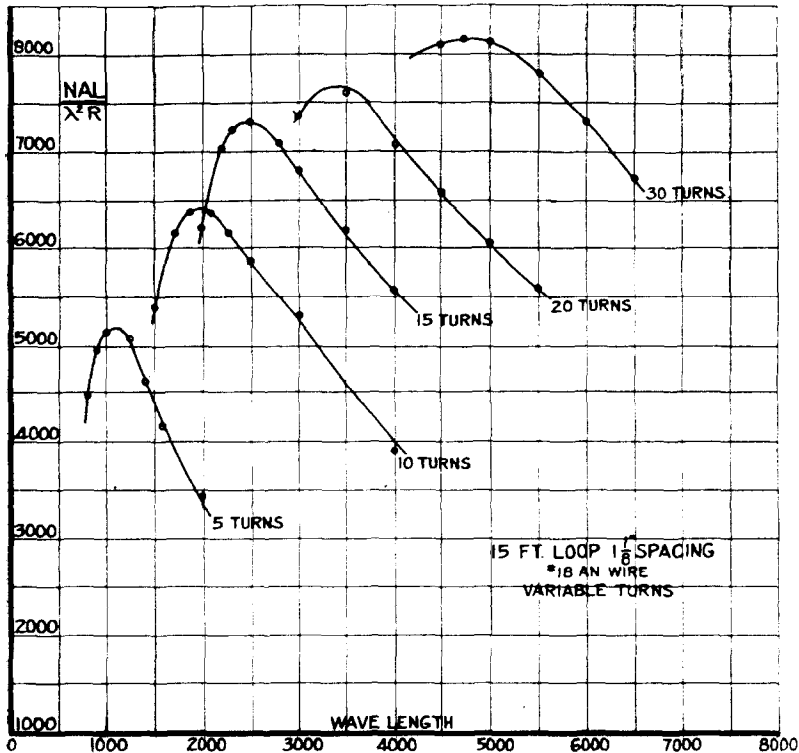


For a given number of turns and given size of loop there is one best wave-length at which to operate. This wave-length may be read off from the curves of Figs. 26, 28, 30, 32 and plotted directly against turn (N) with size of loop as parametre. This has been done in the lower part of Fig. 35, which, therefore, gives correlated optimum values of turns, size of loop and wave-length.

The 8 ft. and 12 ft. curves were interpolated by plotting values of λ against size of loop through several different ordinates of N .

The upper curves of Fig. 33 were also obtained from Figs. 26, 28, 30 and 32 by plotting the maximum reception factors indicated therein against the corresponding number of turns.

FIG. 32.



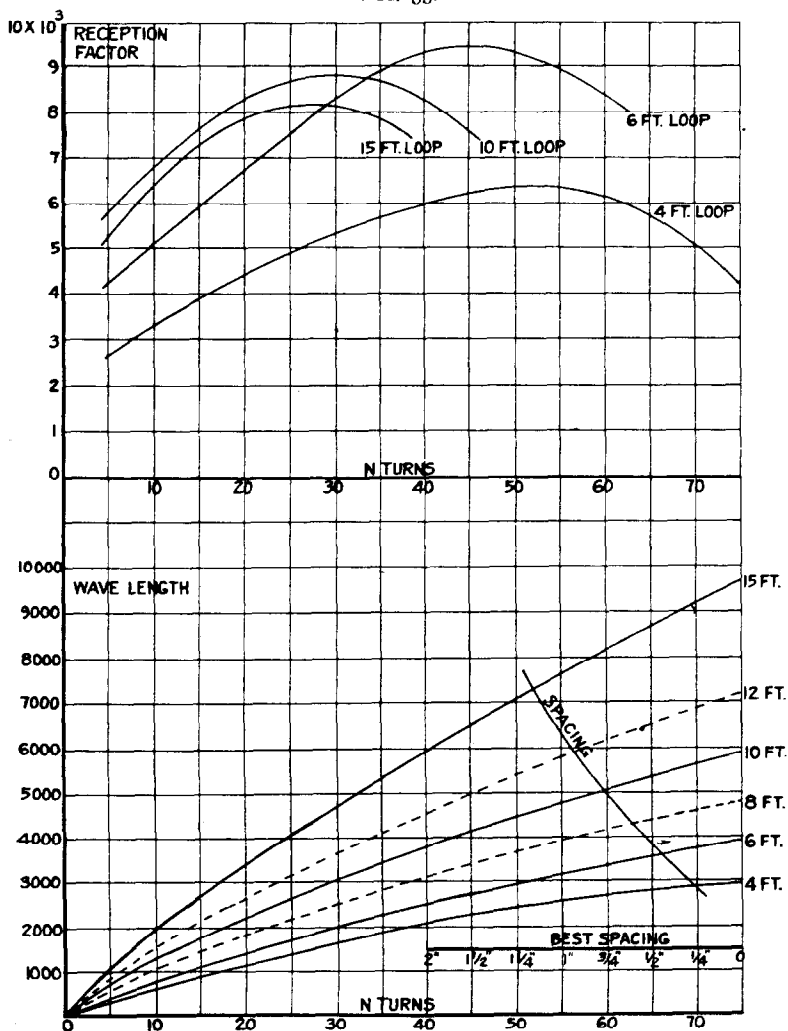
The spacing curve of this figure was drawn from the data of Fig. 21, and thus Fig. 33 becomes a complete working chart which may be used for designing loops of maximum efficiency at any chosen wave-length.

Data of a similar nature to the above, but referring particularly to short wave-lengths (200 metres to 1000 metres), have been taken, but is omitted here because of lack of space.

EXAMPLES OF THE USE OF DESIGN CHART.

As an example of the use of the design chart, let it be required to determine the elements of a loop for receiving a wave-length

FIG. 33.



of 1500 metres. The chart shows the following possible combinations:

Size of loop	No. of turns	Spacing
15 feet	7	$1\frac{1}{8}"$
10 feet	13	$\frac{3}{4}"$
6 feet	22	$\frac{7}{8}"$
4 feet	27	$\frac{1}{4}"$

In order to determine which of these is the best, reference is made to the upper reception factor curves. This gives the following data:

Size of loop	Reception factor
15 feet	5700
10 feet	7300
6 feet	7000
4 feet	5000

The 10 ft. 13 turn loop is the best, although a somewhat smaller loop down to 6 ft. may be used without serious disadvantage.

As a second example, let the required working wave-length be 3000 metres. The following set of values will be found:

Size of loop	No. of turns	Spacing	Reception factor
15 feet	17	$1\frac{1}{8}"$	7500
10 feet	30	$\frac{3}{4}"$	8800
6 feet	50	$\frac{7}{8}"$	9300
4 feet	78	$\frac{1}{4}"$	4000

It thus appears that in this case a 6 ft. 50 turn loop is best.

SIZE OF TUNING CONDENSER.

To complete the design of the receiving system it is necessary to know the size of tuning condenser needed for the loop and wave-length in question. This information can be had directly when the apparent inductance of the given loop is known at different wave-lengths. Data of this sort has been taken for all of the loops described above, though lack of space prevents its inclusion in this paper. The important result obtained from the data is that any loop can be worked at its best wave-length by the use of a variable condenser having a maximum capacity not exceeding 0.001 mf.

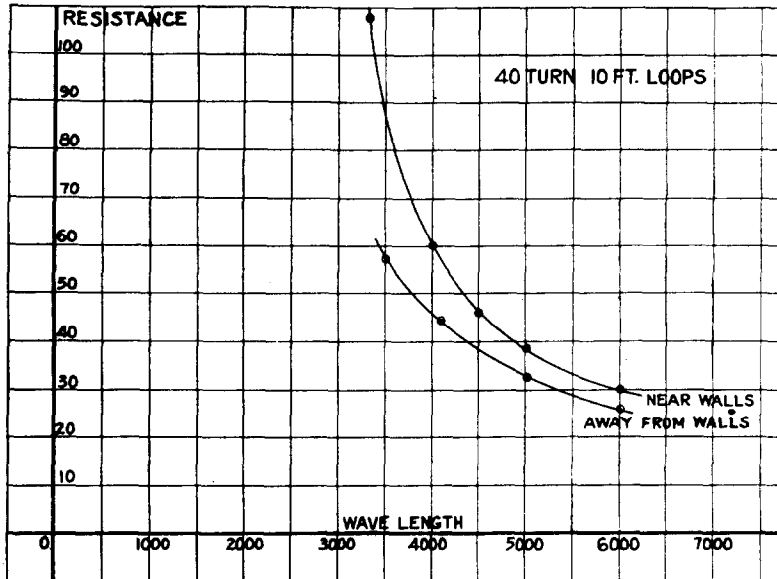
EFFECT OF DEVIATION FROM BEST WAVE-LENGTH.

If, as is often the case, a loop is to be used at several wave-lengths rather than at one fixed value, then the design chart (Fig. 33) does not tell the whole story. In this case reference should also be made to Figs. 26, 28, 30, 32 in order to choose a loop which gives the best *average* efficiency over the desired range of wave-lengths.

EFFECT OF PROXIMITY TO WALLS OF ROOM.

When a loop is used indoors, proximity to the walls or ceiling and floor of the room may cause the appearance of higher effective resistance than otherwise. The magnitude of this effect is shown in Fig. 34. Curve *A* gives the resistance of a 40 turn

FIG. 34.



10 ft. square loop with $\frac{3}{4}$ " spacing when placed vertically in a second-floor room, the upper and lower edges being 6" from ceiling and floor, respectively. The ceiling was plaster, the floor concrete. Curve *B* is for the same loop placed horizontally in the centre of the room with a minimum distance of about 5 ft. from walls, ceiling and floor. The resistance is considerably lower in the latter case.

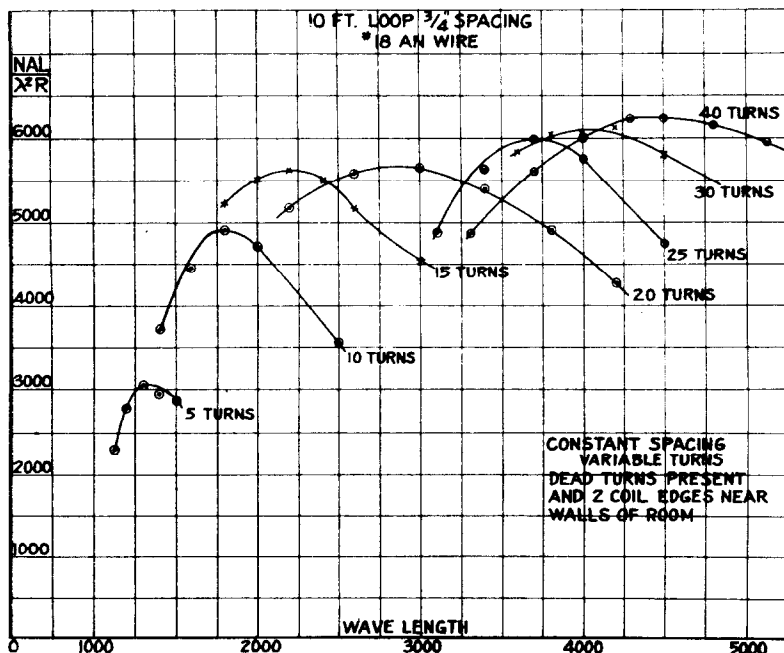
EFFECT OF DEAD TURNS.

The effect of leaving overhanging dead turns on the loop is shown in Fig. 35, which shows the reception factor as function of wave-length. The neighboring imperfect dielectric effect described in a previous paragraph is also present here, as the loop was used vertically with lower and upper edges near floor and

ceiling. The dead turns were broken into sections of 10 turns each, except for the measurement of 5 turns when there was an adjacent 5 turn section.

The exact nature and magnitude of the dead-end effect is much more vividly presented by superposing Fig. 35 on Fig. 30. It may be seen that in general the dead turns materially reduce the efficiency of the used portions of the loop. In fact, so great

FIG. 35.



is this effect on short wave-lengths that the best wave-length is actually much longer (shifted to the right) when there are dead turns present.

GENERAL REMARKS.

The working curves of the last section apply accurately only to loops wound with No. 18 solid wire. However, if wire of different size is used the interrelation of best wave-length, turns, spacing, and size of loop is not appreciably changed, but only the efficiency varies, and it is either decreased or increased for all wave-lengths. This was definitely shown by the data of Sect. 5.

All the reception factor curves are based on sustained wave reception and a detector response proportional to the *effective* undamped voltage across the loop condenser. If damped waves are being received the efficiency is different and, in general, the best wave-length for a given loop is shifted slightly toward shorter values. The reason for this is that for damped waves the reception is a function of transmitter and receiver decrements such that the inverse proportionality of current to loop resistance is not exact.

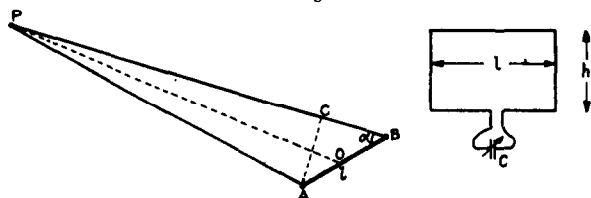
PART II.

THE DIRECTIONAL CHARACTERISTICS OF LOOP RECEIVERS.

GENERAL.

In Fig. 36 is shown a loop receiver of height h and breadth l

FIG. 36.



turned at angle α (in azimuth) to the line of propagation of waves originating at P . There are supposed to be N turns of wire on the loop wound close together, so that at any instant all of the wires on a given edge of the loop A or B occupy sensibly the same place in the wave field; in other words, the winding here is not spaced.

It is further assumed that the wave front at the receiver is plane and perpendicular to the earth's surface.

Let $e = E \sin \omega t$ = electric field intensity
at O produced by P .

The field at B lags that at A by ϕ times degrees.

$$\Phi = \frac{PB - PA}{\lambda} 2\pi \text{ and since } PC \cong PA$$

$$\Phi = \frac{BC}{\lambda} 2\pi = \frac{2\pi l}{\lambda} \cos \alpha$$

At B the electric field (referred in time to o) is:

$$e_b = E \sin \left(\omega t - \frac{\Phi}{2} \right)$$

at A it is:

$$e_a = E \sin \left(\omega t + \frac{\Phi}{2} \right)$$

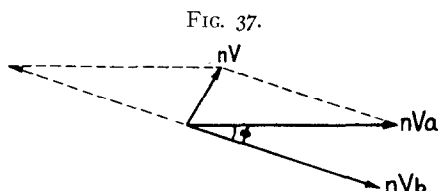
The instantaneous potential on each of the N wires at A is:

$$v_a = \int_0^h e_a dh = e_a h$$

On each of the wires at B it is:

$$v_b = \int_0^h e_b dh = e_b h$$

It is the vector difference of the potentials V_a and V_b summed for N wires which causes current to flow in the loop.⁸ The vector diagram is shown in Fig. 37.



We thus have for the effective instantaneous voltage acting in the serial loop circuit

$$v_r = nv = nEh \left[\sin \left(\omega t + \frac{\Phi}{2} \right) - \sin \left(\omega t - \frac{\Phi}{2} \right) \right] = 2nEh \sin \frac{\Phi}{2} \cos \omega t$$

⁸ There are two ways of thinking of the production of driving electromotive in the loop. It can be considered as being induced by the magnetic flux component of the wave, as was done in Part I, or it can be treated as resulting from the phase difference in the electric field at the two sides of the loop as just outlined. It can easily be shown that the value of the e.m.f. acting in the loop is the same whether it is derived on the basis of flux linkages or from the electric forces. The latter method of considering the situation is more instructive in treating the directional characteristics.

The amplitude of this voltage is thus

$$2nEh \sin \frac{\phi}{2} = 2nEh \sin \left(\frac{\pi l}{\lambda} \cos \alpha \right)$$

For l much less than λ as is usually the case

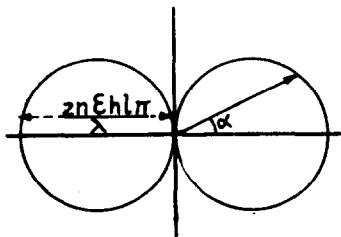
$$\sin \frac{\pi l}{\lambda} \cos \alpha \cong \frac{\pi l}{\lambda} \cos \alpha$$

and amplitude is

$$\frac{2nEh\pi l}{\lambda} \cos \alpha \dots\dots\dots (1)$$

This is the fundamental equation for the directional characteristics of the loop and gives the two tangent circles of Fig. 38.

FIG. 38.



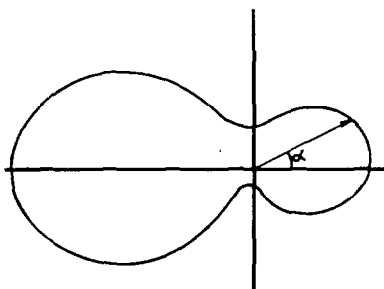
DEVIATION OF THE POLAR CURVE IN PRACTICE FROM THE DOUBLE CIRCLE DERIVED BY THE SIMPLE THEORY.

In practice the directional characteristic of the loop receiver is not so uniform as is indicated by the two tangent circles derived from the simple theory. Its shape has been found to depend in the shape and dimensions of the loop, the manner of winding, proximity to the earth's surface or nearby conductors, the nature of the terrain separating transmitter and receiver and on the arrangement and disposition of the receiving apparatus. A typical curve as obtained by measurement of received signal at different angular positions of the loop may be as shown in Fig. 39. It is seen that there may be a considerable polar dissymmetry with unequal maxima and minima, and although not always as pronounced as is indicated in the figure is nevertheless always present and when augmented by proper design of the apparatus can be readily used for determination of the *absolute* direction or *sense* of a distant transmitter.

It is the purpose of the following discussion to give the reasons for this dissymmetry. The analysis has led to the development of different means of either enhancing or decreasing it so that utility of the loop direction finder is considerably increased.

In general, there are two different types of loops in use: the solenoidal type in which all turns have the same area, and the flat pancake type in which the areas of successive turns decrease toward the centre of the winding. The two types have different directional characteristics, and each will be considered separately.

FIG. 39.



SOLENOIDAL TYPE LOOP.

The type of loop to be considered here is shown in Fig. 40. Its polar characteristic is distorted from the simple circular form, being the combination of three different effects.

1. The displacement current effect.
2. The antenna effect.
3. The shape effect.

1. *The Displacement Current Effect.*—According to the simple theory, when the plane of the loop is at right angles with the direction of wave travel, the electromotive forces developed in wires *a* and *b* are all equal and simultaneously opposite to each other in phase, so that no current flows to the tuning condenser *C*. This conclusion is correct as far as the simple loop effect is concerned, but a certain current does flow to the condenser even at the position $\alpha = 90^\circ$ and this is in part due to what has been here termed the “displacement current effect.”

On account of the spacing of the winding there is a phase difference between the voltages developed in successive wires for

FIG. 40.

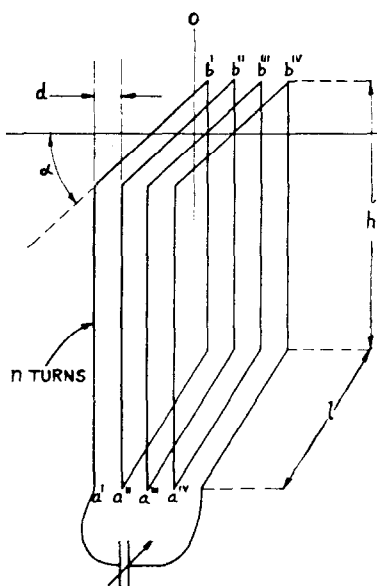
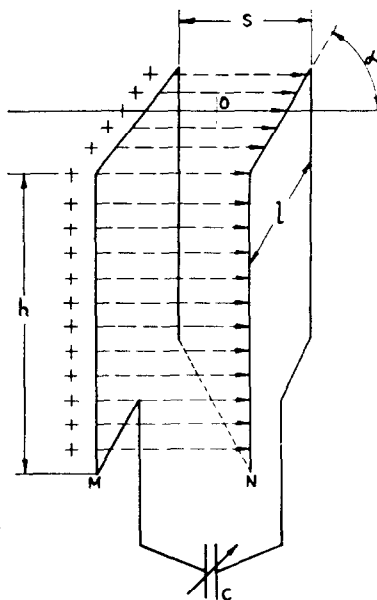


FIG. 41.



all positions except $\alpha = 0^\circ$, and for this reason displacement currents flow across the coil through the series capacities formed by successive convolutions of the winding (see Fig. 41). This current passes out through the tuning condenser C and produces a signal.

In Fig. 41, all the turns have been omitted save the two outer ones. This simplifies the treatment considerably without introducing much error, because what we are really concerned with in any case is the total phase displacement between the first and last turns and the capacity of the $(n-1)$ condensers in series formed by the n successive turns.

If, as before, $e = E \sin \omega t$ at centre of loop O then when the plane of the loop is at right angles to the line of wave propagation the instantaneous electric field at M is

$$e_m = E \sin \left(\omega t + \frac{\pi s}{\lambda} \right)$$

At N it is

$$e_n = E \sin \left(\omega t - \frac{\pi s}{\lambda} \right)$$

It is the difference of these two which gives rise to the displacement current between wires.

$$\begin{aligned} e &= e_m - e_n = E \left[\sin \left(\omega t + \frac{\pi s}{\lambda} \right) - \sin \left(\omega t - \frac{\pi s}{\lambda} \right) \right] \\ &= 2 E \sin \frac{\pi s}{\lambda} \cos \omega t. \end{aligned}$$

The amplitude of this potential difference is thus

$$2 E \sin \frac{\pi s}{\lambda} \cong \frac{2 \pi s}{\lambda} E \text{ since } \frac{s}{\lambda} \text{ is very small.}$$

This expression holds when the loop is at right angles to the wave, that is, $\alpha = 90^\circ$. For any other angular position it becomes

$$\frac{2 \pi s}{\lambda} E \sin \alpha \dots\dots\dots (2)$$

In order to get the effect on the detector this must be integrated through the height h so that we get (this is only approximate; more accurate expression is developed below):

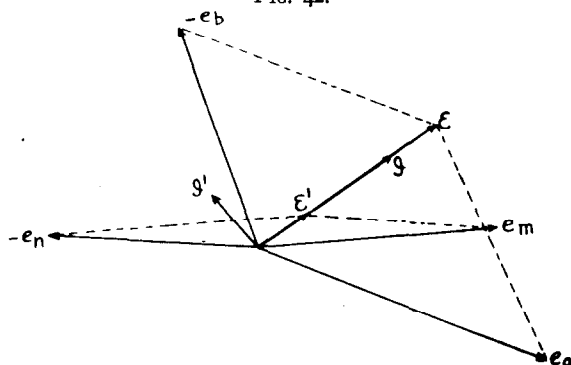
$$\frac{2 \pi s h}{\lambda} E \sin \alpha \dots\dots\dots (3)$$

as the expression which must be compared with (1) if it is de-

sired to know the ratio of signals produced by the straight loop effect and the displacement current effect.

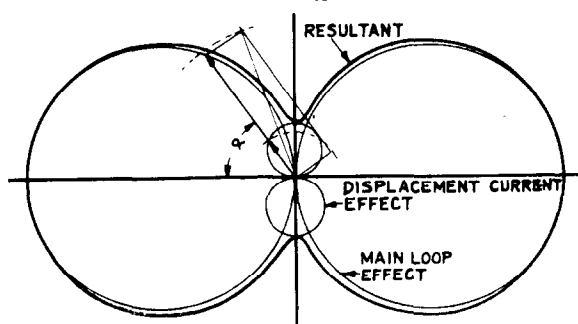
If the displacement current effect is combined with the straight loop effect the result shown in Fig. 43 is obtained. It must be noted in superposing these effects that the two must be added vectorially as at right angles to one another because the *e.m.f.*

FIG. 42.



of the direct loop effect produces current through a tuned circuit and thus in phase with itself while the second effect gives charging current 90° displaced from the voltage. The vector diagram for a given angular coil position is shown in Fig. 42.

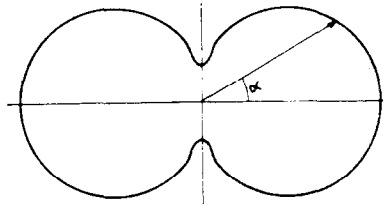
FIG. 43.



There is another displacement current effect besides that first described. It is maximum when the coil is in line with the waves, *i.e.*, in position for maximum signals, and is simply the usual

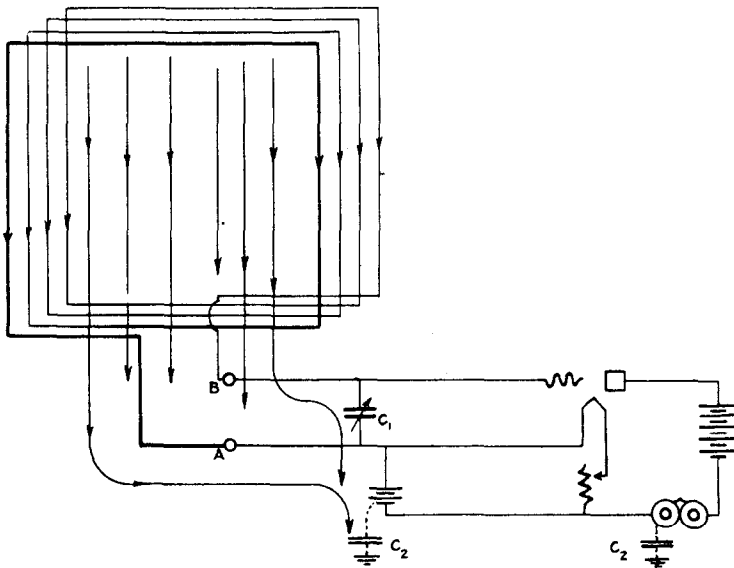
current flowing through the distributed capacity of the coil. It depends on the ratio of inductive reactance to capacity reactance per unit length of the winding, and this, of course, is small (except near the natural frequency of the coil), as is shown by the

FIG. 44.



necessity of having a condenser across the terminals for tuning. It depends, also, of course, on the linear dimensions of the coil, increasing with increase of l and H .

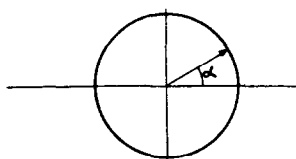
FIG. 45.



The polar curve of the effect would be that shown in Fig. 44, so that if it is taken into consideration its chief effect is to very slightly elongate the major axis of the directional characteristic, and is, therefore, not of great importance.

2. *The Antenna Effect.*—This effect is occasioned by capacity currents to earth from the loop structure acting as a simple antenna and is what produces asymmetry in the polar characteristic. Referring to Fig. 45, it is seen that a certain current flows directly between the loop and ground through the capacity of the filament battery and operator's body; and since the two terminals, *A* and *B*, of the loop have different capacities against ground a voltage is developed between them. The amplitude of this voltage is obvi-

FIG. 46.

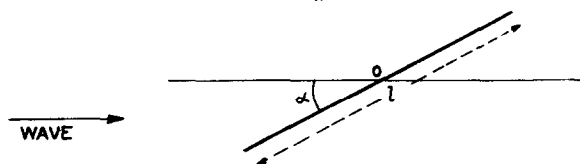


ously independent of the angular position of the loop and hence gives a circular polar characteristic, as in Fig. 46.

The magnitude of the antenna effect is difficult to calculate with any accuracy, but is measured roughly by the height of the antenna (loop).

As regards the detector effect it must be combined with the other voltages in proper phase. It produces essentially a capacity current and hence in time quadrature with the straight loop effect,

FIG. 47.



but this is only approximate because its true phase must be referred to the axis *O* of the loop and hence varies with the angular position. The proper angle to use for the vector combination with the other effects is

$$90^\circ \pm \frac{\pi l}{\lambda} \cos \alpha$$

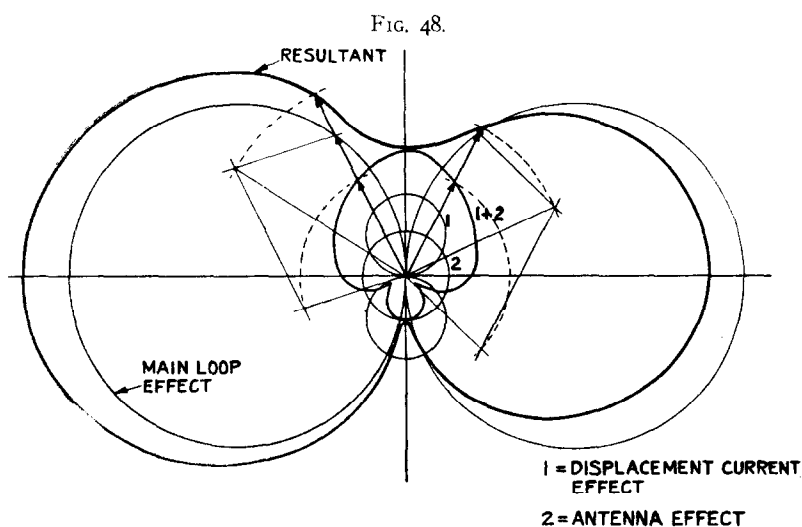
as can be seen from Fig. 47.

This shift in the phase of the antenna effect produces dis-

tortion in the neighborhood of both maxima and minima of the resultant polar curve where all the effects are combined.

In Fig. 48 is shown the characteristic of a solenoidal type loop as derived by the proper superposition of (1) the straight loop effect, (2) the displacement current effect, and (3) the antenna effect.

3. *The Shape Effect.*—There is an additional distortive effect caused by changes in the ratio of height to length of loop. The nature of this effect is shown in Fig. 49, where the dotted curve is derived for a high, narrow coil, and the solid line for a wide,



low coil having half the antenna effect. It is seen that a sharper maximum is to be expected from a tall, narrow coil than for a low, broad one.

The reason for the difference is that the antenna effect for a narrow coil is large and its phase

$$90^\circ \pm \frac{\pi l}{\lambda} \cos \alpha$$

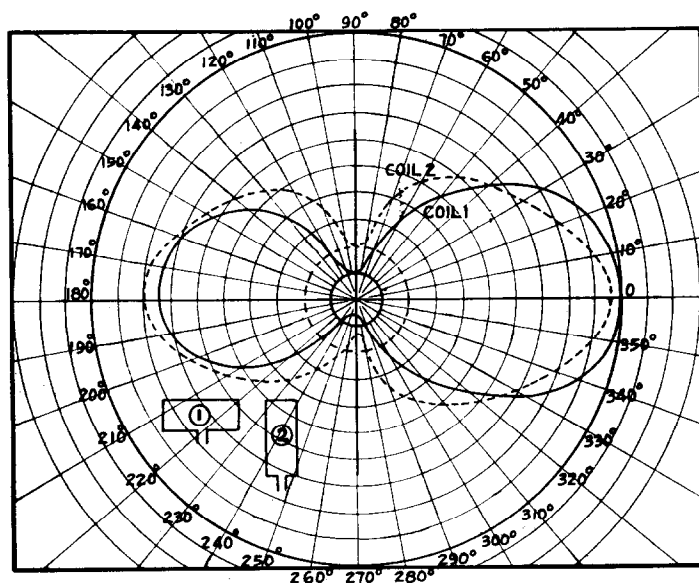
changes only slightly as the coil is turned, while for a broad coil (larger 1) the phase change is greater and since the antenna effect is less (for the same area) the curve is little distorted in the neighborhood of minima but noticeably bulged out toward the maxima.

The shape of the curves of Fig. 49 have been exaggerated for clearness but show the general shape of the total polar characteristic, and have been well checked experimentally.

IMPROVEMENT OF THE ACCURACY OF THE SOLENOIDAL TYPE LOOP AS DIRECTION FINDER.

In all cases the accuracy of the direction finder depends primarily upon obtaining a sharp minimum in the neighborhood of $\alpha = 90^\circ$. Reference to the above discussion and the Fig. 48 shows that the sharpness of the minimum depends

FIG. 49.



1. On the magnitude of the displacement current effect,
2. On the magnitude of the antenna effect.

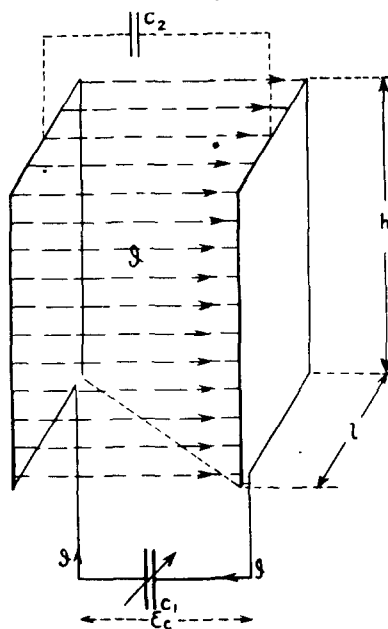
It is necessary to reduce both these effects in order to secure a sharp minimum. Both are affected by the shape of the loop. The displacement current effect for given area is minimum for a *square* loop, because this shape gives shortest possible perimeter and thereby minimum capacity between turns. The antenna effect is less for low coil, *i.e.*, small ratio of h to l .

REDUCTION OF THE DISPLACEMENT CURRENT EFFECT.

The displacement current effect can be reduced to a minimum by proper spacing of the wires constituting the winding.

We have,⁹ referring to Fig. 50, which is a duplication of Fig. 4I, as the voltage across the tuning condenser C_1

FIG. 50.



$$E_c = \frac{I}{\omega c}$$

where I = displacement current through the capacity

C_2 of the winding.

The voltage producing the current I is, by equation (2)

$$\frac{2 \pi s}{\lambda} E$$

Therefore,

$$\begin{aligned} I &= \frac{2 \pi s E}{\lambda} \omega \frac{C_1 C_2}{C_1 + C_2} \\ c &= \frac{2 \pi s E}{\lambda} \omega \frac{C_1 C_2}{C_1 + C_2} \cdot \frac{1}{\omega C_1} \\ &= \frac{2 \pi s E}{\lambda} \cdot \frac{C_2}{C_1 + C_2} \end{aligned}$$

⁹ This treatment is not rigid and is only intended to show approximately what can be accomplished by proper spacing of the winding.

or

$$E_e = K \frac{s C_2}{C_1 + C_2}$$

Now C_2 is the capacity between parallel wires of length $2(h+l)$ diameter d , and separation s and is

$$C_2 = \frac{1}{n-1} \cdot \frac{2(h+l)}{2 \log_{\epsilon} \frac{2s}{d(n-1)}} \text{ cms.}$$

Hence

$$E_e = K \frac{s(h+l)}{(n-1) C_1 \log \frac{2s}{d(n-1)} + (h+l)} \dots\dots\dots (5)$$

The condition for minimum of this function is

$$\frac{dE_e}{ds} = 0 = \left[(n-1) C_1 \log \frac{2s}{d(n-1)} + (h+l) \right] (h+l) - (n-1) C_1 (h+l)$$

or

$$s = \frac{d(n-1)}{2} \epsilon^{\frac{1}{n-1}} - \frac{h+l}{(n-1) C_1}$$

or the spacing between wires $\frac{s}{n-1}$ should be

$$\frac{d}{2} \epsilon^{\frac{1}{n-1}} - \frac{h+l}{(n-1) C_1} \dots\dots\dots (6)$$

$\cong 1.4d$for a many turn winding or where the wave-length is very long so that C_1 is large.

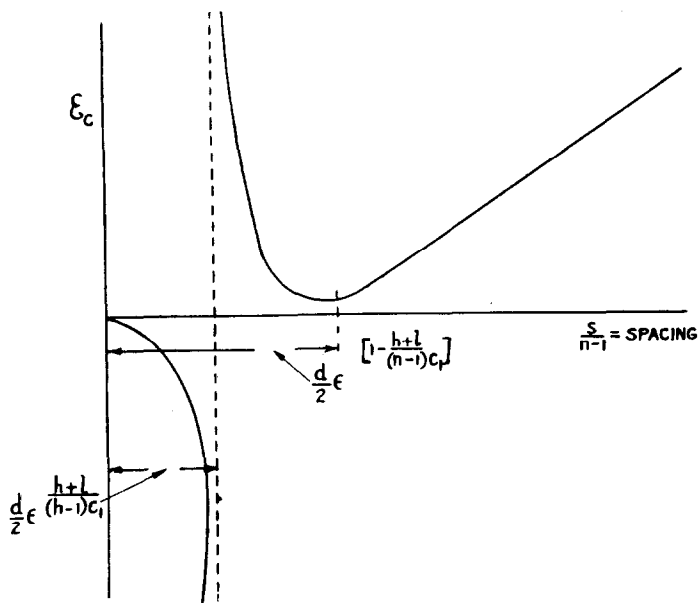
The function (5) is shown graphically in Fig. 51. That is, this figure shows the variation in the magnitude of the displacement current effect with spacing $\frac{s}{n-1}$.

These deductions are of particular value in designing coils for long wave-length work where a large number of turns will be used. For short wave-lengths only a few turns are used and the displacement current is then small in any case, so that usually overall efficiency is more important than the reduction of the displacement currents. For this reason on coils for this class of work using only a few turns the wires will usually be spaced somewhat further apart than the value given by $1.4d$ or (6). As regards long wave-lengths, it was shown in Part I. that the spacing of the wires has not much to do with the efficiency, and hence for such cases a closer spacing may be used, as indicated by $1.4d$, and thus improve the direction finding qualities.

REDUCTION OF THE ANTENNA EFFECT.

As discussed above, the antenna effect is due to capacity currents to ground from the loop through the tuning condenser. In order to eliminate these currents it is necessary that the terminals of the loop, *A* and *B* (Fig. 45), have exactly equal capacities against ground. The condition can be partially achieved by raising the filament lighting battery of the receiver well off the ground.

FIG. 51.

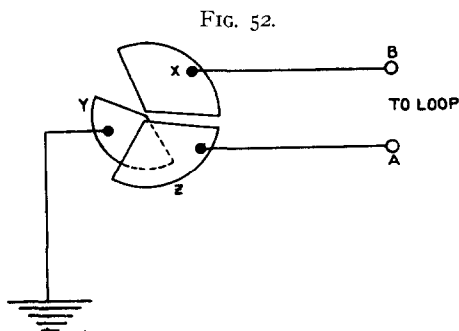


This can never be entirely satisfactory, however, because of the capacity of the operator's body through the telephone (see Fig. 45). If it is desired to obtain complete balance, an auxiliary capacity must be provided from terminal *B* to ground. The compensator shown in Fig. 52 can be used for this purpose. It consists of three metal plates, *x*, *y*, *z*, two of which, *x* and *z*, are stationary and connected respectively to the loop terminals *A* and *B*. The third plate, *y*, is movable and connected to earth. By turning this plate, an exact balance can be obtained for capacity to earth from the loop terminals, and the minimum in the polar curve is thereby sharpened.

Another way in which the antenna effect can be reduced in any loop and the minimum thereby sharpened is by placing a grounded electrostatic shield consisting of several horizontal wires above the loop. The theory would indicate that such arrangement makes for a more symmetrical system electrically and thus excludes, or at least greatly reduces, distortion of the characteristic.

FLAT PANCAKE LOOP.

The flat pancake type loop acts in a somewhat different way from the solenoidal type. The same general discussion of the



simple loop and the shape effect applies to both types, but the antenna effect and the displacement current effect are different.

DISPLACEMENT CURRENT EFFECT.

The main displacement current effect described above is entirely absent in the pancake loop. This is easily understood by considering the loop in the 90° position, *i.e.*, at right angles to the sending station. In this position there is no phase displacement between the electric fields acting on the several wires and hence no displacement current.

ANTENNA EFFECT.

The antenna effect is much the same as in the solenoidal type loop, but greater due to the decrease in length of the vertical wires toward the centre of the winding. Instead of being meas-

ured by the height h of the loop as for the solenoid, it is here measured approximately by

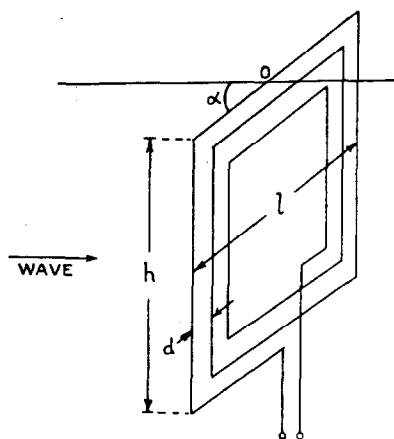
$$h + 2nd$$

where N = number of turns
 d = spacing between turns.

(See Fig. 53.)

As in the case of the solenoid, the polar amplitude curve of the antenna effect is circular, and in combining its radius vectors with those representing the straight loop effect proper recognition must be taken of the time phase angle between the two. The phase of the antenna effect varies with the azimuth of the loop

FIG. 53.



as for the solenoid and referred to the axis of the loop is approximately

$$90^\circ \pm \frac{\pi l}{\lambda} \cos \alpha$$

STRAIGHT LOOP EFFECT.

Referring to Fig. 53, let

v = Total effective instantaneous potential of straight loop effect in loop for any angular position (azimuth).

$$v = E \left\{ h \sin \left(\omega t + \frac{\pi l}{\lambda} \cos \alpha \right) - (h - d) \sin \left(\omega t - \frac{\pi l}{\lambda} \cos \alpha \right) \right. \\ \left. + (h - 2d) \sin \left(\omega t + \frac{\pi(l - 2d)}{\lambda} \cos \alpha \right) - (h - 3d) \sin \left(\omega t - \frac{\pi(l - 2d)}{\lambda} \cos \alpha \right) \right\}$$

$$\begin{aligned}
& + (h-4d) \sin \left(\omega t + \frac{\pi(l-4d)}{\lambda} \cos \alpha \right) - (h-5d) \sin \left(\omega t - \frac{\pi(l-4d)}{\lambda} \cos \alpha \right) \\
& + (h-6d) \sin \left(\omega t + \frac{\pi(l-6d)}{\lambda} \cos \alpha \right) - (h-7d) \sin \left(\omega t - \frac{\pi(l-6d)}{\lambda} \cos \alpha \right) \\
& + \dots \dots \dots \\
& + (h-2(n-1)d) \sin \left(\omega t + \frac{\pi(l-2(n-1)d)}{\lambda} \cos \alpha \right) \\
& \quad - (h-(2n-1)d) \sin \left(\omega t - \frac{\pi(l-2(n-1)d)}{\lambda} \cos \alpha \right) \}
\end{aligned}$$

Let

$$\begin{aligned}
\frac{\pi \cos \alpha}{\lambda} &= k \\
\omega t &= \theta \\
v &= \left\{ \begin{aligned}
& h \sin \theta \cos kl + h \cos \theta \sin kl - (h-d) \sin \theta \cos kl + (h-d) \cos \theta \sin kl \\
& + (h-2d) \sin \theta \cos k(l-2d) + (h-2d) \cos \theta \sin k(l-2d) - (h-3d) \sin \theta \cos \\
& \quad k(l-2d) + (h-3d) \cos \theta \sin k(l-2d) \\
& + (h-4d) \sin \theta \cos k(l-4d) + (h-4d) \cos \theta \sin k(l-4d) - (h-5d) \sin \theta \\
& \quad \cos k(l-4d) + (h-5d) \cos \theta \sin k(l-4d) \\
& + \dots \dots \dots \\
& + [h-2(n-1)d] \sin \theta \cos k(l-2(n-1)d) + [h-2(n-1)d] \cos \theta \sin k \\
& \quad (l-2(n-1)d) \\
& - [h-(2n-1)d] \sin \theta \cos k(l-2(n-1)d) + [h-(2n-1)d] \cos \theta \sin k \\
& \quad (l-2(n-1)d)
\end{aligned} \right\}
\end{aligned}$$

As approximation can be used the first two terms of the cos and sin expansions into series by Maclaurin's theorem.

$$\begin{aligned}
\sin x &= x - \frac{x^3}{L^3} \\
\cos x &= 1 - \frac{x^2}{L^2}
\end{aligned}$$

Now

$$\frac{l}{\lambda} \text{ is never } > 0.01$$

$$\therefore \cos kl = \cos \frac{\pi l}{\lambda} \cos \alpha \cong 1$$

$$\sin kl \cong kl = \frac{\pi l}{\lambda} \cos \alpha$$

Hence

$$\begin{aligned}
v E & \left\{ \begin{aligned}
& h \sin \theta + hkl \cos \theta - (h-d) \sin \theta + (h-d) kl \cos \theta \\
& + (h-2d) \sin \theta + (h-2d) k(l-2d) \cos \theta - (h-3d) \sin \theta + (h-3d) k \\
& \quad (l-2d) \cos \theta \\
& + (h-4d) \sin \theta + (h-4d) k(l-4d) \cos \theta - (h-5d) \sin \theta + (h-5d) k \\
& \quad (l-4d) \cos \theta \\
& + \dots \dots \dots \\
& + [h-2(n-1)d] \sin \theta + [h-2(n-1)d] k(l-2(n-1)d) \cos \theta \\
& \quad - [h-(2n-1)d] \sin \theta + [h-(2n-1)d] k(l-2(n-1)d) \cos \theta
\end{aligned} \right\}
\end{aligned}$$

$$\begin{aligned}
 &= E \left\{ \begin{aligned} &[h - (h-d) + (h-2d) - (h-3d) + (h-4d) - (h-5d) + \dots \\ &+ (h-2(n-1)d) - (h-(2n-1)d] \sin \theta \end{aligned} \right. \\
 &\quad \left. \begin{aligned} &[k + hl + (h-d)l + (h-2d)(l-^2d) + (h-3d)(l-^2d) + (h-4d)(l-4d) \\ &+ (h-5d)(l-4d) \\ &+ \dots + [h-2(n-1)d][l-^2(n-1)d] + [h-(2n-1)d][l-^2 \\ &\quad (n-1)d] \cos \theta \end{aligned} \right\} \\
 &= E \left\{ \begin{aligned} &d [1-2+3-4+5-\dots-2(n-1)+(2n-1)] \sin \theta \\ &+ k [hl + hl - dl + hl - 2dl - ^2hd + 4d^2 + hl - 3dl - ^2hd + 6d^2 + hl - 4dl - 4dh + \\ &\quad 16d^2 + hl - 5dl - 4dh + 20d^2 + \dots \\ &+ hl - 2(n-1)dl - 2(n-1)dh + 4(n-1)^2d^2 + hl - (2n-1)dl - ^2(n-1)dh + ^2 \\ &\quad (2n-1)(n-1)d^2] \cos \theta \end{aligned} \right\} \\
 &= E \left\{ \begin{aligned} &nd \sin \theta + k [2nhl - dl(1+2+3+4+5+\dots+2(n-1)+(2n-1) \\ &\quad - 2hd(1+1+2+2+\dots+(n-1)+(n-1) \\ &\quad + 2d^2(2+3+8+10+\dots+2(n-1)^2+(2n-1)(n-1))] \cos \theta \end{aligned} \right\} \\
 &= E \left\{ \begin{aligned} &nd \sin \theta + k [2nhl - n(2n-1)dl - 2n(n-1)dh \\ &\quad + 2d^2(2+3+8+10+\dots+2(n-1)^2+(2n-1)(n-1))] \cos \theta \end{aligned} \right\} \quad \dots \dots \dots (7)
 \end{aligned}$$

$$v = n E \left\{ \sqrt{d^2 + k^2 [2hl - (2n-1)dl - 2(n-1)dh + \frac{2d^2}{n}(2+3+8+10+\dots+2(n-1)^2+(2n-1)(n-1))]^2 \sin^2(\theta+\gamma)} \right\} \quad \dots \dots \dots (8)$$

where

$$\begin{aligned}
 \gamma &= \tan^{-1} \frac{k [2h - (2n-1)dl - 2(n-1)dh + \frac{2d^2}{n}(2+3+8+10+\dots+2(n-1)^2+(2n-1)(n-1))]}{d} \quad \dots \dots \dots (9)
 \end{aligned}$$

Equations (7), (8) and (9) show that the straight loop effect of the pancake may be thought of as made up of two parts to be added vectorially at 90°. One of these,

$$n d E$$

is independent of angular position and therefore circular; the other,

$$k [2hl - (2n-1)dl - 2(n-1)dh + 2 \frac{d^2}{n}(2+3+8+10+\dots+2(n-1)^2+(2n-1)(n-1))]$$

varies according to k , i.e., the cosine of the angle, and hence appears as two tangent circles. The phase γ of the resultant of these referred to the loop axis varies also with $\cos \alpha$. The

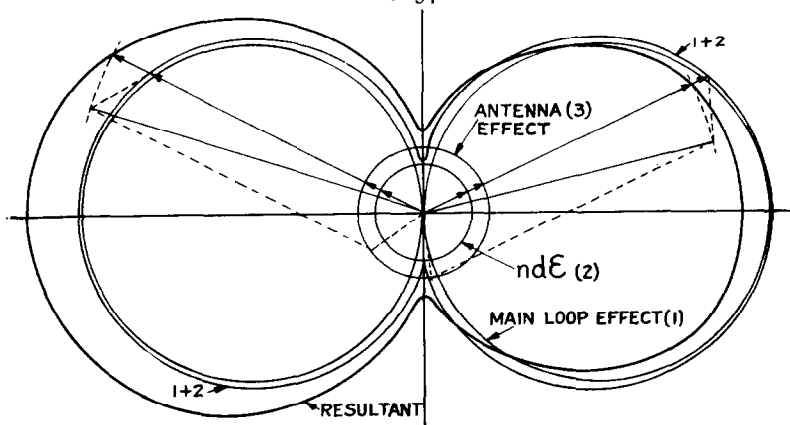
angle to be used, therefore, in combining the antenna and straight loop effect is

$$T = \gamma \pm \left(90^\circ + \frac{\pi l}{\lambda} \cos \alpha \right)$$

$$T \sin^{-1} = 90^\circ \pm \frac{\pi \cos \alpha}{\lambda} \left[2hl - (2n-1)dl - 2(n-1)dh + \frac{2d^2}{h} (2+3+8 \dots) + l \right]$$

It is seen from this expression that the angle T at which the antenna effect and the direct loop effect must be combined changes with different angular coil positions. This is a very significant circumstance. It gives rise to distortion of the polar curve which is particularly noticeable in the neighborhood of maxima. In the pancake loop it is not essentially the cause of a broader mini-

FIG. 54.



um on one side of the curve than on the other. This is due to a combination of the antenna effect with the second displacement current effect mentioned under the solenoid loop, which latter has its maximum value when $\alpha = 0$.

Fig. 54 is drawn to show the various effects in a pancake loop and their resultant. The shape effect is not shown, but, as has been explained, tends principally to elongate the curve along the major axis. The second displacement current effect is also omitted for simplicity, thus giving symmetrical minima.

FACTORS AFFECTING DISTORTION AND SHARPNESS OF MINIMUM.

The sharpness of the minimum can be increased by decreasing the term n [see equation (7)]; that is, by decreasing the radial

depth of the winding. It can be further increased by decreasing the antenna effect; that is, by decreasing the wire spacing or by any of the means described for the solenoid loop. This also reduces dissymmetry in the characteristic.

When the dissymmetry is desirable as for finding *absolute* direction, the pancake type winding should always be used and the antenna effect increased by any means possible. A rather wider spacing of the wires is, therefore, desirable in this case than would ordinarily be used on a solenoid loop.

Increasing the spacing must not be carried to extreme, however, since it seriously impairs the accuracy of the coil as direction finder by broadening the minimum.

It is, in fact, true and a point of practical interest that the pancake loop usually never has as sharp minimum as the solenoidal type, because, even for equal antenna effects in the two cases, the displacement current effect in the solenoid, measured by

$$\frac{2 \pi s E}{\lambda}$$

is much smaller than the equivalent "winding" pitch effect of the pancake which depends on

$$n d E$$

In regard to this statement it should be pointed out that the theoretical characteristics for the two types of loops (Figs. 48, 49 and 54) are not drawn to scale nor with the exact distortion angles, so that they cannot be compared with each other. Tendencies only are indicated.

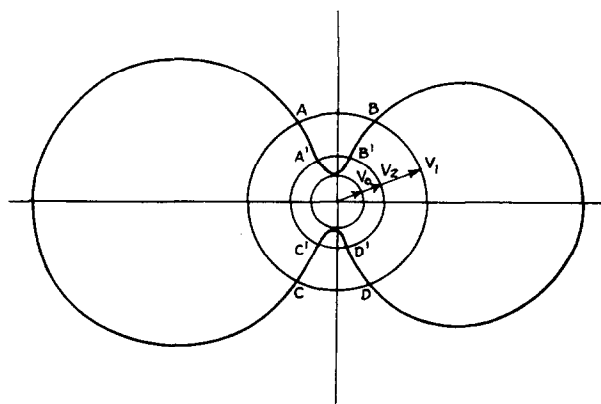
EFFECT OF RECEIVER SENSITIVENESS NECESSITY FOR RADIO FREQUENCY AMPLIFICATION.

The accuracy of the direction finder and the speed with which settings can be made depend on the sharpness of the minimum points in the directional polar characteristic. Some of the factors that effect this have just been discussed, but there is in addition to these another very important one, namely, the sensitiveness of the detecting apparatus.

If the sensitiveness is made very great, it is often difficult to find an absolute zero as the loop is rotated. It will sometimes only be possible to find a more or less restricted region of minimum signal strength, the reasons for which are evident from the

figures and the discussion above. Nevertheless, it is generally desirable to have the detection sensitiveness as great as possible for the following reason: If the polar curve is as shown in Fig. 55 and the sensitiveness of the detecting apparatus is such that it just responds to the potentials of value V_1 , and voltages less than this cannot be detected, then as the loop is rotated zero response will be obtained through the regions AB and CD . If, however, the detector sensitiveness is greater so that smaller voltages down to value V_2 can be detected the zero regions are narrowed down to $A'B'$ and $C'D'$ and the apparatus becomes more accurate. By

FIG. 55.



further increasing the sensitiveness still greater accuracy is obtained as the zero regions are further narrowed and, in the case shown, an increase in sensitiveness to correspond to the potential V_0 would give a single point or position where there would be zero response.

It is very desirable to produce this condition, but to do so requires extremely sensitive detecting apparatus as well as a very sharp antenna (loop) characteristic. If the zero regions are wider than a few degrees so that they cannot be accurately and quickly bisected experimentally, the average of the four readings, A, B, C, D , where the signal becomes inaudible must be taken as an indication of the true minimum, and although this requires time, it has, nevertheless, been found to give good accuracy provided the regions of silence do not exceed about 30° . With the

uncompensated loop midpoints of the regions AB and CD are not 180° apart, as has already been shown, and this makes it necessary to average all four readings as just described.

On account of the exponential relation between current passed and applied potential, all the usual radio detectors respond much more effectively to large impressed voltages, that is strong signals, than they do to weak ones. In other words, the ordinary detector (including the vacuum tube) is insensitive to weak signals, and since it is always in the region of weak signals that the directional setting is made there is a great loss of accuracy. No amount of audio frequency amplification will overcome the difficulty because the audio frequency amplification cannot be brought into play until the detector is "triggered off." It is for these reasons that it has been found necessary to amplify the radio frequency energy before passing it to the detector by means of a multistage radio frequency amplifier.

PART III.

EXPERIMENTAL CHECKING OF RESULTS AND PRACTICAL FORMS OF APPARATUS DEVELOPED.

Space does not permit a full account of the large number of experiments that have been made to check the conclusions arrived at from the above theoretical considerations, nor of those made for the purpose of amplifying the theory and gathering certain additional data necessary for the actual design of apparatus. Neither is it possible here to fully cover descriptions of the various types of loops, loop connections, and associated apparatus that have been developed for special uses. Suffice it to say that continuous experimental effort has been carried on for more than a year following and paralleling the theoretical deductions and not only has the theory been substantiated in every respect but several important applications suggested by the theory have been reduced to practice in a very gratifying way. The present section is divided into three parts:

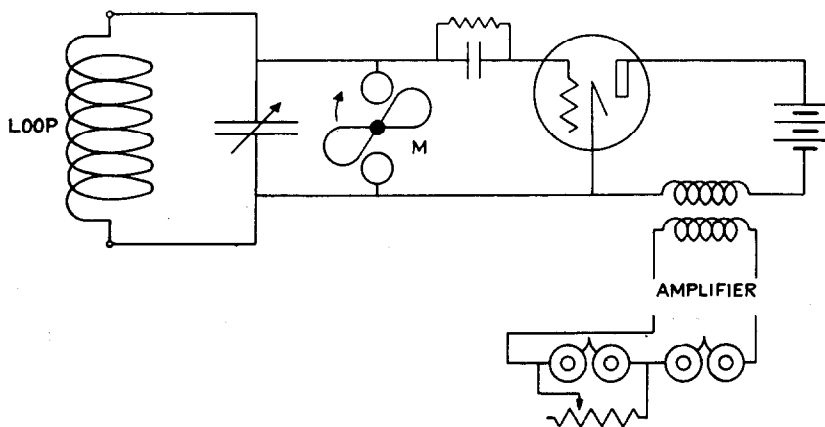
1. Examples and method of checking design data of Part I.
2. Experimental verification of Directional Characteristics and improvement of same.
3. Special developments and uses.

I.

METHODS USED IN VERIFYING DESIGN DATA OF PART I.

In order to check the results of Part I, giving data on the design of loops from the standpoint of high receiving efficiency, a number of measurements were made of received signal strength in actual undamped wave transmissions. For this purpose a vacuum tube transmitter with antenna was set up $1\frac{1}{5}$ mile distant from the loop receiver to be tested and the signal at the receiving end measured on various loops at different wavelengths by the shunted telephone method. The current in the transmitting antenna was adjusted to the same value at all wavelengths by means of a variable resistance placed in the antenna circuit.

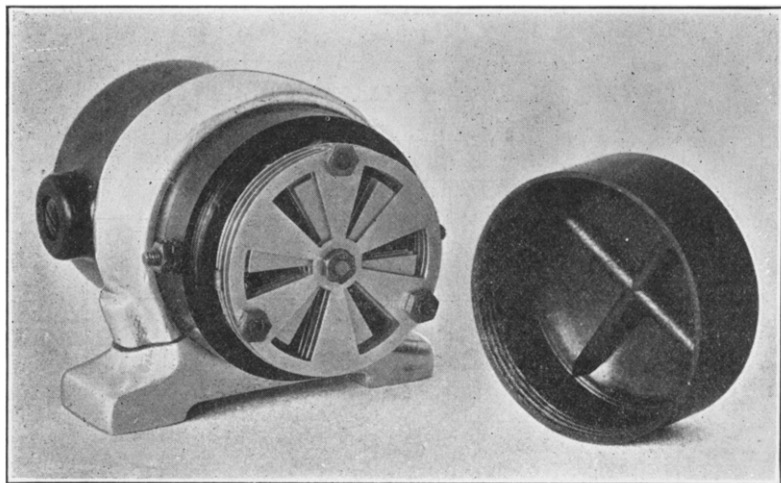
FIG. 56.



The arrangement of receiving apparatus in most of the experiments was that shown in Fig. 56. An ordinary non-oscillating detector tube with a multistage amplifier is connected to the tuned loop circuit in the usual way across the variable condenser. In order to get audible response from the incoming undamped oscillations the modulator *M* is connected across the main tuning condenser. This modulator consists of a set of stationary sectored metal discs and insulated therefrom another set of similarly sectored movable discs fastened to the shaft of a small electric motor. The device thus constitutes a condenser whose

capacity varies continuously from its minimum through its maximum values as the motor rotates. The number of sectors and the speed of rotation is so chosen that the variation of capacity through the extreme values occurs at an audible rate of, say, 300 or 400 times a second. The tuning condenser is adjusted somewhere near to the value of capacity required to tune to the incoming signals; then as the modulating condenser revolves the system is alternately brought into and out of tune at an audible rate by it and the gushes of energy fed to the detector each time resonance is reached cause a signal in the telephones of corre-

FIG. 57.



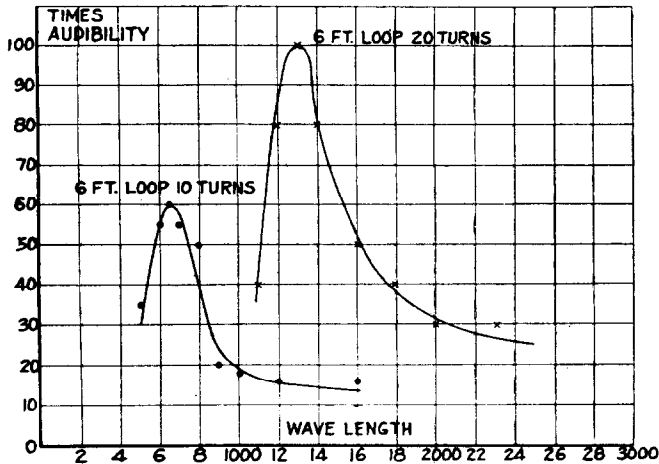
sponding pitch. A photograph of the modulator built for this purpose is shown in Fig. 57. With this method the strength of signal depends only on the amplitude of the signal oscillation, a condition which is not true when reception is carried on by the heterodyne or endodyne methods.

Two of the curves obtained on 6 ft. square 10 and 20 turn loops are shown in Fig. 58. Audibilities are plotted against wavelength. Referring to Fig. 28 of Part I., where the derived characteristics for these loops are shown, it is seen that the present curves check those obtained by calculation very well, and since this agreement has been found to exist for a number of cases investigated in the same way it must be concluded that the design

data of Part I. are satisfactorily representative of the performance of the loops which it is intended to cover.

A word should be said further with regard to reception on the heterodyne or endodyne principles. In the former case where a separate local oscillator is used at the receiver to produce beats with the incoming signal oscillation the functioning of the apparatus does not involve any essentially different points other than those already considered. The larger the voltage impressed on the detector by the incoming oscillation the stronger will be the signal, other adjustments of local oscillation being properly made in every case. In the case of endodyne reception where the receiving circuits are themselves oscillating, conditions are ordi-

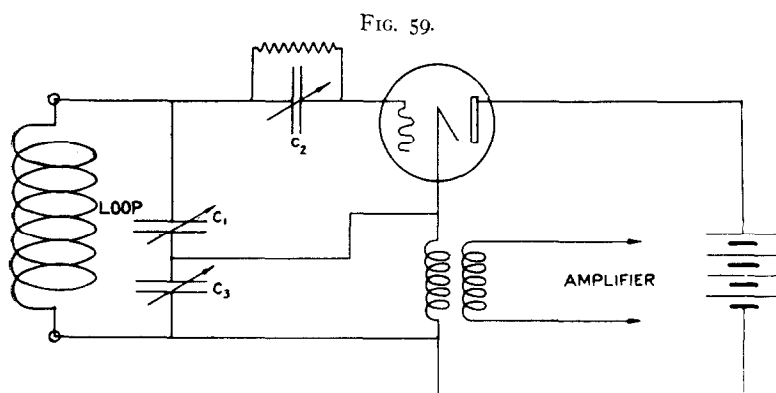
FIG. 58.



narily somewhat different. The impedance of the receiving circuit to the locally produced oscillation is zero and is equal to the resistance of the circuit for incoming oscillations having the same frequency as those produced locally. It is necessary, however, in order to secure audible beats, to adjust the local frequency to a different value than that being received so that the impedance presented to the latter is not equal to the resistance of the circuit but has a higher value depending upon the amount of detuning. The percentage detuning obviously varies with the wave-length and with the note it is desired to produce in the telephones, so that the energy collected does not ordinarily follow exactly the same

variation with wave-length as with the separate heterodyne or with the non-oscillating receiver. At long waves a considerable loss in efficiency results from the large amount of mistuning necessary to get audible beat frequencies. The overall efficiency also depends upon the way in which the receiving circuit is oscillating, upon the ratio of the strength of its oscillations to those of the incoming wave, so that the matter is very complex and, as just stated, the best signals for a given loop may not necessarily come exactly at the wave-lengths indicated in the charts; but their location depends a good deal on the particular adjustment used.

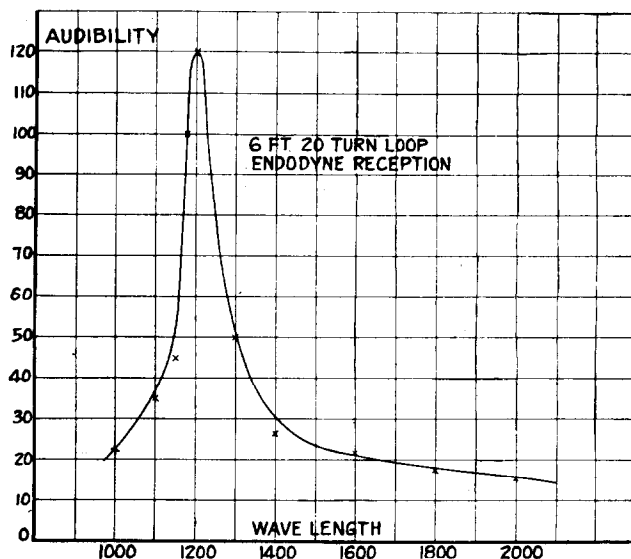
To illustrate the characteristic reception obtained by the endodyne method several curves were taken on different loops using



the receiver shown in Fig. 59. One of these curves is shown in Fig. 60 for the 6 ft. 20 turn loop mentioned above. The beat pitch was held constant for all wave-lengths and was rather high (about 800 cycles per second) corresponding closely to the natural vibration rate of the telephone receiver diaphragms. Condenser C_3 was kept fixed and the adjustments were made each time with the tuning condenser C_1 and the grid condenser C_2 . The curve shows that the best reception for the loop, under the conditions of the test, comes at about 1200 metres instead of 1300 metres as in the case of non-oscillating reception, and that the shape of the curve is different. The latter circumstance, and in particular the rapid falling off for wave-lengths longer than the optimum value, is due in large part to the mistuning required to produce the beat note.

It is possible to considerably increase the efficiency of this type of receiver and to more nearly match its performance with the predicted curves by coupling the oscillating detector inductively with the loop circuit so that the entire system has two free electrical periodicities separated by an amount corresponding to the desired beat frequency. One of these periodicities can be made equal to that of the incoming oscillations, while the other corresponds to the local beating frequency. In this way the impedance

FIG. 60.



of the circuit to the incoming oscillation is equal to its resistance and the voltage produced at the detector by this oscillation, therefore, follows such variations as have already been delineated for the non-oscillating or separate heterodyne cases. A third tuned circuit coupled to the ordinary loop receiving circuit may be used for the same purpose and with similar results.¹⁰

¹⁰ No correction was made in above experiments for change in radiation resistance at transmitting antenna with wave-lengths. The antenna was very low, however, and radiation resistance therefore practically constant for the wave-lengths.

II.

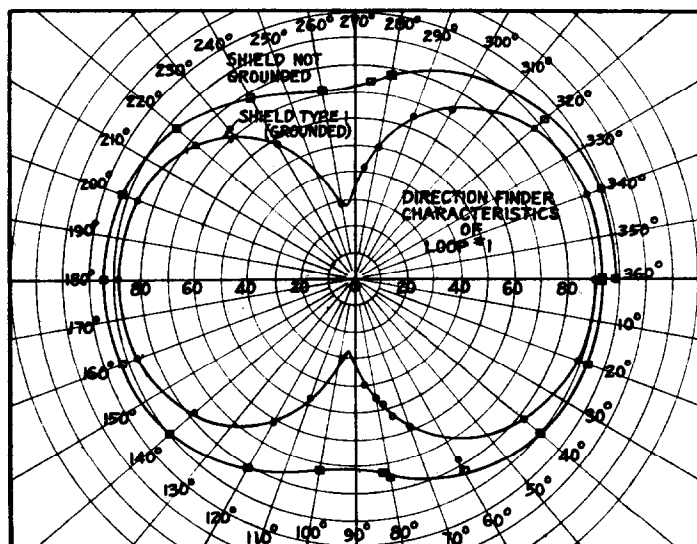
EXPERIMENTAL CHECKING OF DIRECTIONAL CHARACTERISTICS
AND IMPROVEMENT OF SAME.

Several methods have been used for investigating experimentally the directional characteristics of loop antennas. One of these which has given dependable results is the following: A 10 watt vacuum tube transmitter is connected to a small antenna of any of the orthodox types and furnishes a source of electromagnetic waves. In some of the tests which are about to be described a current of 1.0 amp. was obtained in a single wire inverted "L" antenna 20 ft. high by 100 ft. long. The loop whose directional qualities were to be studied was set up, in this case, 1.6 miles distant. It was connected to a tuning condenser and oscillating vacuum tube detector, and the response of the latter was then amplified by four stages of audio frequency amplification. The output of the last tube of the amplifier was used to actuate a thermoelement connected to a galvanometer. Thus, the energy picked up by the loop, as it was rotated through different azimuthal angles, could be recorded by visual indications and with a very little practice extremely accurate polar curve characteristics could be obtained. In the actual set-up the thermoelement was one having 197 ohms heater resistance, and 12 ohms couple resistance, and operating in a vacuum. It was fed from the low side of a 30,000 ohm to 200 ohm step down repeater coil. This repeater coil with the particular values of impedance stated was used in order to match the amplifier tube internal output impedance on the high side, and the thermo-couple impedance on the low side and thus get maximum output. The galvanometer used took the form of a single pivot Paul micrometer giving full scale deflection for 360 micro-amps. Considerable trouble was at first experienced, due to howling of the four stage amplifier, but this was finally overcome by careful wiring and proper disposition of the apparatus. A large number of polar curve characteristics has been taken, using this set-up, of various loops under nearly every conceivable condition and some of the conclusions arrived at are summarized below.

Of particular interest is the study that was made of the possibility of sharpening the minimum and increasing the symmetry of the characteristic by using overhead electrostatic shields as

proposed in the theoretical discussion of Part II above. Twenty-seven different curves were taken in this investigation, covering different designs of shields and arranged differently with respect to their distance from the loop.¹¹ A few of these curves are reproduced herewith to indicate the actual practical improvement obtainable in the loop direction finder through the use of correctly arranged shield superstructure. In Fig. 61 are shown the

FIG. 61.



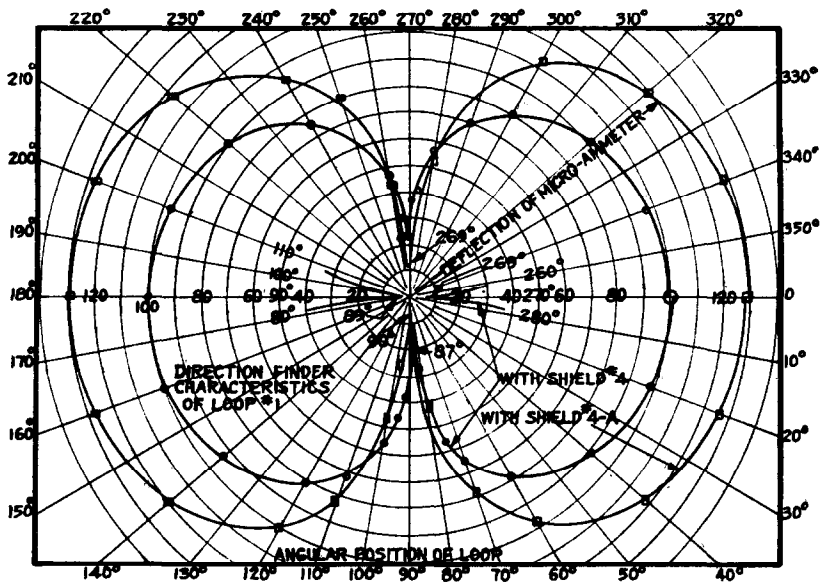
characteristics of a 5 ft. square solenoid type loop having 6 turns of No. 18 wire spaced $\frac{3}{8}$ " apart, both with and without a shield. The shield in this case took the form of a 5 ft. flat pancake wound loop, 3" between turns, mounted on top of the vertical receiving loop with one of its diagonals coincident with the top of the vertical loop and its plane parallel to the earth. The shield was, of course, grounded. It is seen that a much sharper minimum is obtained with the shield than without it.¹²

¹¹ The data of these tests were taken by 2nd Lieutenant Leon T. Wilson, Signal Corps.

¹² It should be noted that all of these curves would be elongated along the major axis were it not that strong signals are not amplified as much as weak ones in the apparatus used due to the curvature of the amplifier characteristic.

The curves of Fig. 62 were taken on the same 5 ft. 6 turn loop with two other type shields. These shields consisted of a harp of 24 No. 16 parallel wires $5\frac{3}{4}$ ft. long spaced $\frac{3}{4}$ " apart and held in horizontal plane $\frac{3}{4}$ " above the loop. The odd numbered wires were all joined together at their middle and the even numbered wires were similarly connected. When all of the wires were used this shield was called No. 4, and when half the wires were used it was called No. 4-A. The loop was set up on a farm near Lincroft, New Jersey. The complete curves were taken on different days.

FIG. 62.

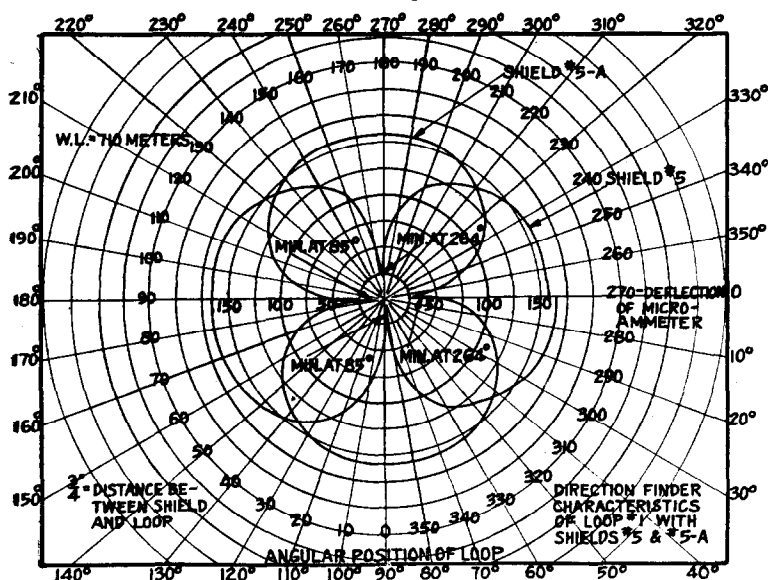


The curve for shield No. 4 was taken with 650 metres and No. 4-A with 710 metres wave-length. The small No. 4 curve and the No. 4-A curve were taken on the same morning and are comparable. It is seen from the curves that shield No. 4 has slightly better shielding qualities than shield No. 4-A, and that the minima are practically 180° apart. The minima checked with the actual direction of the station, being exactly at right angles thereto. The curves show a difference in the sharpness of the minima obtained with shield No. 4 on the two days. This is probably due to the different wave-lengths used and different weather condi-

tions, both of which factors influence the magnitude of the antenna effect.

Still two other shields were used, which were built exactly like No. 4 and No. 4-A, except that there was a total of thirty-five 6 foot long wires spaced 1" apart. The shields were designated No. 5 and No. 5-A for the 1" and 2" spacing, respectively, which was provided in the same way as on shields No. 4 and No. 4-A. The curves for these two shields are shown in Fig. 63. They show that little is to be gained by using the one inch spacing instead of the two inch spacing, a result which checks the performance of shields No. 4 and No. 4-A.

FIG. 63.



Figs. 64 and 65 give an idea of the undesirable effect on the minima caused by extra capacity to ground furnished by the operators wearing the head telephones.

Fig. 66 shows the curves obtained with different distances between the loop and shield. The best distance for shield No. 5 appears to be about $\frac{3}{4}$ ".

Fig. 67 shows a curve taken very near to and partly under a tree. The minima are broadened somewhat and there is a slight distortion.

FIG. 64.

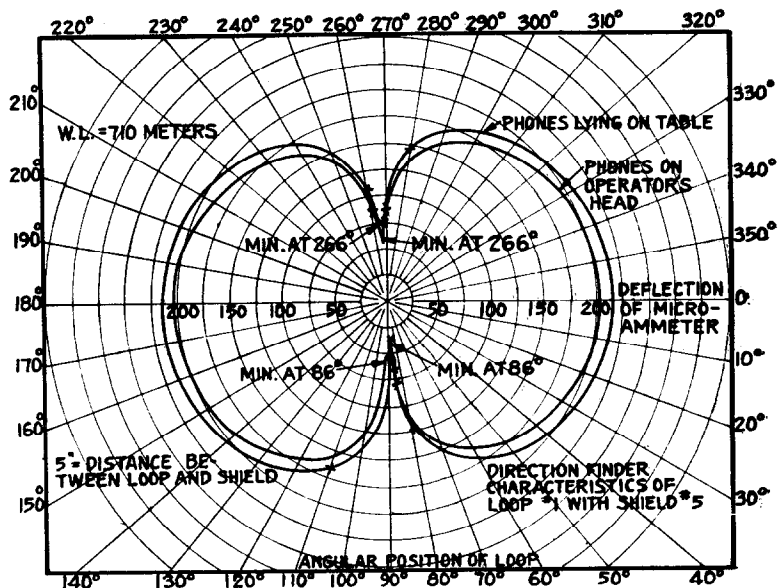


FIG. 65.

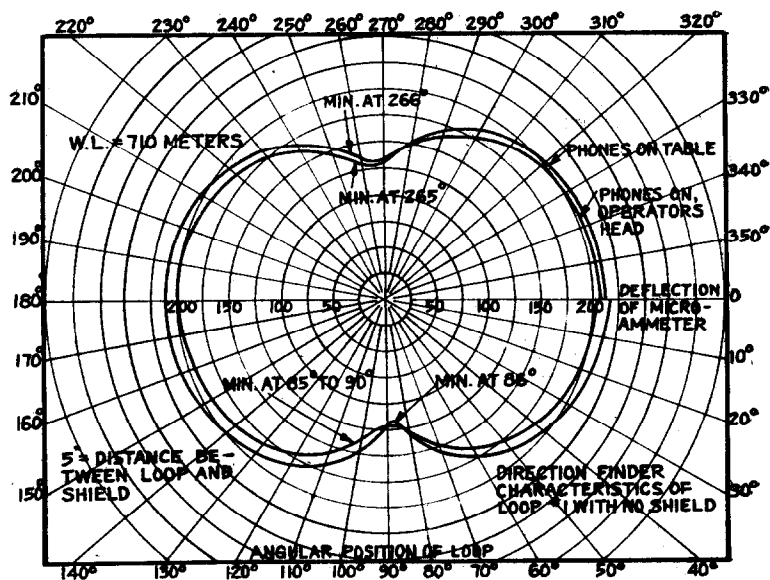


FIG. 66.

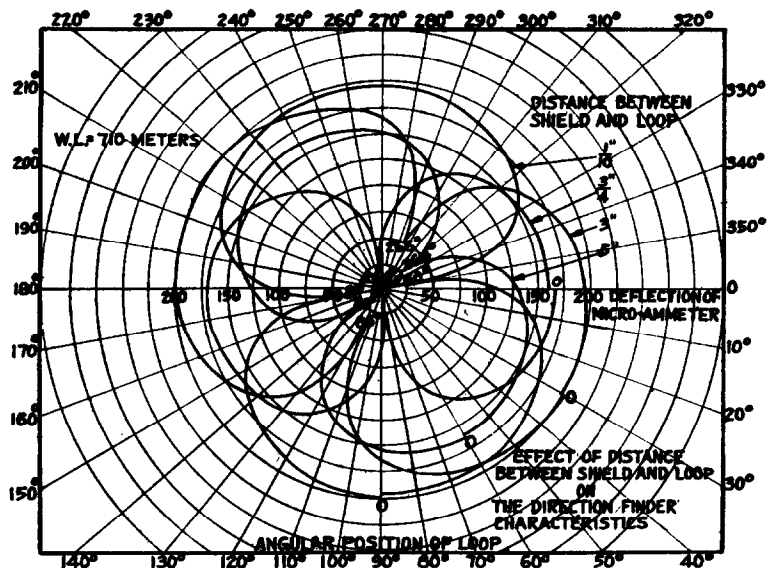


FIG. 67.

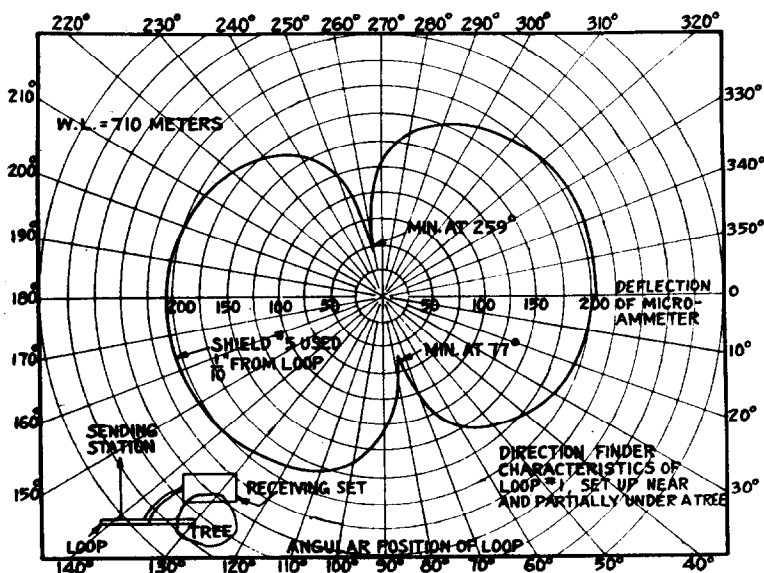
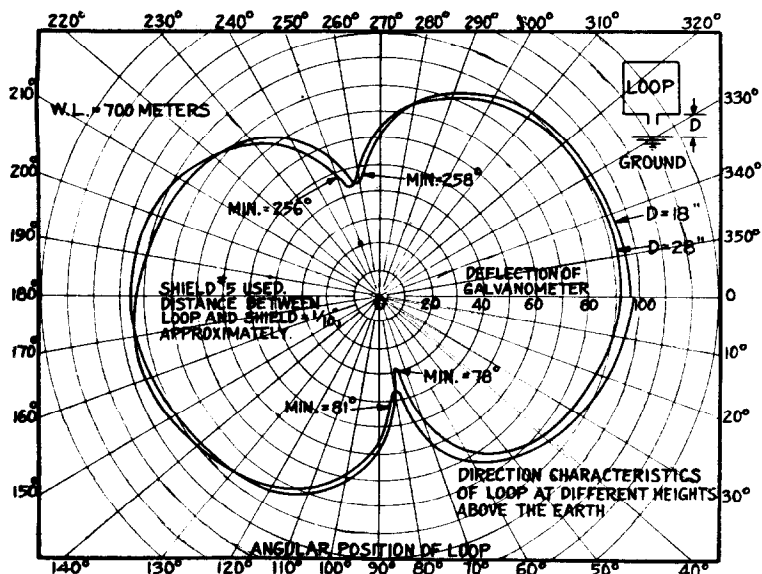


Fig. 68 is a partial record of the effect of changing the distance of the loop above the earth. It is seen that even the relatively small change from a height of 18" to one of 28" causes noticeable improvement in symmetry and sharpness of minima. It has been found that still better results may be had at a height of 4 or 5 ft., and when the entire apparatus was placed in a wooden barn 20 ft. from the ground extremely accurate settings could be made.

FIG. 68.



The general conclusions that were derived from all of these experiments with particular reference to the various factors affecting the accuracy (that is, the sharpness and position of the minima) of the direction finder are as follows:

(a) *Sharpness and Symmetry of Minima.*—With a single simple loop the minima are sometimes sharp and sometimes very broad and are not generally equal nor 180° apart.

(b) *Effect of Electrostatic Shield.*—The use of an electrostatic shield above the loop is in general very advantageous in improving the sharpness and symmetry of the minima. It does not noticeably reduce the strength of received signal.

(c) *Pancake vs. Solenoid Loops*.—The minima of the pancake type loop are generally broader than those of the solenoid type. There is a greater difference in the amplitudes of the two oppositely directed maxima for the pancake than for the solenoid.

(d) *Grounding Any Part of the Receiving Apparatus*.—Either grounding parts of the receiving apparatus (for example, grounding the filament battery of an amplifier to prevent its "howling") or placing parts of the apparatus close to the earth broadens the minima and therefore decreases the accuracy of the loop (partial grounding of the set through the telephone receivers on the operator's head has a small though noticeable effect). The grounded shield was found to partially correct this loss in accuracy but not completely. Therefore, the receiving apparatus and batteries should be kept at least 2 or 3 feet off the ground.

(e) *Proximity of Loop to Earth*.—The proximity of the loop to the earth produces a broadening and a slight distortion of the minima when the shield is used. To obtain good results the lower edge of the loop should be at least 4 feet off the ground.

(f) *Effect of Nearby Metal Objects*.—A Ford truck was placed very close to the loop (with a shield) and was found to have negligible effect, even with the frame of the truck grounded. On the other hand, the loop and shield when used in a building with numerous radiators of a heating system in it, gave minima which were about 4° off from being 180° apart. The loop should, therefore, not be set up near extended masses of metal or near wires.

(g) *Effect of Trees*.—Scattered trees 30 or 40 feet from the loop have negligible effect on the direction finder. A tree which is but a few feet away causes a slight distortion of the minima. Many large trees 30 or 40 feet from the loop and between the loop and the transmitting station appreciably reduce the strength of signal.

(h) *Effect of Atmospherics*.—Certain kinds of atmospherics are considerably reduced by the grounded shield.

(i) *Polarity of Loop*.—Under ordinary conditions the solenoidal loop with or without the shield gives one minimum sharper than the other. Reversing the leads from the loop to the receiving set reverses the sharp minimum.

(j) *The Distance of the Shield Above the Loop*.—The best distance of the shield above the loop was found to be about $\frac{3}{4}$ " to $1\frac{1}{2}$ " for the apparatus of ordinary dimensions.

(k) *Use of Shield When the Complete Direction Finding Apparatus is High Off the Ground.*—Although the shield is very effective in sharpening the minimum when the loop is 3 or 4 feet off the ground, and the receiving apparatus 2 or 3 feet off the ground, it loses its value when all the apparatus is 15 or 20 feet from the ground. Under these conditions the loop has good directional qualities without a shield.

III.

PRACTICAL DEVELOPMENTS AND USES.

While it is not essentially the purpose of this report to describe in detail the several practical developments of radio direction finding apparatus that have been made nor its uses, it is, nevertheless, interesting, in connection with the work described above, to mention certain special applications that have been made of the principles involved which are believed to be novel.

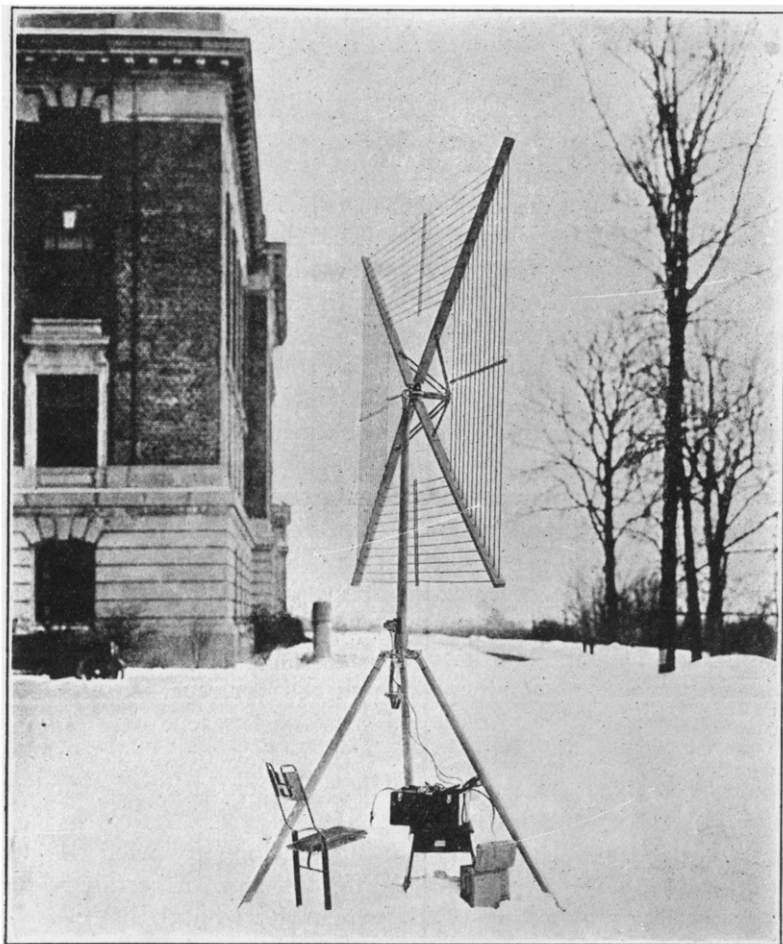
One of these is the construction and use of a single loop for finding *absolute* direction, a result obtained by properly augmenting the antenna effect and the phase of same so as to produce distortion in the polar curve characteristic with unequal maxima and minima. A photograph of a portable field apparatus which accomplishes this in a satisfactory way while retaining sufficiently sharp minima for accuracy in directional settings is shown in Fig. 69. Absolute direction or sense is obtained by a rough setting of the loop in a position for maximum signal strength and then either rotating the loop through 180° or reversing the leads to the detector. The directional sense of the sending station is then determined by noting whether the first or the second arrangement gives the louder signals. The exact line is fixed, as usual, by right angle settings.

A second novel method of using the loop followed the discovery that at certain heights, different from a certain value, above ground a loop placed with its plane horizontal, that is parallel to the earth, acted as a very good receiver and was practically non-directional. Such an arrangement is useful for many purposes, such, for example, as intercept work.

A combination of vertical loop, giving the two-leaved characteristic, with a horizontal loop, giving a circular characteristic, may be used to get absolute direction, and by suitable switching

arrangements the horizontal loop may be used alternately as a shield for improving the sharpness of minimum and for giving antenna effect, as just described, and getting absolute direction.

FIG. 69.



A model has been standardized by the Signal Corps using a carefully designed solenoidal type loop with an electrostatic shield for very accurate direction finding work.

It was found (December, 1917) that when the plane of a loop of certain design was placed at a certain angle with the earth

and at a certain height no radio signals could be received from certain directions. While the uses to which this important discovery have been put cannot be disclosed at the present time, it may be stated that they are concerned with a very great improvement in the reliability of radio communication. Other arrangements of specially constructed loops and associated apparatus have also been developed and are being improved with the same end in view.

In concluding this paper, it should be stated that a great deal of the work that has been done on the loop direction finder itself has been paralleled by investigations and development of multi-stage amplifiers, necessity for the use of which has been pointed out above. A seven tube amplifier comprising three stages of radio frequency amplification, a detector tube, and then three stages of audio frequency amplification, has been developed and standardized by the Signal Corps for direction finding work. This instrument is more sensitive, has fewer adjustments, is less noisy, lighter and more compact, and altogether a more generally satisfactory instrument in operation than any similar apparatus having the same order of amplification that has been developed by either the British, the French, or the Germans. The total overall power amplification obtained on weak signals is of the order of 10^{14} times. A novel feature of the amplifier is the use of iron in the radio frequency transformers which couple the radio stages. Incident to the development of this and similar amplifiers a very thorough study was made of the characteristics of iron at radio frequencies, and data were collected giving the permeability and losses in steel that was found suitable for use in these transformers. The iron that has been used in this work is 0.0015" thick, lacquered with a special enamel to the thickness of 0.002". It is a low carbon steel containing no appreciable amount of silicon.

Using the seven stage amplifier just mentioned and a loop small enough to be easily accommodated in an ordinary size room, it has been possible to receive signals from all of the high power European stations.

The loop has been used for direction finding on both damped and undamped waves. In the latter case, as has been described above, either a separate local heterodyne may be used at the receiver, or the receiving circuits themselves can be made to oscillate. Using a separate heterodyne, care must be taken to prevent

any direct action of the local oscillation on the loop circuit itself, because in such cases the directional setting will be incorrect. This is because the signal produced is due to the combination of the signal wave and the heterodyne wave, and almost any setting can be obtained, depending upon the amplitude of the local wave and upon the direction from which it intercepts the loop. When using a separate heterodyne, the local oscillation must be introduced into the circuits through a small localized coupling with no leakage of the loop system.

Finally, adaptation of the loop receiver has been made to the airplane in another special form of apparatus for direction finding and the same principles and data given above have been applied in the design of the loops for this purpose.

Corrosion in Lenses. (*The British Journal of Photography*, vol. lxvi, No. 3088, p. 389, July 11, 1919.)—If lens users would acquire a little elementary knowledge concerning the nature and properties of glass, their instruments would stand a much better chance of keeping in good condition than they do at present. It should be known that what we call "optical" glass is made in a great variety of qualities, each of which is capable of taking its place in one or other of the many kinds of lenses. Some are as hard and impermeable as the glass we use for windows and tableware, while others are soft enough to be easily scratched or even dented, while injudicious polishing will quickly dim the exquisite surface upon the perfection of which so much depends. This is especially the case in some of the earlier anastigmats in which very soft and easily corroded glasses were used because others were not available. It is perhaps news to many people to learn that some glasses are so susceptible to damp that a single drop of water left upon the surface for a few hours will leave an ineradicable mark, while the presence of a film of condensed moisture will give rise to a general corrosion, which in mild cases shows in prismatic colors like those of a soap-bubble, and in severe ones as a yellow stain accompanied by a distinct depolishing of the surface. Unfortunately, there is no cure for this evil, for even the maker of the lens cannot repolish it to the same accuracy of figure that it originally possessed. Forewarned is forearmed, and knowing what is likely to occur the prudent man does not allow his lenses to stand about exposed to the atmosphere, but keeps them in tightly-closed cases when they are not actually in use. Failing a case, which also protects the brasswork, a well-fitting cap at the back as well as the front is an excellent protection.