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Design of Loop Antennae

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THE use of loop or coil antennae for receiving is too well known to require any introduction. It is not believed, however, that the design of loops for specific wave lengths and for various uses is thoroughly understood. The purpose of this paper will be to explain the factors which enter into the practical design.

Loops serve a two-fold purpose. First, they function as antennae for either transmitting or receiving. Second, they may be used to determine the direction in which a wave is travelling.

It is fairly obvious that such factors as size and shape will affect both the directional and receptional qualities of a loop. Just how these factors together with others, such as number of turns and spacing, do control and limit the proper functions of a loop will be subsequently shown.

For convenience loops will be considered as either (a) spiral or (b) solenoid. (a) Spiral loops are those which are of the pancake type each turn of which encloses an area smaller than the preceding turn. (b) Solenoid loops are those which are of the helical type every turn of which encloses the same area. Two solenoids mounted at right angles to each other constitute a "crossed coil" loop."

In order to determine the effects due to various shapes many loops have been made and actually tried. In each loop the factors N (number of turns) and A (area enclosed by one turn) were kept constant so that the results served as a fair comparison between the different shapes. In each case the loop was shunted by a tuning condenser and connected directly to a vacuum tube detector set. The telephone receivers were shunted by a constant impedance resistance or "audibility meter". The transmitter consisted of a quenched spark set with an aerial of the "umbrella type".

After the signal was tuned in, the loop was rotated and audibility read at every ten degrees. The audibility readings were plotted on polar co-ordinates. Reproductions of the various shapes and windings are shown in Fig. 1. These curves are not drawn to scale and should be considered qualitatively **only.**

In Fig. 1 (a) is a square loop of the spiral type; (b) is a rectangular loop; (c) is the same loop as (b) except that it is turned in a vertical plane so that its longest axis is perpendicular; (d) is a triangular loop; (h) and (i) are "figure 8" loops. (e) and (j) are square loops with "figure 8" windings; loops (e) and (g) had parts of the windings entirely enclosed in a metallic shielding which was grounded.

The polar curves of loops (a) and (b) indicate rather broad maxima and sharp minima. Loops (c) and (d) indicate sharp maxima and rather broad minima. Loops (e), (h), (i) and (j), especially the last, show very little variation between maxima and minima. When the shield of (e) was ungrounded, the curve (f) resulted. In this case the loop effect was practically reversed. (Note: In each case the signal is supposed to be coming along the zero axis from right to left.)

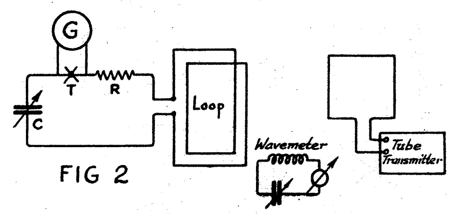

FIG 2

It was found that with almost every loop the signals disappeared when the loop was held in a plane about 30° to the earth as indicated in (m). When the loop is raised to a position parallel with the earth, as in (n), it is practically non-directional and acts as a simple aerial. Further tests were tried to ascertain the properties of loops elevated above ground and placed below ground. In the former case the actions were somewhat erratic; but the tests were too incomplete to be considered. In the latter case no loss in directional properties was noticed in a dugout some twelve feet underground.

The loop of Fig. 1 (k) differed slightly from (a) in that the turns were spaced more and the winding continued further until it nearly filled the area. This loop showed some very interesting features and will be more fully discussed later.

On the whole these tests showed that both for receiving and for direction finding the square loop gave the best signal and quite satisfactory directional qualities.

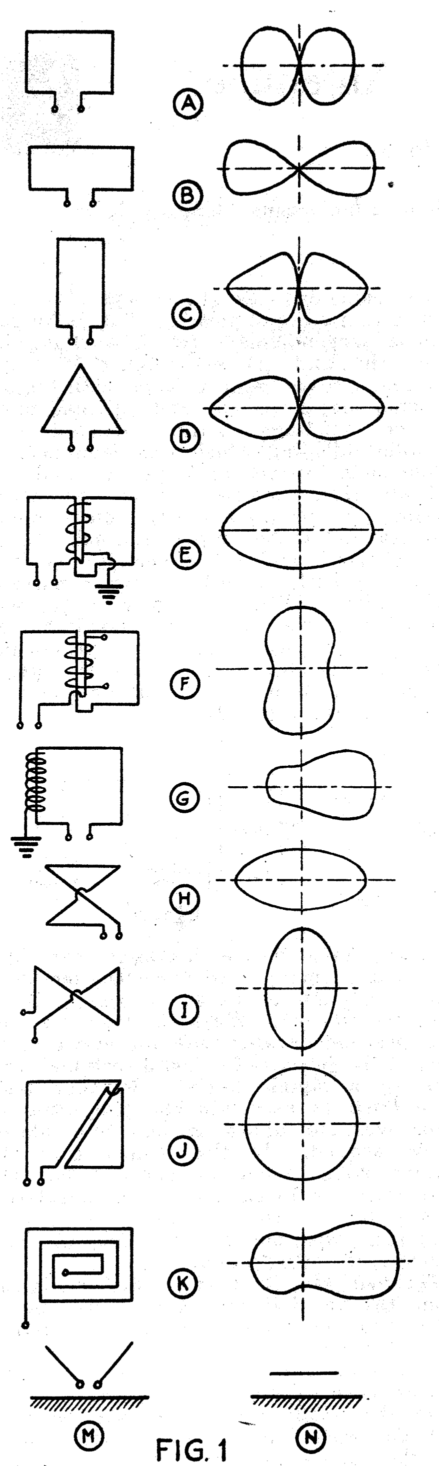

FIG. 1

It is apparent that for any given size of loop more turns can be got on a solenoid than on a spiral. Furthermore, the solenoid is less directional than the spiral. For these reasons the square solenoid will be considered hereafter as standard for ordinary receiving, while the square spiral may be used for direction finding.

In order clearly to understand the methods of design it is necessary to consider the theory of loop reception.

At any instant the value of e.m.f. induced in the loop is

$$e = N\frac{d\varphi}{dt}10^{-8} = NA\frac{dh}{dt}10^{-8}\ *$$

where N is number of turns, A is area of one turn, φ is the flux, e is instantaneous value of e.m.f., h is instantaneous value of field intensity, H_o is maximum h. For a harmonically varying field

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

$$\frac{dh}{dt} = H_o\omega \cos\ (\omega t)$$

Then

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

At resonance the instantaneous value of the current is $\frac{E}{R}$

$$i = \frac{e}{R} = \frac{NAH_o\ \omega\ 10^{-8} \cos\ (\omega t)}{R}$$

The effective (R.M.S.) current is

$$I = \frac{i}{\sqrt{2} \cos\ (\omega t)} = \frac{NAH_o\,\omega\,10^{-8}}{\sqrt{2}\,R}$$

The voltage across a condenser is IZ or $\frac{1}{j\omega c}$ so that the voltage from the loop across the condenser (i.e. the voltage which actuates the detector) is

$$E_c = \frac{NAH_o\ 10^{-8}}{\sqrt{2}\ jRC}$$

$$\lambda = \frac{V}{f} = V\,2\,\pi\,\sqrt{(LC)}$$

$$\frac{1}{c} = \frac{4\,\pi^2 V^2 L}{\lambda^2}$$

Substituting the value of $\frac{1}{C}$ in the equation for E_c and calling all the constant terms K

$$E_c = K\left(\frac{NAL}{\lambda^2 R}\right)$$

The response to any signal, then, may

* For a spiral loop

$$e = \Sigma^n A\ldots\ldots\ldots$$

be said to depend on the value of $\left(\frac{NAL}{\lambda^2 R}\right)$ This term will be called the "Reception Factor" of a loop. The problem would appear to be to make the largest possible loop in order to have a large NAL term. But on the other hand it may be seen that the reception decreases as the wave length squared increases. And, furthermore, if the wave length is decreased (to increase the reception factor), the resistance becomes very high. It is obvious that the reception factor for each and every loop must be studied in order to determine the best size for any desired wave length.

In the expression $\left(\frac{NAL}{\lambda^2 R}\right)$ the terms N and A are arbitrarily fixed for any one loop. L (the inductance) may be either calculated or measured. λ is the wave length at which the loop is operated. R, the resistance of the loop at that wave length, is the only undetermined variable. By tests the actual resistances of loops of different sizes was determined. Fig. 2 shows a loop connected in series with a standard resistance, a low resistance thermo-couple and a standard variable condenser. The thermo-couple is shunted by a current-squared meter. A variable frequency oscillator and a wave meter are also indicated. The oscillator was tuned to any long wave length and the loop tuned in by means of the standard condenser. Readings of the meter were taken when various standard resistances were inserted in the circuit. The inductance was then calculated from the relation

$$L_{cm} = \frac{\lambda^2}{59.6^2 C\mu f}$$

and the resistance by

$$R = \frac{R_2 - R_1\left(\frac{\delta_1}{\delta_2}\right)}{\left(\frac{\delta_1}{\delta_2}\right) - 1} - R_t$$

where R = *loop resistance*

$\left.\begin{matrix} R_1 \\ R_2 \end{matrix}\right\}$ = *standard resistances*

$\left.\begin{matrix} \delta_1 \\ \delta_2 \end{matrix}\right\}$ = *corresponding meter deflections*

R_t = *resistance of thermocouple.*

By making similar calculations of R and L at various wave lengths down almost to the fundamental of the loop circuit and by plotting the results, curves similar to those of Fig. 3 were obtained.

Both curves of Fig. 3 are in accordance with the known facts that near the fundamental period the resistance and inductance are very high and that at long wave lengths both approach the true low frequency values. The value of inductance was assumed to be that shown on the curve at

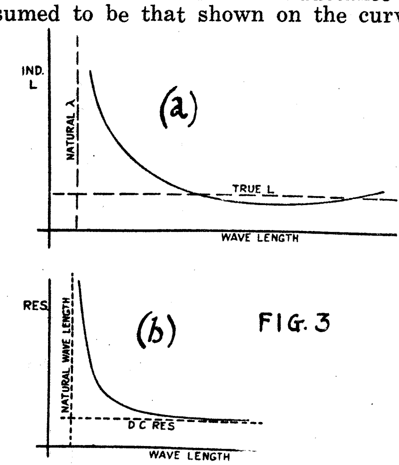

FIG. 3

a point corresponding to a relatively long wave length. The factors N, A and L being known, the values of R at various wave lengths were read from the curve and the corresponding reception factors plotted. As may be seen in Fig. 4, for any given loop there is a decided maximum in the value of the reception factor.

To determine the best spacing of turns, various spacings were tried. Loops of each size, from four to fifteen feet square, were made and the turns were spaced by successive fractions of an inch from one

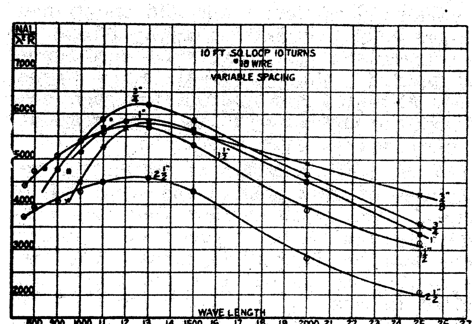

FIG 4

quarter to one and one half inches. At each spacing, the reception factor curve was determined. Fig. 4 shows a representative series of curves for the reception factors of a thirteen foot square loop. The greatest maximum for that loop occurs when the spacing is one inch (center to center of turns). Consequently, one inch may be considered as the best spacing for a loop of that size. The best spacing of all sizes up to fifteen feet is shown in the curve Fig. 5 and similarly in Table A. In all subsequent tests, the loops were made with the spacing indicated by that curve.

TABLE A.
Best Spacing for Solenoid Loops.
(*Center to center between turns.*)

Size loop feet	Spacing inches
4	$\frac{1}{4}$
6	$\frac{7}{16}$
8	$\frac{9}{16}$
10	$\frac{3}{4}$
12	$\frac{15}{16}$
15	$1\frac{1}{8}$

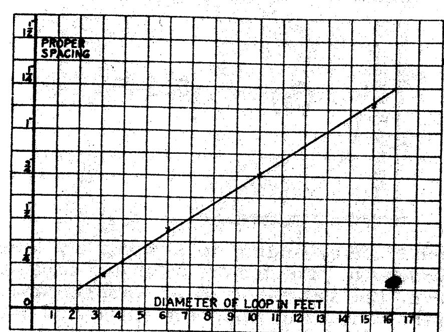

FIG. 5.

Thus far has been determined the criterion for loop reception (i.e. the "Reception Factor) and the best spacing for different sizes. The next problem is to determine the size and number of turns to be used for any given wave length or range of wave lengths. As before, loops of various sizes were made and tested over a large range of wave lengths. From the tests resistance and inductance were found and plotted. The reception factor values were calculated and plotted for each size of loop, the number of turns being gradually increased at each test.

Fig. 6 shows a group of curves for resistances of four foot loops up to 4000 meters. The smallest four foot loop consisted of ten turns (spaced one quarter inch) and the largest 80 turns. The corresponding values of reception factor are plotted in Fig. 7. It is obvious that for any given loop there is some one wave length at which the product of λ^2 and R will have a minimum value. This is clearly indicated by the shape of the curves of Fig. 7. For example, the lower left hand curve shows the reception of a four foot, ten turn loop. The maximum reception factor for that loop (3000) occurs at 800 meters. Below and above 800, the reception is very poor. For the 20 turn loop 1800 is the best wave length. However, at longer waves this loop is much better than the 10 turn loop and, conversely, poorer at the shorter waves. The 60 turn loop is better than any of the others except at short wave lengths; while the 80 turn loop is very poor at any wave length. Two things, then, are apparent: (1) For any given wave length and given size of loop, one number of turns is better than any other, and (2) for any given size of loop, one

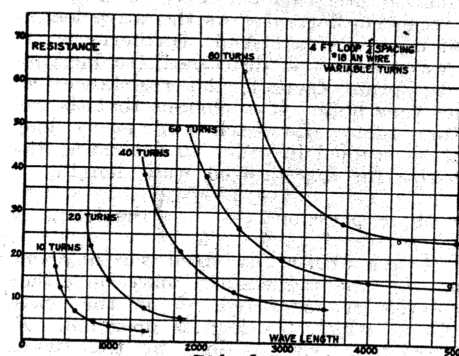

FIG 6

number of turns gives better results over a range of wave lengths than does any other.

Figs. 8 and 9 are respectively the resistances and reception factors for a 6 foot loop. These curves correspond in general character with those for the four foot loop. Curves for all other sizes are substantially the same and tend to confirm the general conclusions of the preceding and of the following paragraph.

Comparing the four and six foot loops it will be seen that for some range one size is better than the other and vice versa. The general conclusions are (1) that for short waves large loops with few turns are

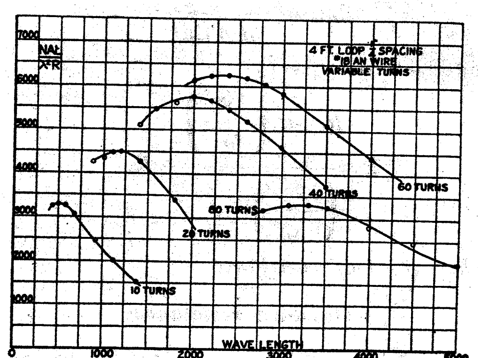

FIG 7

better than small loops with many turns, and (2) that for longer waves large loops are better than small loops. These conclusions may be checked by referring to Fig. 10.

One series of curves of Fig. 10 shows the number of turns (of loops from four to fifteen feet square) plotted against best wave lengths. From these curves may be obtained directly the dimensions of loops which work best on any given wave length. For example, for 2500 meters, any of the following could be used: (1) fifteen foot, thirteen turn, (2) twelve foot, eighteen turn, (3) ten foot, twenty-three, (4) eight foot, thirty turn, (5) six foot, forty turn

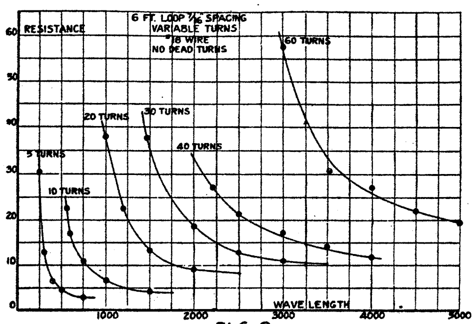

FIG 8

or (6) four foot, fifty-three turn. Numbers of turns for intermediate sizes, (i.e. 5, 7, 9 feet......etc.) may be got by interpolating between the given curves.

The second series of curves of Fig. 10 are the maxima of reception factors for each size. From this set may be found which size of loop is best for a given wave length. In the last paragraph were determined a number of loops giving best results for their respective sizes. Now will be determined which of those loops gives the best results for that wave length. Taking the same example, 2500 meters, and tabulating the points obtained from the second series of curves,

Size	Turns	Rec. Factor
15	13	7000
12	18	7900 (approx.)
10	23	8600
8	30	9000 (approx.)
6	40	9300
4	53	6400

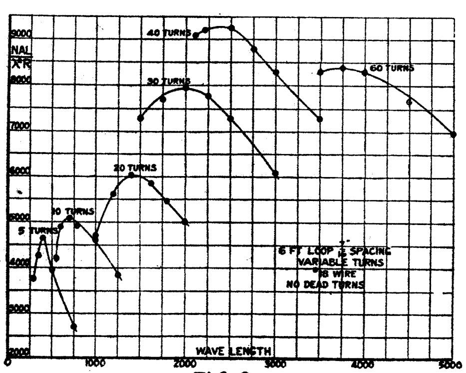

FIG 9

These figures show that of all the possible combinations a six foot loop with forty turns will give the best reception on 2500 meters.

Similar analysis may be made for any other wave length. The following tables summarize results obtained from different sizes and also indicate in order the best sizes for various wave lengths and ranges of wave length.

TABLE B.
Wavelength Range for Four Foot Square Solenoids

Turns	Best Wave Length	Efficient Range
3	250	200-350
4	300	250-400
6	350	300-800
10	600	350-1000
20	1200	900-1800

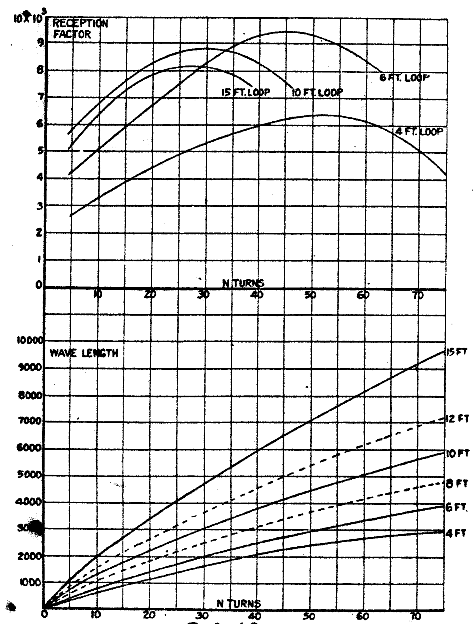

FIG 10

TABLE C.
Wavelength Range for Six Foot Square Solenoids

Turns	Best Wave Length	Efficient Range
3	220	180-400
6	500	400-900
10	700	600-1200
20	1400	1000-2000

TABLE D.
Size of Square Solenoid Loops for Various Wavelengths

Wavelength Meters	Size Feet	Turns N
50 to 100	(4	1
	(3	1

Wavelength Meters	Size Feet	Turns N
200	(8	1
	(6	2
300	(8	2
	(6	4
	(8	4
600	(6	7
	(4	10
	(8	7
800	(6	10
	(4	15
	(8	12
1200	(6	14
	(4	20
	(8	16
1600	(6	20
	(4	30
	(8	30
2500	(6	40
	(4	60
3500	(8	45
	(6	65