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No. 67. *September-December, 1937.*

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THE SERIES PHASE ARRAY

Long experience with the Series Phase Array has proved that it is a worthy successor of the original Marconi " Broadside " Beam Array. Apart from a short discussion by the author in a paper to the British Association last year, no publication has dealt with the Series Phase Array, and the present article sets out fully its method of operation.

The first part of the paper discusses the principles of " End-Fire " arrays generally, and the relationships of space and time phase in the elements of the array line. The second part of the paper deals more specifically with the series phase array and indicates why this array is suitable both for transmitting and receiving purposes. The discussion indicates the use of the loops both for radiating and phasing purposes, and shows the adaptability of this particular design.

THE principles upon which beam array systems are founded, namely, the production of an interference pattern in space from a group of radiating sources are now well known, and since the original Marconi Broadside Array was produced, a great variety of aerial arrangements have been produced to give " beam " effects. In fact the number of wire arrangements to produce the desired uniform current sheet is apparently unlimited, both for use with open wire, and with concentric tube feeder systems.

Now the concentration of energy of a broadside array is a function of its area because directivity in any one plane is determined by the dimensions in that plane. Because it is expensive to build high arrays this means that in general a broadside array will have small directivity in the zenithal plane, and great directivity in the horizontal, Fig. 1A showing the solid polar diagram of a broadside array of two wavelengths wide and half a wavelength high, with reflector.

By misphasing the currents in an array line it is possible to swing the diagram, and if the time misphase between radiators is made the same as their space phase, the maximum of the diagram can be arranged to lie along the line of radiators. In this case the directivity in all planes is now the same, even for an array of limited height, and therefore costing much less than an array of great height, as the directivity is a function of length, not area, Fig. 1B showing the solid polar curve for a single line two wavelengths long and negligible height. If this is compared with Fig. 1A it will be seen that although the horizontal diagram of the latter is not so sharp as the former, the zenithal diagram is sharper, and the overall directivity therefore is practically the same.

An array of this type, that is, one which directs its energy along the array line, is called an " In-Line " or " End-Fire " array, and the Franklin " Series Phase " array is of this type.

Generally speaking, although their directivity is good, "end-fire" arrays, being of low height, have but a poor effective height, and in consequence they are not of very much value for transmission purposes. The series phase array on the contrary is an exception to this rule, as although its actual overall dimensions are small, it nevertheless has very considerable effective height, as will be seen later, and therefore it is equally efficient either for transmission or reception purposes.

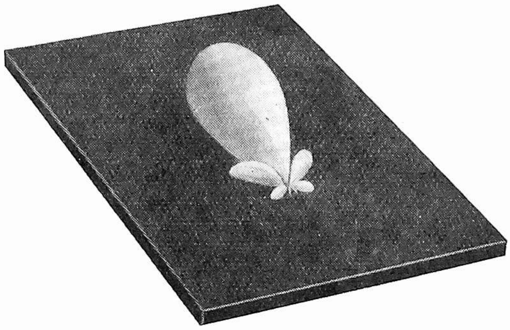


FIG. 1A.

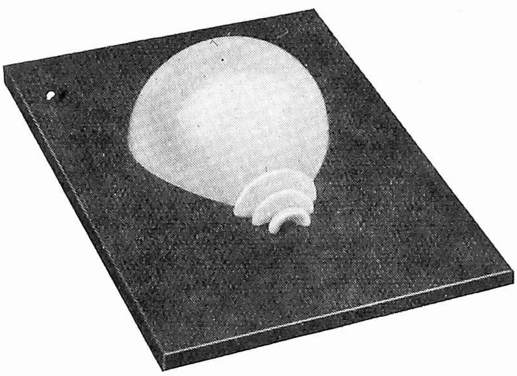


FIG. 1B.

In its simplest form the series phase array consists of a wire folded into a number of loops connected by horizontal wire lengths as shown in Fig. 2, suspended either vertically or horizontally, the dimensions of the loops and the spacing being dependent upon the type of diagram required. In general the most commonly adopted arrays are made with loops approximately one-quarter wavelength long spaced a similar amount, the length of the array line being dependent upon the directivity desired, arrays with 8, 12 and 16 loops being most common. Array lines are often formed into groups of 2 or 4, and of course can be added as for diversity reception. An array line will be fed from one end usually through a short length of non-radiating feeder coupled to a normal concentric tube main feed line, the remote end of the array generally being terminated by a resistance equal to the characteristic resistance of the system, which approximates to 300 ohms.

As will be seen later, the loops perform two separate functions; to act as radiators; and what is as important, to determine the time phase of current between loops; but before explaining exactly how this simple but extremely ingenious array functions we propose to discuss these problems at some length in a general way.

Consider an array line, say two wavelengths (effective) long as shown in plan in Fig. 3; in this case consisting of 8 vertical aerials each spaced one-quarter wavelength apart. The polar curve of such an array can be obtained graphically, or by using the well-known vector method. If we consider the latter treatment and set out the vector fields for the above array assuming each aerial is fed by current in phase, we obtain resultant fields which are maximum normal to the line. The vector sum for normal directions is shown in Fig. 4, and field strength vectors for other directions θ° degrees from the normal are shown in Figs. 4A, 4B, 4C and 4D. In the case of an infinite number of aerials, the ratio of field to the maximum field in any direction θ is equal to $\dfrac{\text{Sin}\,\frac{\phi}{2}}{\frac{\phi}{2}}$ where ϕ is the space phase angle between the first and last aerial for the direction θ under consideration.

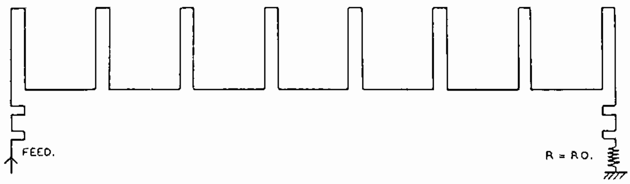


Fig. 2.

It will be observed that the maximum field is normal to the array because the time phase of current to the aerials is zero and the space phase is also zero in this direction, whereas in the other directions the space phase fields do not add. Further a perfectly symmetrical bi-directional polar diagram of radiation is produced as shown in Fig. 5A because the vectors wrap up either in a clockwise, or an anti-clockwise direction from an initial straight line vector both sides of the normal.

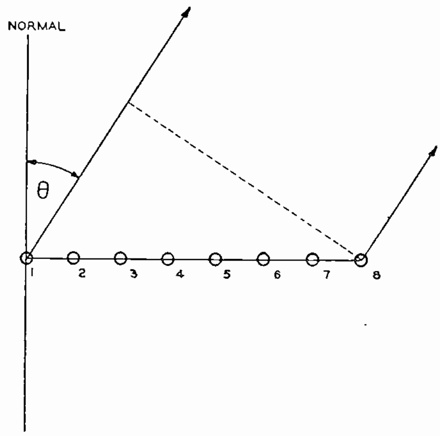


Fig. 3.

Observe that if (within reason) we alter the number of aerials in the array line (and therefore their spacing), this makes but negligible difference to the resultant polar curve as it merely alters the number of vectors making up the diagram, an infinite number of aerials giving arcs and circles for the vector sums, an artifice adopted originally by E. Green to simplify the calculations.

We will now consider the effect of mis-phasing the time phase of currents in the above line. For instance, assume we have a small time phase between aerials, say, with aerial 1 leading 10 degrees on aerial 2, and the same time phase successively throughout. This will result in the vectors having an initial bias because of the time misphase (Fig. 4A, left, might now represent such a vector condition) giving a reduction of field for the direction normal to the array line.

Considering that direction (to the right) where the space phase between aerials is equal to the time phase we have applied, the time phase and space phase will be in opposite sense because in this direction the space phase of No. 1 vector is lagging on No. 2 and so on, whereas the time phase is leading. This will result in the vector sum being straightened again, thus giving maximum field for this direction. Contrariwise at an equal angle θ from the normal in the left hand quadrants, the space phase is additive to the time phase and the field is reduced. The result of this small time phase is therefore to give a bias to the maxima of the polar diagram to that side away from the leading time end and make it asymmetrical as shown in Fig. 5B.

If we now increase the time phase to such an extent that it is exactly equal to the space phase between elements (in this case $\frac{1}{4}\lambda$ = 90 degrees) the vectors for directions normal are the wrapped up vectors for Fig. 4D (left). Thus in directions to the right the vectors unwrap themselves and just become unwrapped for a direction in line with the array, as in this direction the space phase is now equal and opposite to the time phase. To the left the vectors become more wrapped up still and produce small tails. Thus the polar diagram is biassed to such an extent that the maxima

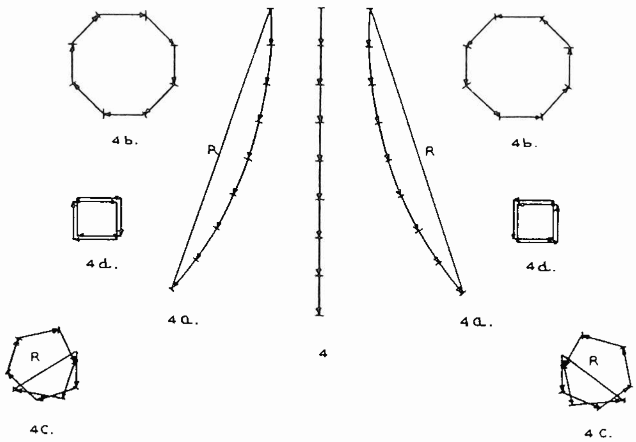


FIG. 4.

now overlap and produce a uni-directional polar curve lying along the array line shown by Fig. 5C, the maximum of this polar curve being away from the end which is leading in time phase, in this case No. 1 aerial. This result could be accomplished by using the normal tree feeder line with phasing pieces inserted, but obviously it can be most simply achieved by using a feeder line running the length of the array and feeding each aerial in turn commencing from No. 1.

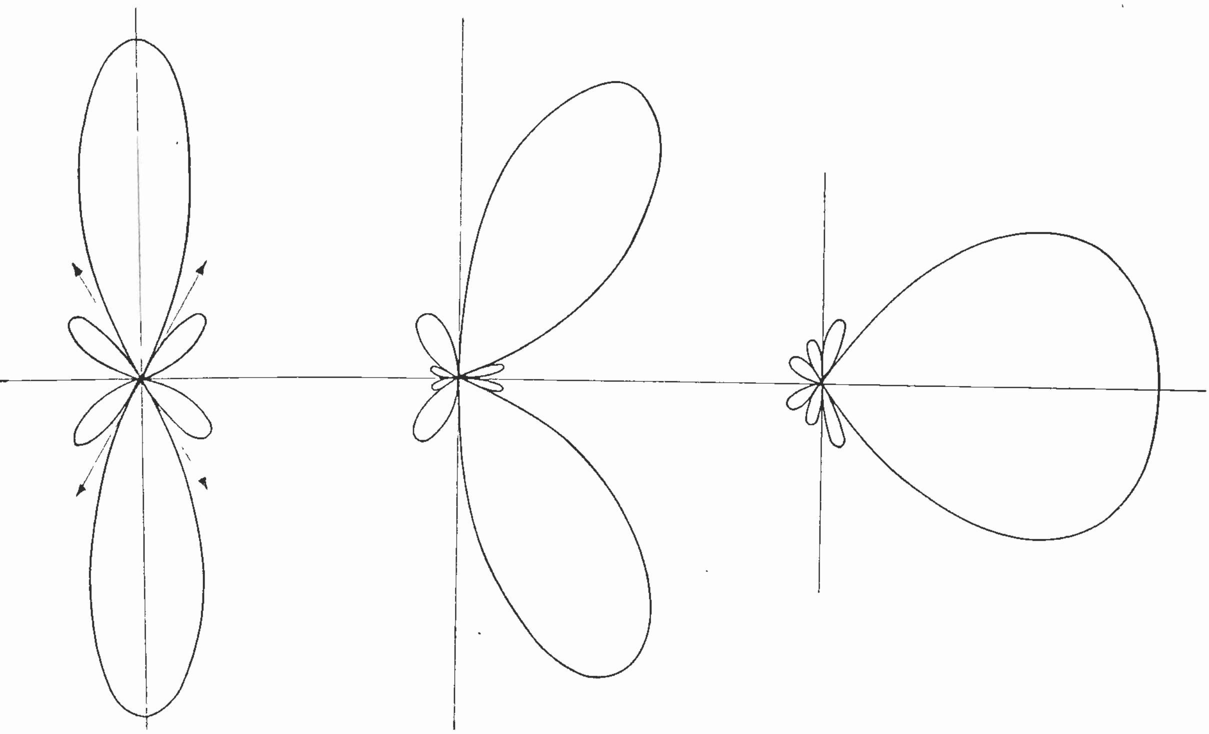
If desired we can completely reverse this polar curve by changing the time phase such that the opposite end (No. 8) is leading in time phase, say by feeding from the end No. 8 instead of No. 1. Alternatively if we still desire to feed the system from the No. 1 end, we must misphase each succeeding aerial by 360 degrees minus the space phase as this is the same as giving the next aerial a lagging current.

From a design point of view an "end-fire" array radiating away from the feed end is somewhat of an advantage if a group of arrays is built fanwise around the transmitting or receiving building, but for other reasons which we will describe later, better results are obtained when the radiation is towards the feed end.

We have considered the case of eight aerials each spaced $\frac{1}{4}\lambda$ apart. If we were to space our aerials more closely together we should obtain the same result if we altered the time phase to equal the new spacing. Thus if our aerials are arranged to be one-sixth of a wavelength apart, i.e., 60 degrees, we should need to produce a time phase between radiating elements of 60 degrees or (360 degrees + 60 degrees) to produce a maximum away from the fed end; or (360 degrees — 60 degrees) to produce a diagram with maximum towards the fed end.

It is interesting to observe that the polar curve in this case would not be materially different from that obtained with $\frac{1}{4}\lambda$ spacing.

If we consider but one more special case of time misphase when each succeeding aerial has opposite time phase, this will result in producing a bi-directional polar diagram with zero radiation normal to the array line, the vectors being shown in Fig. 6, and polar curve in Fig. 7 for the same eight elements. In this case we have reversed the direction of main radiation from the zero time phase condition, but in this case the spacing of elements is rather more important as when the elements are spaced very closely together the fields cannot add in any direction, but the radiation increases to a maximum along the line of radiators when the spacing becomes $\lambda/2$.



5A. 5B. 5C.

FIG. 5.

Thus we have the general rule for a single line of radiators that with zero and opposite time phase, or multiples thereof, bi-directional symmetrical figures are produced, the former with maxima normal, and the latter with maxima in line with the array.

Whereas if the time phase is made equal to the space phase between radiators an uni-directional polar curve is obtained with a maximum away from the feed or leading time phase end. And with a time phase equal to 360 degrees—the space phase, the polar curve is reversed and the maximum now points towards the feed or leading time phase end.

Leaving this question for the time we wish now to discuss loop radiators. Consider an earthed vertical single wire aerial. As is well known when excited from the base, a stationary wave is formed by a wave W_1, travelling up the wire and a

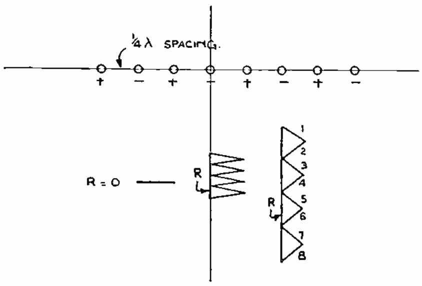


FIG. 6.

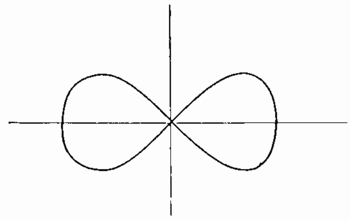


FIG. 7.

similar reflected wave W_2 travelling back. We could imagine wave W_1 travelling up the left hand edge of the wire and the same travelling wave returning down the left hand edge of the wire, and because at all intervals of time the instantaneous values of the current waves I_1 and I_2 at the top are equal but opposite in direction, they form a node of current here. At other points down the wire the instantaneous amplitude of I_1 and I_2 are not always equal and if their values are traced out in time they will be found to form a stationary wave with current antinode at the base when the wire is one-quarter wavelength long. However short or long this wire may be, a stationary wave will be formed by these two travelling waves with a node of current at the top end and current value at the bottom appropriate to the length of the wire.

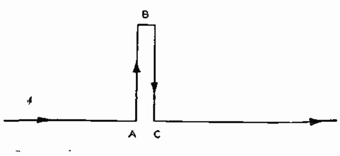


FIG. 8.

Accompanying the current stationary wave is a voltage wave in quadrature time phase with it and with an antinode at the top end.

If instead of providing a single wire we provide a loop of wire, Fig. 8, fed at the lower end, A say, this loop being part of a circuit in which a travelling wave is flowing, the wave will now travel up one wire AB and return by the second BC from which it continues on in the circuit, but provided these wires are sufficiently close together to be regarded as coincident in space from a radiation point of view, the loop may be regarded exactly as a single wire carrying a stationary wave with current node at B.*

These two travelling waves form not only a stationary wave of current with node at the top end, and if the loop is $\frac{\lambda}{4}$ or less, an antinode at the bottom end, but in quadrature time phase with the effective current stationary wave, there will be a voltage stationary wave, but with an antinode at the top end and node at the bottom end. For the voltage does not reverse in sense at the top and in consequence

* In case this simple explanation of the building of a stationary wave from a travelling wave around a loop is not sufficient, an appendix has been added which sets out the argument in greater detail.

no node is produced. At the bottom of the loop the voltages are always equal but opposite in phase. Thus an external field will be produced although there will be a strong field between the wires.

If therefore we have a long wire carrying a travelling wave of whatever frequency, such as would be found in any feeder system terminated by its correct characteristic resistance, we may state that if we fold any part of this wire into a narrow loop with coincident sides, we may regard the travelling wave around this loop, *no matter what its length,* as carrying a stationary wave radiating system ; with this difference, that the radiation resistance of the loop will be four times the radiation resistance of a single wire for the same base current measurement in each case. This is obvious, because a meter placed at the base of one limb of the loop is measuring current in one limb only, and this is half the effective stationary wave current at the base, as the currents add at this point. This means virtually that the effective height of the radiation portion of such a system is high and in consequence the radiation efficiency. For this reason an array built with loop radiators is equally suitable both for transmission and for reception purposes. We stress this point as one is inclined to consider the performance of an array is adequately expressed by its gain or directivity, but obviously in addition to directivity the effective height or coupling to the ether is equally important when considering the transmission problem. It is not so important in the case of the receiving system because we can follow the array up by a high gain receiver.

Since the metre amperes of an earthed wire do not change materially between $\lambda/4$ and smaller loops, the length of the loop radiator is not vastly important from a radiation efficiency point of view, for loops values below $\lambda/4$, and as will be seen shortly the loop dimension is determined largely by how it has to act as a phasing device.

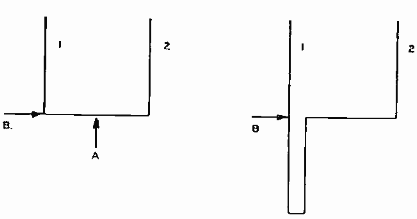


FIG. 9.

(A) (B)

Consider Fig. 9A, which shows two radiators 1 and 2 spaced one quarter wavelength apart and connected by a feeder line. If this system is fed from a point A, halfway between the aerials, zero time phase is supplied to both aerials, but if we move the feed point to B, this automatically creates a time phase difference between 1 and 2 equal to the space phase between them assuming the radiated wave travels to the right at the same velocity as the current along the feeder. In this case maximum directivity is away from the feed point B as has been explained.

Still keeping the feed input at B we can reverse the diagram by looping the feeder to give aerial 2 a lagging current of 90 degrees. To do this the feeder length can be increased as shown in Fig. 9B, such that it equals (360 degrees—90 degrees) or $\frac{3}{4}\lambda$. If we design the loop to have $\frac{1}{4}\lambda$ sides as shown, this loop together with the straight portion of $\frac{1}{4}\lambda$ makes up the $\frac{3}{4}\lambda$, and as we have seen, if the sides of the loop are coincident in space, the loop itself will act as a radiator ; in consequence we can use it not only as a phasing feeder to aerial No. 2 but to replace aerial 1. In a similar way the whole line of radiators can be replaced by loops, whose lengths are made correct to produce the required phasing between the radiating elements. This is the usual series phase array design which therefore has maximum directivity from its fed end, and it is clear that with this particular spacing we could not *reduce* the dimensions of the loops sufficiently to reverse the diagram, i.e., by producing a time phase equal to the space phase as the loops would then have zero dimensions.

But we can obtain this reversal by *increasing* the loop still more, namely to $\frac{\lambda}{2}$ as in this case the total feed length is then $1\frac{1}{4}\lambda$, and this gives the required time phase.

Considering $\frac{1}{4}\lambda$ loops with $\frac{1}{4}\lambda$ spacing, theoretical polar diagrams for 2, 4, 8 and 16 loops are shown in Fig. 10, these diagrams being sections of three dimensional figures having a similar section in all planes. An array placed close to a perfectly conducting earth will have a diagram represented by half these figures, i.e., the axis of the polar curves represents the earth plane, whereas on short wavelengths due to the bad conducting properties of the earth, the diagrams will be modified by a reduction of field amplitude at and near the horizontal plane by an amount appropriate to the particular earth conditions considered.

So far the argument has assumed the horizontal wires act merely as feed connecting wires and contribute nothing to radiation, further that a uniform current distribution throughout the system is obtained, and that the velocity of the wave along the aerial is the same as that of the radiated wave in space.

Dealing first with the horizontal wires these do not materially affect the radiation from the system as if a succession of waves be plotted out they will be found to form the equivalent of a travelling wave on a long straight wire and radiation from such a wire is negligible. What radiation there is will be along the direction of the wire.

The assumption of a uniform current distribution is more serious. In practice the current distribution depends on the radiation efficiency of the loops, and with an accurately tuned array of normal design there is a fall of current along the array such that the value at the 16th loop may be not less than one-tenth that in the first. This would appear to suggest that diagrams based on a uniform current distribution are too removed from reality to be justified, but actually the difference is small, and chiefly affects minima, and the amplitude of back radiation.

This can be seen by considering the vector diagram of an array with tapering current. Thus Fig. 11 shows the vector diagrams for an array in which the decrement is .125. The total vector length has been made the same as the previous Fig. 4, and it is clear that whereas there is practically no difference between the vector diagrams for small angles near the maximum, the vector diagram with attenuation instead of wrapping up completely, takes a spiral convolution. This means that although there is small difference in the shape of the main figure at no time is a complete minimum produced. Contrariwise however the smaller tails produced are not so much in evidence and since the back and side amplitudes are so low anyway compared with the main loop, the effect of the attenuated current along the array is invariably small, the dotted curve in Fig. 10 showing the polar diagram for an 8 loop array with tapering current as above. This can be compared with the full curve for the same 8 loops with uniform current.

The fact that there is not a uniform current is, of course, a good feature, as it shows the efficiency of the system as a radiator. An array fed from a single point in which uniform travelling current flows is not only bad from a radiation point of view ; but since it is terminated by a resistance equal to its characteristic resistance means that a large amount of the total power will be dissipated in the termination.

Regarding the fact that the velocity of current along the feeder is different from that of the wave in free space, this is so but can be allowed for by reducing the dimensions of the array. Actually array dimensions are reduced by quite a fair percentage, but for other reasons ; first to sharpen up the diagram and secondly to control the attenuation along the array a 5 per cent. reduction is made for arrays above 30 metres, 10 per cent. for arrays below 30 metres, and on ultra short waves the reduction may be even more than this.

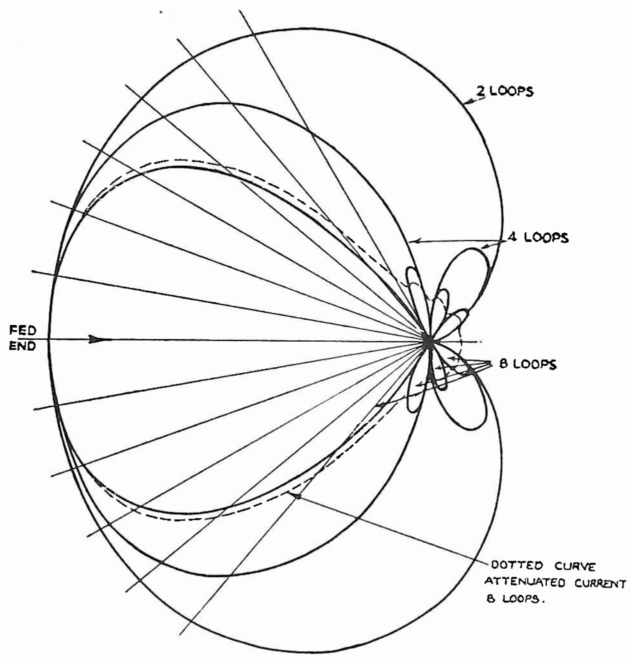


FIG. 10.

Considering Fig. 12, which shows a diagram for 16 $\frac{1}{4}\lambda$ loops with attenuated current, if we reduce the dimensions of the loops by 10 per cent. we obtain a diagram as shown in Fig. 13, whereas if we increase the dimensions 10 per cent. we obtain the two wing type of diagram shown in Fig. 14. It is easy to see why the diagram alters in this way if we refer back to Fig. 5c. This shows that the "end-fire" polar curves can be imagined to be made by the overlapping of the two main loops of a bi-symmetrical diagram coming together. When the misphase is not sufficient to add to the space phase, i.e., on wavelengths shorter than the spacing, the two loops have not yet reached the overlap condition and the wing type figure is produced. Whereas when the misphase is made greater than the space phase they have more than overlapped and their steep sides are now coming together and so produce a sharp pointed polar curve, but at the expense of greater back and side radiation, and we cannot carry this mistuning too far. As mentioned above, the other advantage in misphasing is that because the array is detuned, the current attenuation per loop is less and we thereby can control the current distribution. Instead of detuning each loop the same amount we can control the current value best by varying the dimensions of each loop, detuning the first most and each succeeding loop less and less.

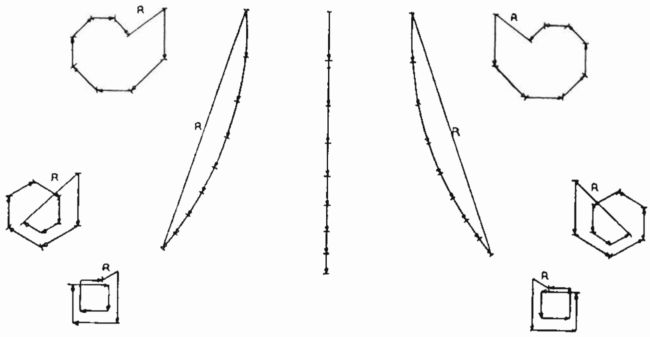


FIG. 11.

Measured gains with series phase arrays having loop sizes similar to those we have been discussing compare favourably with other types of arrays, and where it is desired to increase the directivity, arrays can very easily be paralleled, the table below giving typical figures for array lines of different dimensions.

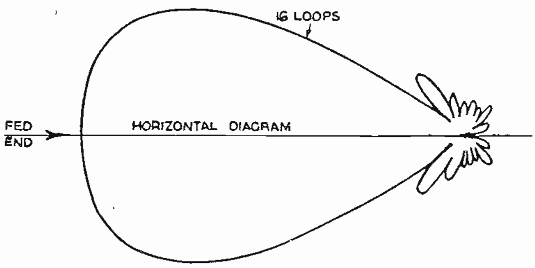


FIG. 12.

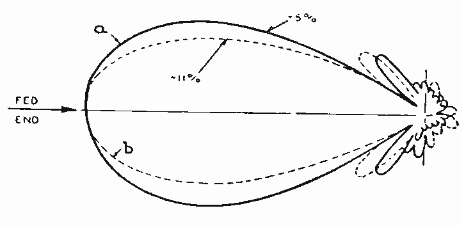


FIG. 13.

4 Wavelength Array.	Gain over half wave aerial under perfect conditions.	Dimensions of equivalent Broadside Array with reflector.
Single	10	1.25 wide, 1 high
2 parallel	14	3.3 wide, 1 high
4 parallel	18	7.5 wide, 1 high

One interesting point in connection with "end-fire" arrays generally is that practical experience with them has led to the suggestion that the transmitting and receiving systems are not strictly reversible. This has resulted in the building of larger arrays for transmission than for reception. That is to say whereas a 16 element transmitting array is used, similar arrays acting at a receiving station have been found to be less effective and for this reason receiving arrays of the series phase type are usually kept down in length to 10 or 12 loops.

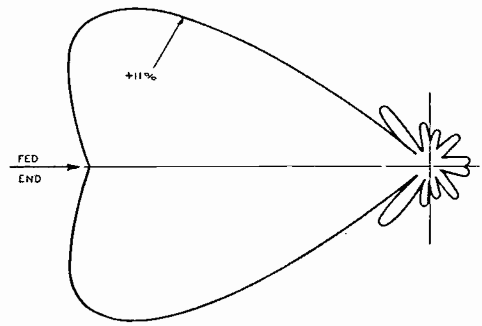


FIG. 14.

The reason for this is explained in the following way. In the case of an array used for transmission, the phase of current in the various loops is fixed by the array dimensions and in consequence the space field resulting is quite defined, and radiation from the system determined by the interference pattern produced.

Whereas in the case of a receiving array, the final current delivered is dependent on the phases of E.M.F.'s set up in the loops, and this in turn depends on the type of ray being received. When conditions are good and only one ray is being received, the phases are correct to ensure full gain, but during fading when a group of rays is being received, since their phases are indeterminate, the array gain may be reduced. It is to be remembered that with an "end-fire" array, its dimensions are in the direction of propagation, not at right angles as in the case of a broadside array, and because of this we are not dealing at any one time with a resultant ray at a common point on the wavefront in space, but with rays at a number of points in space.

Personally the author is not convinced that a full case has yet been made out for non-reversibility, and one can put forward an alternative argument to oppose this theory as follows :—

The protagonists of this non-reversibility theorem suggest that because the phase of currents in a transmitting series phase array are fixed by the array dimensions, the space field resulting is clearly defined, but is this a fair argument? Is it not more correct to consider that radiation is emanating from a number of points in space along the line of propagation and that the resulting field depends upon the interference pattern produced. We would suggest that from a transmitting array because the radiation emanates from a group of points in space along the line of propagation, the probability of fading is very greatly increased because of the space disposition of these radiating elements over an array system of the broadside type.

Before concluding we would like to set out one example showing the extreme flexibility of this folded wire aerial, and the simple manner by which its dimensions may be adapted to produce a variety of diagrams.

Let us choose any convenient spacing for the elements of the array, say one-sixth $\lambda = 60$ degrees. As has been shown previously, we can by adjusting the time phase of feed to the elements produce at will bi-directional or uni-directional diagrams as set out in the table below.

	Time Phase between Radiators.	Directivity.
(1)	0 degrees, 360 degrees, etc. ..	Bi-directional normal.
(2)	180 degrees, 540 degrees, etc. ..	,, "end-fire."
(3)	Equal to space phase feed and leading, 360 degrees+60 degrees	Uni-directional array from feed end.
(4)	Equal in space phase feed and lagging, 360 degrees—60 degrees	Uni-directional toward feed end.

Since we have selected a spacing of one-sixth λ, this sets the space phase as 60 degrees between elements, and we can therefore determine the total length of feed between input of any loop to the next. These total lengths are shown in Column 2, Table No. 2, and subtracting 60 degrees from each of these figures we obtain the total length of loop needed shown in Column 3, half this length being the equivalent stationary wave aerial length, shown in Column 4, from which we can see the effective stationary wave system operative.

	Space Phase also Horizontal Feeder. Degrees.	Time Phase also Total Feeder. Degrees.	Total Length of Loop Wire. Degrees.	Radiation.	Directivity.
(1)	60	360	300	$150=\frac{5}{12}\lambda$	Bi-directional normal.
(2)	60	180	120	$60=\frac{1}{6}\lambda$	Bi-directional "End-fire."
(3)	60	360+60	360	$180=\frac{1}{2}\lambda$	Uni-directional away from feed end.
(4)	60	360+60	240	$120=\frac{1}{3}\lambda$	Uni-directional toward feed end.

Observe that to obtain a uni-directional diagram away from the feed end we again require half wavelength loops, and a moment's consideration reveals the interesting fact that half wavelength loops spaced any distance apart whatever theoretically will produce this type of diagram.

APPENDIX.

The Series Phase Array.

It was stated in the main paper that the effect of a current wave travelling around a looped wire was the same as would be produced by two waves of equal amplitudes travelling in opposite directions, namely, to produce a stationary wave of current with node at the looped end. This can be shown in the present loop example quite simply by considering the current values in the two limbs of the loop ABC, Fig. 15, at different intervals of time, Fig. A, B, C, D and E, showing the total distribution of current along this loop at one-eighth cycle intervals of time.

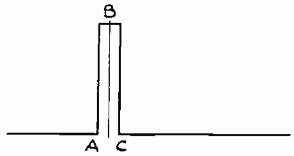


FIG. 15

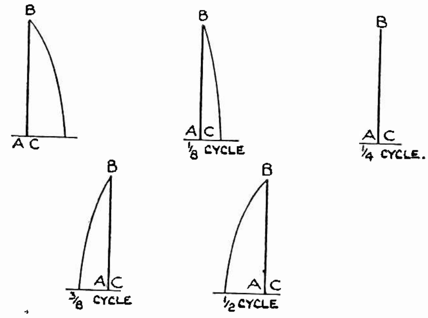


FIG. 17.

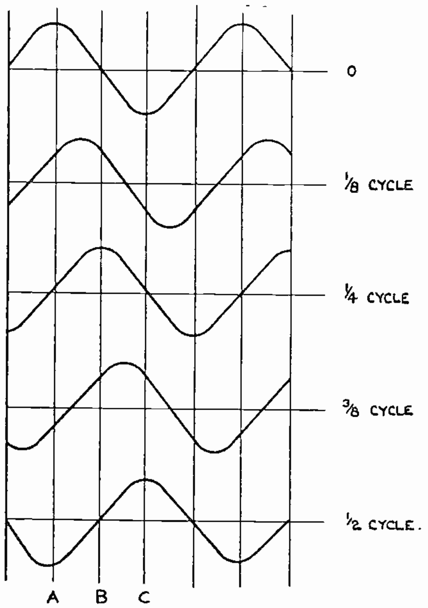


FIG. 16.

If we consider the vertical elements, AB BC, then they are so near together that they may be considered as one from the radiation point of view. Thus the current at any point up this radiator will be proportional to the vector *difference* between the current in AB and BC at the given point, the difference being taken because the current is flowing in opposite directions.

These differences are shown in Fig. 17 being built up from those of Fig. 16 by combining the current along AB with that along BC (*reversed*) as explained.

The radiation at B must always be zero, since here there are effectively two equal currents at all times flowing in opposite directions, and thus this point is an effective current node. But at points below B the currents will be found to add to a resultant which when plotted out form an equivalent stationary wave.

A. W. LADNER.

MARCONI ULTRA SHORT WAVE FIELD STRENGTH MEASURING EQUIPMENT

The increasing use of wavelengths in the ultra short wave band has created the necessity for apparatus capable of field measurement within this band.

As far as is known all existing types of apparatus employed for ultra short wave field strength measurement make use of the method of calibrating a receiver against the calculated field strength at a given distance from a source of known radiated power. In these systems the receiver attenuation is effected at an intermediate frequency.

The design of apparatus embodying facilities for signal frequency attenuation, such as that employed in the apparatus to be described, involved much preliminary research and experimental work, but this has been amply justified in that it has led to the production of an entirely self-checking field strength measuring equipment, the performance of which is independent of frequency and location, is extremely simple to operate and is almost direct reading.

General Description.

IN designing their ultra short wave field strength measuring equipment the Marconi Company realised that the greatest degree of portability consistent with theoretical and operational requirements was essential. The illustration in Fig. 1, in which apparatus is shown ready for operation with a loop type aerial, portrays the measure of success with which this object has been achieved. The supporting tripod stand is fitted with a swivel head which enables the whole receiver to be rotated through 360 degrees, thereby providing any required orientation of the aerial. A degree scale and scale index are fitted to the tripod head. The loop aerial is interchangeable with a dipole aerial over the higher frequency band down to a limit of 35 megacycles. The dipole aerial is capable of rotation in both vertical and horizontal planes.

A useful feature of the equipment is that under proper operating conditions cross check field strength measurements between the loop and dipole aerials agree to within + or — 1 dB. at any frequency.

The instrument is almost direct reading by virtue of the field strength table attached to the panel of the receiver. This table relates the standard local signal to 1 micro-volt per metre for any frequency and for any standard aerial arrangement. To arrive at the field strength figure required it is only necessary to observe the difference between the external signal attenuation and the standard local signal attenuation and then to read off the table the field strength corresponding to this difference in decibels.

The full frequency range of the equipment is from 100 megacycles to 20 megacycles, whilst the voltage range is from two or three microvolts per metre to a maximum of 1 volt per metre. This measuring range is deemed adequate for all normal aerial and transmission studies in the ultra short wave field.

Referring to Fig. 1, the aerial tuning control is seen projecting below the aerial arm unit. The signal frequency circuits, which embody a push-pull frequency changer, are symmetrical and are contained within the aerial end of the screening tube, as also are the arrangements for the injection of the local substitution signal into the aerial circuit. All circuits are easy of access. The remote thumb operated frequency changer tuning control is seen at the side of the aerial arm near to the main case of the receiver. The aerial arm is detachable from the receiver through a plug and socket arrangement.

The main instrument case carries the change frequency and local substitution signal oscillators, the substitution signal attenuator, the intermediate frequency

FIG. 1.

amplifier and attenuator, output detector, checking controls, meters and supply batteries. All controls are located on the front of the instrument.

The respective outputs from the oscillators are fed to the frequency changers and the aerial over independent concentric feeder systems running along inside the aerial arm. Intermediate frequency output from the frequency changers is carried to the amplifier over a spaced feeder line—also located within the aerial arm.

Three loop aerials and three frequency changer ranges are necessary for the full frequency range of the equipment. Five separate lengths of aerial are provided for the dipole to cover all frequencies down to 35 megacycles. The ranging of the oscillators is switch controlled throughout the frequency band of the instrument. The oscillator controls provide a very wide range of frequency discrimination, each giving an equivalent scale length of approximately five feet for each range. Tuning operations even at the highest frequencies are thus rendered comparatively simple.

The radio frequency or local substitution signal voltage attenuator is of a capacitative type and provides an attenuation range of 80 dB. at all frequencies. The frequency change of the local oscillator with change of attenuator setting is very small. Radio frequency current is measured by a thermo-couple located at the output side of the R.F. attenuator. The thermo-couple should have a very long "life" as it is impossible to load it up to its normal maximum load. A total gain of approximately 110 decibels is given by the four stages of pentode amplification with which the intermediate frequency amplifier is equipped. The frequency of this amplifier is 3,000 kilocycles with a band width of approximately 90 kilocycles. The output stage is a diode detector working into a load of 10,000 ohms and providing a very nearly linear output range of 16 dBs.

The output may be modulated at a frequency of 400 cycles if desired through the operation of a panel switch. This modulation is imposed on the carrier by electron coupling in one of the early stages of the intermediate frequency amplifier.

A calibrated attenuator with a total range of 100 decibels and variable in steps of 1 dB. is included in the I.F. amplifier circuit. This unit provides a useful alternative to the use of the radio frequency attenuator for field strength measuring purposes and incidentally supplies a check on the proper functioning of the latter.

With the exception of the radio frequency oscillators all the valves employed in the equipment are of the acorn type. The R.F. oscillators employ valves of a standard two-volt type. All supply circuits can be checked through a meter and selector switch.

Internal batteries are used for all supply voltages.

Brief Technical Description.

The equipment employs the substitution signal method of operation for field strength measurement. By this method the signal under observation is temporarily removed from the aerial, by orientation, and substituted by a signal of equal frequency and magnitude supplied from a local source. The magnitude of the locally substituted signal is derived directly from the constants of the control circuits. Examination of the circuit diagram shown in Fig. 2 will illustrate the method of applying the local substitution signal to the aerial circuit. The aerial circuit embraces two resistances (R_1 and R_2) (independent of frequency), of very low value, disposed symmetrically about the point of lowest potential, i.e., immediately below the receiver input coupling. The local signal voltage is applied across one of these resistance elements (R_1).

Referring to Fig. 2, it will be observed that when the dipole aerial is in use the resistance (R_1) employed for injecting the local signal is included in one dipole arm only. It can be practically demonstrated and also be proved theoretically that this arrangement will only produce equal currents in the dipole arms at or near to the resonant half-wave condition.

The ratio of the currents in the energised and coupled dipole arms for any total dipole length at any frequency is shown in Fig. 3. An outside signal source will, of course, produce equal currents in the dipole arms irrespective of the dipole length up to a half wave. It follows, therefore, that for field strength measurement purposes this equipment must either employ half-wave dipoles or apply a suitable correction when other lengths of dipole are used. In actual practice a series of dipole aerials of fixed lengths are used to cover the frequency band. Each of these dipoles covers a limited frequency band on each side of its resonant point and a small correction is applied when they are used off resonance. These corrections are accounted for in the field strength tables which are attached to the panel of the instrument and therefore do not involve reference to charts.

The coupling between the aerial circuit and input grid circuit of the push-pull frequency changers is carefully balanced to minimise the effects of vertical components induced in the aerial. Stray shunt capacities to "earth" at this point must be maintained at a minimum or serious inaccuracies in the measurement of field strength may result. These errors are referred to later in the paper.

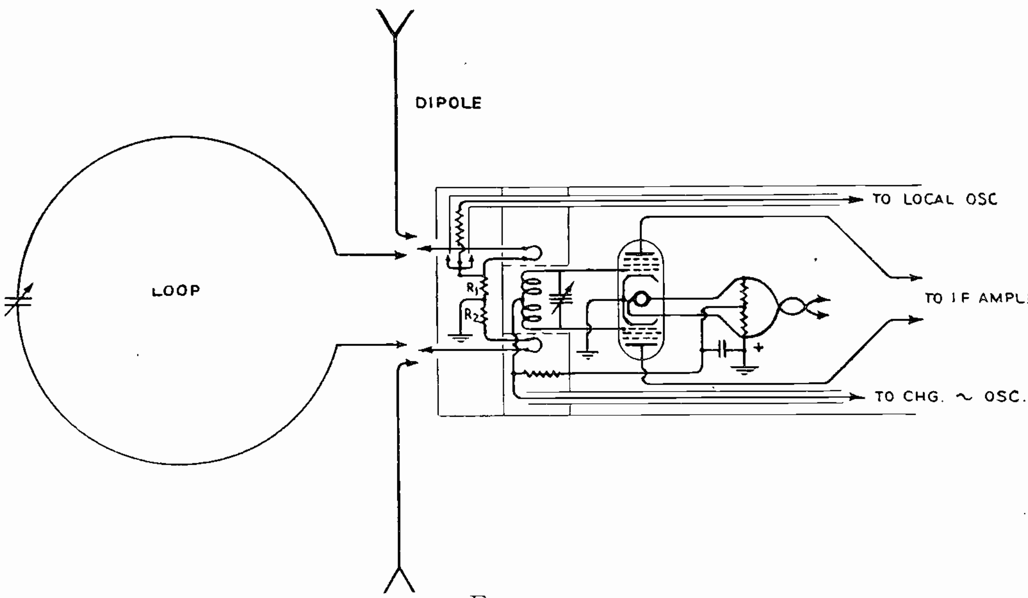


FIG. 2.

The change frequency oscillator voltage is applied to the centre point of the grid inductance of the frequency changers and a spaced wire feeder line carries the 3 Mcs. output from these valves to the I.F. amplifying unit.

Effective Height of Aerials.

The theoretical value for the effective height of a loop aerial is given by the formula 2π NA/λ. The application of this formula to loop aerials employed by the Marconi U.S.W. field strength measuring equipment has been confirmed by a series of carefully effected check measurements.

As a preliminary step in this connection a number of comparative field strength measurements were made employing the Ultra Short Wave and the Marconi Type 476 equipments at frequencies normally common to the ranges of both instruments. The agreement between the instruments was to within 2 dBs. A series of measurements was then made at each of several frequencies spread over the full range of the Ultra Short Wave instrument and employing a number of loop aerials possessing the widest possible area differences. The results proved that the sensitivity ratios of the various loops were proportional to their respective calculated effective height ratios.

The theoretical effective height of a dipole aerial increases from 0.5L to 0.64L when L becomes λ/2. The application of this theoretical value to the dipole aerials employed on the equipment has been checked and confirmed in the following way. A theoretical curve was prepared, using calculated values for effective height, showing the voltage required to be symmetrically injected into the aerial for any dipole length to balance a signal of known field strength. The field strength of the signal source was measured on the appropriate loop aerial. A series of test measurements of the known signal and using dipoles of various lengths was then made and the balancing voltage in each case compared with the relative value shown in the theoretical curve. Similar tests were made later at ground level in which, allowing for

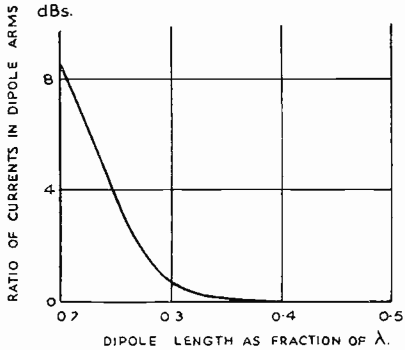


FIG. 3.

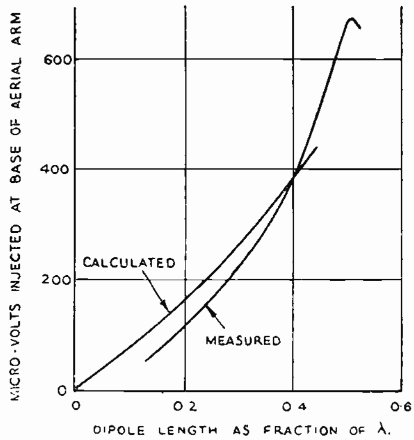


FIG. 4.

the slight unbalance which the ground produces in a vertical dipole, the results were practically identical. The results obtained in the elevated tests are reproduced in Fig. 4, from which it will be observed that the theoretical and measured curves coincide at a dipole length of 0.4λ, which, including the coupling inductance at the aerial centre, is the half-wave resonant condition. This result is what was to be expected in view of the earlier observations regarding the method of injecting the local balancing voltage into the dipole aerial, and confirms the fact that the theoretical value for the effective height of a dipole aerial is applicable to the equipment for the resonant condition.

Performance Checks.

No effort has been spared to ensure the greatest possible accuracy of field strength measurement with the equipment. A great deal of care has been taken in checking the equipment at all parts of the frequency band. The performance of components upon which the accuracy of measurement must depend required detailed investigation. The results of some of the experimental work in this direction in connection with thermo-couples and resistance elements of the types employed in this equipment were published in a previous number of this journal.* The following further possible sources of error have each been investigated and checked :—

(1) Reference was made earlier to possible discrepancies due to stray shunt capacities to " earth " at the receiver coupling, i.e., at the base of the aerial. Shunt

* " Ultra Short Wave Standard Signal Generator," MARCONI REVIEW, No. 61.

capacities at this point would, if of sufficient magnitude, disturb the current distribution around the aerial circuit in such a manner that the voltage induced by the local signal source would not bear the proper relationship to the voltage induced in the aerial by the external signal. Ideally, of course, the circulating current should be equal in every branch of the loop aerial circuit.

The design of the instrument is such that the stray shunt capacities at the aerial base are at the barest possible minimum, but in view of the extremely high frequencies involved assurance was needed that its actual magnitude is not such as would introduce appreciable inaccuracies of measurement. The distributed stray shunt capacities were therefore accurately measured. It was then ascertained through a series of measurements of a field from a constant source (during which the stray shunt capacities were (1) experimentally reduced ; (2) normally included ; and (3) artificially increased by various known amounts) that any error of field strength measurement due to the presence of stray shunt capacities at normal circuit conditions is only of the order of one or two per cent. even at the highest frequencies.

(2) It was further necessary to determine to what extent; if any, the presence of the receiving equipment in the vicinity of the aerial might invalidate field strength measurements. With this possibility in mind the equipment was so designed that its physical dimensions would be as small as possible consistent with considerations of practical operation and to be disposed symmetrically with respect to the aerial. A glance at Fig. 1 will show that if the apparatus is operated at a suitable distance above ground level it is possible for three independent unwanted forces to act upon the aerial due to :

(A) A horizontal force acting along the length of the equipment.

(B) A force due to currents circulating around the periphery of the aerial arm acting as a small loop in the same plane as the loop aerial. (Such a force would be expected to show the greatest effect at the higher frequencies where the loop dimensions become small.)

(C) A similar force to (B) acting around the receiver case.

The symmetrical arrangement of the components should dispose of (A), for the effects of any such force will be self-cancelling in the loop aerial. Proof that this is so was forthcoming from tests in which the aerial feeder arm and receiver were experimentally extended in line in each direction up to half-wave conditions at several frequencies. No observable effect was produced on the aerial voltage for any unit of the horizontal extensions.

With regard to (B) tests at the higher frequencies show either that if such a force exists its magnitude is too small to have any effect on the loop or that the coupling between the loop and the periphery of the tube is zero. The actual tests consisted of presenting a closed loop, of dimensions approximating to those of the tube, at various degrees of coupling to the loop aerial. A comparatively tight coupling was required to produce appreciable effect and when located at a position relative to the loop similar to that of the aerial arm no observable effect could be produced.

Finally, with regard to (C), the relative positions of the receiver case and the loop aerial are such that the effect on the loop of induced circulating currents around the receiver case are negligible. Simple tests were sufficient to prove that the distance between the loop and the case is considerably greater than that at which unwanted effects due to such currents would be produced.

Considering the possible effects produced in the dipole aerial by the forces indicated at (A), (B) and (C) the symmetry of the aerial with respect to the rest of the equipment is again the safety factor.

In case (A) any force acting along the length of the equipment should, ideally, be equally coupled to each of the dipole aerial arms. Then any voltage so induced into the aerial arms will be in phase opposition and therefore self-cancelling. The equipment in its normal operating state provides a ready means by which this condition can be checked. Suppose the receiver be tuned to an outside signal source from which a horizontally polarised component is arriving, then with the dipole set in the vertical position no variation of signal output should occur throughout a 360 degrees rotation of the equipment in the horizontal plane. This presupposes balanced coupling between the aerial and the equipment. In actual practice at ground level the balance is disturbed by the presence of the ground and possibly also by the presence of the operator in the vicinity of the aerial. As, however, the distance above ground level is increased the unbalance becomes progressively smaller. A particular test at ground level produced a signal output variation of 3 dBs. through a complete rotation of the equipment, whilst a similar test at the same frequency but at an elevation of 9.3 metres the variation was only 0.5 dB. To minimise errors in practical measurements at ground level or in disturbed areas the substitution signal is matched against the mean external signal deflection.

With regard to cases (B) and (C) in relation to the use of dipole aerials the symmetrical disposition of the aerial and instrument with regard to each other rules out the possibility of the existence of any coupling between them.

Accuracy.

It is confidently considered that the overall instrumental accuracy with which the equipment is capable of measuring field strengths is to within + or — 1 dB. at a frequency of 20 megacycles varying to within + or — 2.5 dBs. at a frequency of 100 megacycles. Consistency of measurement will, however, depend to a very large extent upon location. The greatest consistency will naturally follow from observations made on clear and open sites, and in the case of the dipole aerials at the lower frequencies an elevated position is to be preferred. On a poor site screening and re-radiation from resonant structures will give rise to field distortion and consequent measurement variation. Cases have been encountered when a combination of disturbing forces have produced three quite good minima on the loop aerial. An aeroplane, though hardly visible in the distance, may produce quite rapid variations in field strength, whilst a flight of planes directly overhead has been observed to produce signal variations of over 20 dBs.

Additional Features.

The readiness with which the equipment can be transported and set up facilitates rapid service area exploration.

The stability of the whole receiving equipment is useful for the observation of fading and transient effects over extended periods of time.

The ability to direct the loop aerial renders the instrument useful as a direction indicator and the facilities for rotating the dipole aerial provide means for determining the polarisation of incoming rays.

F. M. WRIGHT.

THE CALCULATION OF INPUT, OR SENDING-END IMPEDANCE OF FEEDERS AND CABLES TERMINATED BY COMPLEX LOADS

In THE MARCONI REVIEW *for January-February, a chart for calculation of input impedance was given, together with a number of worked examples of use.*

In what follows three further examples of use are given, which in themselves show how wide the application of the chart is.

There follows a discussion of the fundamental principles of the chart, and an explanation of the formulæ used in its preparation, together with their proofs.

(G) Band Pass Filter.

Let it be required to find the input impedance Z, of the filter at a point in the pass band defined by $\frac{f}{f_r} = 1.15$, where $2f_r = \frac{1}{\pi\sqrt{(LC)}}$. (Fig. 1.)

The pass band lies between $\frac{f}{f_r} = 1$ and $\frac{f}{f_r} = 1.182$. The filter has been designed to have an iterative impedance of $Z_i = 100$ ohms to match a pure resistance load $R = 100$ ohms, at the middle of the pass band (i.e. at $\frac{f}{f_r} = 1.09$).

At $\frac{f}{f_r} = 1.15$ the iterative impedance, $Z_i = 73.2$ ohms. The open circuit impedance, $Z_d = j\,59.2 = 59.2\ \underline{/90^\circ}$. The attenuation in the pass band is zero for pure reactance elements.

The " Electrical length " of the filter is first found

$$\frac{Z_i}{Z_d} = \frac{73.2}{59.2\ \underline{/90^\circ}} = 1.235\ \overline{\backslash 90^\circ}$$

By the chart, for $r = 1.235$ and $\phi = -90^\circ$, we have

$$l = 1.434 \text{ quarter-waves.}$$

Now proceed as in all other cases :—

$$r = \left|\frac{R}{Z_i}\right| = \frac{100}{73.2} = 1.365$$
$$\phi = 0$$
$$l = 1.434 \text{ quarter-waves.}$$

By the chart measure 14.34 large squares to the right from the point $r = 1.365$, $\phi = 0$, and read off,

$$r = 0.941 \text{ and } \phi = +17.1^\circ$$

from which the input impedance

$$Z = r.Z_i\ \underline{/\phi} = 0.941 \times 73.2\ \underline{/17.1^\circ} = 68.9\ \underline{/17.1^\circ}$$

(H) General Case, where $\phi > 90^{\circ}$ or $< -90^{\circ}$.

Suppose in a certain case we had $Z_a = (8.68 - j\,49.2) = 50\,\overline{\backslash 80^{\circ}}$ and $Z_o = 100\,\underline{/55^{\circ}}$ so that $r\,\underline{/\phi} = \dfrac{Z_a}{Z_o} = 0.5\,\overline{\backslash 135^{\circ}}$. The question arises, how are we to deal

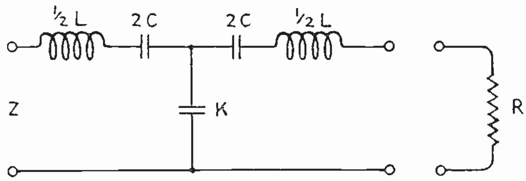


FIG. 1.

with the angle $\overline{\backslash 135^{\circ}}$ which is numerically greater than 90°, seeing that the chart is computed only for angles between —90° and 0, and 0 and +90° ?

In this case we subtract the numerical value of the angle from 180° and use the remainder (after prefixing the sign of the original angle) for the chart in the ordinary way.

Thus in our problem above, we have

$r = 0.5$

$\phi = -45^{\circ}$

Enter the chart with these values and proceed in the ordinary way with the rest of the problem.

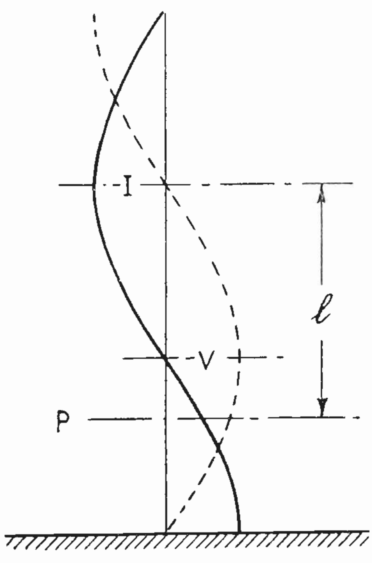


FIG. 2.

(I) To Determine Input Impedance of Transmitting Aerials.

The chart may be used to calculate the impedance Z, from any point P, of a vertical, or flat top aerial, of the type shown in Figs. 2 and 3. The calculations depend upon the validity of the assumption that the radiation resistance may be regarded as located at the current antinode. This assumption is made use of extensively in practice, and may be regarded for practical purposes as valid for aerials of the type shown here. l may have any value between 0 and 2 quarter-waves.

If, as is generally assumed in practice, the distributed losses in the aerial are negligible, then all that is required to be known initially is the value of each of the following :—

Radiation resistance, R_r (ohms).

Surge Impedance, Z_o (ohms and degrees).

" Tail " length, l (quarter-waves).

From R_r and Z_o find $r\,\underline{/\phi} = \dfrac{R_r}{Z_o}$, then entering the chart at r, ϕ, measure to the right l quarter-waves, and emerge with some new value of r and ϕ, say, r_1 and ϕ_1. Then the input impedance is

$$Z = r_1 . \ |Z_o| \ \underline{/\phi_1 + \phi_o}$$

Example : Find the input impedance of a flat-topped "T" aerial designed to transmit on 260 metres wavelength. The length of each arm of the "T" is 65 metres. The vertical height of the radiating portion is 36.3 metres. The radiation resistance $R_r = 36$ ohms, and the surge impedance, $Z_o = 150$ ohms. (Fig. 3.)

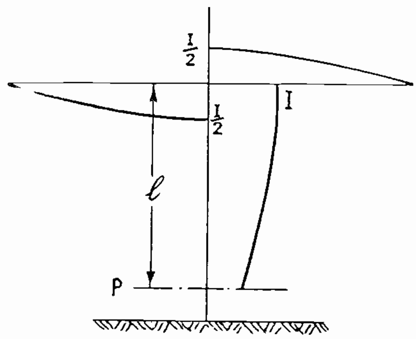


FIG. 3.

From the given data the flat top arms carry one quarter wavelength,* hence the required electrical length, l, of the tail is the same as the vertical height. That is $l = \dfrac{36.3}{65} = 0.559$ quarter-wave. Also $r\,\underline{/\phi} = \dfrac{36}{150} = 0.24\,\underline{/0°}$

Therefore, $r = 0.24$,
$\phi = 0°$
$l = 0.559$

Then by the chart,

$$r_1 = 1.165, \quad \phi_1 = +\,62.8°$$

Therefore input impedance of aerial at point P is,

$$Z = r_1 \ |Z_o| \ \underline{/\phi_1 + \phi_o} = 1.165 \times 150 \ \underline{/62.8°}$$
$$= 174.8 \ \underline{/62.8°}$$
$$= 80 + j\,155.5$$

(Note.—It is usual to add earth-plate resistance to this.)

Principle of the Chart.

The chart originated in the need for a graphical representation of the function.

$$Z = Z_o \cdot \frac{Z_o \sinh \theta_o + Z_a \cosh \theta_o}{Z_o \cosh \theta_o + Z_a \sinh \theta_o} \quad \ldots \quad (1)$$

which expresses the input or sending-end impedance of a feeder or cable of line-angle θ_o, and characteristic impedance Z_o, terminated by an impedance Z_a.

Z, Z_o, Z_a and θ_o are all vectors in the general case; therefore there are eight variables, six of which are independent and two dependent, in the usual type of problem.

The above form of the function is reducible to one in which there are only six variables,

$$\frac{Z}{Z_o} = \frac{\sinh \theta_o + \dfrac{Z_a}{Z_o} \cosh \theta_o}{\cosh \theta_o + \dfrac{Z_a}{Z_o} \sinh \theta_o} \quad \ldots \quad (2)$$

* The effect of contraction of wavelength which occurs with waves on aerials as compared with wavelength in free space has been purposely neglected here to keep the example clear of non-essentials.

The effect should be taken into account, however, in practical computations.

In a given problem of the type for which the chart was produced, there would be four independent, and two dependent variables ; namely, the two vector components of $\frac{Z_a}{Z_o}$ and the two vector components of θ_o as independent, and the two vector components of $\frac{Z}{Z_o}$ as the dependent variables.

The number of variables cannot be further reduced in the general case.

Now it seems obvious that it is impossible to construct a system in two dimensions, such as a plane chart, to contain six variables which it would also be possible to read directly.

The maximum possible number of variables is four. These can be represented by superimposing one two-dimensional network of curves upon another two-dimensional network of curves in suitable mutual relationship ; this assumes that two of the four variables are dependent and the other two are independent.

This fact would be of no value in connection with the particular problem under consideration were it not for the coincidence of the fact that the mathematical characteristics of one pair of the independent variables are identical with those of the pair of dependent variables. To be more explicit :—$\frac{Z_a}{Z_o}$ is identical with $\frac{Z}{Z_o}$ in mathematical form. Therefore $\frac{Z_a}{Z_o}$ can be represented by the same network of curves as $\frac{Z}{Z_o}$.

Thus the six variables can be incorporated in a system comprised of two intersecting networks of curves each of which represents two mathematical variables ; then providing some simple means of correlating $\frac{Z_a}{Z_o}$ and $\frac{Z}{Z_o}$ can be found, a chart can be produced which will yield the required graphical solution of the problem. Mathematically $\frac{Z_a}{Z_o}$ and $\frac{Z}{Z_o}$ are correlated by θ_o and if the mathematical correlation can be represented by some simple geometrical operation in using the chart, it will be possible to enter the chart on one two-dimensional network with $\frac{Z_a}{Z_o}$, then perform the correlating operation on the other two-dimensional network, and finally coming out of the chart via the first two-dimensional network with $\frac{Z}{Z_o}$. Obviously, the curve network which is used for the correlating operation should be an orthogonal cartesian co-ordinate system if its ordinates are to represent the real and imaginary components of θ_o in the simplest possible way. This would simplify as much as possible the operation of correlating $\frac{Z_a}{Z_o}$ and $\frac{Z}{Z_o}$. This is what has been done.

Thus the system is a complex hyperbolic tangent chart which has been plotted with a rectilinear background as argument ; and since it was considered advisable to express $\frac{Z_a}{Z_o}$ in polar co-ordinates, since that is the form which results directly