THE CHARACTERISTICS OF BEAM TRANSMITTING AERIALS.

By J. K. Catterson-Smith.

SYNOPSIS.

The phases of the components of the radiated field of multiple aerial systems are considered and polar distribution diagrams plotted. The production of a single beam with minor secondary rays is dealt with by means of examples. Cylindrical parabolic and plane reflectors of the double grid type are contrasted. Methods of reducing dispersion in both vertical and horizontal planes are considered.

INTRODUCTION.

The extensive experimental work carried out by C. S. Franklin and others of the Marconi Wireless Telegraph Company has resulted in the successful development of several new types of directive aerials. These possess features of considerable interest and promise of practical utility, especially in connection with ultra-short waves. The original sheet-metal reflectors of Hertz were replaced at an early date by vertical tuned wires arranged to form a cylindrical parabolic reflector at the focus of which the oscillator was placed. In this form the reflector gives a considerable degree of concentration in the desired direction and such systems have been utilised (Marconi, *J. Roy. Soc. Arts*, 1924, **72**, 607. C. S. Franklin, *J. Inst. Elec. Eng.*, 1922, [illegible] 930). 60.

The attainment of a beam by this means necessitates the use of a parabolic reflector which, having an aperture of several wavelengths, is consequently not altogether a simple structure excepting with wavelengths of the order of ten metres or less. Further, the whole of the power to be radiated must be supplied to the single oscillator at the focus of the reflector; this constitutes a drawback to the system for large powers.

A better arrangement of both radiator and reflector is the double grid form for the production of a single beam of exceedingly small dispersion. It is relatively simple to erect aerials of this type having, for instance, a width of ten wavelengths even for 100-metre wavelength transmission or reception. The whole of the radiation is then confined to within about six degrees on either side of the centre-line of the beam. Thus it may be concluded the successful generation of beams has at last been accomplished and, unless the transmission from the beam stations now under construction reveals some unexpected phenomena, there is little doubt the majority of point-to-point transmissions of the future will be of the beam type.

POLAR DIAGRAMS AND DISPERSION.

The double grid aerial system comprises two rows of vertical conductors separated by one quarter wavelength. The front row forms the aerial grid supplied with equal in-phase currents, the conductors being spaced so that there is no resultant field in the plane of the conductors.

The whole of the radiation takes place on the two sides of the grid of wires. One half of this is reflected by the adjacent parallel row of reflector conductors, and the resultant field produced by the combined aerial and reflector currents is zero in all directions other than within a few degrees of normal to the aerial on the side opposite to the reflector.

Calculation of the directional properties or concentrating power of the grids does not present any difficulties, but it may nevertheless be of interest to examine the more important cases in some detail.

In the first place the case of a neighbouring pair of identical simple vertical aerials may be considered. It may be assumed that either aerial alone would set up a uniformly distributed field in all directions in the equatorial plane, taken to be the horizontal for present purposes. Also the field at any point may be taken as the resultant of the fields of individual aerials with due respect to their phase relations at that point.

Then, as is well known, under certain conditions the resultant field will possess a certain degree of directive quality; that is, at a distance, great compared to the wavelength, the field will vary with the angle θ in Fig. 1 (*a*) between the receiver and the plane of the two aerial wires. The phase difference in the component fields depends upon the angle θ and the distance separating the two aerials, and also upon the time-phase relation of the current in the two aerials. The time phase difference due to the distance apart of the aerials may be represented by $\phi = 2\pi \frac{d_1 \cos \theta}{\lambda}$ radians while that due to the current phase is represented by Ψ.

The resultant field therefore has components the phase difference of which is $(\phi + \psi)$.

If E_1 be the component due to one aerial then the resultant will be given by

$$E_r = 2E_1 \cos\left[\frac{\phi + \psi}{2}\right] \qquad (1)$$

Case I.—The resultant field when $\theta = 90°$ or $270°$ (normal to AB on either side of the grid) is $n. E_1$ where n is the number of aerial wires; but when $\theta = 0$ or $180°$ the resultant depends upon d_1/λ and E_r is zero when $n\phi$ is an odd multiple of π, that is when $d_1 = \lambda/2$, $3\lambda/2$, etc.

Thus any number of aerials carrying equal in-phase currents may be placed in line so as to radiate a maximum field normal to the plane of the aerials and zero field along the plane of the aerials.

The polar diagram given by equation (1) has double beam directive characteristics which improve as n is increased for a given value of the ratio d_1/λ that is as the width of the grid aerial is increased. This is shown in Fig. 1 (*b*) for $n = 2$, $\psi = 0$, and $d_1 = \lambda/2$.

The polar diagram for other values of n may be plotted as follows:—

(*a*) When n is an even number,

$$E_r = 2\ E_1 \left[\cos\frac{\phi}{2} + \cos\frac{3\phi}{2} + \cos\frac{5\phi}{2} + \ .\ .\ .\ \right] \qquad (2)$$

taken to $\frac{n}{2}$ terms.

(*b*) When n is an odd number,

$$E_r = 2E_1\ [\tfrac{1}{2} + \cos\phi + \cos 2\phi + \cos 3\phi + \ .\ .\ ] \qquad (3)$$

taken to $\frac{n+1}{2}$ terms.

It is useful to denote the ratio of the resultant field at any angle to the maximum field at right angles, i.e., $E_r/n.E_1$, as the 'beam concentration factor' or β, where E_1 is the field which would be produced by a single aerial with I/n amperes.

In a grid aerial there will be I/n amperes per wire each contributing E_1 to the resultant field.

This factor is a measure of the theoretical dispersion of the beam as θ changes from 0 to 90 degrees.

It follows from equations (2) and (3) that the beam concentration factor may be calculated from :—

$$\beta = \frac{2}{n}\left[\cos\frac{\phi}{2} + \cos\frac{3\phi}{2} + \cos\frac{5\phi}{2} + \ . \ . \ . \ \right] \quad (4)$$

when n is even, or

$$\beta = \frac{2}{n}\ [\tfrac{1}{2} + \cos\phi + \cos 2\phi + \cos 3\phi + \ . \ . \ . \ ] \quad (5)$$

when n is odd.

The condition for $E_r = 0$ is that β must be zero, and for a beam of small dispersion this should occur at $\theta = 0{\cdot}1$ or $0{\cdot}2$ radian.

Case II (*Current phases* $\psi = 90°$).—The resultant field for two aerials with d_2 spacing changes its directive characteristics with changes in ψ.

Thus when $n = 2$ and $d_2 = \frac{\lambda}{4}$, if the current phase difference is $\psi = \pm\ \frac{\pi}{2}$, the resultant field is zero in one direction along AB (i.e., $\theta = 0$ or 180 degrees) and equals $2E_1$ along the other direction Fig. 1 (*c*). The field is $\sqrt{2}.E_1$ on each side ($\theta = 90°$ or $270°$) when d_2 exceeds $\lambda/4$.

Two aerials under these conditions give rise to a one-sided radiation but the wide angle dispersion limits its usefulness.

The combination of two rows of conductors such as A_1 B_1, A_2 B_2, A_3 B_3, etc., shown in plan in Fig. 2 (*a*) reduces the dispersion the greater the width of the grids relative to the wavelength.

A single beam of small dispersion is radiated to the left or right according to whether the current in the conductors B_1 B_2 B_3, etc., leads or lags by a quarter of a cycle to the current in the conductors A_1 A_2 A_3, etc., in Fig. 2 (*a*), the two rows being separated exactly one quarter of a wavelength.

REFLECTED WAVES AND REFLECTOR CURRENTS.

If instead of supplying two-phase current to the two rows of conductors the rear row, B_1 B_2 B_3, etc., are disconnected from the supply and tuned to the frequency of the aerial currents in A_1 A_2 A_3, etc., the former will reflect the left hand radiation from the latter group.

The fields due to the aerial currents A_1 A_2 A_3 and the reflected currents B_1 B_2 B_3 combine to give an amplitude in the direction $\theta = 0$ of $2nE_1$ provided the reflector grid is placed at $\lambda/4$ behind the aerial grid and tuned accurately.

The reflector conductors carry currents which differ in phase to the aerial current by $\left(\pi - 2\,\pi.\,\frac{d_2}{\lambda}\right)$ the first term on account of the reversal of the electric field at the reflecting surface, and the second term on account of its distance from the aerial.

Hence when the spacing is $d_2 = \lambda/4$ the current in the reflectors leads by one quarter of a cycle or $\pi/2$ radians.

It may be remarked that the magnetic field is reflected without reversal and the current in the reflector wires is an out-of-phase image of that in the aerial wires.

The reflected and direct rays combine and the resultant field due to the double grid is given by ;—

$E_r = 2\,E_1.\cos\left[\frac{\pi}{4}(1 - \cos\theta)\right]$ for a pair of conductors, e.g., A_1 and B_1.

Thus $E_r = 2\,E_1$ when $\theta = 0$ and has approximately this value up to about $\theta = 45°$ as shown in Fig. 1 (*c*).

LINEAR COMBINATION OF AERIAL AND REFLECTOR WIRES.

Each unit consisting of one aerial and one reflecting conductor contributes $2E_1$ to the distant field along the centre line of the beam.

On either side of the centre line the field E_b for a wide range of θ is $2 \times n \times E_1$ and the dispersion measured by the field E_d at any angle θ is given by :—

$$E_d = E_b \times \text{ the beam concentration factor, or}$$

$$= \beta \times 2.\,n.\,E_1 \qquad (6)$$

where β is given by equations (4) or (5).

Example I. Narrow Aerial and Reflector (*Fig.* 2).—In the case of a double grid having $n = 4$, $d_1 = \frac{\lambda}{2}$ and $d_2 = \frac{\lambda}{4}$

the width of the aerial is $(n - 1)\, d_1 = \frac{3}{2}\lambda$,

the phase angle is $\phi = 2\pi \frac{d_1 \sin\theta}{\lambda} = \pi . \sin\theta$, and

the current phase is $\psi = \frac{\pi}{2}$ leading

from which :—

$\theta = 0$ degrees	$\phi = 0$ radians	$\beta = 1{\cdot}0$	Primary field.
15	0·815	0·63	
30	1·57	0	
45	2·22	− 0·268	Secondary field.
60	2·73	− 0·183	
75	3·04	− 0·052	
90	3·14	0	

RADIATORS SEVERAL WAVELENGTHS WIDE.

The conclusions to be drawn from the foregoing are :—

(1) The amplitude of the distant field on the centre line of the beam is independent of the width of the radiator.

(2) The dispersion is reduced as the width, in terms of wavelength, is increased.

(3) The spacing of the aerial and reflector conductors, (d_1) must be made a small fraction of a wavelength if leakages or secondary fields are to be avoided. The amplitude of the secondary fields at various angles is usually small.

In order, therefore, to obtain a concentrated beam, the width of the aerial may for instance be made equal to ten wavelengths while the spacing of the wires (d_1) is reduced to one-eighth of a wavelength.

BEAM CONCENTRATION FACTOR FOR LARGE VALUES OF 'n'.

The resultant of a large number of vectors each displaced by equal angles (ϕ) is given by the chord of the circular arc subtended by the angle $n.\phi$; the length of the arc is $n.E_1$. Hence the beam concentration factor, is given by:—

$$\beta = \frac{\text{chord}}{\text{arc}} = \frac{\sin\frac{n\phi}{2}}{\frac{n\phi}{2}} \text{ where } \phi = 2\pi\frac{d_1}{\lambda}\sin\theta \text{ radians, and at any}$$

angle θ from the centre line of the beam the dispersion field is

$$E_d = \beta \times 2n.\ E_1 \qquad (7).$$

ANGLE OF DISPERSION.

For present purposes this may be defined as the angle on either side of the centre line of the beam at which the field becomes zero, or θ when $E_b = 0$. This occurs when $n \times \phi = 2\pi$ or any even multiple. (8).

Example II. Wide Aerial and Reflector.—A double grid system about ten wavelengths wide has 80 aerial wires spaced $d_1 = \lambda/8$ in both aerial and reflector which are one quarter wavelength apart.

From (7) and (8) the angle of dispersion is given by:—

$$\theta = \text{arc}\sin\frac{\lambda}{nd_1} = \text{arc}\sin\frac{8}{80} = \mathbf{5^\circ\ 45'}.$$

The field distribution is plotted for this aerial in Fig. 3 from equation No. 7, for which figures are given below:—

TABLE I.

$n = 80$, $d_1 = \lambda/8$, and $d_2 = \lambda/4$.

θ degs.	Sin θ	ϕ radian	$\frac{n\phi}{2}$ radian	β	
0	0	0	0	1·00	Primary.
2½	0·044	0·0349	1·40	0·700	
5	0·087	0·0683	2·73	0·143	
7½	0·130	0·102	4·08	— 0·186	
10	0·174	0·137	5·48	— 0·130	
15	0·259	0·204	8·16	+ 0·038	
20	0·342	0·268	11·7	— 0·083	
25	0·423	0·332	13·3	+ 0·0483	
30	0·500	0·392	15·7	0	
45	0·707	0·555	22·2	— 0·008	
60	0·87	0·68	27·0	+ 0·032	
75	0·97	0·76	30·0	— 0·028	
90	1·00	0·78	31·4	0	

Note.—The function $\frac{\sin\theta}{\theta}$ has been termed 'cursin θ' by Silvanus P. Thompson who gave some values for it in *J. Inst. Elec. Eng.*, 1915, **53**, 240.

Experimental data relating to such small dispersions have not yet been published, but there appears no reason for doubting the practical possibilities of high degrees of concentration in one plane with wavelengths up to about 100 metres.

REFLECTORS OF CYLINDRICAL PARABOLIC FORM

The oscillator A is placed at the focus as shown in Fig. 4 distant $\lambda/4$ from the reflector apex conductor O in which the current leads by 90 degrees. The current in the reflector conductors at B, distant $\lambda/2$, is in-phase with the oscillator current and the reflector current beyond this point has a lagging or leading phase according to the distance.

If the reflector is to confine the radiation within an angle of dispersion θ its size is determined by:—

$$\text{Aperture} = \frac{\lambda}{2} + \left(\frac{1}{\sin\theta} - \frac{1}{\tan\theta}\right) \qquad (9).$$

For instance, if the dispersion is not to exceed 15 degrees on either side of the centre-line the aperture must be 3·85 wavelengths. The aperture increases rapidly with the concentration.

C. S. Franklin has published (*J. Inst. Elec. Eng.*, 1922, **60**, 933) polar diagrams of his observations made with 4·28 metre wavelengths for a reflector of 2·57 aperture etc., measured at four miles, which are in close agreement with the calculated field distribution.

This type of reflector appears more suitable for very short waves and moderate distances of transmission whereas the double grid plane reflector lends itself to great concentration of the beam for wavelengths up to 100 meters and the greatest distances. The reflector aperture required for a dispersion of only 5° 45′ works out from equation (9) as ninety-seven wavelengths compared with a plane reflector (see p. 15) which is ten wavelengths wide.

CONCENTRATION IN THE VERTICAL PLANE.

The aerial conductors must be supplied with equal currents and for this purpose feeder circuits have been developed by the Marconi Wireless Telegraph Company (*Ind. Pat. Spec.*, No. 10,420 and No. 10,421, 1924) which show vertical wires of $\lambda/3$ length spaced $\lambda/8$ as practical dimensions.

The wires being connected in parallel along top and bottom and fed at points along the base separated preferably by $\lambda/2$.

This patent discloses the use of two or more tiers of such grids with electrostatic coupling and giving an in-phase current distribution all over the units forming the grid.

In this way aerials and reflectors may be built with an area of several square wavelengths radiating energy substantially in one direction only. Combined with similar plane reflector receiving aerials it is claimed that a great magnification of the received signals results.

Aerials of one or more wavelengths in height give rise to a concentration in the vertical plane as will be examined for the case of a type, of more recent date, developed for this class of transmitter.

THE MARCONI BEAM AERIAL.

Ind. Pat. Spec., No. 11,543, 1925: Marconi Wireless Telegraph Company, divulges means whereby grid aerials may be made to carry stationary waves of current of the same phase at all points. By this means extreme sharpness of concentration of the field in the vertical, as well as in the horizontal, plane becomes possible and a beam of small solid angular dispersion obtained.

Referring to Fig. 5 which represents a simple oscillator, with current distribution as indicated by the sine curve, the polar distribution of the field in the plane of the oscillator is approximately;—

$$E = E_m . \cos \theta'.$$

The same effect would be produced if the oscillator were replaced by an aerial one half a wavelength long excited at its base by capacity coupling in the ordinary manner.

If now the applied frequency be raised until the aerial is one wavelength long the stationary waves of current take the form of two loops; maximum amplitude occurring at $\frac{1}{4}$ and $\frac{3}{4}$ wavelength up the conductor. In this case there can be no field at right angles to the aerial on account of the phase opposition of the currents in the two loops; on the other hand radiation at about 45° and 135° all round the aerial will take place.

On raising the applied frequency still higher a condition will be reached when three loops of current form, the maxima occurring at $\frac{1}{4}$, $\frac{3}{4}$ and $1\frac{1}{4}$ wavelengths from the base. The aerial is then $1\frac{1}{2}$ wavelengths in height and the phase of the current loops at the $\frac{1}{4}$ and $1\frac{1}{4}$-points will be the same and opposite to that at the $\frac{3}{4}$-point. The polar diagram for the radiated field will become a six-loop figure, as shown in Fig. 6, and it is clear that for m loops of current there will be $2m$ loops in the polar diagram.

If by some means the radiation from alternate current loops such as AB, Fig. 6, be suppressed, the polar diagram reduces from $2m$ to 2 loops only, and a high degree of sharpness obtained as m is increased.

The patent referred to secures this condition, at least approximately, by forming the portions, such as AB in Fig. 6, so as to annul the radiation therefrom. This is accomplished by either doubling that part of the aerial wire back on itself or by replacing it with reactive coils, etc.

The phase of the current in the remaining portions of the long aerial is substantially the same throughout and the effect of the loops is additive at right angles to the aerial. This is indicated in Fig. 7 which is drawn for an aerial of vertical height $\frac{4\lambda}{2}$ carrying four current loops of the same phase and three current loops on the non-radiating portions.

The concentration in the vertical plane for a grid of such aerial conductors may be calculated in the manner already given for the horizontal concentration.

The angle of dispersion in the vertical plane is given approximately by equation (8); thus for m current loops,

$$m\,\phi = 2\pi \text{ or } \phi = 2\pi/m$$

also $$\phi = \pi \sin\theta'$$

hence $$\theta' = \text{arc}\sin\frac{2}{m}.$$

Thus when m has the value given in the first column of Table II the corresponding vertical dispersion is given in column three.

TABLE II.

Without Reflector.

m	$\frac{2}{m}$	VERTICAL DISPERSION
		Degrees and minutes
2	1·00	90° 0′
3	0·67	41° 45′
4	0·50	30° 0′
5	0·40	23° 30′
6	0·33	19° 30′
7	0·286	16° 35′
8	0·25	14° 30′
10	0·20	11° 30′
20	0·10	5° 45′ = (10 λ high)

From this it is seen that a plane reflector grid 10 λ wide and 10 λ high should produce a single beam concentrated within 5° 45′ of its centre line both vertically and horizontally.

A wide field for research is opened in connection with short wave reflectors giving such concentrated rays, the future applications of which appear unlimited.

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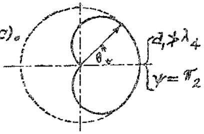
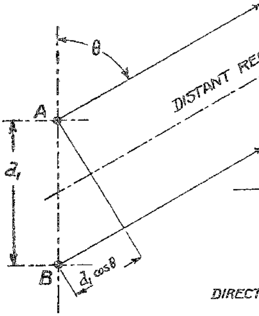
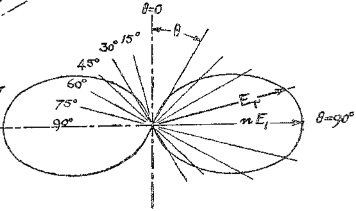
[Accepted, 1-7-26.]

PRINTED AND PUBLISHED
BY GEORGE KENNETH AT THE DIOCESAN PRESS
POST BOX 455, MADRAS—1926. C13108

FIG 1 (C).



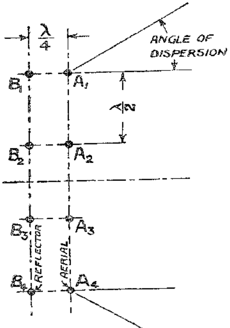




DIRECTIVE FIELD OF TWO AERIALS.

FIG 1 (A).

FIG 1 (B). $d_1 = \lambda_2$ $\psi = 0$



NARROW GRIDS $n = 4$ $d_1 = \lambda_2$ $\psi = 90°$ LEAD.

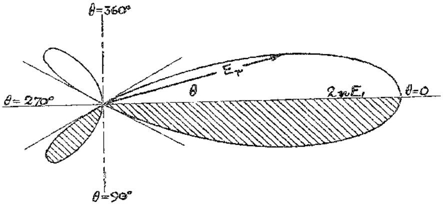
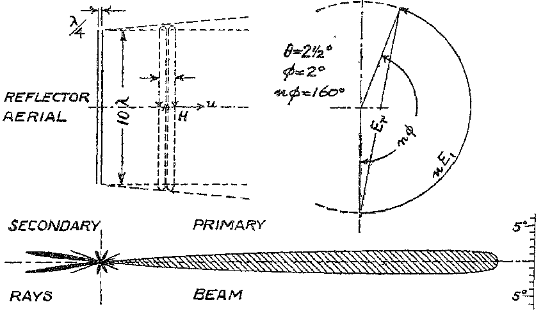


FIG 2 (A).

FIG 2 (B) PRIMARY AND SECONDARY BEAMS.



HORIZONTAL POLAR DISTRIBUTION

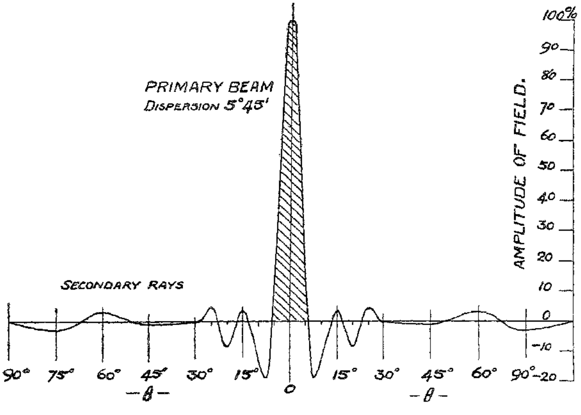


FIG 3 AERIAL AND REFLECTOR (10-WAVELENGTH).

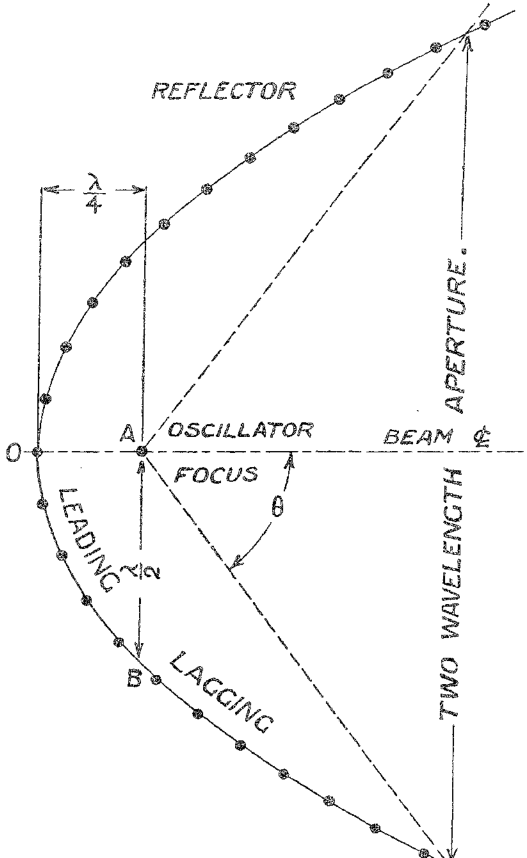


FIG 4. CYLINDRICAL PARABOLIC REFLECTOR.

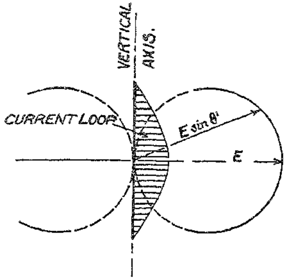


FIG 5. VERTICAL FIELD.

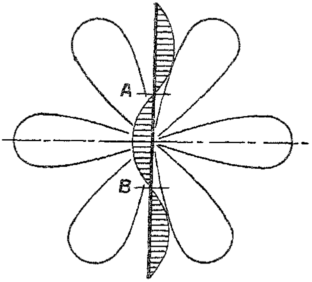


FIG 6.

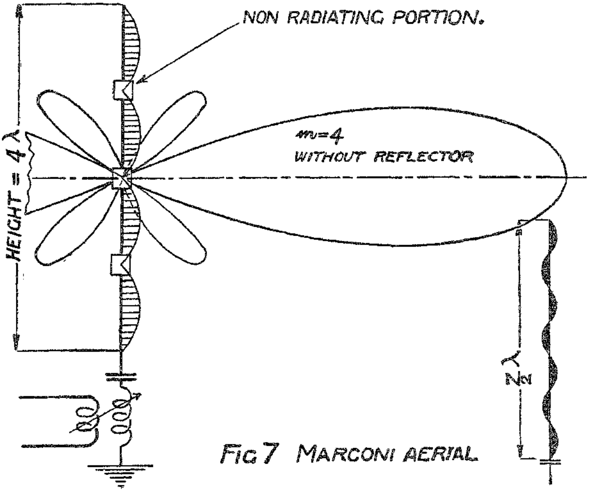


FIG 7 MARCONI AERIAL