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TITLE: AN ANTIFADING AERIAL OF THE RING TYPE FOR MEDIUM FREQUENCY BROADCASTING.

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REPORT NO. 11

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C O N T E N T S

AN ANTIFADING AERIAL OF THE RING TYPE FOR MEDIUM FREQUENCY BROADCASTING

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Introduction:

The subject of ring aerials has been covered by an earlier report of the Australian Broadcasting Control Board.[1] The conclusions reached in that report were based on the assumption that all the aerials in a ring aerial system were of the same height. This report extends the study to an aerial system of the √. type in which the central aerial differs in height from that of the aerials in the ring. It was suggested by Mr. H. Freeman of the Superintending Engineer's Branch of the Postmaster-General's Department, Sydney, that an aerial of this type would be advantageous in the case of 2CR Cumnock. This report originated from investigations made of this suggestion.

General Considerations:

The anti-fading properties of an aerial may be calculated using data obtained from the vertical polar diagram. Knowing the reflecting layer height and absorption, an estimate may be made of the incident sky wave field intensity at the point on the earth where the wave meets it. This is compared with the ground wave at that point. Severe fading is encountered when the two field intensities approach the same value. It is considered that a ratio of 2 : 1 for the ground wave and 10% quasimaximum sky wave field intensities is necessary for acceptable reception.

The optimum vertical characteristic is one which establishes this 2 : 1 ratio at a maximum distance from the aerial. Hence the criterion for an antifading aerial design is to make the aerial as highly directional as possible along the horizon with as little radiation as possible at angles above 30° elevation.

In the design considered in this report a central aerial has been chosen which gives the highest concentration of radiation along the horizon. This aerial also produces a large lobe at high angles of elevation. A suitable ring aerial is used to reduce this lobe, by the process of phase opposition of the radiated field with that of the central aerial.

A single vertical mast fed simultaneously at the base and at the centre also produces an antifading characteristic[9] which is marred by a large lobe at high angles of elevation as the angle of zero radiation is increased from the vertical. Such an aerial may be more attractive economically than the proposed aerial if the desired angle of zero radiation is 40° from the vertical. Curves shown in ref. 9 indicate that for a half wave mast, the high angle lobe becomes excessive for angles of zero radiation greater than 40° from the vertical.

The vertical polar diagram of a J_0 type ring aerial for which $\frac{2\pi a}{\lambda} \simeq 2.6$ and $h \ll \lambda$ is an almost perfect replica of that obtained from a 0.639λ aerial at elevations above $45°$. A combination of these aerials would therefore be expected to produce an antifading characteristic provided the phase between the two fields does not change from point to point on the surface of a sphere with the aerial at its centre.

The theory shows that a phase change does occur due to a change in phase of the current along an aerial. It may be expected that this would be relatively unimportant where all the aerials in the system are of the same height, but special care must be taken when aerials of different height are used.

Calculations below give the vertical radiation characteristic, the effective radiation resistance, and the approximate percentage power lost for a central aerial of height 230 electrical degrees (.639 wavelength) surrounded by a ring of 6 aerials 0.2 wavelength in height at a radius of 0.413 wavelength with the phase between the current to the central aerial and that to the ring aerial adjusted for the best antifading characteristic.

Current Distribution along an Aerial:

Information is available[(2)] for determining the precise form of current distribution along an aerial of given height and radius, but the method is complicated, and time absorbing. Some cases have been calculated, and are published in ref. (2).

If the current distribution is divided into that which is in phase with the applied voltage and that which is in quadrature with the applied voltage it is found that the in phase current is approximately proportional to $(\cos\beta z - \cos\beta h)$ while the quadrature current is approximately proportional to $\sin\beta(h - |z|)$. Expressed mathematically:

$$I_z \simeq V_0\left[G_0\left(\frac{\cos\beta z - \cos\beta h}{1 - \cos\beta h}\right) - jB_0\frac{\sin\beta(h - |z|)}{\sin\beta h}\right] \quad (1)$$

where I_z is the current at a point distance z from the feed end of the aerial

V_0 = applied voltage

G_0 = input conductance

B_0 = input susceptance

$\beta = \frac{2\pi}{\lambda}$

h = aerial height.

The current in quadrature with the applied voltage is termed the main current while that in phase is termed the feed current. In the literature, the feed current is usually referred to as the quadrature current as it is normally given in terms of the loop current.

In the case under investigation, an assumed sinusoidal distribution of main current has a maximum error of 10% which is at the current maximum. By taking a value for the loop current which is 5% less than that calculated for sinusoidal distribution, the error in the vertical polar diagram for assumed sinusoidal current distribution will be small.

In this report the main current will be taken as having a sinusoidal distribution along the aerial as the field strength may then be calculated conveniently. The field due to the feed current is most readily calculated using a graphical integration method with either the precise or approximate current distribution, whichever may be the more readily available.

<u>Vertical polar diagram of 230° central aerial:</u>

The field strength from a vertical grounded aerial for sinusoidal current distribution in the aerial and assuming the earth to be a perfect reflector is given by -

$$f(\theta)_0 = 60\frac{I_\ell}{r}\cos\left(\omega t - \frac{2\pi r}{\lambda}\right)\left[\frac{\cos\left(2\pi\frac{h}{\lambda}\cos\theta\right) - \cos 2\pi\frac{h}{\lambda}}{\sin\theta}\right] \quad (2)$$

where $f(\theta)_0$ is the field strength in volts/metre at an angle θ from the vertical

I_ℓ = loop current in amps

r = distance from base of aerial in metres.

The shape of the polar curve is determined by the last term in brackets. To obtain a value of unity at $\theta = \frac{\pi}{2}$ for comparison with other curves, the following expression has been used in which a factor independent of θ has been added in the denominator.

$$\frac{\cos\left(2\pi\frac{h}{\lambda}\cos\theta\right) - \cos 2\pi\frac{h}{\lambda}}{\sin\theta\left(1 - \cos 2\pi\frac{h}{\lambda}\right)}$$

This has been plotted as curve 1 fig. 1 for $h = 0.639\lambda$
To this, the field $f(\theta)_{0f}$ due to the feed current must be added.

Assuming perfect reflection at the ground

$$f(\theta)_{0f} = \sum \frac{60\pi}{r}\frac{\Delta l}{\lambda} I_z \sin\theta\left[\cos\omega\left(t - \frac{d_1}{c}\right) + \cos\omega\left(t - \frac{d_2}{c}\right)\right] \quad (3)$$

where $f(\theta)_{0f}$ volts/metre is the field due to the feed current at an angle θ from the vertical

I_z = feed current at point distance z from ground

Δl = elementary length of aerial at z

r = distance from base of aerial

d_1 = distance from point z

d_2 = distance from mirror image of point z

c = veolcity of propagation = 3×10^8 metre/sec

$$f(\theta)_{of} = \sum_{l=0}^{l=h} \frac{60\pi}{r} \frac{\Delta l}{r} I_z \sin\theta \left[\cos\left(2\pi \frac{z\cos\theta}{\lambda}\right) + \cos\left(-\frac{2\pi z\cos\theta}{\lambda}\right)\right]$$

$$= \sum_{l=0}^{l=h} \frac{120\pi}{r} \frac{\Delta l}{\lambda} I_z \sin\theta \cos\left(\frac{2\pi z\cos\theta}{\lambda}\right) \qquad (4)$$

$$\simeq \sum_{l=0}^{l=h} \frac{120\pi}{r} V_0 G_0 \frac{\Delta l}{\lambda} \left(\frac{\cos\beta z - \cos\beta h}{1-\cos\beta h}\right) \sin\theta \cos\left(\frac{2\pi z\cos\theta}{\lambda}\right)$$

Equation 4 divided by $f(\theta)_{o_{\theta=\frac{\pi}{2}}}$ is plotted as curve 3 in fig. 1 and represents the field in quadrature with the main field.

<u>Compensating Field from Ring Aerial:</u>

It has been shown by Page(3) that the field from a ring aerial is given by

$$f(\theta)_r = f(\theta)_o \, J_n\left(\frac{2\pi r_1}{\lambda} \sin\theta\right)$$

where $f(\theta)_o$ = field from a single aerial similar to those in the ring and with the same current as the ring

= $K \sin\theta$ for short aerials

K = constant

$J_n(\gamma)$ = Bessel function of the first kind and order n

$2\pi n$ = phase change of current to aerials around the whole ring

n = zero in the present case

r_1 = radius of ring

For a 0.639λ central aerial the best compensation is obtained by putting $\frac{2\pi r_1}{\lambda} = 2 \cdot 6$

$$f(\theta)_r = K \sin\theta \; J_0(2 \cdot 6 \sin\theta) \qquad (6)$$

This equation is plotted as curve 2 in fig. 1 and represents the field from the ring aerial which is 180° out of phase with the main field at $\theta = \frac{\pi}{2}$ This cancels the high angle radiation from the main current of the central aerial but still leaves the field due to the feed current. A further improvement is obtained by adding a small field 180° out of phase with that from the feed current at high angles of elevation. This field is plotted as curve 4 in fig. 1. It is obtained by shifting the phase of the current to the ring aerial in the appropriate direction and increasing the amplitude so that the same degree of compensation is obtained for the main field.

The vectorial sum of these four fields is plotted as curve 5 fig. 1 and represents the resultant vertical radiator characteristic in relation to the other vertical radiation characteristics provided the currents to each aerial are maintained at the same values obtained before superposition.

Fig. 2 gives, in order to facilitate comparison, the vertical radiation characteristics of

an aerial of 0.25 wavelength height

an aerial of 0.53 wavelength height

the proposed aerial of 0.639 wavelength height with a ring of 6 aerials of height 0.2 wavelength surrounding it at a radius of 0.41 wavelength.

Input Resistance of Ring Aerials:

From the Poynting vector method of calculating the radiated power we have, neglecting earth losses

$$\text{Power radiated} = \sum f(\theta)_r^2 \, \triangle A = I_r^2 R_r \qquad (7)$$

where $\triangle A$ = element of area on a sphere with the aerial at its centre

$f(\theta)_r$ = field strength of wave crossing this elementary area

I_r = input current to aerial

R_r = input resistance of aerial

$$\text{Power radiated by one aerial similar to those in the ring} = \sum f(\theta)_0^2 \, \triangle A = I_0^2 R_0 \qquad (8)$$

where I_0 = input current to aerial

R_0 = input resistance of aerial

Provided $I_r = I_o$

$$\frac{R_r}{R_o} = \frac{\Sigma\, f(\theta)_r^2\, \Delta A}{\Sigma\, f(\theta)_o^2\, \Delta A}$$

$$\Sigma\, f(\theta)_o^2 \Delta A = 2\pi r^2 K^2 \int_0^{\frac{\pi}{2}} \sin^3\theta\, d\theta$$
$$= \frac{4\pi}{3} \quad \text{for } K = 1,\ r = 1$$

By graphical integration $\Sigma\, f(\theta)_r^2\, \Delta A = 0.178$

$$\frac{R_r}{R_o} = 0.0426$$

For 0.2λ aerials assume $R_o = 20\ \Omega$

$$\therefore R_r = 0.85\ \Omega$$

Ratio of Currents to Central and Ring Aerials:

By graphical integration $\Sigma\, f(\theta)_c^2\, \Delta A = 1.974$

For a 0.639λ aerial assume $R_c = 65\ \Omega$

$$\frac{\Sigma\, f(\theta)_c^2\, \Delta A}{\Sigma\, f(\theta)_r^2\, \Delta A} = \frac{I_c^2 R_c}{I_r^2 R_r} = \frac{I_c^2 \times 65}{I_r^2 \times .85} = \frac{1.974}{0.178} \qquad \frac{I_c}{I_r} = 0.38 = k$$

Mutual Resistance and Effective Input Resistance of Aerial:

Let $I_r = 1$ amp and $I_c = 0.38$ amps.

For the ring and central aerials separated from one another the power radiated by the central aerial $= 0.38^2 \times 65 = 9.4$ watts

$$f(\theta)_{c\ \theta=\frac{\pi}{2}} = 270\sqrt{\frac{9.4}{1000}} = 26.2 \text{ mV/m at 1 mile}$$

From fig. 1 $f(\theta)_{r\ \theta=\frac{\pi}{2}} = -26.2 \times 0.095 = -2.5$ mV/m at 1 mile

Let R_m be the mutual resistance between the central and ring aerials when brought together,

The effective input resistance of the central aerial is then $65 + \frac{R_m}{k}$ and that of the ring aerial is $0.85 + R_m k$

The total radiated power $= \sum f(\theta)^2 \Delta A$

$$= \left(65 + \frac{R_m}{k}\right)k^2 + 0.85 + R_m k$$

Where $f(\theta)$ = sum of the fields.

The power passing through each square metre of spherical surface $= 0.00265\, f(\theta_1)^2$ watts

where $f(\theta_1)$ = field strength in RMS vol/metre

By graphical integration $\sum f(\theta)^2 \Delta A = 1.524$

for $f(\theta)_{r,\ \theta=\frac{\pi}{2}} = 1$ at unit radius.

For a current of 1 amp in the ring aerial, the unattenuated power at 1 mile $= 1.524\left(\frac{26.2}{1000}\right)^2 \times 1610^2 \times 0.00265$

$= 725$ watts

$$\therefore \left(65 + \frac{R_m}{k}\right)k^2 + 0.85 + R_m k = 725$$

$$\therefore R_m = -4\ \Omega$$

$$R_{eff_c} = 65 - \frac{4}{.38} = 54.5\ \Omega$$

$$R_{eff_r} = 0.85 - 4 \times .38 = -0.67\ \Omega$$

Neglecting losses we have

Power to central aerial $= 0.38^2 \times 54.5 = 7.9$ watts

Power received by ring aerial $= 0.67$ watts

Total power to aerial system $= 7.23$ watts
or power radiated.

For 50 KW radiated power these figures become

Power to central aerial 54.5 KW

Power received by ring aerial 4.5 KW

The unattenuated field at 1 mile for 1 KW radiated power is given by $\dfrac{26.2 \times 0.9}{\sqrt{\frac{7.23}{1000}}} = 278$ mV/m

<u>Losses:</u>

For a radiated power of 50 KW

The current in the central aerial I_c = $\sqrt{\frac{4500}{54.5}}$ = 31.6 amps

It is reasonable to assume the Q of the loading coil be 300 and the reactance 100 ohms.

$\therefore$ Loading coil resistance = $\frac{1}{3}$ ohm

Watts loss in central aerial loading coil = $\frac{31.6^2}{3}$ = 330 watts.

Without carrying out a precise calculation it may be assumed without serious error that the earth losses of the central aerial are equal to those for a quarter wave aerial since the effective base resistance of the former is 54.5 ohms and that of the latter is 40 ohms. With an earth system consisting of 113 radials of No. 8 gauge copper wire extending out to 0.274 wave lengths and an earth conductivity of 10×10^{-14} e.m.u. the watts loss out to a radius of half a wave length for a quarter wave aerial is 4.3%.

Earth losses for central aerial = 54.5 x 0.043 = 2.4 K.W.

Central aerial power loss = 2.7 K.W.

Each aerial in the ring has an effective resistance of 4 ohms and receives 0.75 K.W.

Assume the Q of the loading coils to be 300 and the effective reactance of each aerial 150 ohms

$\therefore$ Resistance of loading coils = 0.5 ohms.

Current to each aerial = $\sqrt{\frac{750}{4}}$ = 13.7 amps

Watts loss in ring aerial loading coils = $6 \times 13.7^2 \times 0.5$ = 0.6 K.

As in the case of the central aerial the earth loss of each aerial in the ring may be assumed to be equal to that for an aerial of height 0.[illegible] wave length since the base resistances are the same.

With an earth system of 113 radials of No. 8 gauge copper wire extending out to 0.274 wave lengths and an earth conductivity of 10×10^{-14} e.m.u. the earth losses out to a radius of half a wave length are 5.4%.

Earth loss for ring aerial = 4.5 x .054 = 0.25 K.W.

Ring aerial power loss = 0.85 K.W.

Total power loss = 3.5 K.W. or 7%

This radius at earth system would not be sustained in all directions from the ring aerials, but it is reasonable to assume that the losses for a suitable practical form of earth system would not be greater than those estimated.

Sky Wave Field Strength:

Fig. 3 shows the calculated sky wave field strengths for aerials of different heights and for the proposed ring aerial. The power to each is such that it produces an unattenuated field of 712 mv/m at 1 mile for $\theta = \frac{\pi}{2}$ These calculations are based on the 10% sky wave curve for an $h = 0.25$ wavelength aerial published in the N.A.B. Handbook 1940.

From fig. 3 it will be seen that estimated limits of the fading free service are as follows:-

	Range miles		
	500 kc/s	500 kc/sec.	1500 kc/s
	Cond 15×10^{-14} e.m.u.	Cond. 5×10^{-14} e.m.u	Cond. 10×10^{-14} e.m.u
Quarter wavelength aerial	115	62	35
0.53 wavelength aerial	153	104	72
0.639 wavelength aerial with 0.2 wavelength ring of 0.41 wavelength spacing	195	149	78

These figures are of course relative only, the actual ranges of the fading rings depending on the field strength of the indirect rays which vary widely from night to night. The figures however are regarded as typical and fair to each type of aerial.

When inspecting fig. 3 it should be borne in mind that variations in the 10% sky wave curve of 100% can be expected so that although the single mast of height 0.639 wavelength appears to be a good proposition for high conductivity country, in extending the primary service area it can give very large areas of severe fading and distortion when high sky wave field intensities are encountered.

Waves reflected from the Earth:

Throughout these calculations it has been assumed that the earth is a perfect reflector. In a practical case the characteristics of the earth and angle of incidence of the wave will effect the phase and magnitude of the ground reflected wave. This will have no effect on the calculations for aerial resistance as the aerial characteristics are unaffected by changes in the ground constants beyond the range of the induction field. Within this range the earth system renders the ground characteristics virtually those of a perfect reflector. The more convenient calculation $\sum f(\theta)^2 \Delta A$ for perfect earth must yield an identical result with the calculation $\sum f(\theta)^2 \Delta A$ + dissipation losses for imperfect earth. For earth of finite conductivity the curves in figure 1 do not give the true vertical characteristic in the region $70^\circ < \theta < 90^\circ$ Large changes in the phase of the ground reflected wave are restricted to this region while the change in magnitude is only 20% in the region $0 < \theta < 70^\circ$ A third component, the surface wave appears for θ close to 90°.

It can therefore be expected that the error involved in equation (2) will be small for $\theta < 70^\circ$ This more than covers the important angles of elevation for sky wave propagation which effect ground wave reception.

Experimental Verification Proposals:

Because of the large cost of a medium frequency installation to the proposed design and obvious difficulties in measuring the vertical polar diagram, the use of a model ring and central aerial appears to be a simple and economical method of supplying experimental verification of the calculated characteristics of the proposed aerial. This can only be done satisfactorily by increasing the frequency so that all linear measurements are the same when expressed in wavelengths. Since the ratio $\frac{\sigma}{\omega\mu}$ has to be preserved as well as the ratio between $\frac{\epsilon}{\mu}$ and $\frac{\sigma}{\omega\mu}$, it may be necessary to use a tank filled with water to simulate the earth.

Where σ = conductivity of the soil

ω = $2\pi f$

f = frequency cycles/sec.

μ = the permeability of the soil M.K.S.

ϵ = the dielectric constant of the soil M.K.S.

In most cases $\frac{\epsilon}{\mu}$ is small compared with $\frac{\sigma}{\omega\mu}$ so that we are only interested in increasing the conductivity by the same ratio that the frequency is increased. Sea water would satisfy this condition if a frequency of 100 m.c/s were used, the conductivity of 5000×10^{-14} emu for sea water at 100 Mc/s being equivalent to 27×10^{-14} e.m.u. at 550 kc/s.
The vertical polar diagram could be measured by a small dipole, crystal detector and meter mounted on a pole.

It would be desirable to measure the reactive component of the input impedance of the ring aerial as the literature suggests that this is large. It would also be desirable to determine experimentally the reactive component of the mutual impedance between the ring and central aerials so that a corrective network could be inserted to maintain the correct phase between the central and ring aerial currents.

Parasitic operation of the ring aerial should be possible by inserting the correct impedance between the base of the aerials and earth. In this case the power that would be fed back to the line under non-parasitic operation would be dissipated in the resistive component of this impedance while the reactive component would maintain the correct current phase. Power loss in this way would be of the order of 10%.

It would be of value to investigate the effect of withdrawing the aerials on one side of the ring. In practice the case may occur in which small sky wave radiation at high angles is not required in all directions so that it may be possible to operate with anti-fading in the required directions and with fewer masts. Some observations could also be made for the optimum number of aerials in the ring.

Conclusion:

The proposed ring aerial will increase the primary service area (as limited by the 50% fading contour) obtained from an $h = 0.53\lambda$ aerial at night be amounts varying from zero to 100% depending on the frequency, ground conductivity and sky wave absorption. There is little advantage to be gained at high frequency over poor conductivity country. At low frequency and high conductivity and for normal skywave field strengths there would be a slight advantage over the proposed aerial in favour of a single mast of height 0.639 wavelength. However, during periods of high indirect ray field strength, the range to the fading zone could be very seriously reduced. By a suitable choice of q and h other designs may give even greater increases in the primary service area but result in higher sky wave field strengths closer to the transmitter. This may be objectionable in low conductivity country.

Calculations have been made assuming a simple vertical mast for a central radiator. The general conclusions of this report would apply to the case where this is replaced by a central loaded radiator such as is used at a number of Australian national stations.

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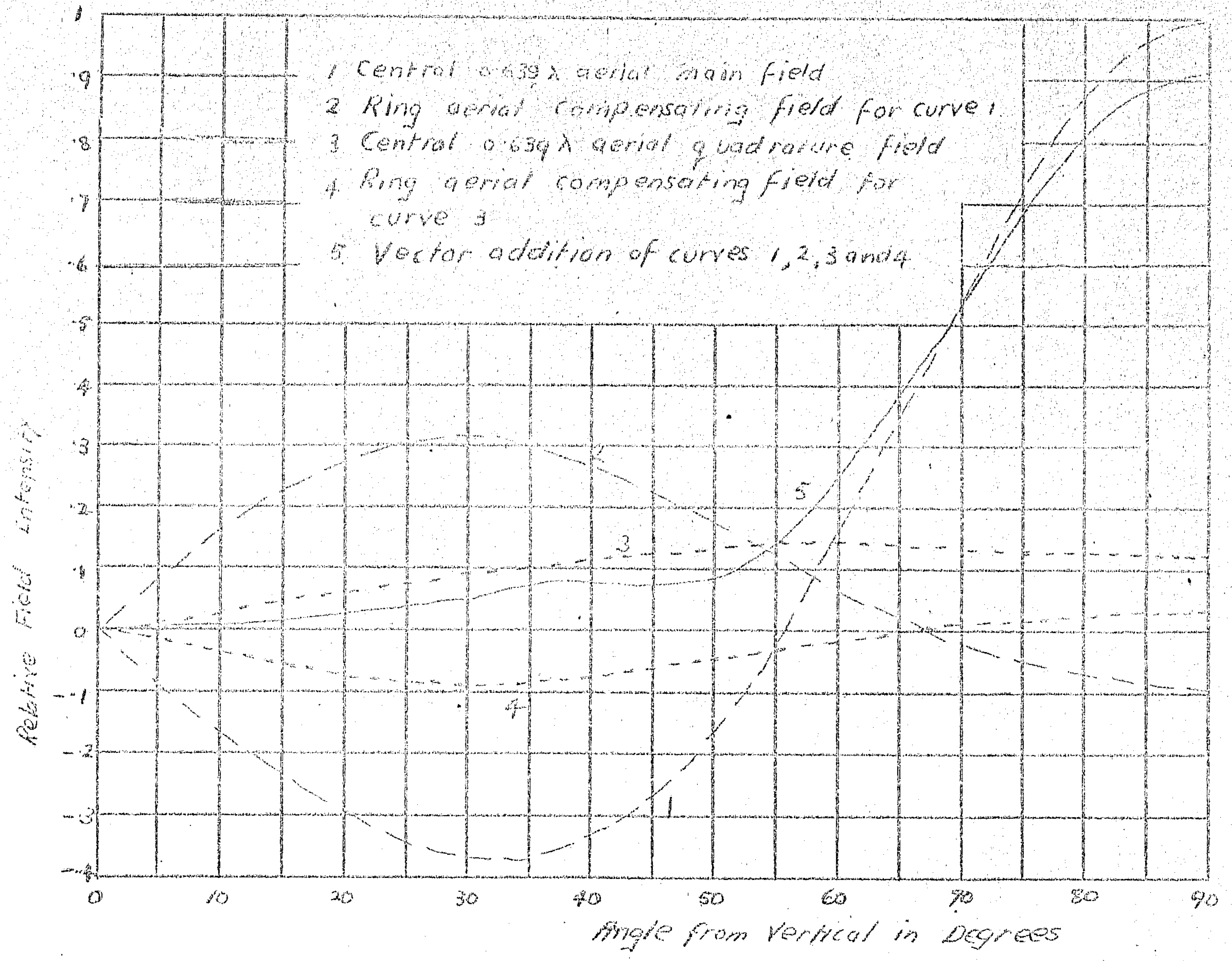
The Measured Radiation Patterns of Vertical Aerials over an Imperfectly Conducting Earth.

Fig. 1 Vertical Radiation Characteristics



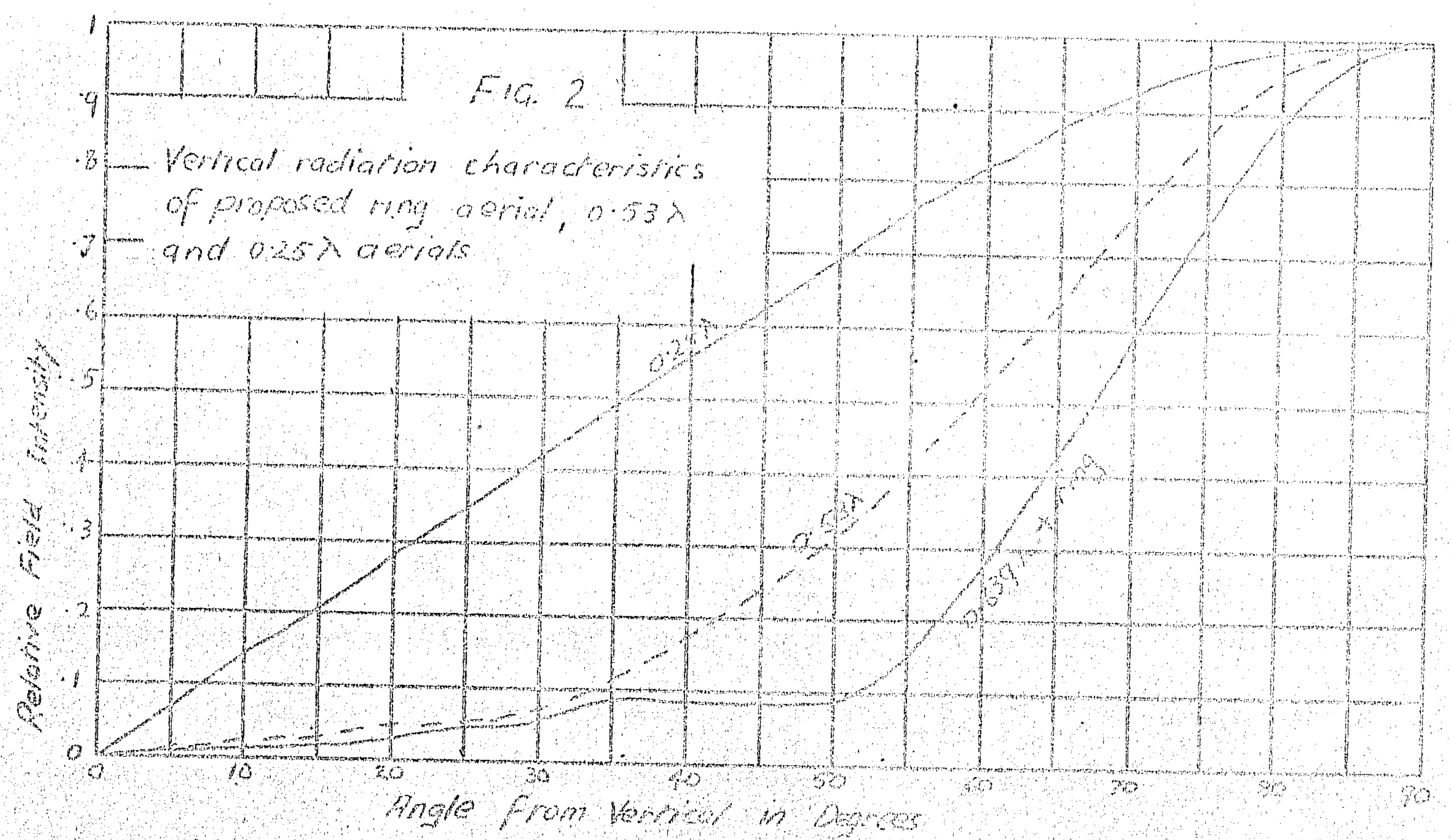
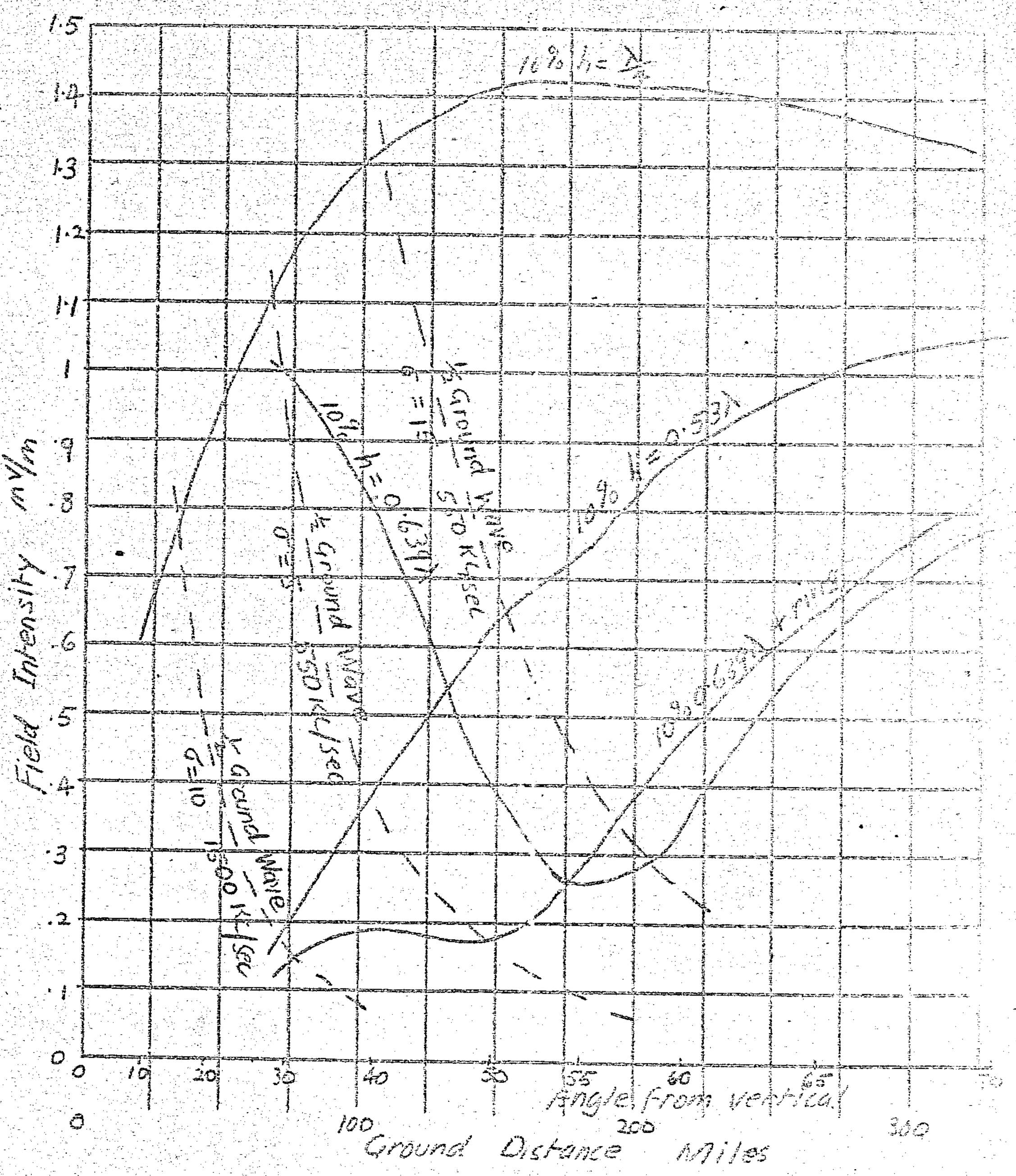


FIG. 2

Vertical radiation characteristics of proposed ring aerial, 0·53λ and 0.25λ aerials

E Layer Height 105 KM.
7/2 mV/m at 1 mile

FIG. 3



FIELD STRENGTH OF DIRECT AND INDIRECT R...
THE PROPOSED RING AERIAL AND FOR 0.5...
AND 0.639 λ AERIALS