THE SERVICE AREA OF BROADCASTING STATIONS

BY

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SYMBOLS USED, AND DEFINITIONS

$\frac{1}{4}\lambda$ aerial, an aerial having a vertical height $= \frac{1}{4}\lambda = h$.

$\frac{1}{2}\lambda$ aerial, an aerial having a vertical height $= \frac{1}{2}\lambda = h$.

h = physical height of the vertical part of an aerial.

λ = wavelength.

λ_0 = natural wavelength of an aerial.

f = frequency.

f_c = frequency of carrier wave.

f_m = frequency of low frequency modulation.

I = aerial current, defined as the maximum current in the aerial.

W = total aerial power.

E = field strength.

E_d = field strength of direct ray.

E_n = field strength of indirect ray.

d = distance from the transmitting aerial before attenuation is noticeable.

x = distance from the transmitting aerial after attenuation is noticeable.

h_1 = effective height of aerial derived from the expression $E\lambda d/(377I)$.

R_D = dead-loss resistance of an aerial.

R_R = radiation resistance of an aerial.

R = total resistance of an aerial.

η = relative power efficiency $= h_1^2(\lambda^2 R)$.

σ = conductivity of the earth.

S = reduction factor for numerical distance d_n.

d_n = numerical distance $= (\pi x/\lambda)\left\{1/(2\sigma\lambda c)\right\}$ approx.

c = velocity of light.

THE SERVICE AREA OF BROADCASTING STATIONS

I

SCOPE OF THE PAMPHLET

The object of this pamphlet is to give engineers, occupied in designing national or regional schemes of broadcasting, certain relevant information in a compact form. It summarises the work of the author, his staff, and collaborators, which has been set out in papers read before the Institution of Electrical Engineers, London.*

The extent and importance of broadcasting makes it imperative, before embarking upon costly schemes, to know, in general, what service can be expected over a given area, suburban or rural, in terms of the power of the station, wavelength used, design of aerial, earth conductivity, etc., etc. It must be insisted that the forecast of service area can never be given to any great accuracy; the number of incalculable variables is too great to permit of anything but approximations. In general it may be said that well-known, and previously published, theory has been used to help arrive at the required approximations, while the soundness of the conclusions has been, as will be gathered from the text, well tested by direct experiment.

II

DEFINITION OF SERVICE AREA

It is considered that degree of service is a function of the clarity with which a programme can be heard. The degree of unwanted interruption to the programme is the degree of failure to give service. The majority of listeners in all countries find their continued interest in broadcasting due to what they hear, not the means by which they hear it. If what they hear is variable in strength, frequently distorted and accompanied by a background of extraneous noises, their enjoyment comes from causes for which the broadcasting engineer cannot hold himself responsible in any way. We are here concerned with broadcasting, not the art of fishing for microvolts in the eddies of the ether. The excellence of the transmitting service at a given point must be expressed quantitatively as a ratio of wanted signal field strength to interference field strength. This is, of course, largely independent of the type of the receiver; the response characteristic of the transmitter and the receiver will, however, be influencing factors.

* P. P. Eckersley, 'The design and distribution of wireless broadcasting stations for a national service.' *Journal of the Institution of Electrical Engineers*, Vol. 66, No. 377, May 1928.

P. P. Eckersley, T. L. Eckersley, H. L. Kirke, 'Design of transmitting aerials for broadcasting stations.' *Journal of the Institution of Electrical Engineers*, Vol. 67, No. 388, April 1929.

P. P. Eckersley and A. B. Howe, 'The operation of several broadcasting stations on the same wavelength.' *Journal of the Institution of Electrical Engineers*, Vol. 67, No. 390, June 1929.

In previous publications* I have defined, arbitrarily, three types of service area as follows:—

(1) 'A' service area, in which the field strength is greater than 10 millivolts per metre.
(2) 'B' service area, in which the field strength is greater than 5 millivolts per metre.
(3) 'C' service area, in which the field strength is greater than 2·5 millivolts per metre.

Extracts from the paper referred to read as follows:—

'A listener within an "A" service area can be absolutely 'guaranteed a service whatever (within obvious limits) 'the sources of extraneous interference, but will require 'a reasonably selective receiver to hear relatively distant 'or weak stations.

'A listener within a "B" service area can be guaranteed 'crystal reception with a good outdoor aerial, but will be 'at the mercy of the worst types of interference which 'occur in perhaps 5 per cent of cases normally met with.

'A listener within a "C" service area will be subject to 'interference from spark sets, electric trains, atmospherics, 'etc., but in time should be assured of (say) an 80 per cent 'service, because it is hoped that some of the interference 'under the above categories will be eliminated at the 'source.'

Notwithstanding the above definitions, the boundaries of the service area will always be determined where the (variable) strength of the space or indirect ray is frequently equal to or greater than the direct or ground ray.†

It is perhaps not irrelevant at this stage to point out that one does not seek, in including the majority of listeners within an 'A' or 'B' service area, to make it impossible for listeners of whatever nationality or district to listen to stations other than local. As an engineer responsible, however, for giving pure quality reception, it would seem that one's first concern is to give a service to populations inside the service area of the stations under one's control, i.e. to the 'local', not the 'distant', listener. Broadcasting has an undeniable international significance, but this is only based upon secure foundations when listeners of different nationalities find themselves inside the service area of the same station. Owing to the unfortunate unsuitability of the wavelengths allocated to broadcasting by international Governmental agreement, service area is usually (with the notable exception of the long-wave stations) too limited to embrace any but one group of nationals. We must thus, for the present, look to the internationalization of broadcasting in the linking of distant studio and local transmitter by wire, so that the 'distant' programme is radiated by the 'local' station.

* P. P. Eckersley, 'The design and distribution of wireless broadcasting stations for a national service.' *Journal of the Institution of Electrical Engineers*, Vol. 66, No. 377, May 1928.

† This point is dealt with later in much greater detail.

This pamphlet is thus confined wholly to a study of true service conditions, and is, therefore, concerned only with the problem of the listener anxious to hear the 'local' programme, whatever it may be, foreign, regional, or national.

III

THE ATTENUATION OF THE DIRECT OR GROUND RAY

Service area has been defined. Our object now is to forecast the field strengths set up in the area around the transmitting antenna. An antenna radiates rays both parallel to and at an upward angle to the earth's surface. Let us first consider only the rays parallel to the earth's surface—the so-called ground rays. A complete theory of radiation of ground waves has been set out by Sommer-

The relation between S and d_n is given in curve form in Fig. 1.* It is thus only required to determine d_n, of which the unknown quantity is σ, the conductivity of the earth. σ is a complex term, and involves not only the actual earth's conductivity, but is influenced also by anything on the earth which tends to absorb energy from the waves. Thus Barfield† shows that σ can be said to include a term for the number of trees of given condition per unit area.

A complete set of attenuation curves has been worked out according to the Sommerfeld theory. It is insisted that these curves are not purely theoretical; they have been verified experimentally by Barfield and the B.B.C. research staff. The former experimented with radiations on one wavelength; the latter have checked the curves for all wavelengths between 600 and 200 metres over all sorts of different types of country. These curves are given in Figs. 2 *a, b, c, d*.‡ They are given for an earth resistance

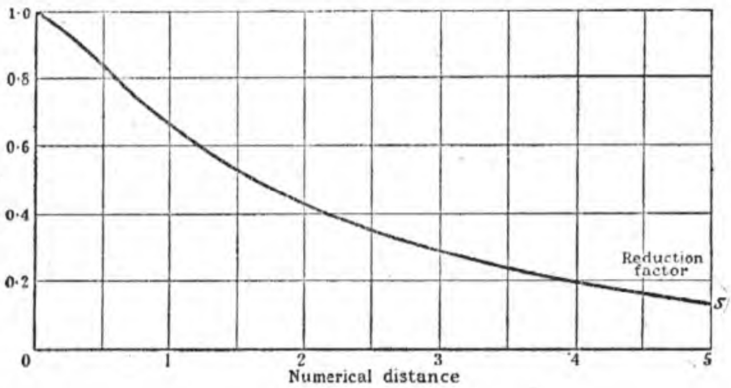

FIG. 1.—Sommerfeld's theory.

feld.* The theory has been applied to broadcasting problems in other publications.†

Summarizing, one can say that in general and for wavelengths within the broadcasting band, the field strength E_x at a point distant x from the transmitter can be determined as $E_x \propto \frac{1}{x}(S)$, where S is a multiplier of value always less than unity which takes into account ~~for~~ the attenuation due to the effect of the earth's finite conductivity.

S is said to be proportional to d_n, the numerical distance, which is in turn dependent upon the earth conductivity (σ), wavelength (λ) of the emitted ray, the distance x from the transmitting aerial in the following relation:

$$d_n = (\pi x/\lambda)\left\{\frac{1}{2\sigma\lambda c}\right\}$$ where c is the velocity of light.

of $\sigma = 10^{-13}$ c.g.s. units. But attenuation varies with the type of ground, thus $d_n \propto \frac{1}{\lambda 2\sigma}$. Thus to produce the same value of d_n (and hence the same value of attenuation), if σ is decreased 100 times, λ must be increased 10 times. This means that if we assume ordinary pastoral country to have a value of $\sigma = 10^{-13}$ c.g.s. units, while sea water has a value of $\sigma = 10^{-11}$ c.g.s. units, then a 200-metre wave over water has the same (small) attenuation as a 2,000-metre wave over land. Thus, in order to find the attenuation of waves over different types of ground one can use the curves of Figs. 2 *a, b, c*, etc., but substitute a new labelling. Thus, for instance, if we have an earth conductivity of 10^{-14} c.g.s. units, this is, then, obviously 10 times smaller than 10^{-13} c.g.s. units, for which the curves are drawn. The labelling of Figs. 2 *a, b, c, d* for an earth conductivity of 10^{-14} will thus

* *Annalen der Physic* 1909, Vol. 28, p. 665.
† R. H. Barfield, *Journal of the Institution of Electrical Engineers*, Vol. 66, p. 204, 1928.
P. P. Eckersley, T. L. Eckersley, and H. L. Kirke, *loc cit.*

* Fig. 14 in paper on 'Design of transmitting aerials', P. P. Eckersley, T. L. Eckersley, and H. L. Kirke, *loc cit.*
† *Loc. cit.*
‡ These will be found in the pocket at the back of this pamphlet.

have to be divided by the square root of the ratio of 10^{-13} divided by 10^{-14}, namely, by the square root of 10. Take, for instance, Fig. 2 *b*, and suppose it is desired to find out the attenuation of a wave of 316 metres, but over a ground having an effective earth resistance of 10^{-14}. It is then necessary to look at the curve for $316/\sqrt{(10)}$ metres, i.e. 100 metres in Fig. 2 *b*. It is seen at once that for 1 k.w. radiated the radius of the 'B' service area, namely, the radius of the 5 millivolts per metre contour (assumed circular) is, for 316 metres and for 10^{-13} c.g.s. units conductivity, about 30 kilometres, but for the lower conductivity (equivalent curve 100 metres) it is roughly 10 kilometres, or one-third the radius. This shows the great importance of knowing the earth conductivity before attempting to forecast service area. In order to make it easy to interpret the curves from one earth conductivity to another a conversion chart is given in Fig. 3.* Some examples are given to show how the curves may be used in conjunction with the conversion diagram.

EXAMPLE I

The earth conductivity is known to be 10^{-13}. The radiation efficiency is known to be 50 per cent. What is the 'A' service area of a station using a 500-metre wave and a power of 20 k.w. in the aerial?

ANSWER

The curves in Figs. 2 *a*, *b*, *c*, *d* can be used directly. 20 k.w. in the aerial means, with 50 per cent efficiency, 10 k.w. radiated; this means that the millivolts scale must be divided by $\sqrt{(10)} = \frac{1}{3 \cdot 15}$. Thus 10 m.v. per metre (i.e. 'A' service area) becomes (near enough) 3·0 m.v. per metre line on curves of Figs. 2 *a*, *b*, *c*, *d*. The result is thus, that the radius of the 'A' service area (assumed circular) is about 55 kilometres, or around 30 miles.

EXAMPLE II

As above, but earth conductivity 10^{-14}.

ANSWER

We find the point on the conversion curves $\sigma = 10^{-14}\lambda = 500$ metres. Follow the line down until it crosses the (standard) 10^{-13} line and read off the new equivalent wavelength. This is 160 metres. Now look on Figs. 2 *a*, *b*, *c*, *d* for the 160-metre curve, where it crosses the 3·0 millivolt per metre line ('A' service area with 10 k.w. radiated), and read off the radius of the 'A' service area as just about 20 km., or 12 miles. Notice how greatly the service area has decreased.

EXAMPLE III

A certain curve of attenuation has been found experimentally; what is the value of σ? λ is of course known from the experiment.

ANSWER

Lay the points on Fig. 2 and find the curve to which it is nearest. (The power radiated has no influence in this case.) Say this curve is the 200-metre curve, but the wavelength used in the experiment is 500 metres. Thus, look up the curve, Fig. 3, for 200 metres at 10^{-13}, follow this up until it crosses 500 metres, and read off the earth conductivity as $0 \cdot 15 \times 10^{-13}$.

ATTENUATION OVER TOWNS

These conclusions would be incomplete without referring to the work of Barfield and Munro on the 'Attenuation of wireless waves over towns'.* It will be sufficient to give, *in extenso*, the author's conclusion to that paper as follows:—

'The experimental results described above have shown 'clearly that the attenuation of waves over a large town is 'different from the attenuation of waves over the country. 'There appear to be two distinct effects, according to the 'nature of the surface which the waves traverse. Over the 'town itself the attenuation is determined by the absorp-'tion of energy in the vertical metal conductors, such as 'pipes of all kinds, electric wiring, steel frames, etc., and 'possibly by the dielectric losses in the bricks, cement, 'stone, and woodwork. The particular feature of the 'attenuation is that it increases very rapidly with the 'frequency of the waves. Thus, when the amount of town 'traversed is of the order of 3 miles or more, the signal 'strength decreases as the fifth power of the wavelength 'over the range dealt with in these experiments (roughly 'the broadcast range). From a theoretical investigation, 'based on an extension of Sommerfeld's theory, this rapid 'change appears to be consistent with the assumption 'that the losses occur in vertical conductors.

'It appears that tuned aerials occurring in the dense 'part of the town do not affect the attenuation, the energy 'they absorb being negligible compared with that ab-'sorbed by the masses of other conductors. This is no 'doubt due to the fact that such aerials are usually very 'inefficient and heavily screened.

'Over the suburbs, however, the extra rapid rate of 'change of attenuation with wavelength disappears, but 'if there are aerials tuned to the same wavelength these 'play an important part.

'The experiments show that a comparatively small area 'of about 5 km.^{2} may produce a selective decrease of 'signal strength to half its normal value, and that the 'wavelength for lowest signal strength is slightly below 'the wavelength to which the aerials are tuned. The 'actual position of the minimum appears to vary with 'the number of aerials traversed. An explanation of this 'effect is obtained by considering the shadow effect pro-'duced by the aerials, as well as the energy they absorb, 'and a calculation based on rough estimates of the density

* Fig. 3 is to be found in the pocket at the back of this pamphlet.

* *Journal of the Institution of Electrical Engineers*, Vol. 67, No. 386, February 1929.

'of distribution and constants of typical aerials confirms 'that they should produce an appreciable effect.

'The results can be used to a certain extent to discuss 'the effect of towns in connection with proposed schemes 'of broadcasting. Suppose a transmitter is situated just 'outside a large town and works on two wavelengths, '440 m and 260 m respectively. Consider two receivers ' "A" and "B", say 30 km distant from the transmitter, 'one "A" placed so that the waves have to travel right 'across the town, the other, "B", so that the waves travel 'free of the town. Assume that at "B" the intensity on '440 m is 6 mV/metre, then at the same point, and with 'the same power radiated, it will be about 2 mV/metre 'on 260 m. At "A" the experiments show that on the 'higher wave the strength will be about the same as at ' "B", whereas on 260 m it will drop to about 0·4 'mV/metre. In other words, it seems that, at the upper 'limit of the broadcasting range, towns have little effect, 'whereas on the lower range they cast a very decided 'shadow. Again, assuming now that the two wavelengths 'were only about 20 m apart, the field strength on the 'lower one might be appreciably affected by the aerials 'tuned to the upper wavelength, but that of the lower one 'would probably not be influenced to any great extent by 'any of the tuned aerials.'

It is impossible, from the results set out by Barfield and Munro in this paper, to give an absolutely definite attenuation curve for town conditions, but the broadcasting engineer would do well to realize that the densely populated areas are bound to cause very considerable shadows, and, if it is desired to feed a certain town from a broadcasting station on its periphery, it is well to see that the terrain on the side of the town remote from the station is of lesser extent than that in juxtaposition to the station. It was decided, for instance, to put the London station on the north side of the city because it was desired in some measure to feed large tracts of country on the north-east of London, whereas those to the south of London are less extensive, terminating after 60 miles on the coast.

We shall need a great deal more experimental data before being able to lay down definite values of earth conductivity for definite types of ground, but the following may act as some guide. The figures are approximate, but in most cases have been tested by experiment.

TABLE I

σ	Type of ground
$0{\cdot}5 \times 10^{-14}$	Very broken, mountainous country, thickly covered with forests
10^{-14}	Forest or mountainous country, or wooded hilly country
$0{\cdot}5 \times 10^{-13}$	Wooded flat country or hilly country
10^{-13}	Pastoral country, sparsely wooded
10^{-12}	Flat marshy ground
10^{-11}	Sea water

IV

CALCULATION OF THE FIELD STRENGTH OF THE INDIRECT RAY AT LARGE DISTANCES

An aerial radiates rays parallel to, as well as at an upward angle to, the earth's surface. We have so far showed how to calculate the value of the direct or ground ray. This section confines itself to a calculation of the indirect ray. The calculations are extremely general, and the results cannot be relied upon to more than the order of 2 or 3 to 1. As has been mentioned before, however, this is not a very serious matter.

The following is an extract of a paper read before the Institution of Electrical Engineers by the author and Mr. Howe, of the B.B.C. staff, which shows how an indirect ray value has been calculated and partially checked by experiment.

'The authors in the absence of complete data as to the 'measured absolute value of the indirect ray, have at-'tempted to estimate it to a sufficient accuracy.

'Their method to estimate the field strength value of 'the indirect ray has been as follows:—

'They assume that the transmitting aerial (T) radiates 'rays typically A, B, C, D, etc. (see Fig. 3*), D is the 'direct ray, while C, B, A are angular radiations. Rays 'A, B, C travel in a straight line until they meet the 'Heaviside layer, where they are bent earthwards again 'and impinge on the earth at points P_1, P_2, P_3, distant 'x_1, x_2, x_3, etc., from the transmitting station, T. In order 'to estimate the value of the reflected ray at points P_1, 'P_2, P_3, etc., the authors have made the following assump-'tions:—

'(1) That the strength of upward radiation from a 'transmitter is determined by multiplying the 'full radiation in a horizontal direction by the 'cosine of the angle between the upward and 'horizontal radiations, i.e. the transmitting aerial 'has a semicircular vertical polar diagram.

'(2) That the minimum absorption coefficient of the 'Heaviside layer is 0·9. That is to say, if E_1 is 'the strength of any ray A, B, C (Fig. 3*) before 'entering the layer, and E_2 the maximum 'strength of the same ray after leaving the layer, 'then $E_2/E_1 = 1/10$. (Note that it is the maxi-'mum field strength value of the indirect ray 'which determines the interferences.)

'(3) That the absorption coefficient is constant for all 'angles of impinging rays.

'(4) That the field strength of the indirect ray varies 'inversely as the distance travelled from earth to 'layer and from layer back to earth, i.e. the dis-'tance travelled is TQP_1 or TQ_2P_2, etc. (Fig. 3*).

* Fig. 4 of this paper.

Distance along earth's surface = x	Distance along path of ray = s	Maximum field strength at x. Distance given by $E_{x_1}a\frac{1}{s}$	Multiplier M to reduce field strength at distance x owing to semicircular vertical polar diagram
1	2	3	4
km	km	mV/metre	
25	200	1·3	0·2
50	220	1·25	0·32
100	240	1·2	0·45
200	280	0·91	0·70
300	350	0·72	0·83
400	444	0·58	0·9
500	540	0·48	0·925
600	624	0·42	0·94

Maximum value of indirect ray assumed $E_{n0}=\frac{E_nT}{10}$	Fluctuation $\left(\frac{E_n+E_d}{E_d}\right)$		
	$\lambda = 500$	$\lambda = 300$	$\lambda = 200$
16	17	18	19
mV/metre			
0·03	—	—	—
0·040	—	—	—
0·054	—	1·20	2·1
0·064	1·025	2·9	11·0
0·06	1·83	7·0	33·0
0·052	2·56	13·0	60·0
0·044	4·0	22·0	100·0
0·04	5·0	41·0	160·0

'TABLE 2

Maximum theoretical field strength of indirect ray is given by $E_{nT}=ME_{z_1}$ and assuming no absorption at layer	Field strength of direct ray (taken from attenuation curves) = E_d				Test of theory: Ratio $\frac{E_{nT}}{E_d}=R_T$ (Theory)		Test of theory: Ratio $\frac{E_{n0}}{E_d}=R_0$ (Note E_{n0} is average)*		Test of theory: $\frac{R_T}{R_0}=C=$ constant if the author's assumptions are correct	
	λ = 500 m	λ = 375 m	λ = 300 m	λ = 200 m	λ = 375 m	λ = 300 m			λ = 375	λ = 300
5	6	7	8	9	10	11	12	13	14	15
mV/metre	millivolts per metre									
0·26	8·6	7·5	6·1	3·0	—	—	—	—	—	—
0·40	3·5	2·4	1·6	0·43	—	—	—	—	—	—
0·54	1·05	0·56	0·3	0·05	0·965	1·8	—	—	—	—
0·637	0·26	0·830	0·033	0·0065	7·7	19	0·8	1·35	9·6	14
0·6	0·068	0·024	0·01	0·0021	25	60	2	3·5	12	17
0·52	0·032	0·01	0·0042	0·00085	52	125	4	9·0	13	14
0·44	0·015	0·0055	0·0021	0·00042	80	220	7	15	11	14·6
0·4	0·009	0·003	0·001	0·00025	130	400	10	24·0	13	16·5

'TABLE 2—*continued.*

Total radiation (E_n+E_d)			Distance apart of equal-power stations = D	Range of stations sharing one wavelength = R			Distance apart of equal-power stations = D	Range of stations sharing one wavelength = R*		
λ = 500	λ = 300	λ = 200	10 factor	λ = 500 m	λ = 300 m	λ = 200 m	5 factor	λ = 500 m	λ = 300 m	λ = 200 m
20	21	22	23	24	25	26	27	28	29	30
millivolts per metre				kilometres				kilometres		
8·63	6·13	3·03	600	130	80	50	600	180	110	60
3·54	1·64	0·47	400	95	70	45	400	120	90	55
1·1	0·35	0·104	200	40	42	40	200	55	50	48
0·32	0·10	0·07	100	16	22	30	100	23	24	35
0·13	0·07	0·062	50	5	6	13	50	5	6	14
0·082	0·056	0·053	—	—	—	—	—	—	—	—
0·06	0·046	0·044	—	—	—	—	—	—	—	—
0·05	0·045	0·04	—	—	—	—	—	—	—	—

* Observed by Bureau of Standards, *loc. cit.*

'(5) That the angle of incidence of the ray to the layer 'is equal to the angle of reflection from it, i.e that 'rays A, B, C, etc., always follow the path shown 'diagrammatically in Fig. 3.*

'(6) That the height of the layer is 100 km.

'(7) That the value of the horizontal radiation (for a 'calculation of the indirect and direct ray values) 'shall be that given by P. P. Eckersley, T. L. 'Eckersley, and H. L. Kirke in a paper recently 'read before the Institution.†

'The curves in Fig. 12‡ of that paper form the 'basis of this and subsequent calculations on the 'relative value of direct and indirect rays.

'It is appreciated that these are somewhat wide assump-'tions. The fact that they bring a result which agrees with 'observations must be some justification for their adop-'tion. In support of the assumptions we have, under (1), 'reasons this need not greatly upset the final calculations. 'Under (7) we are justified as the figures are the direct 'results of observation. Table 2 gives details of the calcu-'lations.

'Prof. Appleton, in co-operation with the Radio 'Research Board, has taken measurements of the indi-'rect ray at various distances. The station used was 5GB, 'and the direction northerly. The B.B.C. are in possession 'of sufficient data to deduce from Prof. Appleton's 'figures the value of the indirect ray for 1 k.w. radiated. 'This enables a comparison to be made between the 'theoretical value and the observed value of the indirect 'ray. By the kind permission of Prof. Appleton, Table 3 'is given, showing a comparison of theory and measure-'ment.

'The chief interest is, considering that the authors are 'aiming always at estimating a maximum field-strength 'value, the remarkable agreement in quantity and the fact,

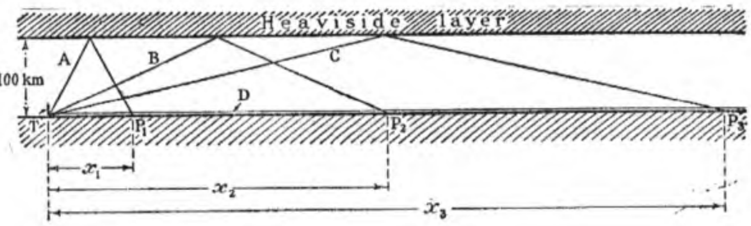

FIG. 4.

'most transmitting aerials at present in use have a semi-'circular vertical polar diagram. (2) The reason for choos-'ing this value of absorption coefficient is explained later; 'it is sufficient at this stage to say that the figure is based 'on the results of observations. Under (3), Prof. E. V. 'Appleton has postulated a multi-layer structure of the 'electrified upper atmosphere. A shallow-angle imping-'ing radiation (i.e. a ray nearly parallel to the under 'surface of the layers) would make a considerable penetra-'tion, even if it were better reflected, whereas a sharp-'angle ray (i.e. one nearly normal to the layer), while it 'may be worse reflected, has a shorter path in the layer, 'and therefore loses less of its energy. The absorption 'coefficient 0·9 is chosen because, as will be shown later, 'it fits observed results. Under (4), it is fair to assume no 'ground attenuation. As to (5), it is probably quite wrong 'to state that the angle of incidence to the layer always 'equals the angle of reflection, but it is arguable, on what 'is known, that if the indirect ray does not always take 'this path it takes another of equal length, and its value 'on the earth's surface does not therefore greatly change. 'We are trying to find a maximum field-strength value of 'the indirect ray. Under (6), the height is derived from 'Prof. Appleton's calculations, and is taken as a round 'figure. It is admittedly an approximation, but for stated 'taking into account that not a great many measurements 'were taken, that the measured values are largely inde-'pendent of distance, as the authors' theory indicates they 'should be (within limits).

'The values of the direct ray beyond 100 km. have 'been calculated by the Sommerfeld formulæ, assuming

'TABLE 3

Distance from transmitting station	Measurement	The authors' assumptions
	Value of indirect ray	Value of indirect ray
km	millivolts per metre	millivolts per metre
120	0·0425	0·056
144	0·0250	0·059
240	0·0325	0·062
320	0·045	0·060

'an earth's conductivity equal to 10^{-13} c.g.s. units. They 'fit observed results for the first 100 km.

'The figures in cols. 10–15 of Table 2 require ex-'planation. Observations on the ratio of the indirect to 'the direct ray are given in a paper by the Bureau of 'Standards, Washington.* This is conveniently shown in

* Fig 4. of this paper. † *Loc. cit.*

‡ Same curves as Fig. 2 of this pamphlet.

* *Co-operative Measurements of Radio Fading in* 1925, No. 561.

'curve form in that paper. Now the authors have proceeded to the final result by finding a value E_{nT} in col. 5 'which would be the value of the indirect ray if there 'were no absorption of energy at the layer. We can then 'find a ratio E_{nT}/E_d which is fictitious, but which would 'be correct if there were no absorption, i.e. if the field 'strength of the ray entering the layer equalled the field-'strength value of the ray leaving the layer. But the ratio '$E_{nT}/E_d = R_T$ (i.e. a theoretical ratio) should bear a constant relation to the observed ratio $R_o = E_{no}/E_d$. We 'see in cols. 14 and 15 that there is in fact a fairly constant 'ratio, showing that the assumptions are not very wide 'of the mark. Compared for the same wavelength (col. 14) 'we find an average ratio of R_T/R_o of 11·7. Dividing R_T 'by 11·7 should therefore give a measure of the indirect 'ray value. It has been preferred to divide by 10 (see 'col. 16) because it is desired always to have a maximum 'value. The observed values of R_o were for average values 'only.'

Thus the authors found an average value of indirect ray of about 0·06 m.v. per metre for 1 k.w. radiated. Later observations and various other considerations make it appear wiser to put this at a somewhat higher value, and, still insisting that the figure merely gives the order of the quantity we shall assume that *for all distances between* 30 and 1,000 *km. the value of the indirect ray is* 0·1 *m.v. per metre for* 1 *k.w. radiated.*

The simplicity and boldness of the assumption will, it is hoped, appeal to engineers. To justify the rough-and-ready character of the assumption one can say this: it is only necessary to know the value of the indirect ray to assess where severe fading sets in or to calculate the range of stations using the same wavelength (see Section VIII). As the radiations along the ground are so difficult to calculate to a great accuracy, as 'service' cannot be defined to a millivolt or so, as the whole calculations must take on a most rough-and-ready character, errors of 2 or 3 to 1 are allowable. Nevertheless the calculations, made possible by the aid of the curves, are essential to the engineer mapping out a new scheme of distribution of transmitting stations.

V

THE DESIGN OF TRANSMITTING AERIALS

The curves of Fig. 2 are plotted on the basis of 1 k.w. radiated. This means that the radiation resistance of the aerial multiplied by the square of the aerial current gives a power of 1 kilowatt. But the design of the transmitting aerial must influence its efficiency as a radiator of the ground ray, and the engineer occupied with the particulars of broadcasting must know this efficiency, expressing and meaning his power as power in the aerial, not power radiated.

The following analysis is copied from a previous paper of which the writer was part author.*

'It has been shown† that radiation from an aerial situated at ground level can be resolved into radiation due 'to the aerial itself, and radiation from an image of the 'aerial in the earth.

'Consider that the aerial and its image are composed 'of elements dh of h, the height, each with elements of 'high frequency current i; then the radiation in any direction can be calculated by adding vectorially the radiation 'from each element of height, provided the height above 'the earth of this element is small compared with $\sqrt{(\lambda d)}$, 'where λ is the wavelength and d is the distance of the 'point of measurement of the radiation from the aerial.

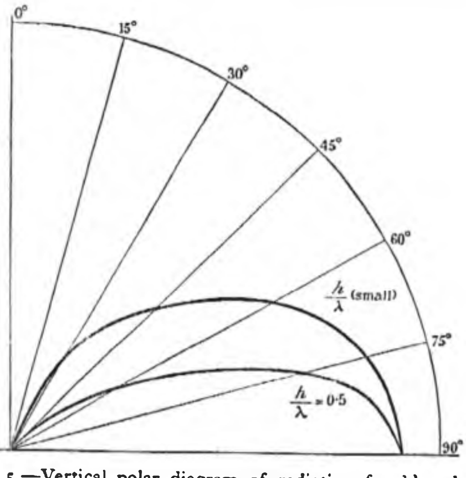

FIG. 5.—Vertical polar diagram of radiation for $\frac{1}{2}\lambda$ and $\frac{1}{4}\lambda$ (or less) aerials. Drawn for the same maximum radiation intensity in the horizontal plane.

'Clearly if the currents in the elements are in phase, the 'field strength on the ground nearby is the arithmetical 'sum of the radiations from the elements.

'For aerials of vertical height h, less than $\frac{1}{4}\lambda$, the space 'phase of the element currents in the real aerial, and its 'image will not be sufficiently different to cause cancellation of radiation in non-horizontal directions. As h is 'increased to $\frac{1}{2}\lambda$, however, the maximum current I in the 'aerial is at a distance $\frac{1}{2}\lambda(180°)$ from the maximum image 'current. There will be in this case considerable cancellation of radiations at high angles. As h is still further 'increased, then, provided the currents are in phase all 'along the aerial, the cancellation will be greater still in 'all directions other than the horizontal.

'Fig. 1‡ gives the vertical polar diagrams, calculated by 'Stuart Ballantine for $\frac{1}{4}\lambda$ and $\frac{1}{2}\lambda$ aerials for the same field 'strength on the ground. It is assumed that the earth is

* 'Design of transmitting aerials for broadcasting stations', P. P. Eckersley, T. L. Eckersley, and H. L. Kirke.

† T. L. Eckersley, *Journal of the Institution of Electrical Engineers*, 1927, Vol. 65, p. 600.

‡ Fig. 5 of this pamphlet.

'a perfectly conducting medium. (Note that the vertical 'polar diagram of the $\frac{1}{2}\lambda$ aerial is flatter than that of the '$\frac{1}{4}\lambda$ aerial, due to angular radiation cancellations.) It will 'be seen that radiation horizontally will be proportional 'to $\int idh$. Consequently a given field strength can be 'obtained by the use of a high aerial with small current, 'or a small aerial with large current, i.e. the metre-'amperes must be the same.

'All energy not radiated horizontally is, from the broad-'casting point of view, wasted. It will therefore appear 'obvious that the high aerial with small current will be 'the most efficient.

'Most wireless engineers have been educated to con-

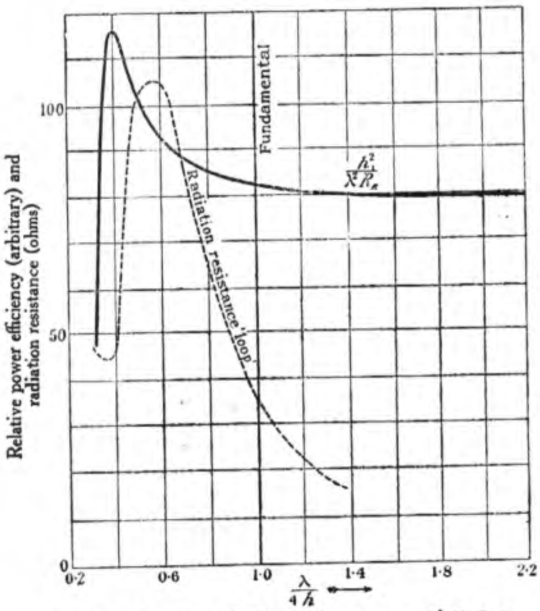

Fig. 6.—Ordinate (thick curve) represents $h_1^2/(\lambda^2 R_R)$.

h = height of vertical aerial.
λ = wavelength.
R_R = radiation resistance.
h_1 = effective height.

'sider only the problems concerned with $\frac{1}{4}\lambda$ aerials. This 'is only necessary when very long waves are used. The 'radiation resistance R_R can, for $\frac{1}{4}\lambda$ aerials, be found from 'the expression $1{,}580\, h_1^2/\lambda^2$, where h_1 is the effective 'height of the aerial. Radiation efficiency has been ex-'pressed as $R_R/(R_R + R_D)$, where R_D is the dead-loss 'resistance. In the past it has been considered desirable 'to make this expression as nearly unity as possible; that 'is, to get as much radiated energy from a given power as 'possible. The broadcasting engineer, however, requires 'only ground radiation, and is not concerned with total 'radiation, which might, as a *reductio ad absurdum*, be 'all in a vertical direction. Thus radiation efficiency is not 'so important as power efficiency to produce a given field 'strength on the ground.

'The field strength on the ground for a given wave-'length is proportional to metre-amperes $(h_1 I)$. For a 'given power we must therefore produce a maximum 'value of $h_1 I/\lambda$. We must answer the question: What is 'the relative power required to produce a given value of '$h_1 I/\lambda$ with $\frac{1}{4}\lambda$ and $\frac{1}{2}\lambda$ aerials? For the reasons explained 'above, increasing the height of the aerial, by producing 'cancellations of angular rather than horizontal radiation, 'flattens the vertical polar diagram while the ground 'vector proportional to $h_1 I/\lambda$ remains the same. Thus *less 'power is radiated with the high aerial, while the horizontal 'vector remains the same.* This means that less power is 'required with a high aerial to produce a given value of 'metre-amperes. Analysing this in more detail, we can 'find a relative power efficiency for each aerial. For a '$\frac{1}{4}\lambda$ aerial this efficiency is

$$\eta = \frac{A(h_1^2/\lambda^2)I^2}{(R_R + R_D)I^2} = \frac{\text{watts output}}{\text{watts input}} = \frac{Ah_1^2}{\lambda^2(R_R + R_D)}$$

'where A is constant.

'Now if, on increasing h, the radiation resistance

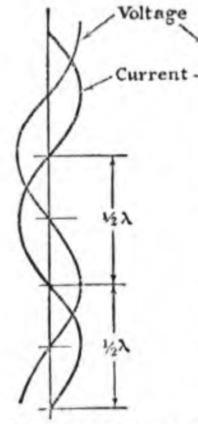

Fig. 7.—Current and voltage in a long uniform aerial.

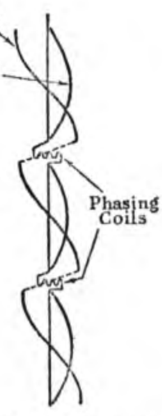

Fig. 8.—Current and voltage in a Franklin aerial.

'remained proportional to h_1^2 (given a constant small 'value of R_D) the above term would remain nearly con-'stant for any value of h. But less power is radiated as we 'increase height, and so R_R does not go up in proportion 'to h_1^2, but at a lower rate.

'Consider then the term $h_1^2/(\lambda^2 R_R)$. This should be 'nearly constant for all aerials of height h less than $\frac{1}{4}\lambda$, 'but should increase rapidly thereafter. Stuart Ballantine 'has calculated $h_1^2/(\lambda^2 R_R)$, and Fig. 2* shows the results 'of his theoretical calculation.

'The x axis of Fig. 2* is drawn on a scale of the ratio 'of $\lambda/(4h)$, and the y axis represents the expression '$h_1^2/(\lambda^2 R_R)$ plotted on a purely relative scale. It is reiter-

* Fig. 6 of this pamphlet.

'ated that this curve represents, in fact, $\int idh$ and shows 'the increase of horizontal radiation due to the decreased 'total radiation for a given power as the number of 'elements dh, are added together vertically. A curve of 'radiation resistance is plotted for future reference. It is

'in his beam system for short wave telegraphy. Fig. 8* 'shows the relative power required to produce a given 'field strength with different values of $4h/\lambda$ up to a value 'of 2. Obviously from the expression for metre-ampere 'efficiency, $h_s^2/\{\lambda^2(R_R + R_D)\}$, the value of the dead-

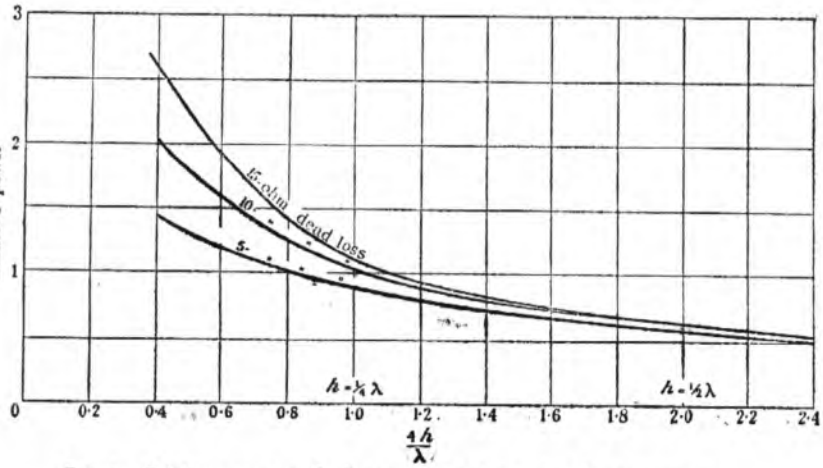

FIG. 9.—Relative power required to produce a given value of metre-amperes.

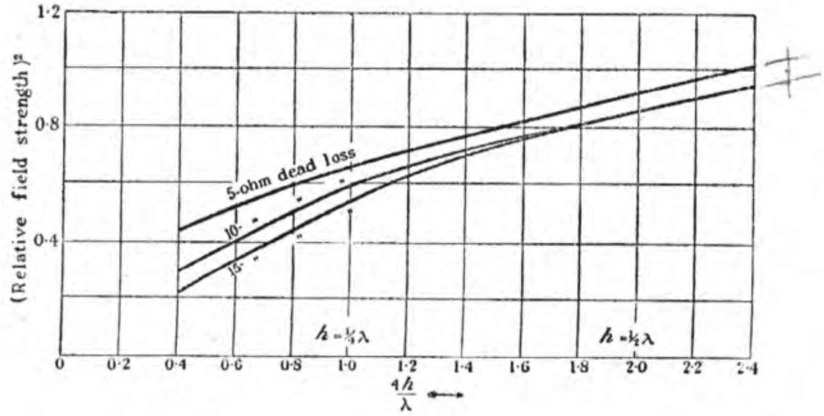

FIG. 10.—Relative field strength for a given power for various values of h/λ.

'also a purely theoretical curve. It will be seen that the 'curve for radiation resistance gives a value, for $\frac{1}{2}\lambda$ aerials, '*less than* that given, by $1{,}580\, h_s^2/\lambda^2$.

'It will be remarked that after the value of h/λ is 'increased beyond 0·4 the expression $h_s^2/(\lambda^2 R_R)$ decreases 'abruptly. This is explained by realizing, as shown in 'Fig. 3,* that the phase reverses in the upper part of a 'long homogeneous aerial unless precautions are taken 'to avoid this effect. The obvious line to take is to add '(see Fig. 4†) $\frac{1}{2}\lambda$ aerials, one above the other, and to intro-'duce a "phasing coil" to reverse the phase at each join. 'This device has been adopted by Mr. C. M. Franklin

'loss resistance R_D affects the result, and so curves are 'shown for various values of dead-loss resistance.

'It will be seen that theoretically, and with 10 ohms 'dead-loss resistance, we save about 40 per cent of 'power by using $\frac{1}{2}\lambda$ instead of $\frac{1}{4}\lambda$ aerials to produce the 'same field strength at a given point. Fig. 6† shows the 'increase of field strength using different heights of aerial 'with the same aerial power, W.'

FADING

In the paper from which the above is extracted a figure (No. 7 of that paper) is given showing that

* Fig. 7 of this pamphlet. † Fig. 8 of this pamphlet.

* Fig. 9 of this pamphlet. † Fig. 10 of this pamphlet.

theoretically we should expect a considerable reduction in the indirect ray. All that we can say at present is that using $\frac{1}{2}\lambda$ aerials the indirect ray does not seem to suffer reduction to any extent—we can say, however, that fading appears to be reduced because of the increase of the direct ray. This may seem rather contradictory because theoretically an increase of the direct must mean a reduction of the indirect ray. However, in Prof. Appleton's phrase, when an aerial transmits, 'the whole sky is lighted up', and in practice there is no appreciable reduction of the indirect ray, we only gain by increasing the direct.

Continuing extracts from the paper on transmitting aerials, we read:—

'NOTE ON EFFECTIVE HEIGHT

'There may be some confusion as to the meaning of 'h_1, the effective height. For instance, it is well known 'that the theoretical effective height h_1 for a $\frac{1}{4}\lambda$ aerial is '$(2/\pi) \times$ actual height h. But it is important not to use 'this value for h_1 if an aerial less than $\frac{1}{4}\lambda$ in height has to 'be loaded by added inductance to give it the natural 'wavelength as if it were a vertical wire of length $\frac{1}{4}\lambda$. 'Effective height is a misleading term for loaded aerials '—effective current is more definite. This would mean 'the average value of the current in the vertical part of 'the aerial and metre-amperes would be found by multi'plying the actual height of the vertical part by the 'average current in that part.

'Conversely, effective height could be worked back 'from a measure of the field strength at a distance of a 'few wavelengths from the aerial calculated from the 'formula $E = 377\, h_1 I/(\lambda d)$, where d is the distance of 'the point of measurement from the aerial. The authors 'feel that effective height is best expressed therefore as '$h_1 = E\lambda d/(377 I)$ (I being the maximum current in the 'aerial, d the distance at which the field strength is 'measured, and λ the wavelength), whatever the form of 'aerial. Effective height taken in this way depends upon 'the distance d. This distance must be chosen so that the 'field strength at that distance does not suffer attenuation. 'In practice this distance is safely taken as 5 wavelengths.'

The above theoretical considerations have been verified in practice by experimenting with definite types of aerial hung from a kite balloon.

The practical value of these results is considerable, and we need to take the design of aerial fully into account when considering the important curves of Fig. 2. A set of curves is therefore given in Figs. 9* and 10† which give the required information.

This information is presented in a more practical form in Fig. 11. It is required to find the field strength obtainable from aerials supported by masts between 200 and 800 feet high, and between wavelengths of 200 and 500 metres, it being assumed that in each particular case of masts and wavelengths the aerial has been designed to give the maximum efficiency, i.e the maximum field-strength at a given power input. The following assumptions have been made with the calculations:—

Mast height (feet)	Sag (feet)	Height of vertical portion (feet)	Height of vertical portion (metres)
200	40	160	49
300	55	245	75
450	75	375	115
600	100	500	152
800	120	680	207

Dead-loss resistance in all cases 10 ohms. Total input power to aerial, 50 kilowatts in all cases.

In cases where the actual height is of the order of $\frac{1}{2}\lambda$ or over, it is probable that greater efficiency would result from the use of one of the new type Franklin aerials, assuming that the top $\frac{1}{2}\lambda$ aerial in each case had its current antinode at the junction of the vertical portion and top hamper.

In cases where h/λ lies between $\frac{1}{4}$ and $\frac{1}{2}$ allowance has been made for the lowering of the radiation resistance, as the polar diagram will be flattened due to the current antinode being well above earth, i.e. all aerials have a top hamper except in the case of the $\frac{1}{2}$ wave aerial not arranged in Franklin system.

The reduction in radiation resistance is largely guesswork; but as the estimate is only approximate, it is thought that the approximation is sufficiently good for all practical purposes.

The method adopted in the calculation is as follows:—

In each case plot the current distribution in the vertical portion, assuming a reasonable top hamper. Calculate from this the average current in the downlead, the ratio of average current to maximum current giving the ratio of effective height to actual height. From the value of h_1 so obtained calculate the radiation resistance from $R_R = 1{,}580\, h_1^2/\lambda^2$. Make any reduction necessary in the radiation resistance according to the value of h/λ. Add 10 ohms dead loss. This gives the total resistance. The current in the aerial is then obtained from $I = \sqrt{(W/R)}$, where W is the total input power to the aerial. $h_1 I/\lambda$ can then be calculated.

The radiation resistance of a $\frac{1}{4}\lambda$ aerial is about 30 ohms. The dead-loss resistance is assumed (just as it appears from measurements) as 10 ohms, so that the radiation efficiency is 75 per cent. Thus the curves of Figs. 2 *a*, *b*, *c*, *d* for a $\frac{1}{4}\lambda$ aerial represent 1·25 k.w. power in the aerial. The curves of Fig. 9 therefore give a multiplier to show the power in the aerial required to produce the field strength of Fig. 2 for various heights of aerial expressed as a ratio to the wavelength. Thus a $\frac{1}{2}\lambda$ aerial will require, from the curves of Fig. 9, and with a 10 ohm dead loss, $0{\cdot}6 \times 1{\cdot}25 = 0{\cdot}750$ kilowatt in the aerial to produce the radiations as shown in Fig. 2. This is perhaps a curious curious way of putting the matter, as the curves are

* Fig. 5 of the paper on 'Design of transmitting aerials'.
† Fig. 6 of the paper on 'Design of transmitting aerials'.

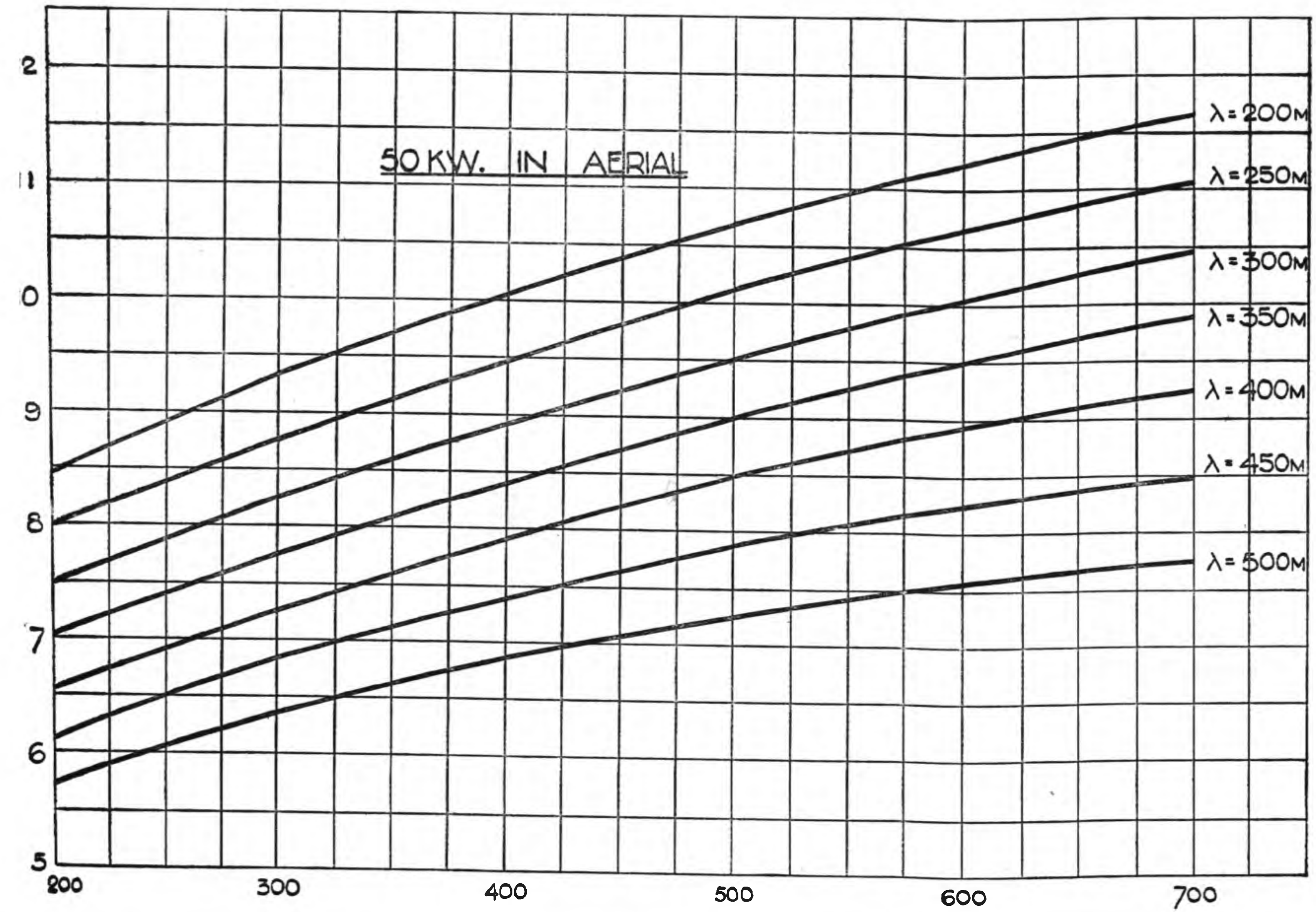

FIG. 11 HEIGHT OF MAST IN FEET

drawn for 1 k.w. radiated, and yet we say that they can be produced by a power of 0·75 k.w. in the aerial. It must be remembered, however, that with a $\frac{1}{4}\lambda$ aerial much of the power is radiated upwards, and is not useful. The practical engineer requires to know what field strengths will be produced with a given power in the aerial, and this seems, to the author at any rate, the simplest way of presenting the relevant data. The $\frac{1}{4}\lambda$ aerial has to be used so frequently that it seemed most relevant to give the curves of Fig. 2 for a radiated power, and thereafter apply corrections for less conventional aerials.

Too little is known at present about the effect of mast absorption to give any but the vaguest hints on this subject. The writer believes that it is always best to insulate the masts (they can then be earthed through any given circuit afterwards if so desired), and place them as far as mechanically possible from the aerial proper. When using a **T** aerial the free ends of the horizontal part should be left well away from the masts. Wooden masts have been built, notably in Germany, to overcome the disadvantage of the possible distortion of the required symmetry of the horizontal polar diagram of radiation, but there is always the danger of fire with this type of arrangement.

This section cannot conclude without pointing out that Dr. Balth. Van der Pol, Jun., communicated in 1917 a paper on the wavelengths and radiation of loaded antennæ to the Physical Society of London, which dealt with the theoretical considerations underlying the above practical conclusions.

VI

MAXIMUM ECONOMIC POWER OF A BROADCASTING STATION

Considering the foregoing, we see that it is useless to increase the power of a broadcasting station beyond that amount which will give service conditions at the point where the indirect ray becomes comparable with the direct. Obviously fading will be sufficiently pronounced at this point to prevent real service conditions, whatever the power of the station; if we double the value of the direct ray by increasing the power of the station we equally double the value of the indirect ray, and so the fading remains the same, independently of power. But the power of the station will determine the ***absolute value of the direct ray*** at this point of intolerable fading, and hence the degree of service just within the boundary. This theoretical boundary cannot be traced to a few miles; it is best, however, to proceed as though exact definition were possible, and then derive the orders of quantity desirable. Let us then confirm that, since we have assumed a high value of indirect ray, the boundary of the service area, whatever the millivolts per metre, will fall where the direct ray from the transmitting aerial is equal to the indirect ray from that transmitting aerial. The distance of this point from the transmitting aerial is given by the value of the abscissæ of curve 2 at the point of the intersection of the attenuation curve with the 0·1 m.v. per metre line, i.e. the place where the attenuation curve crosses the x axis. (The curves were purposely drawn in this way for this reason.)

It is required, ideally, at any wavelength, to produce 2·5 m.v. per metre at this distance from the transmitting station, i.e. to produce the lower limit of 'C' service conditions at the point where the direct and indirect rays are equal. Since the curves of Fig. 2 are for a power of 1 k.w. radiated, this power must be multiplied by $(2\cdot5/0\cdot1)^2$ to get the ideal theoretical power radiated to produce the above conditions. Thus, the power radiated for any wavelength must be 625 k.w. Naturally with higher aerials, for longer waves, and for greater earth conductivity the point at which the direct and indirect rays become equal is further and further away from the transmitter: nevertheless it should be particularly noted that the maximum economic power of a station is independent of all these variables.

A power of 625 k.w. radiated is quite impractical, even assuming the use of a $\frac{1}{2}\lambda$ aerial. We must realize, however, that it is seldom necessary to produce 'C' service area conditions for every listener within range of a station. Thus, if a condition arose, using one of the shorter waves, that 90 per cent of the people to be served lived within a very small radius from the station, it would be foolish, for the sake of a very small minority, enormously to increase its power. We could say that where minorities were found in the outer limits of the service area of the station it was sufficient to produce 1 m.v. per metre at the point of intolerable fading. A simple calculation shows that in this case the maximum economic power radiated comes to 100 k.w. In sum it will be seen that the rigid definition of the maximum economic power of a station is impossible, and must depend upon conditions.

TABLE A

λ	Suggested practical maximum power
200–250	20 kW
250–300	50 kW
300–~~400~~ 500	75 kW
Above 1,000	200 kW

The question has, however, a further important aspect. The reader will realize that the interference-producing qualities of a station are independent of wavelength, and yet directly dependent upon power (always assuming that the indirect ray has a constant value at all wavelengths and at all distances between 50 and 1,000 km.). Thus a 200-metre, 200-k.w. station has a very limited service area, and therefore does little good locally in most cases, but produces very severe interference in a continental area, and does much harm over large tracts of country. It is thus uneconomic and against the general interests unduly to increase the power of the shorter wave stations. Assuming European conditions of broadcasting, and realizing that the figures will be taken only as a guide, it is suggested that Table A represents the maximum economic power (in the aerial) of typical broadcasting stations. Although it has been proved above that, theoretically, this figure is independent of wavelength, other considerations show that in the general interest it is important to keep the power to the low values when using the shorter wave. This point will be dealt with later when considering the unsuitability of the present wavelengths allocated by Governments for broadcasting.

bility of their solution in terms of present wavelength allocation. Perhaps it is best to illustrate the argument by an example. Take, for instance, the question of providing a national broadcasting service for Canada. Canada embraces a vast tract of country, mountainous in some parts, flat in others, densely wooded here, agricultural there, but throughout inhabited by a thinly scattered population largely cut off from any recreation. These people would appear to deserve the advantages that broadcasting alone can bring. The numbers of free wavelengths available for Canada (even if the North American continent solves its problem of station channel allocations, as has been done in Europe) might

TABLE B

f(kc/s)	λ metres	Equivalent λ for $\sigma = 10^{-13}$	Maximum Possible Radius of Service Area = R		Area = πR^2	
			Kilometres	Miles	Square kilometres	Square miles
560	536	375	172	103	93,100	33,400
600	500	355	155	93	75,500	27,200
640	469	332	138	83	59,900	21,600
680	442	320	130	78	53,000	19,200
720	416	295	125	75	49,000	17,600
760	394	280	120	72	45,200	16,300
800	375	268	115	69	41,500	15,000
840	357	253	110	66	38,000	13,700
880	341	245	105	63	34,600	12,500
920	326	231	100	60	31,400	11,300
960	312	224	98	59	30,200	10,950
1,000	300	215	87	52	23,800	8,500
1,040	288·5	210	84	50·4	22,200	8,000
1,080	278	200	80	48	20,100	7,230
1,120	268	189	74	44·4	17,200	6,200
1,160	258·5	182	68	41	14,550	5,290
1,200	250	174	63	38	12,450	4,540
1,240	242	169	59	35·4	10,950	3,940
1,280	234	165	57	34·2	10,200	3,670
1,320	227·5	160	55	33	9,500	3,420
1,360	220·5	155	53	31·8	8,810	3,180
1,400	214	151	51	30·6	8,180	2,945
1,440	208·5	146	48	28·8	7,230	2,610
1,480	202·5	142	46	27·6	6,650	2,390
Total area of 24 channels					723,220	260,665

Total area of Canada = 10,360,000 sq. km., or 3,730,000 sq. miles.
Therefore percentage served = 6·9 per cent.

VII
THE UNSUITABILITY OF THE WAVELENGTHS AT PRESENT USED FOR BROADCASTING

The reader of this section is referred in turn to certain outstanding problems in broadcasting, and to the impossi-

not exceed 25 out of the total 100 or so available. The largest wave available for broadcasting in the American continent is 545 metres. Assume that in general the earth conductivity in Canada is $0{\cdot}5 \times 10^{-13}$. This will mean that the curves of Fig. 2 must alter their labelling, and that a wavelength of 545 metres in Canada has an attenuation represented by the 380 metres (roughly) curves of Fig. 2.

Let us with the aid of the foregoing data find out the total extent of possible service area in Canada, using the existing facilities. We will take 24 equally spaced waves between 545 and 200 metres, each separated one from another by 40 k.c. Table B, on page 17, sets out the results, and we see that 260,665 square miles (approx.) of Canadian territory can be covered by service conditions if each station has sufficient power. (The limit chosen is set by fading conditions, as indicated in Section VI.)

Now let us assume that we start with the highest wave available as 2,000 metres (150 k.c.), and again take 24 waves 40 k.c. apart, and again find the service area possible, using these much more suitable waves (Table C).

Taking the total area of Canada as 3,730,000 square miles, we see that existing facilities allow us to cover 6·9 per cent of the surface by service conditions, whereas by using the same number of channels, but in a more suitable part of the wave-band, we cover 83 per cent of the surface, or twelve times as much.

No doubt critics of the conclusions reached in this section, after they have made a complete perusal of the pamphlet, will insist that by using the same wavelength for several stations a much better case could be made out for the existing state of affairs. They will argue furthermore that 5 k.c. separation between the east and west coast of Canada is perfectly possible, that a 'little fading makes no difference really', and that people work in the daytime and only want the amusement of broadcasting at night.

It is true that the synchronization of stations on the same wavelength does help to solve the difficult problem of the lack of sufficient facilities, but no one can suggest that this denies the essential fact that this would nevertheless cost more, and would not give universal service

TABLE C

f(kc/s)	λ metres	Equivalent λ for $\sigma = 10^{-13}$	Maximum Possible Radius of Service Area $= R$		Area $= \pi R^2$	
			Kilometres	Miles	Square kilometres	Square miles
150	2,000	1,420	940	564	2,775,000	1,000,000
190	1,580	1,120	710	426	1,581,000	570,000
230	1,305	915	600	360	1,130,000	407,000
270	1,140	805	490	294	754,000	272,000
310	968	700	430	258	580,000	209,000
350	858	602	330	198	342,000	121,700
390	770	540	295	177	274,000	98,400
430	698	490	255	153	204,000	73,600
470	639	454	230	138	166,000	59,900
510	589	410	200	120	125,600	45,200
550	546	385	180	108	102,000	36,600
590	508	355	155	93·0	75,500	27,200
630	476	337	137	82·2	58,900	21,200
670	448	320	130	78·0	53,000	19,200
710	422	302	125	75·0	49,000	17,600
750	400	284	120	72·0	45,200	16,300
790	380	270	115	69·0	41,500	15,000
830	362	260	111	66·6	38,600	13,950
870	344·5	248	106	63·5	35,300	12,650
910	330	236	103	61·8	33,400	12,000
950	316	225	98	58·8	30,200	10,850
990	303	218	90	54·0	25,500	9,180
1,030	291·5	210	84	50·4	22,100	8,000
1,070	280	200	80	48·0	20,100	7,230
		Total of service areas			8,561,900	3,083,760

Total area of Canada = 10,360,000 sq. km., or 3,730,000 sq. miles.
Therefore percentage served = 83·0 per cent.

conditions; synchronization economizes channels, but those channels should be in the first case suitable for economic synchronization. (To this end, see curves, Fig. 14.) Synchronization implies the radiation of the same programme from all stations synchronized, and it is essential to give regional to supplement national programmes.

The argument that the indirect ray constitutes a service can be dismissed on two counts, first that programmes throughout the world must in time have a cultural significance which could not tolerate so serious a technical imperfection as their periodic disappearance as coherent sound; and secondly, that since indirect rays only form at night this enormously limits service. Daylight broadcasting would seem essential in any community; in the highly developed industrial state for the night worker, the housewife, children (and even the idle!); in the sparse agricultural populations, for the housewife whose leisure is more probable in the afternoon hours, and for educational work. There is the further question of the older people, children, and invalids, to all of whom broadcasting is more than a casual evening pastime.

Broadcasting is a newcomer to wireless, and its presence is coming to be recognized by the officials of the State, who at world conferences and elsewhere decide the principles of ether partition among the claimant services. It is hoped that decisions as to its future will be based alone upon technical considerations.

We return therefore to the fundamental fact of the entire unsuitability of the 600–200 metre wave-band for broadcasting. The example given is sufficiently striking to require no argumentative embellishments. It should, however, be realized that for a given capital expenditure the running and capital cost per unit area is 12 times what it need be, if the present unsuitable waves are used. The reader's attention is called to the conclusion to the paper on 'Attentuation of wireless waves over towns', where the authors point out, that for long waves the effect of absorption is not great, but increases enormously rapidly as the wavelength approaches the 300–200 region —another factor to show the unsuitability of the shorter wavelengths for broadcasting. Lastly, the interference-producing qualities of all wavelengths are the same, but the service possibilities change enormously. The present wavelengths are trebly wasteful in energy—they give relatively poor ~~relatively~~ local service, great distant interference, and great waste of power.

We must naturally, before attempting to give the broadcasting service the more favourable treatment it so obviously deserves, see whether we make other important services suffer unwarrantably in the process.

Generally speaking, we find the ship and aviation wireless services occupying wave-bands ideally suitable for broadcasting. Speaking from the technical point of view ships could use the shorter waves; it has been shown that a 200-metre wave has an attenuation over the sea not greater than that of a 2,000-metre wave over land. It seems wrong, therefore, to allocate waves for over-sea transmission that are ideal for direct-ray broadcasting service over land, and waves for over-land transmission that are superlative for over-sea communication! It will be argued that ships cannot change their apparatus, the money involved being too great. To this one can only suggest that most services have set aside a fund to cover obsolescence, and one wonders, in view of the demands upon the ether for equally important services, if such expenditure cannot in the general interest be faced as others have faced expenditure in their particular interest. It seems, therefore, that the question of expenditure alone stands in the way of progress. One should add that the problems of expenditure must in any case be faced by those responsible, since it is agreed that all Spark ~~speech~~ transmitters shall be substituted by more modern apparatus before 1940.

Telegraph services between aerodrome and aerodrome could be perfectly well accommodated on wavelengths above 2,000 metres, and there is, with modern technique, no reason why a separation of 0·5 k.c. between stations should not be undertaken, meaning that 20 telegraph stations could be accommodated in the space taken up by one broadcasting station. It is argued that the ground to aeroplane service must be by wireless telephone. It is not impossible to conduct commercial telephony on wavelengths above 2,000 metres.*

In sum, given goodwill, the ether could be repartitioned to give each service good and sufficient facility. The above argument shows how in practice no service need suffer in the process if the rearrangement was based upon technical knowledge.

VIII

THE WORKING OF SEVERAL BROADCASTING STATIONS ON THE SAME WAVELENGTH

The interested reader is referred to a paper written by the author and Mr. A. B. Howe on this question.† The following extract is relevant:—

'*GENERAL THEORY*

'If two broadcasting stations emit carrier waves of 'identical frequency, we presume that an interference 'pattern will be set up in areas where the field strength 'of both is appreciable. Taking a simple case, we shall 'consider two stations to be of equal power, and to be 'exactly synchronized.

'Let us first consider that there is no modulation of 'the carrier wave, and that the stations are emitting

* It should here be remarked that the broadcasting authorities have done everything by research, experiment, and practical application to use the very best technical means to carry on their service, and millions of pounds worth of apparatus has been disposed of as obsolete; it would appear only reasonable that other services should adopt similar means for the benefit of all.

† P. P. Eckersley and A. B. Howe, 'The operation of several broadcasting stations on the same wavelength.' *Journal of the Institution of Electrical Engineers*, Vol. 67, No. 390, June 1929.

'radiation of a single frequency. The interference pattern 'at points taken along a straight line drawn between the 'stations will take the form of stationary waves, with 'maxima and minima each a distance apart equal to half 'the wavelength of the carrier wave. At points nearly 'equidistant from both stations the minima of the 'stationary waves will be practically zero, and the maxima 'practically double the field strength of one station work- 'ing alone.

'Now consider that the stations are modulated by the 'same "low" frequency. A carrier wave of frequency f_c, 'modulated by a "low" frequency f_m, can be represented 'as the simultaneous existence in the ether of frequencies 'f_c, $(f_c + f_m)$ and $(f_c - f_m)$. We call the frequencies '$(f_c + f_m)$ and $(f_c - f_m)$ side-bands. Interpreting this in 'terms of wavelengths, the radiation of a carrier wave of 'frequency f_c modulated by a low frequency f_m can be 'represented as the radiation of 3 wavelengths $\lambda = c/f_c$, '$\lambda_1 = c/(f_c + f_m)$, $\lambda_2 = c/(f_c - f_m)$, where $\lambda =$ carrier 'wavelength, $c =$ a constant, and λ_1 and $\lambda_2 =$ wavelengths 'of the side-bands.

'Modulation of the carrier waves of each station thus 'produces additional waves of length λ_1 and λ_2 (λ_1 being 'a shorter and λ_2 a longer wavelength than λ). The inter- 'ference patterns caused by λ_1 and λ_2 will be dissimilar, 'and the maxima and minima will each be $\frac{1}{2}\lambda_1$ and $\frac{1}{2}\lambda_2$ 'apart. But since $\lambda_1 \neq \lambda_2 \neq \lambda$, the points of maximum 'or minimum for one side-band, for the other side-band 'and for the carrier will not in general be coincident. To 'make this point very clear, let us refer to Fig. 1,* which, 'to render the diagram manageable, has been drawn for 'a frequency of carrier wave of 150 kilocycles per sec. '(2,000 m. wavelength), modulated by the "low" fre- 'quency of 10,000 cycles per sec. The diagram is conven- 'tionalized to the extent of assuming the strength of the 'two stations to remain the same along the line A B of 'length 20 wavelengths. The sine curves of Fig. 1* are 'the envelopes of the stationary waves. They give a 'representation of the field strengths of the resultant 'carrier, and of the two resultant side-bands produced, 'at any point A B, by the addition of the radiations from 'the two sources. By moving from place to place in the 'interference pattern we find different states of energy.

'TABLE D

Point	Condition	Result to a receiver installed at the given points
C and E	Zero energy	No reception
D	Strong side-bands. No carrier	Carrierless tele- phony, and distortion for ordinary reception
F	Double carrier and double side-bands	No distortion
G	Strong carrier and no side-bands	No modulation
H	Elimination of one side-band; relative strengthening of other	Distortion with most types of detector

'The results are shown in the table (D of this pam- 'phlet).

'It is important to note that the distortion referred to 'in the above table is that of the wave-form of the single 'low frequency with which we have supposed our trans- 'mitters to be modulated. In addition, frequency dis- 'tortion, or distortion of the low-frequency response 'characteristic of the combined transmitters, will occur. 'In fact, at no point in the interference pattern will this 'form of distortion be entirely absent unless the two 'transmitters are approximately equidistant from the 'receiver. This point will be appreciated if it is realized 'that the interference bands shown for the side-bands 'in Fig. 1* refer to one particular modulation frequency 'only. For other modulation frequencies the nodes and

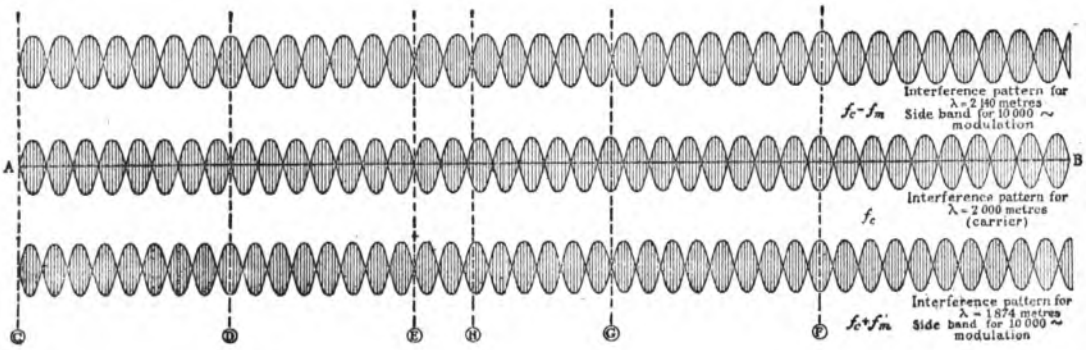

FIG. 12.—Interference pattern produced by two broadcasting stations using the same wavelength of 2,000 m. and having the same modulation of 10,000 cycles per sec.

* Fig. 12 of this pamphlet.

* Fig. 12 of this pamphlet.

'loops of the side-band interference patterns will be 'formed in different localities.

'Thus, points F and G, in Fig. 1* for example, at 'which conditions for the carrier are the same, but for 'the side-bands are different, can be taken as representing 'conditions which will occur at one locality for different 'modulation frequencies. That is to say, even at a point 'where the carriers from the two transmitters are 'received in phase, and no distortion of wave-form can 'occur, there will be distortion of the frequency/response 'characteristic, since as we swing through the gamut of 'audible frequencies the respective side-bands received 'from the two stations will alternately be in and out of 'phase. The same plainly occurs for all the other condi- 'tions referred to in the table.

'The frequency distortion is, however, of such a 'nature that in many cases, so long as the carriers are 'received approximately in phase it will not be noticed 'in an ordinary receiver. In the eliminated-carrier case, 'however, frequency distortion may be more serious, the 'higher modulation frequencies alone being strongly 'reproduced; hence the introduction of a local carrier 'would not suffice to produce good reception.

'There are other and intermediate states of distortion, 'notably the disturbance of the phase relationships 'between resultant carrier and resultant side-bands, but 'the above is typical and sufficient to point what follows. 'Thus we see that, where the field strengths of both 'stations are practically equal, good reception is fortuitous 'and distortion highly probable. In general we may say 'that this distortion will take the form of over-modulation '(where the carrier suffers diminution), frequency distor- 'tion (where portions of the side-band spectrum are 'blotted out), elimination of carrier (where intelligible 'reception could only be obtained by the introduction 'of a homodyne at correct phase), and distortion due to 'the disturbing of the relative magnitudes and phase 'relationships of the two side-bands. Distortion will not 'be greatly influenced by the relative phases of the low- 'frequency modulation component at each station; a 'change of modulation phase at one station relative to the 'other merely shifts the side-band interference pattern 'of Fig. 1* horizontally right or left, and changes the 'type of frequency distortion at any given point. The 'typical states indicated in the table will still occur, 'though, in the case of modulation with a single-frequency 'side-band, elimination will occur at a different point.

'We have so far investigated the condition where both 'transmissions are sensibly equal. But consider a point 'close to one station (so close that the field strength of 'that station is enormously greater than that of the other 'sharing the wave). At such points we should expect no 'distortion, the interference from the distant station 'being too feeble to produce an appreciable interference 'pattern. As we move away from close proximity to one 'station towards the other, the distortion produced by 'the interference pattern becomes more and more appre- 'ciable until a point is reached at which the interfering 'station produces noticeable distortion, and we may say 'that we can no longer expect good service from the 'nearer station. There must be, practically speaking, a 'definable boundary inside which reception is good, 'while outside it is bad. There will be round each of the 'stations an area in which the distortion will not be 'noticeable, but there will also be a large area between 'and round the stations which we decide to call a "mush" 'area where service conditions cannot be said to exist '(see Fig. 2).' *

An experiment was undertaken to determine what relative field strength between the local and the distant interfering station was required to give good service conditions for the local station. The results are given in the paper referred to above as follows:—

'It was found that whenever the strength of one station 'at a point was five, or more, times the strength of the

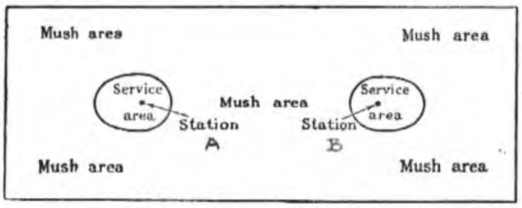

FIG. 13.—Showing small service area and large 'mush' area (where quality of transmission is bad) around two stations sharing the same wavelength.

'other station working on the same wavelength, reception 'from that station was normal. In other words, the 'boundary of the service area of a station A sharing a 'wavelength with a station B, the carrier waves being 'exactly synchronized, is found by drawing a line through 'the points where the field strength of station A is five 'times that of station B. Similarly, the boundary of the 'service area of station B is found by drawing a line 'through the points where the field strength of station B 'is five times that of station A.

'This statement, quantitatively fundamental to single- 'wavelength working, comes directly from observation. 'It will be seen that the results justify the fundamental 'theory given above.

'We have so far assumed the stations to be exactly 'synchronized. Let us now assume that the stations 'differ in frequency by an amount Δf which makes a 'beat between carrier waves so slow as to be inaudible '(below 20 cycles per sec., say). It is obvious, referring 'to Fig. 1† that a receiver anywhere on the line A B will 'experience states C, D, E, F, G, and H, and the interme- 'diate stages thereof, consecutively. It is as if we were to 'move through the stationary interference pattern at a 'velocity determined by the frequency difference of the 'stations; a greater velocity for greater difference of 'frequency. From the point of view of the interference

* Fig. 12 of this pamphlet.

* Fig. 13 of this pamphlet. † Fig. 12 of this pamphlet.

'pattern distortion, therefore, there should be no differ-
'ence between perfect and imperfect synchronization, so
'long as the actual carrier-wave heterodyne is inaudible.
'But this mal-synchronization produces an extra distor-
'tion, not concerned with those due to the interferences.
'Thus, suppose we have a carrier-wave frequency of f_c
'for station A, and of $(f_c + \Delta f)$ for station B. Suppose
'each to be modulated by a frequency f_m, then, at a
'point where the field strength of both stations is appreci-
'able, there will be side-bands of frequency $(f_c + f_m)$,
'$(f_c - f_m)$, $(f_c + \Delta f + f_m)$ and $(f_c + \Delta f - f_m)$. There
'are thus extra frequencies $(\Delta f + f_m)$ and $(\Delta f - f_m)$
'which are audible, after rectification, and produce dis-
'tortion. There can thus be said to be distortion caused
'by the addition of a frequency Δf to every modulation
'frequency when stations are imperfectly synchronized.

'It is obvious that in addition to distortion due to
'interference effects one will hear two superimposed
'programmes. It was proved by experiment that the
'strength of one station, if it was to give good service,
'had to be, at a given point, 100 to 200 times that of the
'interfering station at that point if the interfering station
'was transmitting a different programme from that of the
'given station. The service area of a station sharing a
'wave with another is vastly smaller if each station trans-
'mits a different programme.

'THE RANGE OF STATIONS SHARING WAVELENGTHS

'The question as to whether single-wavelength working
'is feasible for service conditions can only be answered
'by quantitative study of typical cases. It is easier to

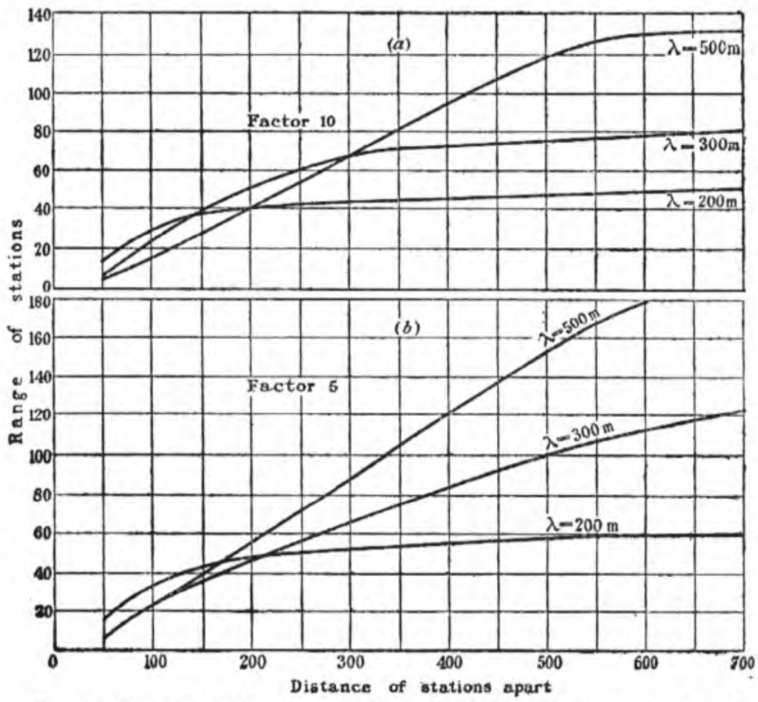

FIG. 14.—Range of two equal power stations sharing same wavelength, at different distances apart and different factors.

'It was proved by experiment that if Δf was greater
'than 5 cycles per sec. the strength of the one station
'when sharing a wavelength with another had to be, at
'the boundaries of the service area, at least 10 times
'greater than the other station to preserve good quality
'within that service area. This factor 10 compares with
'a factor 5 obtained for perfect synchronization.

'Finally, let us consider the conditions if the modula-
'tions of the two transmitters, using the same wavelength,
'are different, i.e. if it is attempted to use the same wave
'for two stations each radiating different programmes.

'arrive at the order of service area from a given station
'by considering simple cases. Thus we shall in the follow-
'ing analysis assume two stations radiating the same
'programme, and we shall assume that they are perfectly
'synchronized.

'So long as the stations are of equal power, their
'service areas will not be changed whatever the value
'of such power. Geographical separation alone deter-
'mines the service areas of stations of equal power sharing
'the same wavelength. It will be useless to consider day-
'light conditions; we must, before even the most approxi-

'mate estimates of ranges can be given, and if the stations 'are separated by over 100 km., assume the presence of 'a strong indirect ray from the "interfering" station. The 'indirect ray vanishes in the daytime when the service 'areas of stations sharing waves will be, where they are 'fairly far apart, greater.'

Previous discussion gave us values for the total value of radiation from a station of given power. This enables us to draw curves to determine the boundaries of the service areas of synchronized stations in terms of their geographical separation. This has been done, and is shown in Fig. 14* for perfect and imperfect synchronization and for three wavelengths, earth resistance of 10^{-13} being assumed. It is natural that if these values are required for different values of earth resistance it is only necessary to change the labels according to the conversion chart of Fig. 3.

Following the paper read before the Institution of Electrical Engineers on this subject, we read:—

'It is important to consider what happens if and when 'more than two stations share the same wavelength. We 'wish to find the total maximum field strength at a point 'produced by n stations sharing one wavelength. Should 'this field strength at a point equidistant (say) from 'n stations be n times the field strength of one station? 'If not, what fraction of n? There are so many variables 'that we must take a simple case to give general indica'tions for the solution where more complications are 'involved. The simple case chosen is to assume n stations 'equidistant from a point P, or most simply that the 'point P is the centre of a circle on the circumference of 'which are equally spaced n stations bombarding P. 'What is the field strength at P? With perfect synchroni'zation obviously the strength at P could be made n times 'the strength of one station, or it could be made zero by 'adjusting the relative phases of the stations. With casual 'phases and imperfect synchronizations, however, it is 'obvious that the field strength might vary between 0 'and nE, where E is the field strength produced by one 'station alone. The practical questions to be answered are: 'At what intervals of time may we expect the strength to 'be nE, and on an average will the maximum be some frac'tion of nE; and if so, what fraction, and how will this 'depend upon n?'

The answer can be given on the basis of Lord Rayleigh's well-known physical theory, and we can say at once that the average maximum peaks due to n stations imperfectly synchronized is proportional if n is large to $\sqrt{n}$. Note that this result is independent of geographical separation provided the value of the direct ray is negligible compared to the indirect. The general conclusions given in the paper on single wavelength working is as follows:—

'It will be appreciated that many of the above state'ments are based on theoretical calculations. The values 'of the indirect ray cannot be taken as exact, although 'they are remarkably confirmed by observations in two 'separate cases. The crucial experiment of single-wave'length working when the empirical conditions were 'determined is wholly reliable. The section (Section 'II of the paper), however, answers in general the ques'tions whether single-wavelength working is a practical 'proposition if means to carry it out can be found. 'Obviously from what has been shown, even if there are 'large errors, we may say in general that shared waves 'between local low-power stations will be useful to cover 'large towns with good conditions of broadcasting if such 'towns happen to be outside the range of high-power 'regional stations.'

The paper goes on to deal in detail with methods of synchronization. This pamphlet can hardly be said to contain such discussions within its scope. It is only necessary to say that entire success has attended the B.B.C.'s method of synchronization which relies upon separate tuning-fork drive at each of the 10 stations sharing the wavelength of 288·5 metres. The method of driving all stations from a common source which is linked to each station by land line has been entirely successful, particularly in Germany. It is a moot point which method is the better; one involves more maintenance care, the other more maintenance cost.

The conclusions drawn from the successful operation of the method over 3 or 4 months are that it represents an extremely simple way of economizing wavelengths and covering, with one programme, dense centres of population otherwise likely to receive a worse service. It is hoped that in time the international common wave will be done away with in favour of using one national exclusive wave as a national common wave. It is indefensible to allow continuous interference to several stations sharing waves, but doing different programmes when so simple a solution for the trouble exists.

IX

CONCLUSION

The pamphlet has attempted to give data for the calculation of service area. It has departed in only one respect from the strict limits set on its scope in the introduction, when a section was devoted to discussing the vexed question of international agreements as to wave-band allocation. The arguments are so convincing and follow so naturally upon the facts set out before that it is only necessary to forestall criticism that a scientific paper has been devoted to propaganda by disposing of it in pointing out that the propaganda was purely scientific. The pamphlet should have real use, but its author wishes to stress once more that its conclusions are in the nature of approximations, and to point out that a great deal more investigation must be carried out before it could be revised in detail to conform more exactly to a strict, but probably quite unnecessary, scientific accuracy.

* Fig. 7 of the paper on single wavelength working.

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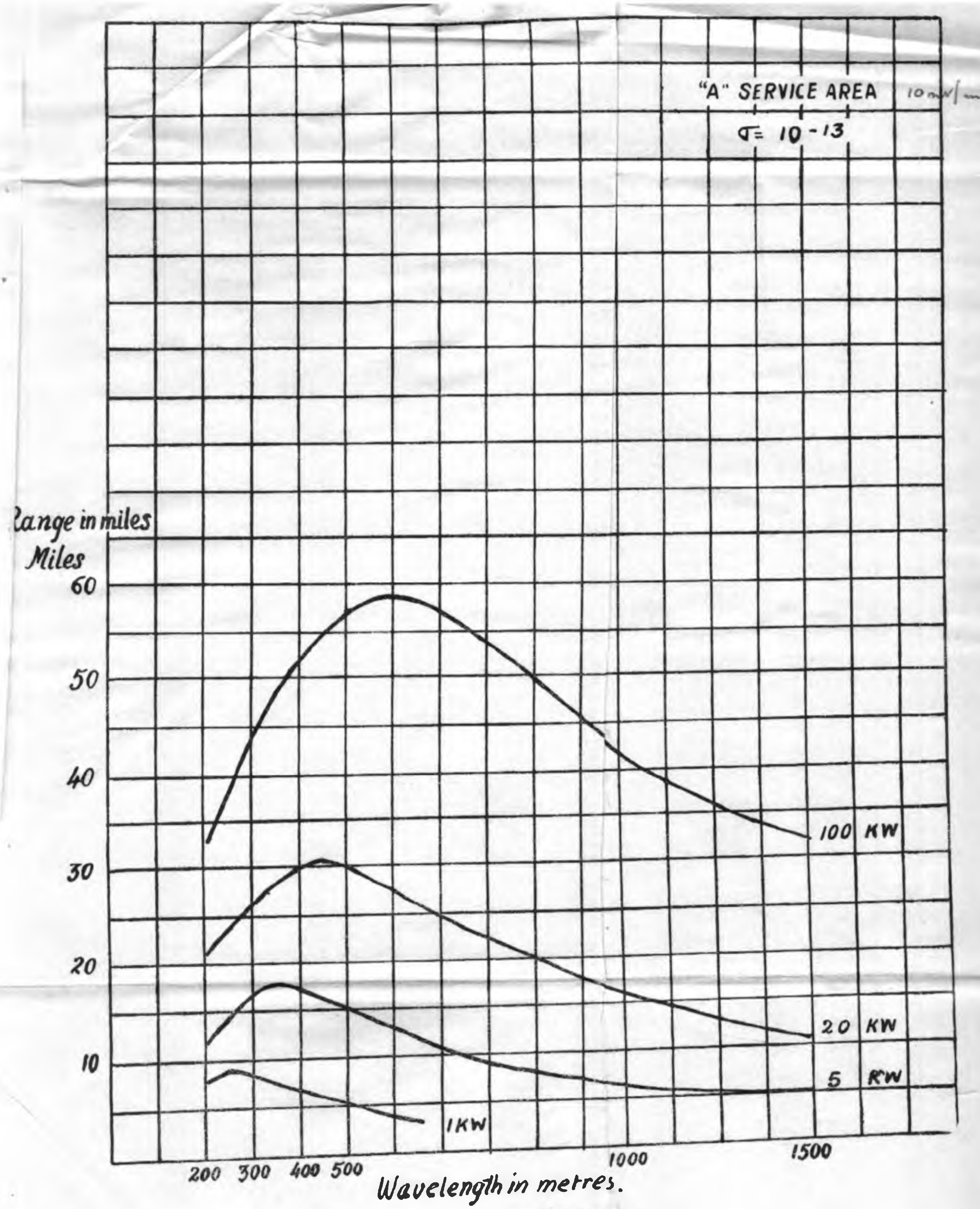
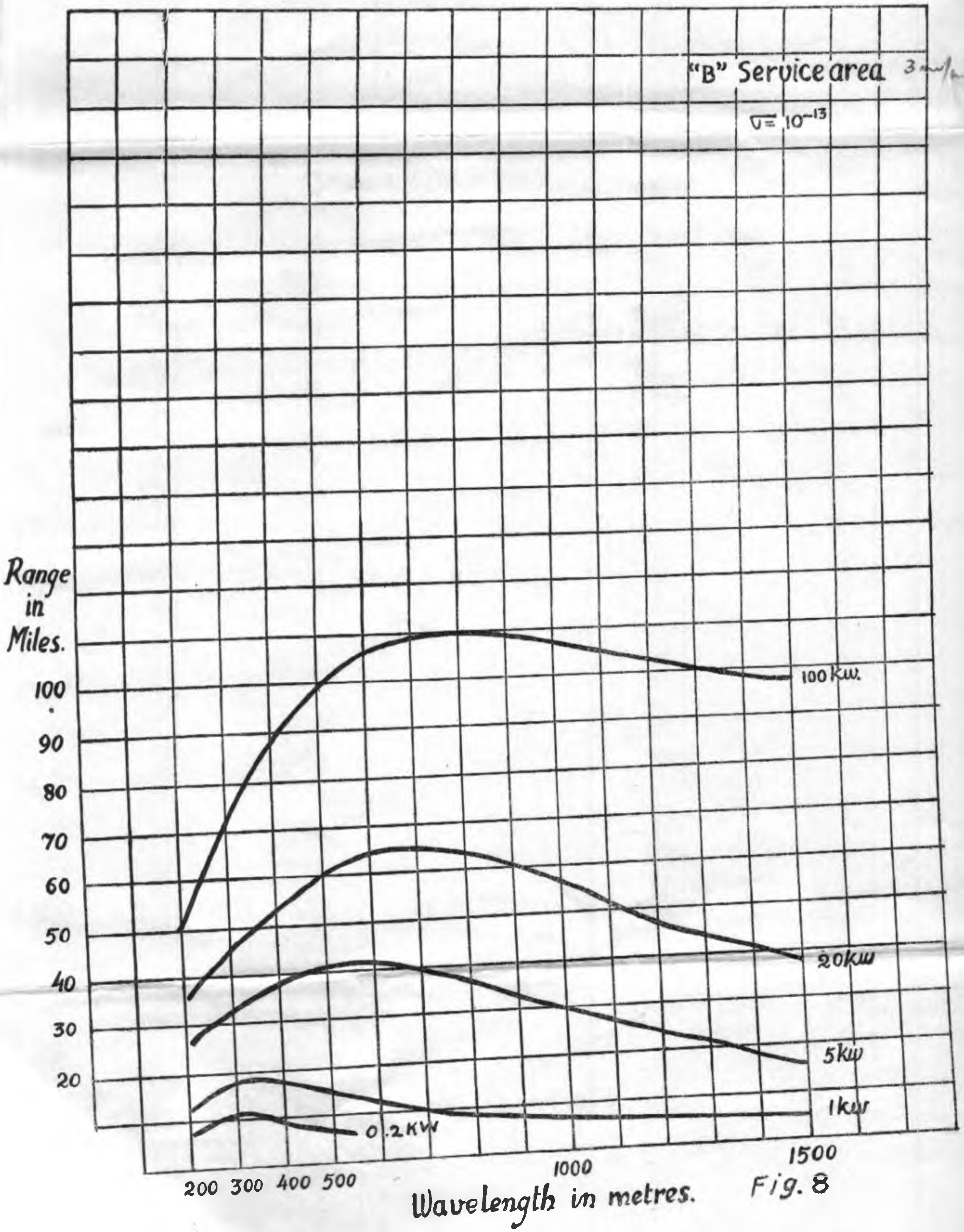
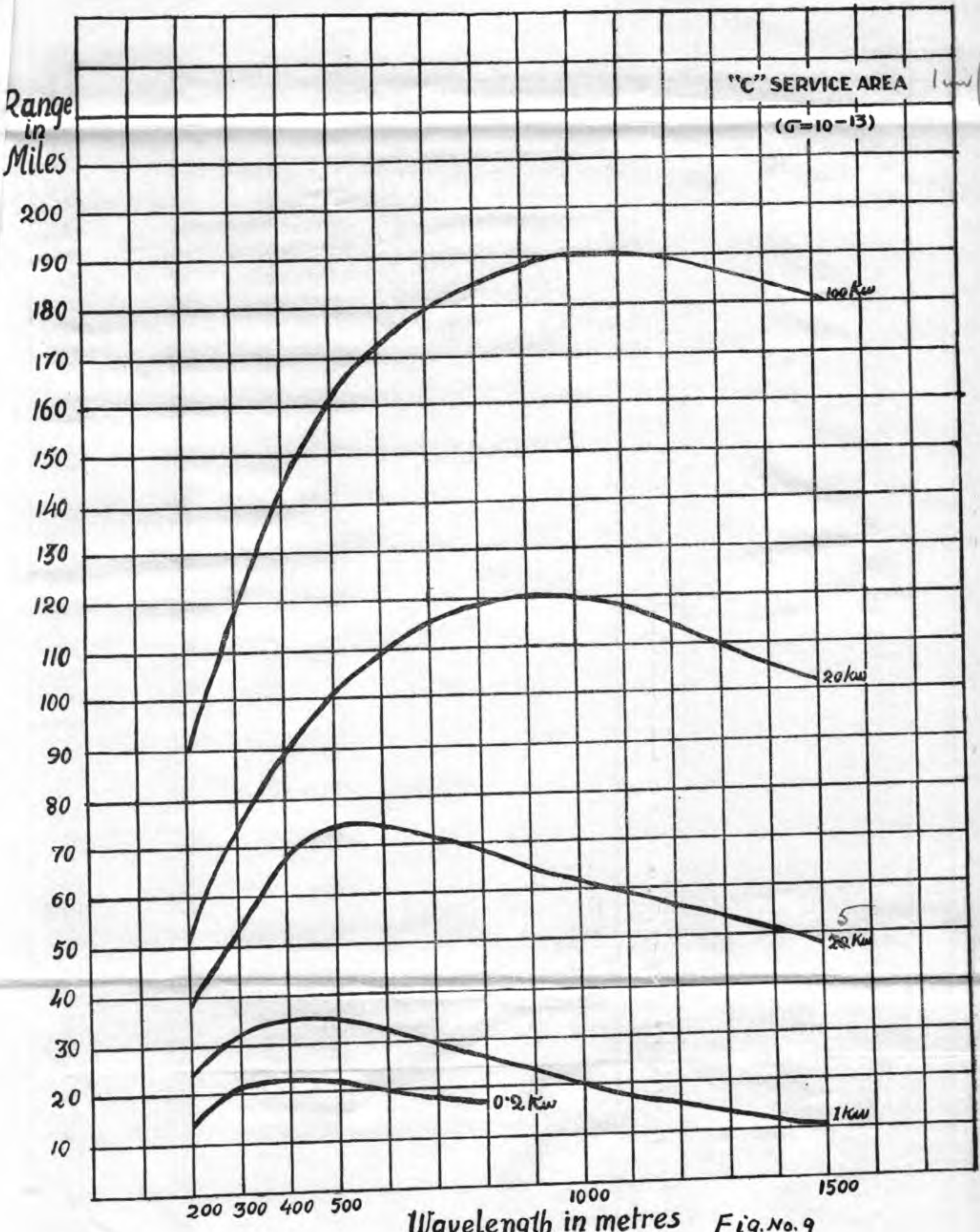

"A" SERVICE AREA
10 mV/m
σ = 10 -13
Range in miles
Miles
60
50
40
30
20
10
100 KW
20 KW
5 KW
1KW
200
300
400
500
1000
1500
Wavelength in metres.
Fig. No. 7



"B" Service area
$\sigma = 10^{-13}$
Range in Miles.
100
90
80
70
60
50
40
30
20
100 Kw.
20kw
5kw
1kw
0.2KW
200 300 400 500
1000
1500
Wavelength in metres.

Fig. 8


"C" SERVICE AREA
(σ=10^{-13})
Range in Miles
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
100 Kw
20 kw
5
~~20~~ Kw
1 Kw
0·2 Kw
200 300 400 500
1000
1500
Wavelength in metres
Fig. No. 9

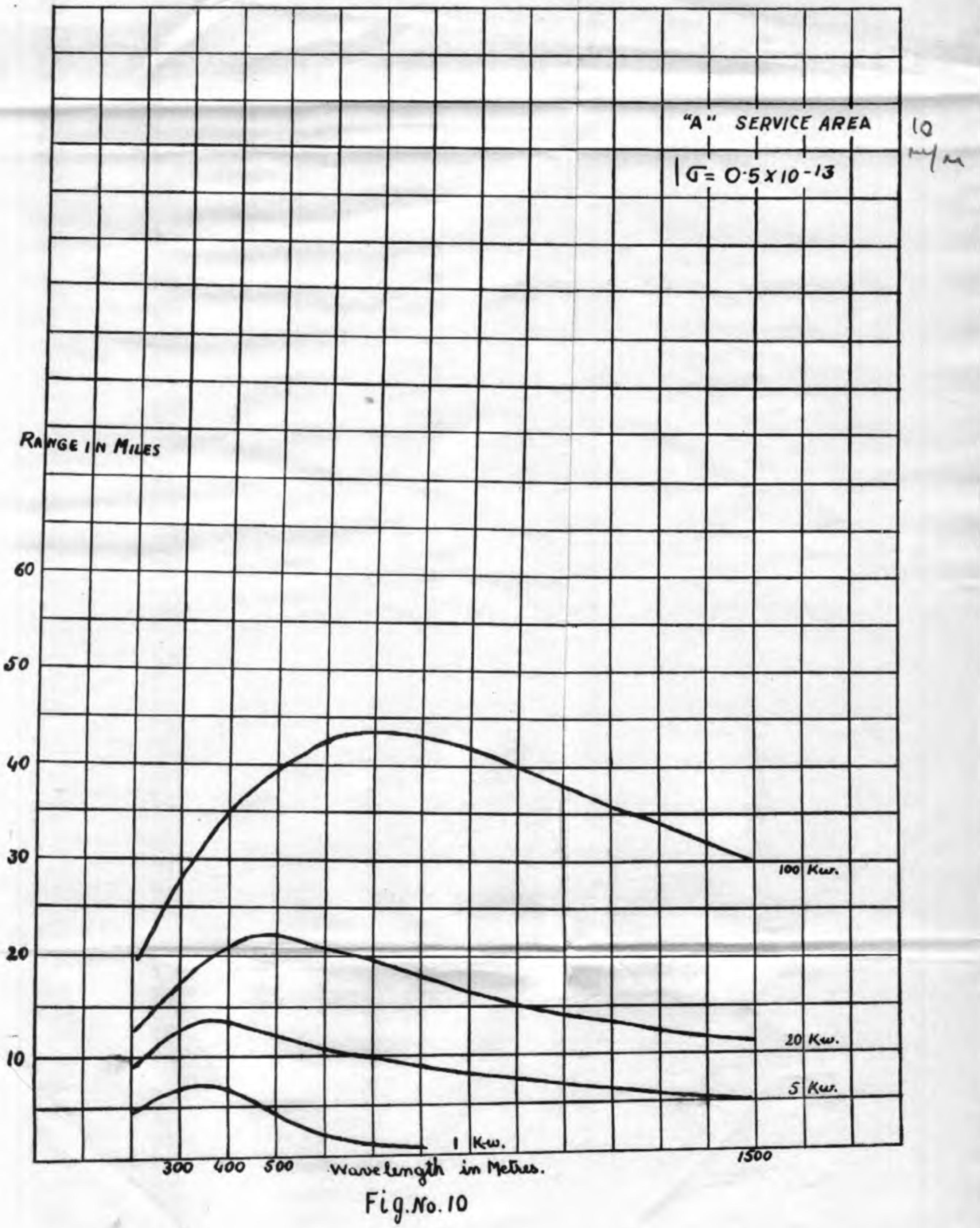

"A" SERVICE AREA
$\sigma = 0{\cdot}5 \times 10^{-13}$
10 mV/m
RANGE IN MILES
60
50
40
30
20
10
100 Kw.
20 Kw.
5 Kw.
1 Kw.
300 400 500
1500
Wavelength in Metres.

Fig. No. 10

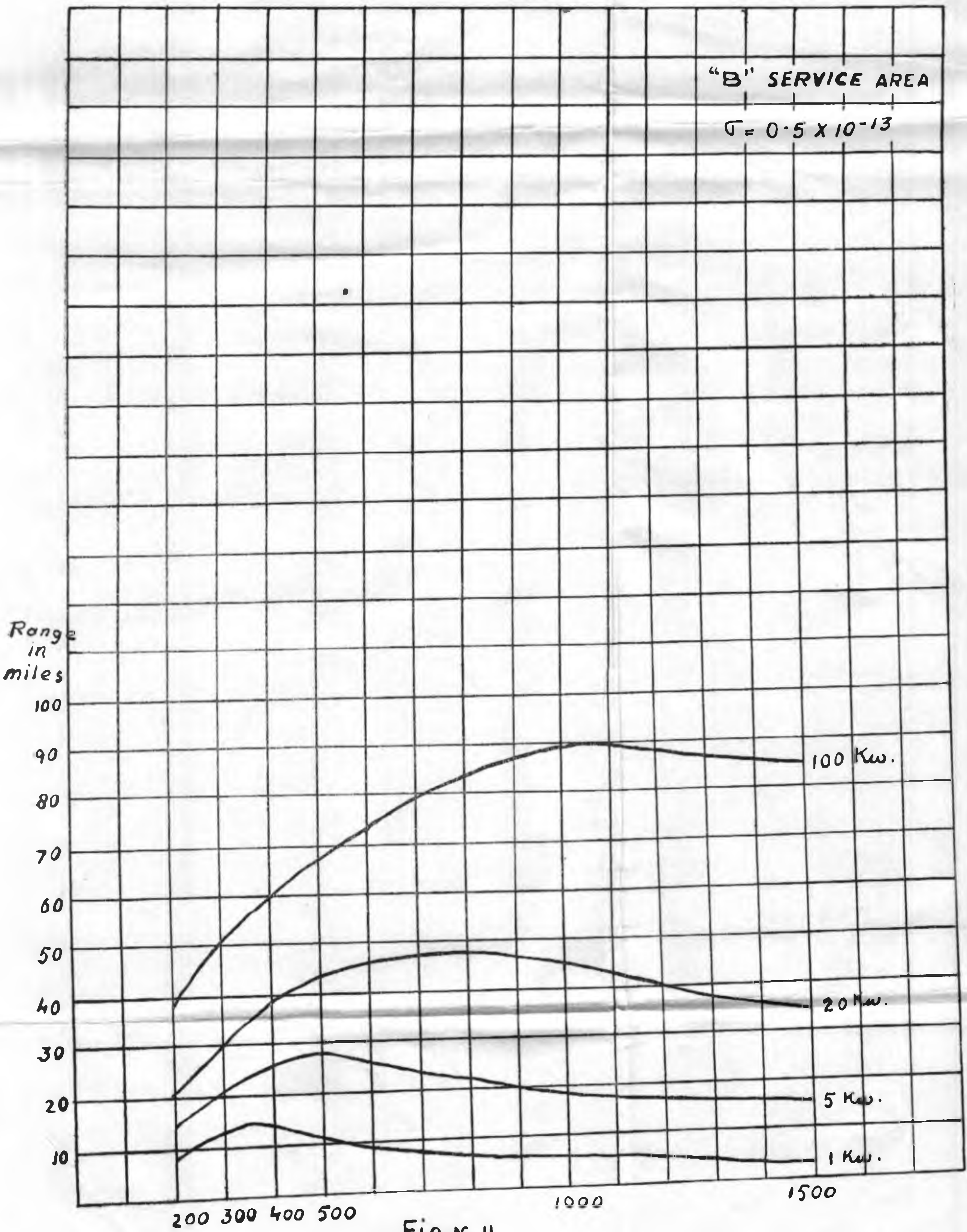

"B" SERVICE AREA
$\sigma = 0 \cdot 5 \times 10^{-13}$
Range in miles
100
90
80
70
60
50
40
30
20
10
100 Kw.
20 Kw.
5 Kw.
1 Kw.
200 300 400 500
1000
1500

Fig. No. 11

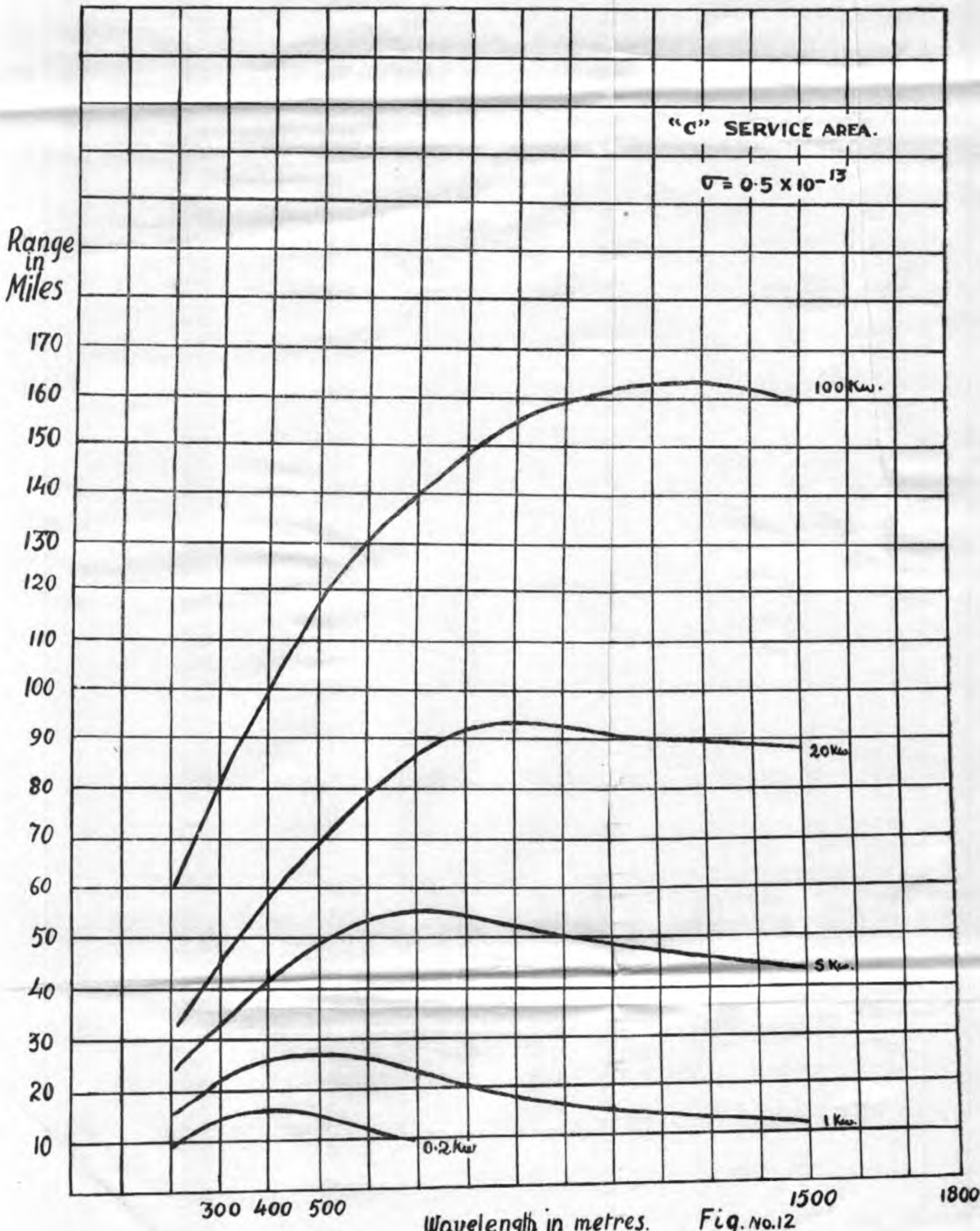

"C" SERVICE AREA.
σ = 0·5 x 10^-13
Range in Miles
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
100Kw.
20Kw
5Kw.
1Kw.
0·2Kw
300 400 500
1500
1800
Wavelength in metres.

Fig. No.12