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THE MARCONI REVIEW

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Editor: L. E. Q. WALKER, A.R.C.S.

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THE COMPUTATION OF GREAT CIRCLE BEARINGS AND DISTANCES

BY G. MILLINGTON, M.A., B.Sc.,

The standard formulæ for the computation of great circle bearings and distances are subject to small difference difficulties necessitating under some conditions the use of seven figure logarithms to obtain four figure accuracy. This trouble is overcome by trigonometrical transformations, so that the accuracy of the tables does not need to be higher than that of the final answer.

At the same time, the rule of signs associated with the formulæ is simplified and embodied in a standard table used for the computation of any given case. It is shown that the transformed equations degenerate directly to the simple projection formulæ for short distances where the effect of the earth's curvature is negligible.

Introduction.

TO THE engineer who is concerned with the erection of beam aerial arrays, or who is engaged on wireless direction finding work, the problem of the computation of great circle bearings is of special importance. The research engineer is also interested in the determination of great circle distances, when for instance, he seeks to interpet long distance transmission phenomena in terms of reflections from the ionosphere at oblique incidence.

Standard methods are in use for making such computations, but in general, they are cumbersome to use, and they involve conventions and rules of signs which are apt to be confusing. It was felt, therefore, that it would be useful to discuss the general aspects of the problem, and to suggest a modified procedure which, it is hoped, will be found to be free from some of the disadvantages of the existing methods.

Any method of computing great circle data which is exact, and not merely an approximation applicable, say, to short distances, must involve the use of the fundamental formulæ of spherical trigonometry. The really remarkable extent to which these formulæ lend themselves to transformation is very helpful, since it enables one to choose a form which is most suitable to the purpose in hand. Inspection of the problem shows that most of the disadvantages of the existing methods can be removed by adopting alternative transformations of the fundamental formulæ.

In discussing these disadvantages and the proposed modifications, it will be useful to state the features to be desired, namely, that the method should be straightforward and applicable to the most general cases, including short distance routes, and that the necessary rules of signs should be reduced to a simple self-explanatory scheme, involving no conventions that will lead to possible confusion, or imply a preliminary investigation of the type to which any particular case may belong.

The Accuracy required in Practice.

In considering the accuracy to which the great circle bearing must be computed, we can say that it will be sufficient to give the angle to one or two minutes of arc ; but it is important to notice that this accuracy is required whatever the numerical value of the angle measured E. of N. This is obvious when we consider that a direction finder is really only concerned with the limits within which it can define the direction of arrival of a wave, and that these limits are independent of the arbitrary datum, the great circle through the north pole, from which we choose to measure the direction.

On the other hand, when we are dealing with great circle distances, and these are expressed in terms of angles subtended at the centre of the earth, we are concerned with percentage accuracy, and we must interpret our formulæ accordingly. If, for instance, we have a short distance which is only 1° in angular measure, i.e., 111·1 kilometres, we must measure this angle to within 3·6 seconds if we wish to express the distance to 1 part in 1,000, i.e., to within 100 m. It is, therefore, necessary to remember that the accuracy of the final answer, expressed as an angle, has to be interpreted differently, according as the angle refers to a great circle bearing or a distance.

The accuracy for the distance measurement suggested above, i.e., 1 part in 1,000, may be taken as sufficient for all likely requirements. As we have seen, this means that for short distances we must know the equivalent angles to within fractions of a second of arc, e.g., a distance of 1 km. measured to an accuracy of 1 m. implies an angle of 32·40 seconds measured to within 0·03 seconds. In practice, of course, such short distance routes are usually measured on a map or on a gnomonic chart, but it is useful to be able to include them within the scope of a standard method.

The working out of the bearings and distances to the accuracy suggested implies, naturally, that the initial data will warrant it. For instance, for a short distance route we must be given the differences of latitude and longitude involved to within, perhaps, a fraction of a second of arc, even though the absolute values of the latitude and longitude at each end may not be accurate to several minutes of arc. But in all cases the proposed accuracy should be within the scope of four figure logarithm tables, and it should be one of our aims to devise a method in which four figure tables only need be used throughout the working to ensure the desired accuracy in the final results.

Now it is well known that seven figure logarithms have often to be employed to obtain only four figure accuracy, due to the inconvenient form of the formulæ used under certain conditions, and indeed it is usual to use them in all cases, even though four figure logarithms would be adequate in the majority of cases. This inevitably makes the process cumbersome, since the use of seven figure logarithms involves much page turning and large difference values. Apart from the question of the labour entailed, it would seem to be more logical to use a method in which four figure logarithms can be made to give in all cases the required accuracy.

The difficulty arises from the fact that the usual forms express the functions of the angles required as the difference between two terms, which may be very small when the separate terms themselves are very large. One method of overcoming this difficulty is to transform the formulæ so that they involve only products. Such a scheme is outlined in Keen's book on " Wireless Direction Finding " (cf. pp. 990–992 of the fourth edition). But this scheme inter-relates the calculations of the angles and distances, and involves conventions (such as that B shall be the place of greater latitude) which may lead to confusion, while considerable care is needed in handling the equations in certain limiting cases. It is interesting to notice that in the example given, the six figure logarithms used are only necessary in so far as the bearings are calculated to 0·5 minutes of arc.

Conventions and Rules of Signs.

Before proceeding to propose an alternative scheme, we will briefly discuss the question of conventions and rules of signs. The necessity for these really arises from the fact that the various trigonometric functions are positive or negative in value according to the quadrant in which the angle happens to be. To avoid having to remember the rules deciding the signs of these functions, it is desirable to evolve a new set of rules and conventions especially adapted to the problem in hand, and embracing all possible cases. The various cases are necessitated by consideration of whether the two places are both in the same hemisphere or in opposite hemispheres, and whether the difference of longitude is less or greater than 90°, and finally, whether the bearing is less or greater than 90° E. (or W.) of N. These alternatives give rise to as many as eight possible types still involving further conventions common to them all.

The ideal would be to make the rules self-explanatory by embodying them as part of the actual process, so that the necessary signs are obtained when wanted by a logical deduction as the work proceeds. We shall seek, therefore, to present the working in a tabular form, so that one has only to fill the table in according to a standard routine, and to include the necessary instructions in the table itself, without need to refer to any separate description of the process.

The Fundamental Formulæ and Transformations.

We come now to the discussion of the fundamental formulæ upon which our modifications are to be based. They are essentially derived from the solution of a spherical triangle, two points of which are the places under consideration, while the third point is one or other of the poles. We are, therefore, really concerned with the co-latitudes of the two places, i.e., the angles measured not from the equator but from one of the poles. We notice that we should measure these angles from the same pole, even when the places are in different hemispheres, and this suggests that our first convention should be to work from the same pole under all conditions, and we choose this to be the north pole. Thus we keep to this rule even when both places are in the southern hemisphere. But since we normally think in terms of latitude, rather than co-latitude, we must transform our formulæ accordingly, and it will be seen that our convention simply reduces to the rule that under all conditions latitudes in the northern hemisphere are to be reckoned positive, and those in the southern hemisphere negative.

A further obvious convention is that we should always compute the short route, i.e., the great circle arc joining the two places which is less than 180°. This is equivalent to the convention that the difference of longitude should be taken as less than 180°. This naturally decides whether the one place is to be considered E. or W. of the other, and the formulæ will then give the bearing in terms of an angle E. or W. of N.

With these conventions in mind, we use the following notation :—

(1) The two places are called A and B.
(2) The latitudes of A and B are L_A and L_B respectively.
(3) The difference of longitude is D.
(4) The bearing of B measured at A is θ_A, E. or W. of N.
(5) The bearing of A measured at B is θ_B, E. or W. of N.
(6) The distance between A and B is d measured in degrees.

We can now state the fundamental formulæ for θ_A and d, which are as follows :—

$$\cot \theta_A = \cos L_A \tan L_B \operatorname{cosec} D - \sin L_A \cot D \qquad (1)$$

$$\cos d = \cos L_A \cos L_B \cos D + \sin L_A \sin L_B \qquad (2)$$

To obtain $\cot \theta_B$ we merely interchange the suffixes A and B in (1).

We can see at once from (1) that confusion may arise with regard to the signs of the two terms composing the expression for $\cot \theta_A$, since when L_A or L_B changes sign, the sine and the tangent functions also change sign but the cosine does not. Also when D is greater than 90° the cotangent becomes negative while the cosecant remains positive. When D is very small, cosec D and cot D are both very large, and should the bearing be nearly 90° E. or W. of N., $\cot \theta_A$ will be very small, and in this case the small value of $\cot \theta_A$ will have to be determined as the difference of two very large terms (unless, of course, either place happens to be very near to the equator, when $\sin L_A$ and $\tan L_B$ will be very small). This difficulty is the one which has been referred to above, which necessitates the use of seven figure logarithms to obtain four figure accuracy, for which they may even be inadequate in extreme cases.

This is the major objection to the use of the form for $\cot \theta_A$ given in (1), which we must try to remove by some convenient transformation, but at the same time we will aim at simplifying the rule of signs involved, and at making the expression more symmetrical than that in (1). The clue to our problem is found in converting cosec D and cot D into functions of $D/2$, which will remove the change of sign which occurs when D becomes greater than 90°. The required relations are :—

$$\operatorname{cosec} D = \tfrac{1}{2}\left[\cot \frac{D}{2} + \tan \frac{D}{2}\right] \qquad \cot D = \tfrac{1}{2}\left[\cot \frac{D}{2} - \tan \frac{D}{2}\right]$$

Also if we take $\dfrac{1}{2 \cos L_B}$ outside as a factor of the expression in (1), we have inside terms of $2 \cos L_A \sin L_B$ and $2 \sin L_A \cos L_B$ which can be written as $\sin (L_A + L_B) - \sin (L_A - L_B)$ and $\sin (L_A + L_B) + \sin (L_A - L_B)$ respectively.

On making these substitutions and re-arranging, we have

$$\cot \theta_A = \frac{1}{2 \cos L_B}\left[\sin (L_A + L_B) \,.\, \tan \frac{D}{2} - \frac{\sin (L_A - L_B)}{\tan D/2}\right] \qquad (3)$$

where we have replaced $\cot \frac{D}{2}$ by $\frac{1}{\tan D/2}$ since we then have only a single function o D to consider, involving only one logarithm to be looked up in the tables.

Now if we interchange the suffixes B and A we have after a slight re-arrangement,

$$\cot \theta_B = \frac{1}{2 \cos L_A} \left[\sin (L_A + L_B) \cdot \tan \frac{D}{2} + \frac{\sin (L_A - L_B)}{\tan D/2} \right] \tag{4}$$

and we see at once that (3) and (4) can be written in the form

$$\cot \theta_A = \frac{1}{2 \cos L_B} \left[X - Y \right] \tag{5}$$

and

$$\cot \theta_B = \frac{1}{2 \cos L_A} \left[X + Y \right] \tag{6}$$

where $X = \sin (L_A + L_B) \cdot \tan D/2$ (7) and $Y = \sin (L_A - L_B) \big/ \tan D/2$ (8)

We have thus obtained a degree of symmetry which was not apparent in (1), and although we can use the method to determine θ_A or θ_B independently, when we have found one, we have already performed most of the computation necessary to find the other. It is not difficult to make use of this connection between $\cot \theta_A$ and $\cot \theta_B$ to inter-relate the values of θ_A and θ_B, and obtain the formulæ used by Keen and referred to above.

At first sight it may appear that we have not removed the difficulty arising from the fact that our expression still involves the difference of two terms which may be nearly equal. But we see from (7) and (8) that since the factor $\tan D/2$ appears in the numerator of X and in the denominator of Y, when X is large (which it can only be by $\tan D/2$ becoming large) Y must be small, and similarly if $\tan D/2$ is small, so that Y can be large, X must be small. Thus X and Y cannot be large together, and it therefore follows that when X and Y are nearly equal, and $X - Y$ or $X + Y$ may be very small, they must both be reasonably small. It is not difficult to see that even in the most extreme cases, our transformation has removed the objection, and that the angle θ_A or θ_B can be evaluated to within the stipulated limits of 1 or 2 minutes of arc.

Considering now the signs of the terms X and Y, the factor $\tan D/2$ is always positive, since by convention D is less than 180°. The signs of X and Y are therefore simply the signs of $\sin (L_A + L_B)$ and $\sin (L_A - L_B)$ respectively, and since $L_A + L_B$ and $L_A - L_B$ must both be numerically less than 180°, and the sine of an angle changes sign with the angle, it follows that the signs of X and Y are those of $L_A + L_B$ and $L_A - L_B$ respectively. Having thus determined the signs of X and Y, we see from (5) and (6) that the signs of $\cot \theta_A$ and $\cot \theta_B$ are those of $X - Y$ and $X + Y$ respectively, since $\cos L_A$ and $\cos L_B$ are positive independently of the signs of L_A and L_B, as these angles are numerically less than 90°.

If the sign of $\cot \theta_A$ is positive, it means that θ_A measured E. or W. of N. is less than 90°, while if the sign is negative, θ_A is greater than 90°. Now in practice we shall obtain the value of θ_A from a computed value of $\log \cot \theta_A$ by looking up the appropriate table, and, disregarding the sign of $X - Y$, this will yield an angle which is less than 90°. It is therefore simpler at this stage to modify our definition of θ_A,

TABLE I

θ_A = Bearing of B from A	θ_B = Bearing of A from B	d = Angular Distance	
Place	Latitude	Longitude	
A = B =	L_A = L_B =		Difference $D < 180^\circ$
N. Latitudes + VE S. Latitudes − VE	$L_A + L_B$ = $L_A - L_B$ =	D = $\frac{D}{2}$ =	

$L_X (<90^\circ) = \lvert L_A + L_B \rvert$ or $180^\circ - \lvert L_A + L_B \rvert$ = Log sin L_X = + Log tan $\frac{D}{2}$ = ______ Log X =	$L_Y (<90^\circ) = \lvert L_A - L_B \rvert$ or $180^\circ - \lvert L_A - L_B \rvert$ = Log sin L_Y = − Log tan $\frac{D}{2}$ = ______ Log Y =
X has the sign of $L_A + L_B$ X = Y = ______ X − Y =	Y has the sign of $L_A - L_B$ Y = X = ______ X + Y =
$\left\lvert \frac{X - Y}{2} \right\rvert$ = Log $\left\lvert \frac{X - Y}{2} \right\rvert$ = − Log cos L_B = ______ Log cot θ_A =	$\left\lvert \frac{X + Y}{2} \right\rvert$ Log $\left\lvert \frac{X + Y}{2} \right\rvert$ = − Log cos L_A = ______ Log cot θ_B =
$\theta_A (<90^\circ)$ = For $D<180^\circ$, B is $\frac{E}{W}$ of A X − Y is ± ∴ θ_A is measured from $\frac{N}{S}$ ∴ θ_A = $\frac{E}{W}$ of $\frac{N}{S}$ = E of N	$\theta_B (<90^\circ)$ = For $D<180^\circ$, A is $\frac{E}{W}$ of B X + Y is ± ∴ θ_B is measured from $\frac{N}{S}$ ∴ θ_B = $\frac{E}{W}$ of $\frac{N}{S}$ = E of N
$L_M = \left\lvert \frac{L_A + L_B}{2} \right\rvert$ = $L_M + 45^\circ$ = (to nearest degree)	$L_N = \left\lvert \frac{L_A - L_B}{2} \right\rvert$ = $L_N + \frac{D}{2}$ = (to nearest degree)

$L_M + 45^\circ \gtrless L_N + \frac{D}{2}$ ∴ Use $\frac{\text{upper}}{\text{lower}}$ alternatives throughout

Log $\frac{\cos}{\sin} L_M$ = + Log sin $\frac{D}{2}$ = ______ Log M =	Log $\frac{\sin}{\cos} L_N$ = + Log cos $\frac{D}{2}$ = ______ Log N =
Log M^2 = 2 Log M = M^2 = N^2 = ______ $M^2 + N^2$ =	Log N^2 = 2 Log N = N^2 =
2 Log $\frac{\sin}{\cos} \frac{d}{2}$ = Log $(M^2 + N^2)$ = Log $\frac{\sin}{\cos} \frac{d}{2}$ = $\frac{d}{2}$ =	d = (decimals) = (degrees) (x 111.1) = (kilometres) (x 69.1) = (miles) (x 60.0) = (nautical miles)

TABLE II

θ_A = Bearing of B from A	θ_B = Bearing of A from B	d = Angular Distance	
Place	Latitude	Longitude	
A = BADDOW B = ONGAR	$L_A = 51^\circ\ 42'\ 20''$ N $L_B = 51^\circ\ 42'\ 47''$ N	$0^\circ\ 30'\ 15''$ E $0^\circ\ 10'\ 47''$ E	Difference $D < 180^\circ$
N. Latitudes + VE S. Latitudes − VE	$L_A + L_B = 103^\circ\ 25'\ 7''$ $L_A - L_B = -0^\circ\ 0'\ 27''$	$D = 0^\circ\ 19'\ 28''$ $\frac{D}{2} = 0^\circ\ 9'\ 44''$	

$L_X\ (<90^\circ) = \lvert L_A + L_B \rvert$ or $180^\circ - \lvert L_A + L_B \rvert$ $= 76^\circ\ 34'\ 53''$ Log sin L_X = $\bar{1}.9880$ + Log tan $\frac{D}{2}$ = $\bar{3}.4519$ Log X = $\bar{3}.4399$	$L_Y\ (<90^\circ) = \lvert L_A - L_B \rvert$ or $180^\circ - \lvert L_A - L_B \rvert$ $= 0^\circ\ 0'\ 27''$ Log sin L_Y = $\bar{4}.1170$ − Log tan $\frac{D}{2}$ = $\bar{3}.4519$ Log Y = $\bar{2}.6651$
X has the sign of $L_A + L_B$ X = 0.002754 Y = − 0.04625 X − Y = 0.04900	Y has the sign of $L_A - L_B$ Y = − 0.04625 X = 0.002754 X + Y = − 0.04350
$\left\lvert \frac{X-Y}{2} \right\rvert$ = 0.02450 Log $\left\lvert \frac{X-Y}{2} \right\rvert$ = $\bar{2}.3892$ − Log cos L_B = $\bar{1}.7920$ Log cot θ_A = $\bar{2}.5972$	$\left\lvert \frac{X+Y}{2} \right\rvert$ = 0.02175 Log $\left\lvert \frac{X+Y}{2} \right\rvert$ = $\bar{2}.3375$ − Log cos L_B = $\bar{1}.7922$ Log cot θ_B = $\bar{2}.5433$
$\theta_A\ (<90^\circ)$ = $87^\circ\ 44'$ For $D<180^\circ$, B is ~~E~~ W of A X − Y is + ∴ θ_A is measured from N ~~S~~ ∴ θ_A = $87^\circ\ 44'$ ~~E~~ W of N ~~S~~ = $272^\circ\ 16'$ E of N	$\theta_B\ (<90^\circ)$ = $87^\circ\ 59'$ For $D<180^\circ$, A is E ~~W~~ of B X + Y is − ∴ θ_B is measured from ~~N~~ S ∴ θ_B = $87^\circ\ 59'$ E ~~W~~ of ~~N~~ S = $92^\circ\ 1'$ E of N
$L_M = \left\lvert \frac{L_A + L_B}{2} \right\rvert = 51^\circ\ 43'$ $L_M + 45^\circ$ = 97° (to nearest degree)	$L_N = \left\lvert \frac{L_A - L_B}{2} \right\rvert = 0^\circ\ 0'\ 13.5''$ $L_N + \frac{D}{2}$ = 0° (to nearest degree)

$L_M + 45^\circ > L_N + \frac{D}{2}$ ∴ Use upper ~~lower~~ alternatives throughout

Log cos ~~sin~~ L_M = $\bar{1}.7920$ + Log sin $\frac{D}{2}$ = $\bar{3}.4519$ Log M = $\bar{3}.2439$	Log sin ~~cos~~ L_N = $\bar{5}.8160$ + Log cos $\frac{D}{2}$ = 0.0000 Log N = $\bar{5}.8160$
Log M^2 = 2 Log M = $\bar{6}.4878$ M^2 = 3.075×10^{-6} N^2 = 4.285×10^{-9} $M^2 + N^2$ = 3.079×10^{-6}	Log N^2 = 2 Log N = $\bar{9}.6320$ N^2 = 4.285×10^{-9}
2 Log sin ~~cos~~ $\frac{d}{2}$ = Log $(M^2 + N^2)$ = $\bar{6}.4884$ Log sin ~~cos~~ $\frac{d}{2}$ = $\bar{3}.2442$ $\frac{d}{2}$ = 0.1006°	d = (decimals) = 0.2012 (degrees) (x 111.1) = 22.33 (kilometres) (x 69.1) = 13.90 (miles) (x 60.0) = 12.07 (nautical miles)

and to say that it is an angle less than 90°, which is measured from N. or S. according as $X - Y$ is positive or negative. A similar definition can now be adopted for θ_B with respect to $X + Y$. In this way the computation determines an angle less than 90°, and a simple and rigid rule of signs tells at once whether the angle is to be reckoned with respect to N. or S., the question as to whether it is E. or W. having already been decided in defining the difference of longitude D to be less than 180°. The bearing can then be immediately converted to a standard E. of N.

This scheme obviously lends itself to a simple tabular presentation, and it is proposed to set the process out as in the upper part of Table I. This table is meant to be self-explanatory, in that it contains all the necessary rules as part of the process, and an engineer should be able to use it, who is at all conversant with the problem of computing bearings, without reference to any other description, and without previous knowledge of the formula on which the method is based. It will be seen that the table employs a system of alternatives, in which those which do not apply are crossed out by a logical deduction as the work proceeds, as shown in the example in Table II.

In the computation of the numerical values of X and Y by means of logarithms we have written $|X|$ and $|Y|$ from (7) and (8) in the forms

$$|X| = \sin L_X . \tan D/2 \qquad \text{and} \qquad |Y| = \sin L_Y \Big/ \tan D/2$$

where L_X and L_Y are positive angles less than 90°, which are given by $|L_A + L_B|$ and $|L_A - L_B|$ respectively when these angles are less than 90°, and by $180° - |L_A + L_B|$ and $180° - |L_A - L_B|$ when $|L_A + L_B|$ and $|L_A - L_B|$ are greater than 90°. These definitions of L_X and L_Y are clearly indicated in the table.

The lower part of the table refers to the computation of the distance d, and to develop the method upon which it is based we return to a consideration of the expression for $\cos d$ in (2). In this form there is similarly a likely confusion in the signs, and we seek to remove this disadvantage and to make the formula more symmetrical. We shall proceed to convert $\cos D$ into functions of $D/2$, and similarly to express the formula for $d/2$ instead of d, but first we notice that $\cos d$ is an unsuitable function for determining d when the angle is small, since it approaches unity and is very insensitive to changes of d in this region. We therefore replace $\cos d$ by $1 - 2\sin^2\frac{d}{2}$, and then (2) can be transformed into an equation for $\sin^2\frac{d}{2}$, namely

$$\sin^2\frac{d}{2} = \cos^2\left(\frac{L_A + L_B}{2}\right) . \sin^2\frac{D}{2} + \sin^2\left(\frac{L_A - L_B}{2}\right) . \cos^2\frac{D}{2} \tag{9}$$

which may be written

$$\sin^2\frac{d}{2} = M^2 + N^2$$

where $$M = \cos L_M \sin D/2 \tag{10}$$

and $$N = \sin L_N \cos D/2 \tag{11}$$

in which $$L_M = \left|\frac{L_A + L_B}{2}\right|$$

and $$L_N = \left| \frac{L_A - L_B}{2} \right|$$

L_M and L_N are both positive angles less than 90°, and M and N are both positive. Sin $\frac{d}{2}$ is also positive, and $\frac{d}{2}$ is by definition less than 90°. We do not therefore need any rule of signs, except of course that implied in our convention concerning the signs of L_A and L_B which enters into the determination of the values of L_M and L_N.

There is one slight drawback in formula (9) as it stands, which is that as d approaches 180°, $\sin \frac{d}{2}$ approaches unity and is insensitive to changes in d. This effect is not so serious as the similar effect in $\cos d$ when d is small, but it involves a possible error in determining d which may be as great as 1%, and is outside our stipulated limits of accuracy. We can overcome this difficulty by converting (9) into an analogous expression for $\cos^2 \frac{d}{2}$ instead of $\sin^2 \frac{d}{2}$, for use when the distance becomes large. The required formula is

$$\cos^2 d = \sin^2 \left(\frac{L_A + L_B}{2}\right) . \sin^2 \frac{D}{2} + \cos^2 \left(\frac{L_A - L_B}{2}\right) . \cos^2 \frac{D}{2} \qquad (12)$$

This may also be written as $M^2 + N^2$ provided we now define M and N, instead of by (10) and (11), by

$$M = \sin L_M \sin \frac{D}{2} \qquad \text{and} \qquad N = \cos L_N \cos \frac{D}{2}$$

It would be cumbersome to have to use two different formulæ according as the distance is small or large, except that the similarity of form between (9) and (12) admits of the two equations being combined as follows :—

$$\begin{matrix}\sin^2\\ \cos^2\end{matrix} \frac{d}{2} = M^2 + N^2$$

where $$M = \begin{matrix}\cos\\ \sin\end{matrix} L_M \sin \frac{D}{2} \quad \text{and} \quad N = \begin{matrix}\sin\\ \cos\end{matrix} L_N \cos \frac{D}{2}$$

where we choose either the upper or the lower alternatives throughout. The working can therefore be set out as in the lower part of Table I, and we need a simple criterion for deciding which alternative to use.

The two formulæ become equivalent in accuracy when $d = 90°$, i.e., $\frac{d}{2} = 45°$. The simplest accurate expression for $d = 90°$ is obtained by putting $\cos d = 0$ in (2), which gives $\cos D = - \tan L_A \tan L_B$, where we must take account of the signs of L_A and L_B, but obviously this is not a convenient criterion to have to apply. On the other hand it would be too vague to say that we use the $\sin^2 \frac{d}{2}$ form when the distance is obviously smaller than 90°, and the $\cos^2 \frac{d}{2}$ form when the distance is obviously greater than 90°, especially if we were to estimate the rough value of the distance on a Mercator projection with its large distortion of the higher latitudes.

But fortunately we can make a compromise by using a very simple rule, which is exact for certain conditions, and can be shown to give the dividing line within $\pm 13°$ of $45°$ for $\frac{d}{2}$ for all cases. As the accuracy of either formula varies only slightly within this range, this rule can therefore be adopted, and it is simply that we use the $\sin^2 \frac{d}{2}$ or the $\cos^2 \frac{d}{2}$ form according as $L_M + 45°$ is greater or less than $L_N + \frac{D}{2}$. In applying this rule we need, of course, only express these angles to the nearest degree, and thus it can be very easily introduced into the scheme, as has been done in Table I.

The application of this rule involves practically no labour, and as it enables one to maintain the desired accuracy of computation even on the longest routes, it is well worth while including this slight complication of the process. It falls into line with the method of presenting the rules of signs as a system of alternatives adopted in the upper part of Table I, and it is intended that likewise the scheme should be self-explanatory to the engineer who may not be conversant with the reasoning upon which it is based.

Procedure when Certain Angles are Less than 3° or Greater than 87°.

In the course of the work it may be found that the logarithm cannot be looked up accurately in the four figure tables because of the large differences involved. It may conversely be found that when the logarithm has been computed, the angle cannot be accurately deduced from it by means of the tables. These cases occur for the sine, tangent and cotangent functions when the angle is less than 3°, and for the cosine, tangent and cotangent functions when the angle is greater than 87°.

This at first sight implies a limitation on the method, but it is only in the reading of the tables, and not in the use of the four figure logarithms as such. The accuracy required is still only to four figures, and within the scope of four figure logarithms. We need, therefore, a method of obtaining or interpreting the four figure logarithms accurately in these cases, and we can find a solution of the difficulty in the fact that for a small angle the sine and tangent approximate to the value of the angle itself measured in radians.

If an angle measured in degrees is x, we have, when x is small,

$$\sin x = \tan x = \frac{\pi \,.\, x}{180} = \frac{x}{57.30}$$

so that

$$\log_{10} \sin x = \log_{10} \tan x = \log_{10} x - 1.7581$$

The value of $\log \sin x$ so obtained is only two units too big in the last figure of the four figure logarithm, and the value of $\log \tan x$ four units too small, when x is 3°, and the approximation rapidly improves as x decreases. We can, therefore, use this approximation for all cases when x is less than 3°. By using the relations

$$\cos(90° - x) = \sin x \quad \text{and} \quad \cot(90° - x) = \tan x = 1/\cot x$$

we can enlarge our rule to obtain similar approximations for all the functions which need special treatment when x is less than 3° or greater than 87°.

In Table III are given the functions of this type which may occur in the use of Table I, together with the appropriate formulæ for their computation, in which the angle is expressed in decimals of a degree.

TABLE III.

(*a*) When $x < 3°$:

(1) Given x, to find log sin x. $\log \sin x = \log x - 1.7581.$
(2) Given x, to find log tan x. $\log \tan x = \log x - 1.7581.$
(3) Given log cot x, to find x. $\log x = 1.7581 - \log \cot x.$
(4) Given log sin x, to find x. $\log x = \log \sin x + 1.7581.$

(*b*) When $x > 87°$:

(1) Given x, to find log tan x. $\log \tan x = 1.7581 - \log (90° - x).$
(2) Given x, to find log cos x. $\log \cos x = \log (90° - x) - 1.7581.$
(3) Given log cot x, to find x. $\log (90° - x) = \log \cot x + 1.7581.$
(4) Given log cos x, to find x. $\log (90° - x) = \log \cos x + 1.7581.$

As an alternative method, it may be preferable to use a special four figure table calculated for angles near to 0° and 90° with a fine interval where available. It may also be desirable to work throughout in decimals of a degree and to use tables that have been tabulated in this way. These are, however, matters of detail which do not affect the process as a whole. In any case, an apprenticeship will be needed to handle it fluently and the computor must decide for himself the precise technique he adopts.

As an example, Table II shows the process worked out for the short distance route between the Marconi Research Laboratories at Great Baddow, and the Ongar Wireless Station of Cable & Wireless, Ltd. It will be seen that there are several places where recourse has been made to Table III. We notice especially that the final value of $\frac{d}{2}$ is of the order of 6 minutes of arc and we are justified in interpreting the angle to within 0·3 seconds of arc from the computed value of log sin $\frac{d}{2}$.

Comparison with Approximate Short Distance Formulæ.

Stress has been laid on the applicability of the method outlined above to all possible cases, including those which usually present special difficulties. Such cases are :—

(1) when the places are near to one another ;
(2) when they are antipodal, and
(3) when they are in the polar regions.

All these cases repay a careful examination to convince one of the generality of the method, but it will be interesting to consider here the first one, which is the one of most practical importance.

When the two points A and B are close together, to obtain an accurate computation of the bearings and the distance we need to know the difference of latitude and the difference of longitude to the required accuracy, however small the absolute values in degrees may be, and, of course, any method of computation assumes that his necessary information is given. But we see at once the advantage of a formula which explicitly involves the angle $L_A - L_B$ and the sum of the latitudes $L_A + L_B$, when we have to know the difference of latitude to a fraction of 1 second of arc while we may not know either latitude itself to closer than 1 minute of arc.

Consider now in Fig. 1 a map showing A and B in close proximity, where for convenience we have chosen them to be in the northern hemisphere, and A to be further N. than B and to the west of it. The point C represents the intersection of the line of latitude through B with the line of longitude through A, and C′ the intersection of the line of latitude through A with the line of longitude through B.

In this approximate projection picture, the lines all become straight, and angles ACB and AC′B are nearly right angles. The bearings θ_A and θ_B, considered as angles less than 90°, are given by ∠CAB and ∠C′BA respectively. If r_0 is the radius of the earth, and we consider the angles to be measured in radians, we have :—

$$\mathrm{AC} = \mathrm{BC}' = r_0 (L_A - L_B),\ \mathrm{BC} = r_0 D \cos L_B,\ \mathrm{AC}' = r_0 D \cos L_A,\ \mathrm{AB} = r_0 d.$$

Thus

$$\cot \theta_A = \frac{\mathrm{AC}}{\mathrm{BC}} = \frac{L_A - L_B}{D \cos L_B} \tag{13}$$

and

$$\cot \theta_B = \frac{\mathrm{BC}'}{\mathrm{AC}'} = \frac{L_A - L_B}{D \cos L_A} \tag{14}$$

AB^2 is greater than $\mathrm{AC}'^2 + \mathrm{BC}'^2$, i.e., $r_0^2 \left[D^2 \cos^2 L_A + (L_A - L_B)^2\right]$, and is less than $\mathrm{BC}^2 + \mathrm{AC}^2$, i.e., $r_0^2 \left[D^2 \cos^2 L_B + (L_A - L_B)^2\right]$, and so we may write as a close approximation,

$$\mathrm{AB}^2 = r_0^2 \left[D^2 \cos^2 \left(\frac{L_A + L_B}{2}\right) + (L_A - L_B)^2\right]$$

or if d is measured in radians,

$$d^2 = D^2 \cos^2 \left(\frac{L_A + L_B}{2}\right) + (L_A - L_B)^2 \tag{15}$$

Now if in (3) were place $\tan \frac{D}{2}$ by $\frac{D}{2}$, and $\sin (L_A - L_B)$ by $L_A - L_B$, we obtain

$$\cot \theta = \frac{D \sin (L_A + L_B)}{4 \cos L_B} - \frac{L_A - L_B}{D \cos L_B} \tag{16}$$

Now since $L_A - L_B$ and D are both small, the second term of (16) usually predominates over the first term, and this second term is identical with (13). (The negative sign indicates that the angle is measured from S. instead of from N., agreeing with Fig. 1). Similarly, we can compare (4) with (14). When the points A and B happen to be on the same latitude, the first term of (16) represents the small angle by which the great circle path joining A and B diverges from the line of latitude at A and B, as is represented diagrammatically in Fig. 2. This term becomes zero when both points are on the equator, and the line of latitude becomes a great circle.

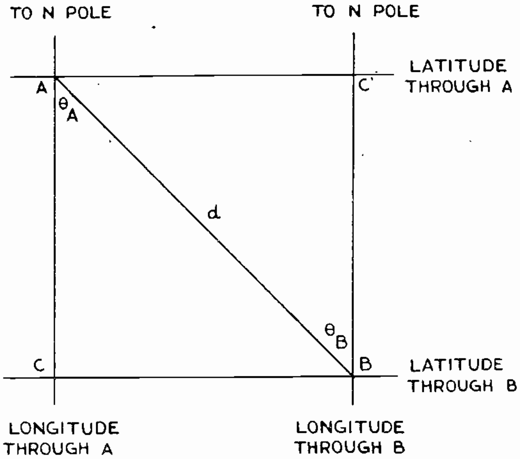

FIG. 1

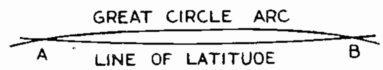

FIG. 2

Turning now to (9), which is the distance formula suitable for computing short distances, and putting

$$\sin\frac{d}{2} = \frac{d}{2},\ \sin\frac{D}{2} = \frac{D}{2},\ \sin\left(\frac{L_A - L_B}{2}\right) = \frac{L_A - L_B}{2},\ \text{and}\ \cos\frac{D}{2} = 1,$$

we have, on multiplying through by 4,

$$d^2 = D^2\cos^2\left(\frac{L_A + L_B}{2}\right) + (L_A - L_B)^2$$

which is identical with (15).

Thus we see that the forms of exact formulæ which we have developed degenerate directly into the simple projection formulæ as A and B approach one another. In practice, if one is dealing wholly with short distances, one would use a map, or compute from the simple projection formulæ, but in general it is better to use the accurate formulæ, if there is any doubt as to the error involved in using the projection formulæ. We have seen from the worked out example given in Table II that the standard method is quite easy to use with short distances, and in this case the correction due to the first term in (16) is just noticeable.

In conclusion, it may be emphasised that as the form of the equations which we have used is exact, since they are obtained by a rigid transformation from the standard formulæ, they are not restricted to the four figure accuracy with which we have been mainly concerned. They are equally applicable, with the use of correspondingly more accurate tables, where higher accuracy is required than is usually envisaged in direction finding work of the kind considered in the introduction. It must be remembered, however, that in such cases, e.g., in the use of high precision navigational aids of the type such as " GEE " and " OBOE", account may have to be taken of the fact that the earth is not a perfect sphere. It should be possible, however, to obtain the necessary modification by means of a correction term applied to the equations in the form in which we have used them.

THE EFFECT OF RAIN ON MARINE RADAR ECHOES.

By S. E. Barden, B.Sc.

There have been occasions when targets in the vicinity of a ship carrying P.P.I. type radar gear, have remained undetected by the radar operator when heavy rain has been falling. Such a failure of the radar system is explained and analysed below, and a set of curves prepared to assist the operator to determine the ranges within which target echoes ought to be visible.

IT HAS been known for some time that rain both reflects and attenuates radar microwaves. The former effect results in a spread of echoes on the P.P.I. screen, increasing in brightness with intensity of the rainfall, measured in millimetres per hour. The latter effect decreases the intensity of target echoes, by both scattering and absorption. Attenuation also increases with the intensity of the rainfall. Both these effects limit the ranges of targets below the free space value, and are treated separately below.

Consider first microwave reflections from rainfall, neglecting the attenuation for the time being. We shall define the equivalent echoing area A of a target as the projected area of a perfectly reflecting sphere which would scatter backwards, to a radar receiver, the same power as does the target. Then, if the target is a rainstorm, it has been shown by Ryde[1] that the equivalent echoing area of the rain belt is given approximately by :—

$$A = 0{\cdot}9\ \mu r^2\ \theta^2\ N.S.\ 10^8\ \varphi\ \psi \text{ sq. metres}$$

where :—

μ = pulse length in μsecs,
r = distance of storm in km.
θ = divergence, in degrees, of beam, measured to half power.
N = number of drops /c.c. in ideal cases.
S = appropriate scattering function for a single drop.
φ = fraction of energy in wavefront that falls on the supposed uniform storm.
ψ = correction factor to allow for attenuation.

Neglecting attenuation, i.e. taking $\psi = 1$, we also suppose $\varphi = 1$. The term $N.S.$ x 10^8 is a function of wavelength and precipitation, in mm/hour, of rainfall.

In Fig. 1 the area of the rainfall, as defined above, is plotted against r in kms., for various precipitation rates, using a wavelength of 3 cms., a beam divergence of 1·5°, and pulse length of 1/5μsecs.

Based on a similar definition of equivalent echoing area, values of A have been obtained for various sizes of surface targets, and are also shown in Fig. 1. Since echo intensity is proportional to A/r^4, then the distances at which the equivalent

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[1] *Ryde* — Page 174 of the report of a conference held by the Physical Society in April 1946 — "Meteorological Factors in Radio Wave Propagation".

echoing areas of target and rain are equal, are the distances at which the target echoes and the rain echoes have the same intensity. Thus the target echoes are masked by

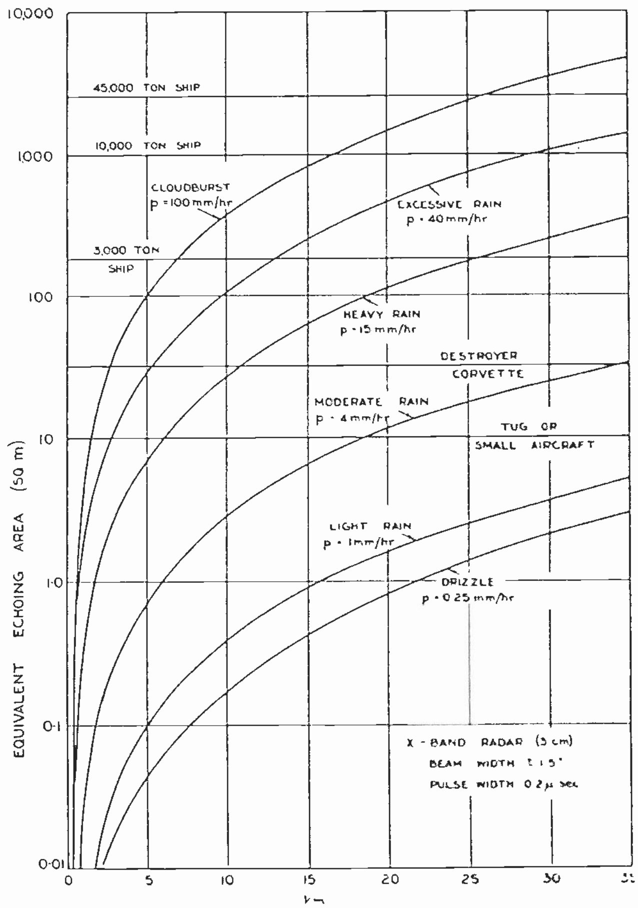


FIG. 1

those of the rain. Within these distances, the target echoes can at the limit be made visible by reducing receiver gain. Beyond them target echoes merge irretrievably into the belt of rain echoes on the screen.

Let us take an example. Suppose heavy rain is falling—of the order of 15 mm/hour. Referring to Fig. 1, a small target like a tug or a small aircraft ought to be visible up to about 6 kms. from the ship, beyond which rain echoes mask them entirely. On the other hand a 10,000-ton vessel ought to be visible up to the limiting free space distance, while a 3,000-ton vessel should be detected up to 25 kms.

These conditions hold as long as rain is falling on the target. It need not extend to the ship carrying the radar gear.

So far we have neglected the attenuation that raindrops produce on target echoes. Ryde has shown that, over the centimetre band, attenuation values approximate to those given by the simple relation

$$\text{decibels/kilometre} \doteqdot k.p. \quad (\lambda = 1 \text{ to } 10 \text{ cm.})$$

in which p is expressed in mm/hour, and the value of k depends on wavelength and temperature. The value of k chosen for the curves in Figs. 2 and 3 is for $\lambda = 3$ cms., and $T = 18°C$.

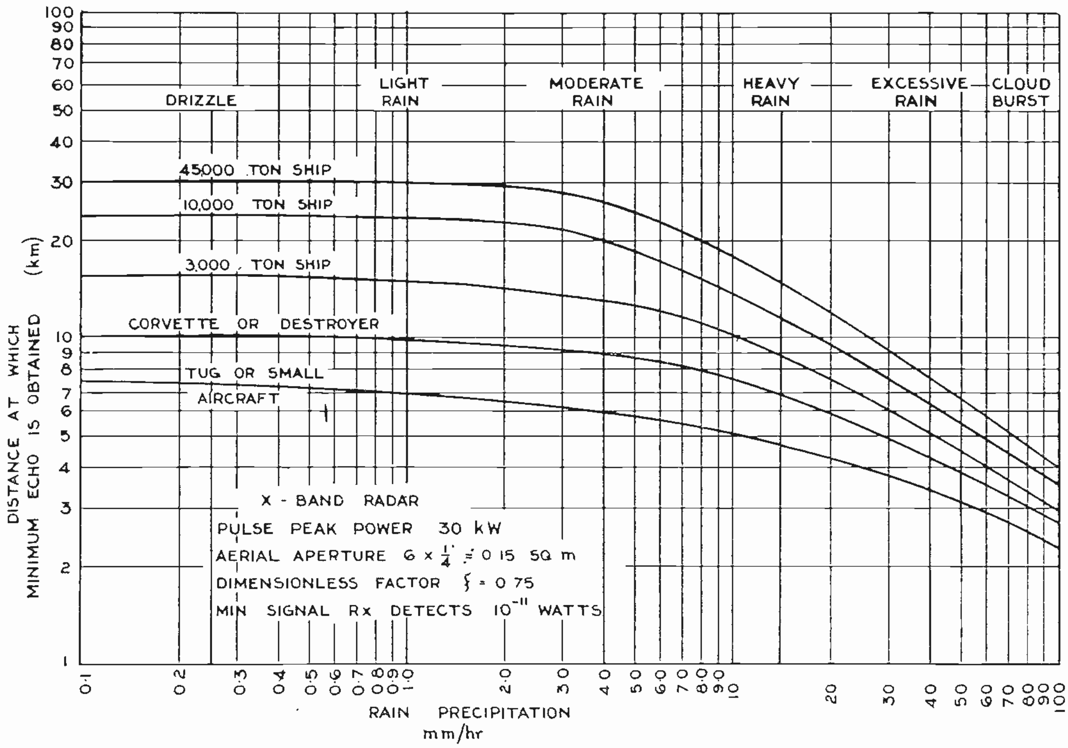


FIG. 2

There are two cases for which a slightly different treatment is given. The first is the case when a rainstorm envelops both target and the radar ship. It is for this case that Fig. 2 has been drawn. The second is for the case when a belt of rain intervenes between target and radar ship, and involves either one or neither. For this case, curve 3(a) gives attenuation in decibels for various widths of rainbelt and rainfall precipitation rates. For such attenuation Fig. 3(b) gives the maximum distance at which a given size of target ought to be visible. These curves assume a transmitted pulse of 30 kW and minimum signal power (as limited by the radar receiver) of 10^{-11} watts.

Tables 1 and 2 give the factors by which the maximum ranges obtained by these curves have to be multiplied for various other transmitted powers and minimum signal powers.

TABLE 1

Transmitter Pulse Peak Power.	Factor by which max. range has to be multiplied.
5,000 watts	0·64
10,000 ,,	0·76
15,000 ,,	0·84
20,000 ,,	0·905
25,000 ,,	0·990
30,000 ,,	1·00
35,000 ,,	1·01
40,000 ,,	1·07
50,000 ,,	1·136

TABLE 2

Min. signal power receiver can handle.	Factor by which max. range has to be multiplied.
10^{-10} watts	0·562
10^{-11} ,,	1·00
10^{-12} ,,	1·78
10^{-13} ,,	3·16
10^{-14} ,,	5·62
10^{-15} ,,	10·00
10^{-16} ,,	17·80

These factors hold accurately for Fig. 3(b), but only for the free space value of Fig. 2.

Of the two factors discussed separately above, i.e. masking and attenuation, the dominant one is that which results in a lower value for maximum range.

Let us consider the following examples :—

Example A :—

A ship is ploughing through " heavy " rain. The operator, knowing his pulse peak power to be 30 kW and minimum signal power 10^{-11} watts, looks up his attenuation curves (Fig. 2) and discovers that a tug or similar small vessel ought to be visible within 4½ kms., a battleship within 14–15 kms., and so on.

From his " masking curves " he finds that a small tug ought to be visible within 6 kms., and a 45,000-ton battleship or vessel of similar size within the whole free space range (approx. 40 kms.).

Thus for heavy rain, for the conditions specified above, attenuation is the dominating factor. If, however, the receiver has a minimum signal power limit of 10^{-14} watts, the "attenuation range" increases beyond 6 kms., for a small vessel, so that "masking" is the factor which renders the small tug unable to be detected beyond 6 kms. in heavy rain.

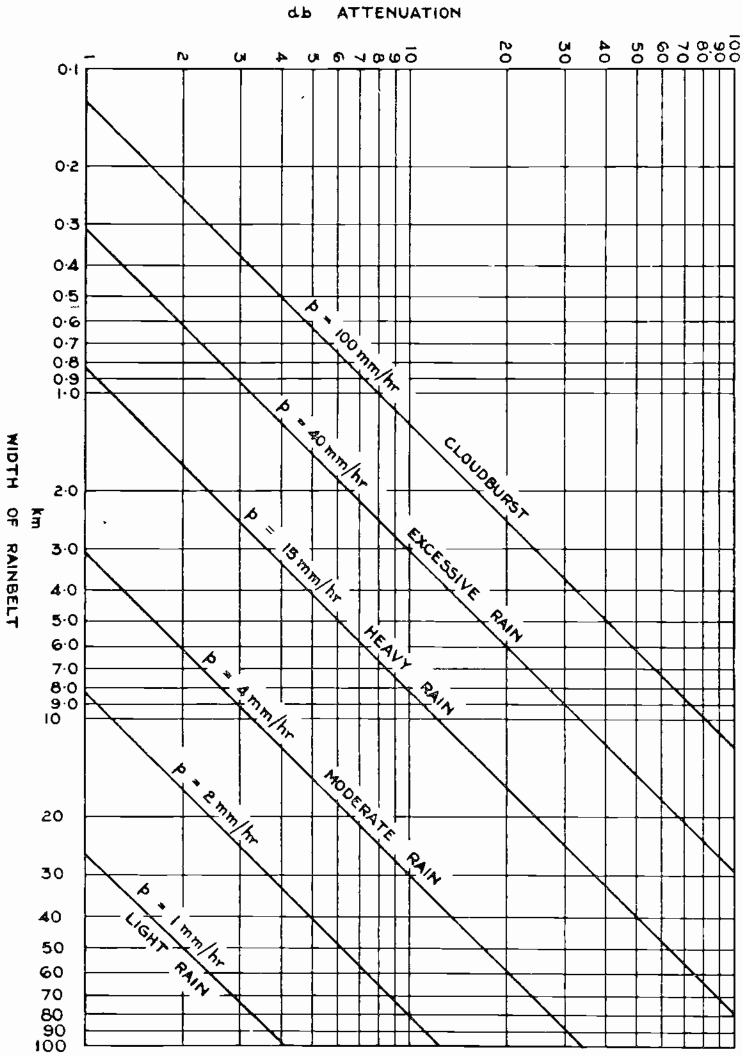


FIG. 3(a)

From similar examples we see that the heavier the rain, the more likely it is that "masking" is the factor which hides small targets. Moreover, the greater the sensitivity of the set, the less effect attenuation has on the determination of maximum ranges.

Example B :—

Let us consider now a use of the curves in Figs. 3(a) and 3(b).

Suppose, from echoes on his P.P.I. screen, the radar operator estimates a belt of heavy rain 5 kms. from his vessel and 1 km. wide (say $p = 20$ mm/hour).

From curves in Fig. 3(a) he obtains a value of 1·75 decibels. Then from Fig. 3(b) he finds that the maximum range of a small tug has to be 7 kms. if it is to be detected. Thus a small tug ought to be visible up to 2 kms. from the far side of the rain belt.

Under the same conditions, a destroyer will be visible up to 4 kms., a 3,000-ton vessel up to 9 kms., and a 45,000-ton vessel up to 24 kms. from the far side of the rain belt.

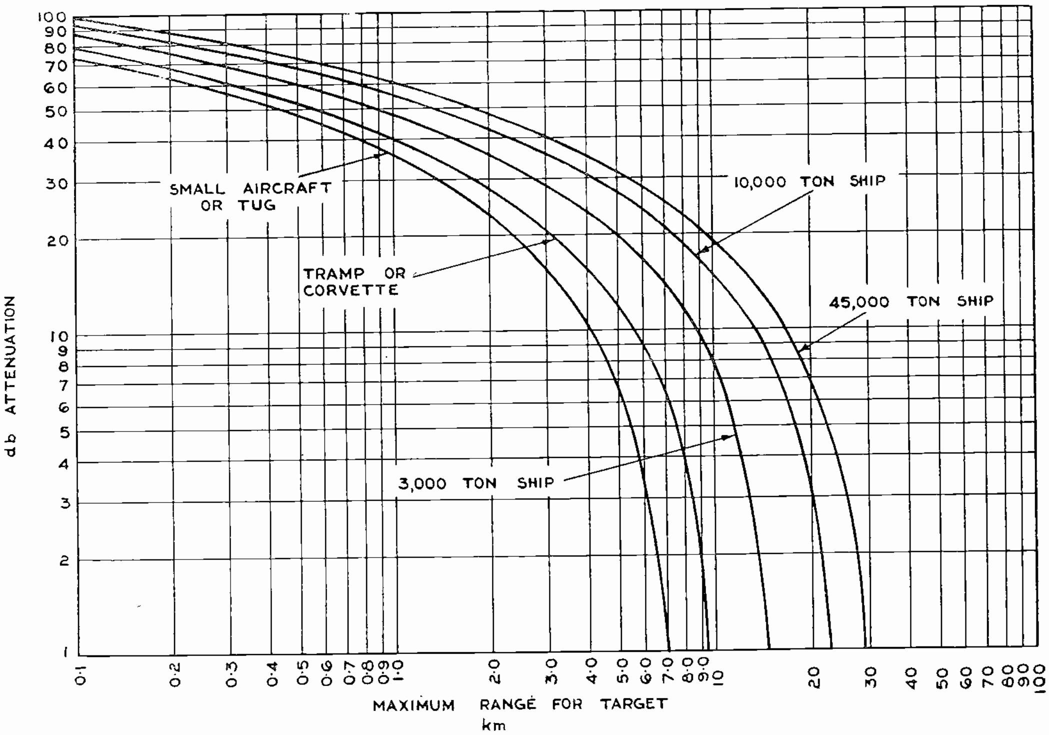
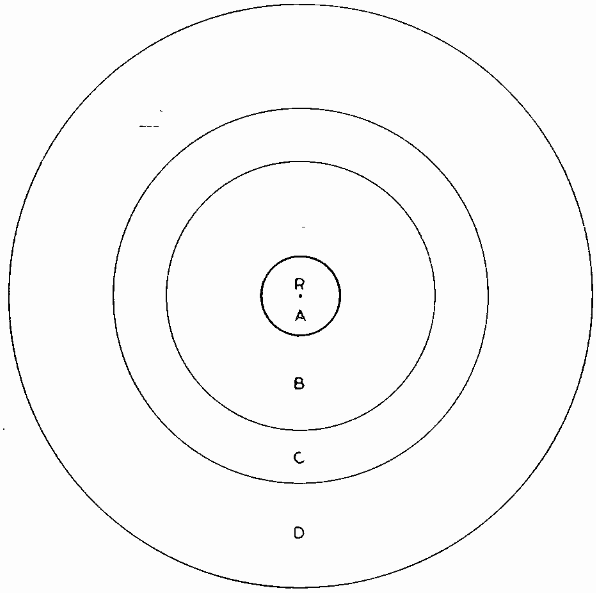


FIG. 3(b)

These are exceptionally good conditions, but, though attenuation alone enables ships to be seen beyond the rain belt, small targets within the rain belt will be "masked" by rain echoes. This can be shown in the following example. Referring to Fig. 1, we find that a rain belt 5 kms. away returns echoes that, at the near edge, are just weaker than those of a small target. As the target, however, moves towards the far boundary of the rain belt it is masked by the rain echoes, and is thus indistinguishable from them. This masking, however, only occurs during the last few metres of its journey to the far boundary of the rain belt. Beyond the rain belt a clear echo is again obtained from it, which persists with gradually diminishing intensity until the vessel is 7 kms. away when attenuation would render it incapable of being amplified above noise by the radar receiver.

Of course, "masking" effects would obviously be more frequent with small targets than with large targets.

In conclusion, the author would like to emphasize that no very great accuracy should be imputed to these curves, though this is in no way the fault of the technique. These curves could be drawn to greater accuracy, if the need arose. Unfortunately, such need does not exist in current radar practice as the operator has no way of accurately determining the rate or extent of rainfall, other than by mere observation of rain echoes on his screen.



R – SHIP CARRYING RADAR GEAR

A – REGION DOMINATED BY SEA - SCATTER

B – REGION GIVEN BY CURVES, WITHIN WHICH, IF NO DOMINANT TARGET ECHOES ARE VISIBLE, NO TARGET OF THE SIZE DEFINING ITS BOUNDARY COULD EXIST IN SPECIFIED CONDITIONS OF RAIN.

C – REGION WHOSE OUTER LIMIT IS DETERMINED FROM PURELY THEORETICAL CONSIDERATIONS INVOLVING EXACT KNOWLEDGE OF EXTENT AND INTENSITY OF RAINFALL AND TARGET SIZE

D – REGION LIMITED BY EARTH CURVATURE AND Tx - Rx CHARACTERISTICS

FIG. 4

Comparatively accurate estimates of the extent and intensity of rainfall can be given by a small modification of existing radar equipment, namely the introduction of an auxiliary "A" display on a monitor tube. This is, however, beyond the scope of the present paper.

Further, no allowances have been made for sea "clutter," it being assumed that this is confined to the immediate vicinity of the ship, and therefore of rather less importance.

Within the limitations mentioned above, the operator can obtain useful — though rough—estimates of the ranges within which target echoes ought to be visible on his screen, despite the bad weather. It should help to give him greater confidence in his predictions.

Attenuation and Masking of Target Echoes by Rain.

It should be noted that, so far, we have supposed conditions of actual operation by individuals little appreciative of the theoretical foundations of the analysis, with the consequent necessity of predicting areas within which, if no target echoes were visible, then, under the worst rain conditions possible, no targets could exist. The curves of Figs. 1, 2 and 3 were therefore drawn to allow for certain factors inherent in the system of observation.

The theoretical values for the attenuation of 3 cm. radiation by rain have been modified (multiplied by a factor of 1·75) to allow :—

(*a*) For under-estimation of the precipitation rate of the rainfall. This was done, in spite of the fact that the empirical nature of estimating the precipitation rate of rainfall was as likely to yield an over-estimation as an under-estimation, for the very good reason given above.

(*b*) For under-estimation of the width of a belt of rain. This would allow for the fact that the regions of the rain belt further from the radar operator would present rather fainter echoes, liable to be unobservable should the operator find it necessary to reduce receiver gain.

In the "masking" curves (Fig. 1), the modification was applied to the equivalent echoing areas of the targets rather than to the curves, which are accurate representations of the Ryde formula. For these curves, therefore, the target echoing areas have been slightly under-estimated.

Any calculations based on these curves will therefore give a region B, in Fig. 4, in which no outstanding echoes, under conditions of the worst possible scatter from rain, would mean that no such target of a particular size existed.

Referring to Fig. 4, therefore, it is obvious that regions B, C and D are wholly dependent on the size of the target and the extent and intensity of the rainfall, any one boundary being defined by all of these three parameters, together with the important factors of the transmitter power and the sensitivity of the receiver.

BOOK REVIEW.

WE HAVE received from the publishers (MacDonald & Co. (Publishers), Ltd.) a recently published volume on electrical measurements.* Part I deals only with D.C. measures and instruments, and aims at presenting to the young electrical engineer the fundamental principles and technique of the standard methods of electrical measurement. In electrical engineering, perhaps to a greater extent than in most other engineering sciences, reliable measurments must be the foundation on which all work is built. An adequate understanding of the methods available for making these measurements is, therefore, most necessary.

The opening chapters of the book deal with questions of accuracy and reliability, and explain the sources of error usually inseparable from all measurement observations. The varying extent to which this kind of error may invalidate the result is discussed. The succeeding chapters cover in detail standard methods used for the determination of current, potential difference, resistance and the like. In each case, the associated sources of error are quantitatively discussed. The mathematical treatment in many places is somewhat laboured, and could very profitably have been abbreviated and condensed. In other places, further explanations might have been an advantage. A differentiation of type size, especially in the case of indices and integral limits might also have improved the clarity of the analysis.

The book is commendably self-sufficient, but the very few references to other sources which do appear, refer mostly to foreign books which could not normally be available to English readers.

The volume should be a most useful source of reference to beginners and, indeed, on occasion to experts when called upon to complete an unaccustomed measurement.

* *Electrical Measurements and the Calculations of the Errors Involved*, Part I, by D. Karo, pp. viii +191. MacDonald & Co. (Publishers), Ltd., London, 18s. net.

A SET FOR NOISE AND DISTORTION TESTS ON CARRIER AND BROADCAST SYSTEMS

By A. F. Boff, B.Sc.

The limitations of conventional harmonic testing of transmission systems are indicated and the salient features of multi-tone testing outlined. It is shown that the use of two simultaneous test tones enables distortion measurements to be made at frequencies up to the limit of the pass band. A complete test equipment is described which provides the facilities required for noise and distortion tests on a V.H.F. link.

IN the testing of carrier and broadcast systems it is customary to make measurements of overall linearity by injection of a pure tone at the sending or transmitting end. The performance is then specified in terms of the harmonic levels in the received signal which are expressed either as percentages of the fundamental or in decibels relative thereto. The application of this method is limited to tests at the lower frequencies of the transmitter band owing to the removal of harmonics of higher frequencies by the normal band-pass of the system. For instance, a system having a bandwidth of 100 kc/s cannot be tested for second harmonics above 50 kc/s or for third harmonics above 33⅓ kc/s. It may appear that generation of harmonic components which are subsequently suppressed in any case, is of no practical importance, and indeed this would be so if a single tone were to be transmitted. However, when many tones are transmitted simultaneously, as for example in speech or music, distortion arises owing to the formation of modulation products. It is not possible to deduce distortion performance at high frequencies from measurements made at lower frequencies since levels cannot be predicted with certainty at all points of the system as a function of frequency. Also, it is a practical limitation of many transmission systems that distortion is inherently greater as the modulation frequency is raised, owing perhaps to the never quite perfect band-pass characteristics or to the failure of feedback networks and it is thus doubly important to measure distortion at high modulation frequencies. Since, as mentioned previously, direct measurement of harmonic generation is not possible except at the lowest frequencies, measurements of intermodulation must be made. By this means the test range may be extended to include all harmonic combinations which may cause distortion in practice.

The Two Tone Method

If two tones are injected simultaneously into a non-linear system the output contains, in addition to the fundamental frequencies, a spectrum of "beat tones" or modulation products which are related to the terms of the power series representing the system performance, i.e.

$$a_1v+a_2v^2+a_3v^3+\dots\dots\dots+a_nv^n+\dots\dots\dots$$

It has been shown * that any particular beat frequency is dependent on an infinite

* Harmonic Production and Cross Modulation in Thermionic Valves with Resistance Loads—D. C. Espley. Proc. I.R.E. June 1934.

series involving the coefficients a_n which cannot, therefore, be individually determined by measurement of a tone. There is no particular disadvantage in this, except in so far as it may be desirable to correlate intermodulation measurements with those made by the harmonic method. However, in practice, it is often more useful to know separately the contributions made by odd and even order terms and this may be arranged by choice of test frequencies so that the beat tones formed by even powers of modulation products have no common frequency with those of the odd powers except, perhaps, for very high order terms. With this precaution, therefore, the method is applied as now described.

Tones of equal amplitudes but different angular frequencies ω_1 and ω_2 are injected simultaneously into the system under test. At the receiver, or output, the amplitudes of the tones $(\omega_1 \sim \omega_2)$ and $(2\omega_1 \sim \omega_2)$ are measured. Then it can be shown (*loc. cit*) that the relative amplitudes are respectively :

$$\text{Amplitude } (\omega_1 \sim \omega_2) = a_2 + \frac{3}{2}a_4 + \frac{15}{2}a_6 + \ldots\ldots\ldots$$

$$\text{Amplitude } (2\omega_1 \sim \omega_2) = \frac{3}{4}a_3 + \frac{25}{8}a_5 + \frac{735}{64}a_7 + \ldots\ldots\ldots$$

In practical systems the first term of each of these series is often much greater than the subsequent ones and in such cases it is a fair approximation to write the amplitudes as a_2 and $\frac{3}{4}a_3$ respectively.

Choice of Test Frequencies

To ensure that all parts of the system are tested, it is essential for both fundamental frequencies to lie within the normal pass band. Other factors affecting the choice are intimately connected with the design and construction of practical filters of sufficiently sharp discrimination. To avoid the risk of confusion between even and odd coefficients referred to in the previous section, the tones $(\omega_1 \sim \omega_2)$ and $(2\omega_1 \sim \omega_2)$ must be spaced sufficiently far apart to permit adequate filtering and must also be selected so that $(n'\omega_1 \sim n''\omega_2)$ has no value when the sum $n' + n''$ is odd which coincides with $(\omega_1 \sim \omega_2)$ and similarly $(2n'\omega \sim n''\omega_2)$ must have no value equal to $(2\omega_1 \sim \omega_2)$ when $n' + n''$ is even. Filter considerations lead to a spacing of the test frequencies so that the required modulation product is well separated from the strong fundamental tones. Since tones of higher

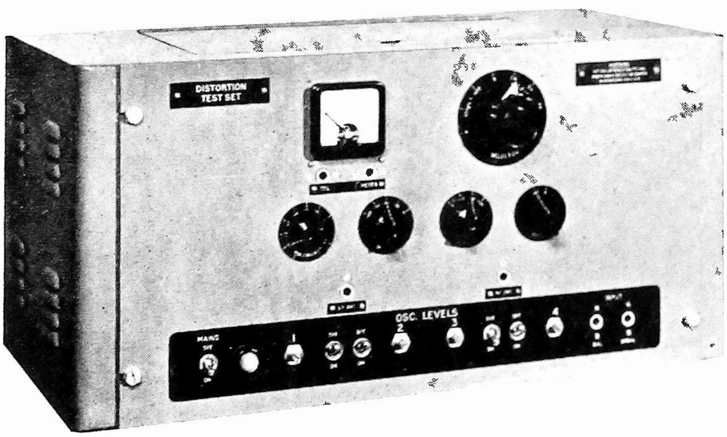


Fig. 1

frequency than the fundamentals may be suppressed by the band-pass effect of the system under test, a modulation tone much lower than the fundamental is implied by the requirement of the preceding restriction. However, this feature must not be carried too far or the frequency stability of the test tones becomes critical. In the test set described here, a compromise is obtained between oscillator and filter performance and a further economy is achieved by changing ω_2 to ω_2' when measuring the odd power terms, so that $\omega_1 \sim \omega_2$ is equal to $2\omega_1 \sim \omega_2'$ and a common band-pass filter may be used for both tests.

The Noise and Distortion Test Set

The apparatus described here, and illustrated in Fig. 1, was designed for testing V.H.F. links having a bandwidth of 150 kc/s or more. An effort was made to combine, in one compact unit, the ancillary equipment required for distortion and noise testing which is usually available only by combination of a number of subsidiary laboratory instruments in the form of oscillators, amplifiers, filters, wave analysers, etc.

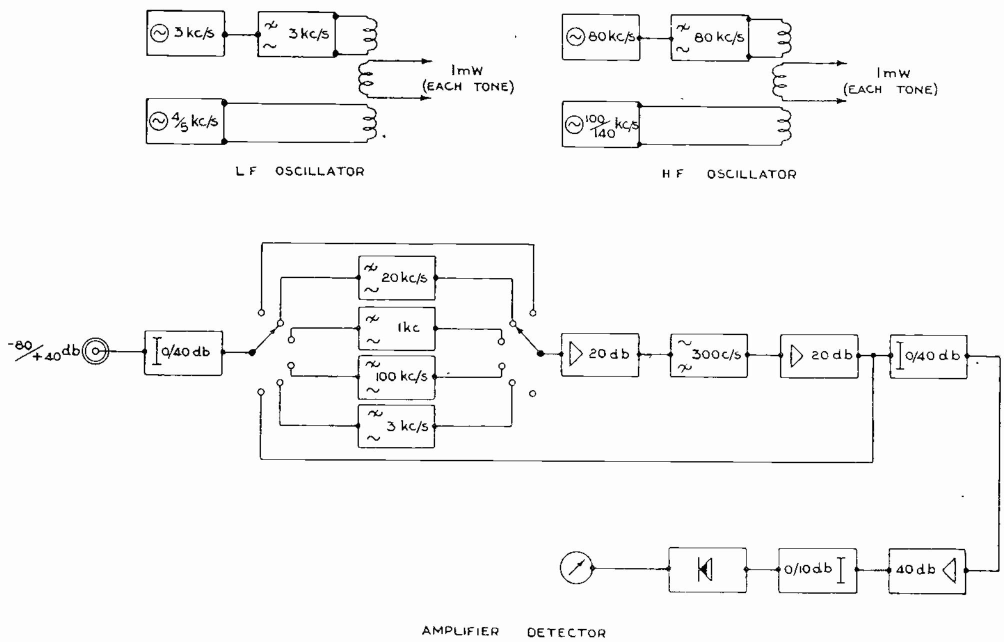


FIG. 2

The following tests are provided and may be studied in conjunction with the general scheme shown in Fig. 2 :

(*a*) Distortion in the frequency band 3–5 kc/s.
(*b*) Distortion in the frequency band 80–140 kc/s.
(*c*) Noise in the frequency band 300 c/s–3 kc/s.
(*d*) Noise in the frequency band 300 c/s–100 kc/s.
(*e*) Sensitive valve voltmeter —80 db to +40 db.

Oscillators are available in pairs coupled to an output jack via a balanced hybrid coil. These sources are used when making the tests (*a*) and (*b*) itemised above and in accordance with the table below.

Frequencies	Tone measured	Distortion coefficients deduced
3 kc/s and 4 kc/s	1 kc/s	Even
3 kc/s and 5 kc/s	1 kc/s	Odd
80 kc/s and 100 kc/s	20 kc/s	Even
80 kc/s and 140 kc/s	20 kc/s	Odd

The amplifier is shown in Fig. 2 preceded by four wave filters. Two of these are the means for selecting the combination tones referred to above and the others

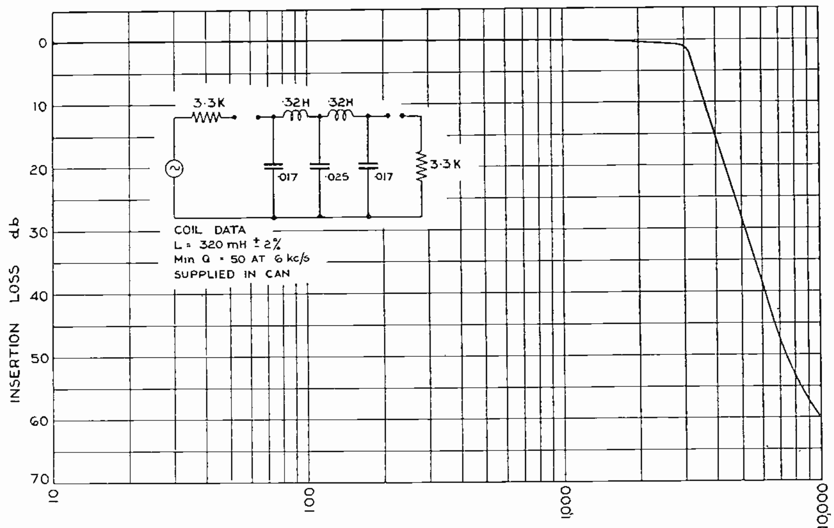


FIG. 3

provide 3 kc/s and 100 kc/s pass-bands for use when measuring noise. (Figs. 3 and 4.) Other positions of the selector switch permit measurements without preliminary filtering and are useful for measuring fundamental tones and for general purposes.

Circuit Description

(1) *The amplifier and filters.* The input signal, which may be balanced or unbalanced to earth, is injected at the appropriate jack (Fig. 5) and fed via a single step attenuator to selector switch S_1. The signal reaches the grid of V_5 through one of four filters or a resistive attenuator, each path having the same attenuation at the frequency at which it is used for measurements. It will be seen that the input impedance is 600 ohms which follows standard practice in carrier telephony,

and levels where quoted are expressed in decibels relative to 1 mW. The measurement of distortion must often be made in the presence of noise and the bandwidth of the filters used for distortion tests requires some consideration. The more narrow

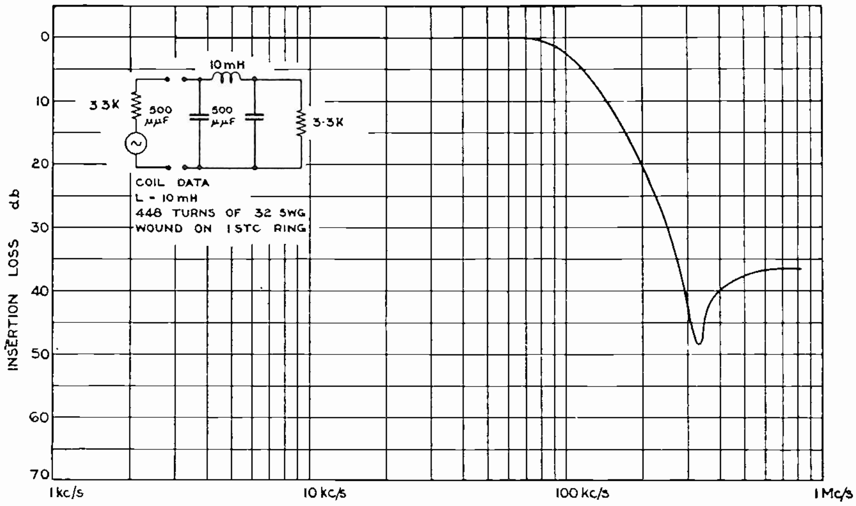


FIG. 4

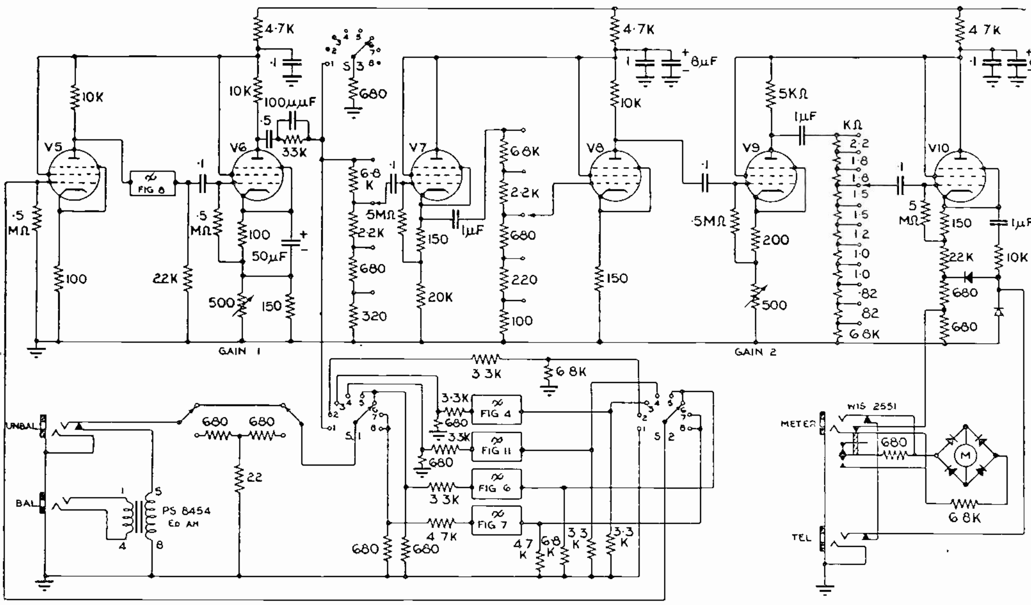


FIG. 5

the band the more the noise that can be tolerated, but at the same time frequency alignment of oscillators and filters becomes more critical. A reasonable compromise using inexpensive band-pass filters, permits measurements down to —80 db. on most practical equipments without requiring frequency alignment closer than 1%. The practical filter characteristics and circuits are shown in Figs. 6 and 7. The filter following V_5 (shown in Fig. 8) is a 300 c/s high pass design which is required for noise measurements and is conveniently placed in this position to suppress hum picked up in the rather extensive grid circuit of V_5. A slight fall of response is caused

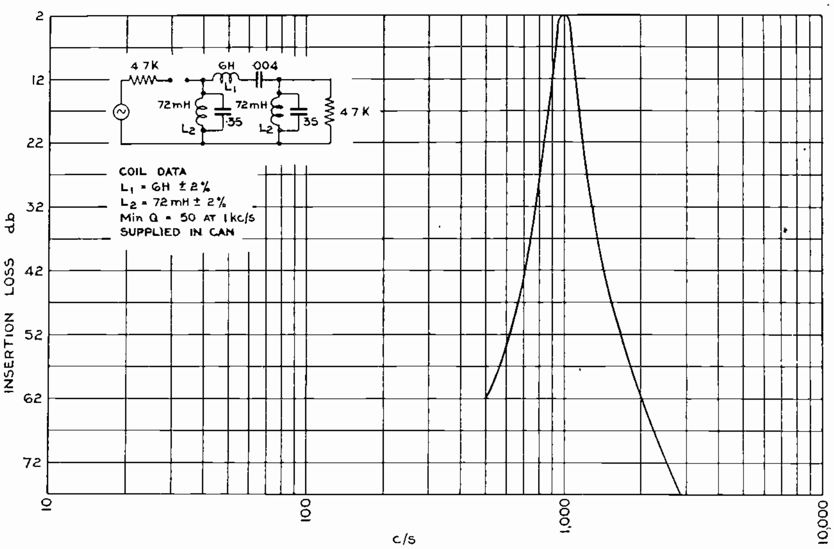


FIG. 6

by this filter in the region of 100 kc/s which is, therefore, corrected by the simple resistance capacitance network following V_6. The net gain from input to grid of V_7 is 40 db. when the first and second attenuators are in positions of zero attenuation.

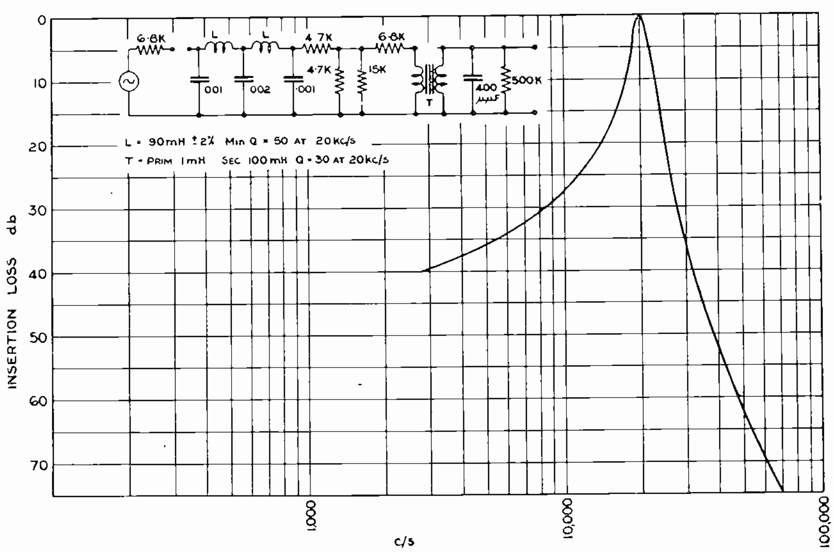


FIG. 7

The following valves V_7 to V_{10} comprise an amplifier of 40 db. net gain incorporating two further attenuators 0–40 db. in 10 db. steps and 0–10 db. in steps of 1 db. A position of switch S_1 passes the input signal directly to the grid of V_7 (impedance

600 ohms) providing an amplifier for measurements from +40 to —40 db. over a frequency band 30 c/s to 170 kc/s (Fig. 9) and is useful as a general purpose level meter. Two pre-set gain controls are shown in the circuit of the amplifier, these are

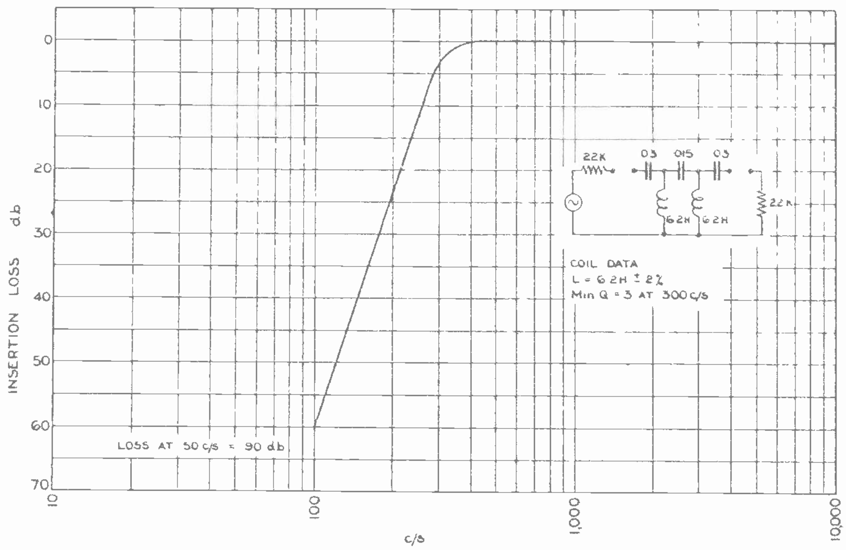


FIG. 8

used to set the gains of V_5 and V_6, and V_7 to V_{10} respectively, and are referred to later in connection with the alignment technique. The bridge type meter circuit supplied from V_{10} is returned, not to earth, but to a point on the cathode load.

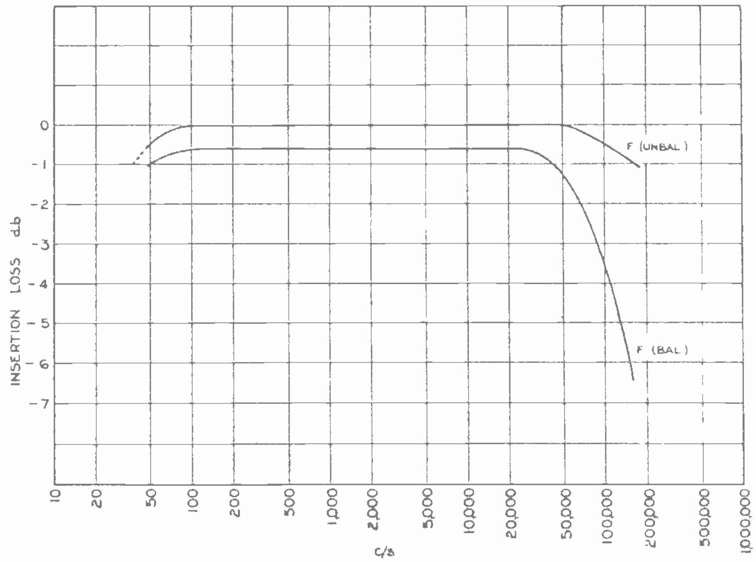


FIG. 9

This enables crystal rectifiers X_1 and X_2 to be used as meter overload protectors without introduction of a separate negative bias supply. When an input is plugged into the jack marked " meter ", the meter circuit is used alone and the overload protection is inoperative. A signal of 0·8 volts r.m.s. (1 mW when impedance is 600 ohms) will deflect the meter to half scale (50 μA). Consideration of the amplifier and attenuator locations will show that whilst the meter is on scale, overload at any stage is impossible whatever the individual settings of the attenuators.

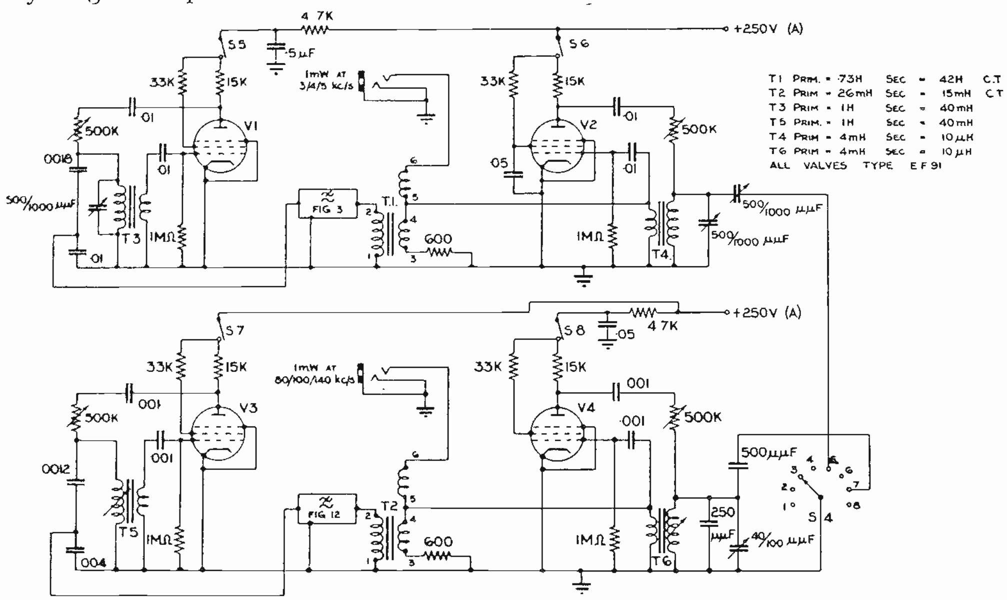


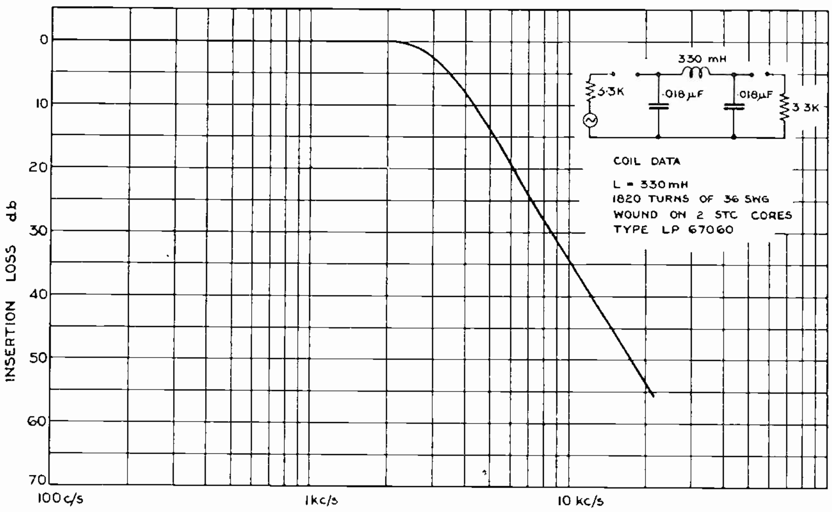
FIG. 10

(2) *Oscillators.* The oscillator circuits, as shown in Fig. 10, are of conventional design having resistive control of feedback for use as a level adjustment. For measurement of a beat tone depending on the product cos $\omega_1 t$. cos $\omega_2 t$ the purity of each tone is of only secondary importance but it is evident that measurement of odd power terms depending on the product cos $2\omega_1 t$ cos $\omega_2 t$ demands a pure fundamental tone of frequency ω_1. One oscillator in each band is therefore filtered to remove harmonics (Figs. 11 and 12). Balance hybrid coils are necessary for the output circuits in order that each oscillator may be injected into a common input circuit without causing modulation of the other. In practice this has not been found difficult and approximate resistance balance is adequate. The equipment may be readily checked for self-distortion by connecting oscillator outputs directly to the amplifier input and making measurements of even and odd distortion coefficients in the usual way. Results obtained in this model were :—

L.F. —Even	...	—75 db.	H.F. —Even	...	—82 db.
—Odd	...	—80 db.	—Odd	...	—80 db.

(3) *Alignment.* Alignment of the set is straightforward and when once carried out requires only occasional checking and correction. Since the oscillators are brought out to jacks, they may be connected directly into the meter at 600 ohms impedance (socket provided) and adjusted to deliver 1 mW. One of the oscillators may then be used to calibrate the amplifier. Switch positions 1 and 3 respectively of selector S_1 enable " gain 2 " and " gain 1 " to be used separately to set the gain of each section of the amplifier. If the oscillators or filters become off-tuned the required signal may suffer some attenuation and false readings would then be

obtained. Since oscillator levels are set up after filtering, automatic correction is obtained for change in filter insertion loss and the only critical relationship is between the band-pass filter, preceding the amplifier, and the difference tone, which



FIG, 11

is being used as the basis of measurement. Alignment is carried out by connecting a non-linear load for distortion test in the usual way and adjusting oscillator

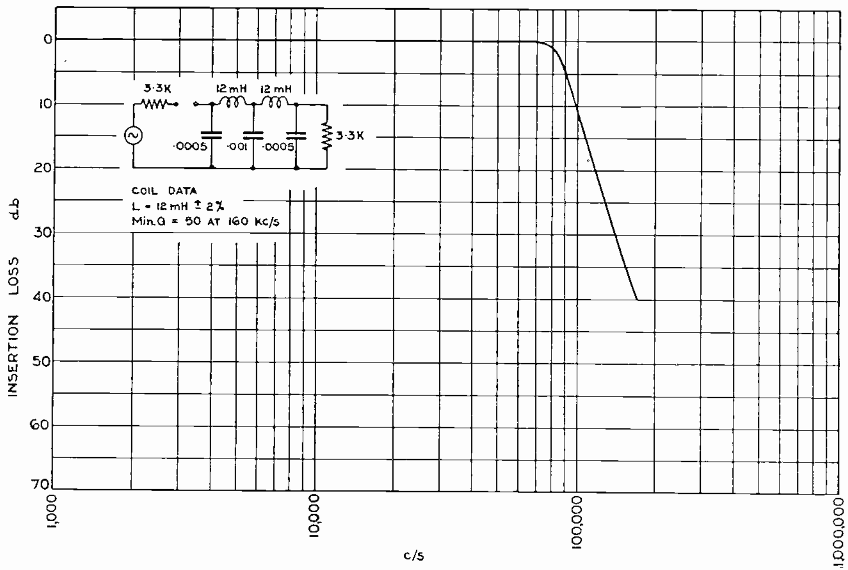


FIG. 12

trimmers for maximum response. By this method, although the absolute test frequencies may drift slightly, the beat tone is always accurately aligned with the amplifier filter.

THE MARCONI-FARMER INTEGRATING X-RAY DOSEMETER.

By A. W. Lay, A.M.I.E.E., F.Inst.P.

The following article describes an instrument designed to measure indirectly the dosage rate and the total dose of X-radiation administered to a patient.

The medical use of X-rays can be divided into two main categories :—

(*a*) Radiographic and Diagnostic, used for X-ray photography and screen examination of biological material.

(*b*) Therapeutic, for the treatment of disease by X-radiations.

In both these cases it is essential to be able to correlate the effect on the living tissue with the ionisation produced by the radiation.

This information is very difficult to obtain as there is no direct way of measuring the ionisation produced in tissue either alive or dead.

The usual method of determining the degree of ionisation in gases, by measuring the saturation current which the ions are capable of producing, cannot be used in tissues, for even if it were possible to apply an electric field across a biological material to obtain the saturation current, this would set up simultaneously a much larger current independent of ionisation.

To determine ionisation in living tissue we must therefore resort to indirect means.

When a beam of ionising radiations impinges upon a material, ions are liberated during the whole period of exposure, and during this time a definite number of ion pairs will have been produced, which represents the total amount of energy transferred from the beam to the material. The total number of ions may be distributed through a large or small volume and the ionisation is seldom strictly uniform. The effect on the individual cells may thus be different. It is therefore important to know the number of ion pairs created by the radiation. Assuming that sufficient of the above information is available it is then possible to correlate the observed biological change with the amount of energy, represented by the ionisation supplied to the living cells, and this correlation will be quantitative if means, either direct or indirect, are also available which will enable the biological changes to be measured.

The inter-action of radiation and matter depends almost entirely on the atomic numbers of the elements, and their respective proportions in the materials, and not on their state of aggregation.

Nearly all the ionisation produced in organic material is due to oxygen, nitrogen and carbon components since the atomic number of hydrogen is 1·0, and therefore it contributes almost negligible ionisation.

Atmospheric air consists mainly of nitrogen and oxygen and therefore gives very close approximation to living tissue as far as its quantitative reaction to radiation is concerned. The ionisation which is produced by the radiation in air can also be easily measured.

We may say then that the number of ions created in one gramme of living matter is nearly the same as the number of ions created in one gramme of atmospheric air when exposed to the same conditions of radiation, and the one to one correspondence is almost independent of the quality of the radiation.

Ionisation measurements and their significance.

In practice, the energies which are absorbed by the volume from the beam are too small for measurement by thermal methods, so recourse is made to the fact that when absorption of the beam takes place in air the latter is rendered conducting, and the saturation current through a given volume of air becomes a measure of the rate of absorption of energy in the specified volume. It is upon this basis that the International Committee for Radiology Units, which met in 1937, defined the unit of X-rays and of gamma rays.

This unit is known as the roentgen. It is usually symbolised by " r ", and is defined as the quantity of X-radiation or gamma radiation that produces, in 1 c.c. of dry air at 0° C. and 760 mm. of mercury (or 0·001293 g) ions carrying 1·0 electrostatic unit of electricity.

The unit so defined corresponds to $2{\cdot}082 \times 10^9$ ion pairs under the conditions specified. Radiation quantity is thus expressed in roentgens, and the measurement of dosage rate is expressed in roentgens per minute.

When considering dosage, some specific points must, however, be emphasised. Firstly, the secondary electrons should be fully utilised in producing ions, and therefore they must not strike the wall of the ionisation chamber—yet to be described—before their energy is completely expended ; furthermore, there should be no wall effect, which means that neither the primary X-rays nor the secondary electrons should impinge upon any scattering material which can introduce secondary radiation.

The strict fulfilment of these conditions involves practical difficulties when dealing with a small portable instrument such as we are about to consider. They can, however, be met, and are essential in setting up a standard against which a portable instrument may be calibrated. Such a standard, briefly, takes the form of two large plates with an air space between them ; guard plates and other precautions must be taken to ensure accuracy. The spacing between the plates must be wide enough to ensure that if any photo-electrons strike them, their contribution to the ionisation is negligibly small. For a parallel plate type of standard chamber, 12 cm. spacing is satisfactory for 200 kilovolts. An electrometer device is used to measure the current through the condenser plates as a result of the ionisation of the air dielectric under the influence of the X-ray beam.

A full description and theory of absolute standard chambers is beyond the scope of this article, but the basic considerations may be summarised thus :—

Since the degree of ionisation is determined by the mass absorption coefficient of X-radiation by the gas, corrections must be made for the temperature and pressure of the air in the chamber. Under these circumstances, if I represents the current measured by the electrometer in electrostatic units, L the effective length of the collecting electrode, A the area of the limiting diaphragm in sq. cms., T the absolute temperature, and p the pressure in millimetres of mercury, then the intensity of the X-ray beam under measurement is, in roentgens per second :—

$$\frac{r}{\sec} = \frac{I}{L \times A} \cdot \frac{T}{273} \cdot \frac{760}{p}$$

By the use of an absolute standard, the number of roentgens per unit time at any specified place in air can be determined, but such an instrument is not suitable for general calibrating purposes as it cannot easily be made in portable form, and it would demand more precautions than can generally be made in a hospital X-ray department.

However, small and convenient ionisation chambers can be easily calibrated against an absolute standard and these can be used as secondary standards for use in hospitals and clinics for measuring the plant rate (or X-ray output) of X-ray installations.

When, however, comparison is made by using the absolute standard and the small enclosed thimble type of chamber (later to be fully described) to measure the intensity of an X-ray beam at the same point under the same conditions, the measured values as indicated by the two types of instrument will not be the same even if both are of the same material. This is because the wall of the small thimble chamber absorbs some of the primary radiation, it sets up its own secondary radiation, and does not allow space for the complete utilisation of the secondaries. The relation between the readings of the two types of chambers may therefore be expected to be different for every quality of primary radiation. This is especially so when the secondary chambers are made of metal, and other materials of high atomic number, and these are of little use for calibrating purposes.

If, however, the thimble chamber is made of an organic material of approximately unit density, with an effective atomic number as nearly as practicable the same as air,* and properly designed and compensated, the ratio of its readings to that of the standard can be made very nearly constant over the range of quality (80 kilovolts to 250 kilovolts) in which we are at present interested. Thimble chambers so compensated are said to be " air wall," and they are satisfactory for use as secondary standards.

For X-radiations above 250 kilovolts, other factors must be given consideration. Similarly, for radiations of less than 45 kilovolts the effect of photo-electrons from the walls of the chamber introduces another factor.

The inner walls of small ionisation thimble type chambers are coated with carbon, or carbon preparations, such as " Aquadag," or colloidal graphite, to render them electrically conducting without introducing elements of atomic number greater than those of which the walls of the chamber are made. The atomic number of carbon is less than the effective atomic number of air. This means less ionisation than if all the secondary radiations were from air. With proper precautions, however, measurements can be made with thimble type of ionisation chambers within accuracies of 1·0 or 2·0 per cent.

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* If the wall of an ionisation chamber is made of the same atomic number as air, that is 7·3, the ionisation of the volume of air in the chamber should, theoretically, be the same as the free air in a large standard chamber.

Also, if a chamber wall material has the same effective number, N_{eff}, as air, it will, over a range of wavelengths from 0·1 to 1·5 A have the same effect on the ionising current as air.

The effective atomic number N_{eff} can be calculated from the relation :—

$$N_{eff} = \sqrt[3]{\frac{a_1N_1^4 + a_2N_2^4 + \ldots\ldots}{a_1N_1 + a_2N_2 + \ldots\ldots}}$$

In this equation a is the fractional part of the material or atomic number N. By a suitable choice of N and a, the effective atomic number of the materials composing the chamber can be adjusted to 7·3.

The functional details of the Instrument.

An idea of the general scheme of the design of the Marconi-Farmer Integrating Dosemeter can be obtained from Fig. 1. Photographs of the instrument with cover on and off are shown in Figs. 2 and 3. Let us consider first the ionisation chamber, which, with the directly associated electrometer valve V1, may be considered as the heart of the instrument.

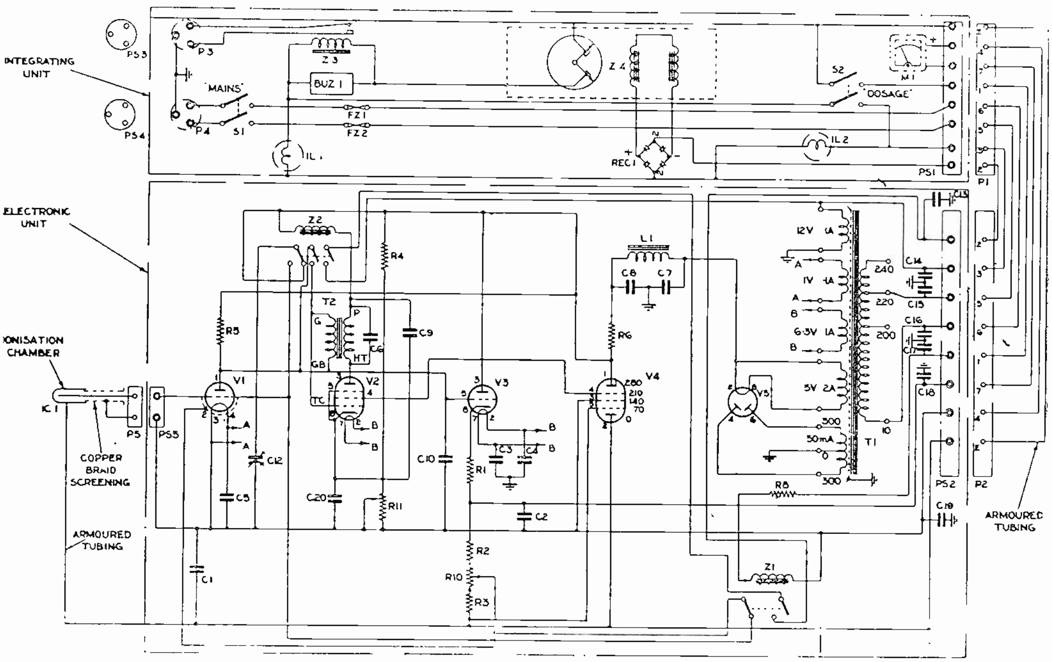


FIG. 1

In the design of this ionisation chamber the atomic number of the material chosen for the chamber must be as near as possible to that of air, or 7·3. Some organic compositions, such as certain grades of Bakelite, Tufnol and Nylon, meet this requirement to a fairly close approximation, and give the necessary mechanical strength and rigidity.

It will be seen from the diagram that the ionisation chamber actually constitutes a small cylindrical condenser of which the centre electrode is a small aluminium wire chosen because of its low atomic number and ease of manufacture. A suitable material for this would be the same as for the chamber wall, but a Bakelite or Tufnol wire of 0·20 inches diameter would be too expensive to manufacture in quantities. A few have been made, however, under laboratory conditions.

However, the organic materials already mentioned can be taken as being suitable for the requirements of this instrument, and within practical limits the ionisation chamber may be considered as being "air walled," which renders it suitable for measurements in the range of X-radiation covered by the specification of the dosemeter as a whole. It should be emphasised, however, that for measurements outside the range specified, calibration against N.P.L. standards should be made and correction supplied. For X-radiation above 500 kilovolts peak, the chamber would have to be designed with thicker walls.

Before proceeding to describe the general functioning of the circuits, it may be as well to recapitulate the factors which influence the current of the electrometer valve. When the grid is biassed negatively the grid current is influenced by :—

(1) Electrons passing from cathode to the grid.
(2) Positive ions which are produced in the residual gas.
(3) Positive ions produced on the anode due to electron bombardment.
(4) Positive ions from the anode.
(5) Poor insulation between the grid and other electrodes.
(6) Primary electron emission from the grid.
(7) Positive ions from the cathode.
(8) Photo-electric emission from the grid.
(9) Secondary emission from the grid due to positive ion bombardment.
(10) The relatively high velocity secondary electrons from the cathode due to positive ion bombardment.

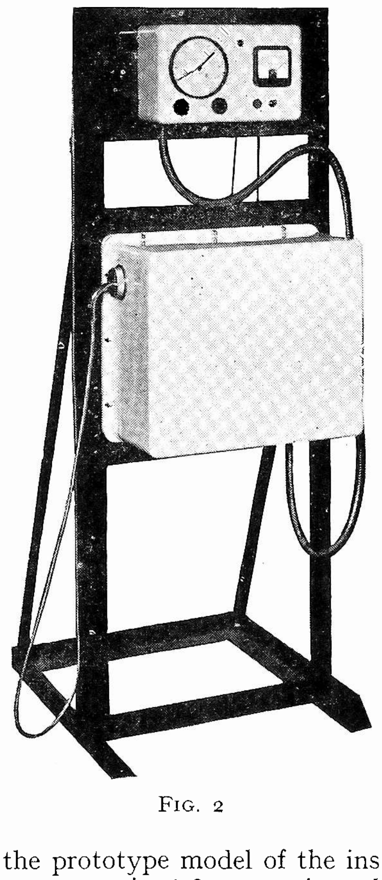


FIG. 2

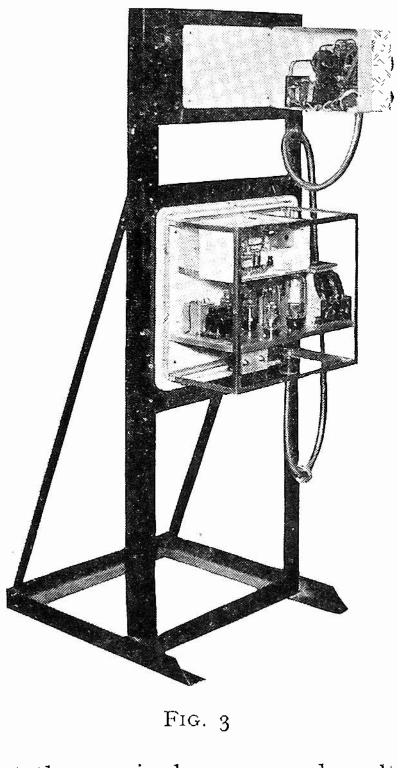


FIG. 3

In the prototype model of the instrument the nominal mean anode voltage on the electrometer is 4·6 approximately ; this swings about 1·1 volts when the ionisation chamber is active under the influence of the charging condenser and

X-ray beam in turn. This low anode voltage is less than the ionisation potential of the residual gas in the valve and therefore positive ionisation within the valve will be eliminated. For the same reason there will be practically no ionisation produced on the anode surface due to electron bombardment.

Furthermore, since the emission of ions from the anode is a function of temperature, this will be reduced; from this it follows that the physical phenomena enumerated by (9) and (10) will also be reduced to values which are practically negligible.

The insulation resistance of the grid circuit of the electrometer valve is of the order of 10^{17} ohms to avoid leakage, but to maintain this the valve must be kept chemically clean and dry. It is also essential to reduce as far as possible the photo-electric emission from the grid. To accomplish this, the valve should be operated in the dark, or in low ambient light intensity.

Under suitable operating conditions the grid current can be kept as low as 10^{-14} to 10^{-15} amps. In the prototype model the grid system, comprising the grid of the valve and the central electrode of the ionisation chamber, was biassed to 6·3 volts negative with respect to the electrometer valve cathode, which is 140 volts positive with respect to earth. This gives the active central electrode of the chamber a positive potential of 133·7 volts to earth.

When the X-rays pass through the ionisation chamber at the end of the cable, a current of the order of 10^{-12} amps. is produced across the chamber and this current flowing into the cable capacity causes a gradual change of potential on the grid of valve V_1, which in its normal working cycle has no other connection to the high insulation electrode.

This valve (E.T.1) is of low impedance, and to keep the grid current small, must be worked at the low anode voltage mentioned later.

V_1 is in series with the high anode resistance, R_5, which effectively forms a constant current circuit, and during exposure of the ionisation chamber to X-rays, the anode potential rises by an amount which is approximately equal to the fall of grid potential.

The changing anode voltage is applied through the winding of the transformer T_2 to the grid of the oscillator valve V_2, the cathode of which is held at a potential of about 8 volts above the cathode of V_1 by the resistances R_4 and R_{11}, and during most of the cycle its anode current is completely cut off.

As the grid potential rises, a point is reached at which this valve starts passing current and when this reaches a fraction of a micro-ampere the valve breaks into oscillation causing a sudden increase in current to about 2·0 mA and this closes the relay Z_2.

When the relay is energised it actuates three contacts as follows :—

(1) It switches the high insulation terminal of the charging condenser C_{12} from the H.T. point of the stabilovolt momentarily to the grid of the electrometer valve ; thus applying a small positive charge to the grid.

As the H.T. voltage is high compared with the grid swing, this charge is practically independent of the grid potential at the instant, and the bias given to the chamber is therefore independent of the valve characteristics.

(2) It quenches the oscillator by short circuiting the primary winding of the transformer T_2.

(3) It switches an impulse to the dial circuit which advances the black pointer on the instrument by 5 roentgens on the scale. When the charge is applied to the grid of V_1 it drives the grid of the oscillator below the cut off point again, and the circuit is thus rendered quiescent until the next trip.

Since the grid of V_1 is floating it is essential that it must be activated at an appropriate fixed potential when the instrument is switched on. To accomplish this the relay Z_1 is operated by turning the Dosage Switch in the dial unit which disconnects the grid from its pre-set tapping point on R_{10}.

The stabilovolt maintains a P.D. of 140 volts between the cathode of the electrometer valve and earth. This ensures the necessary saturation conditions in the ionisation chamber. It also provides a constant charging voltage of 140.

The valve V_3 is an indicator which shows the instantaneous potential of V_1 and therefore the point in the cycle which the discharge has reached. It is a cathode follower system in which the anode current passes through the meter M_1 on the dial unit, in opposition to a fixed backing current, therefore the fall in the meter reading corresponds to a fall in potential of the chamber electrode.

This is useful in radiological practice, and it also facilitates fault location.

When the mains are switched on, the H.T. working voltage is established and the meter should read full scale deflection.

As the valves warm up, opposition current will flow through V_3 and the meter should settle down to about mid-scale, in which position it should remain until relay Z_1 is operated and X-rays pass across the chamber.

The meter indication should then fall steadily over about 10 divisions until the oscillator bursts into activity when it will return to the upper limit of its cycle and proceed to repeat as long as the X-ray tube radiates.

When radiation stops, the pointer should dwell at whatever position in the range it may be at that instant.

Assuming that the radiographer has set for the prescribed dose, with the patient in position, he now switches on the mains (S_1) and energises the transformer ; the cathodes of the valves are then heated to their working temperature. The mains should be left switched on during the daily working sessions.

At the end of a period of not less than 10 seconds, the H.T. switch S_2 should be thrown on. This closes all the valve anode circuits and the energising circuits of relays Z_1 and Z_2.

The relay Z_1 acts to switch over and energise, through the associated rectifier, the pulsating coils of the integrating mechanism, symbolised in simple form as Z_4. The grid and screen of the electrometer valve, and active central electrode of the chamber, have been biassed to the 6·3 volts negative with respect to the cathode, as shown in Fig. 4. The grid system of the electrometer valve is thus left isolated at that working bias. It is important that this bias is maintained until the X-ray beam is switched on to the chamber. There may be some delay by the radiographer in doing this, hence the paramount importance of high insulation of the electrometer grid system and of the chamber being maintained.

The meter M.1, which has the engraving " Charge Indicator " on its dial, is for the purpose of indicating the charge condition of the ionisation chamber. This meter is also a leakage indicator. Its pointer should show no discernible movement when the dosemeter as a whole has settled down after switching on, and when no X-rays are being applied to the chamber.

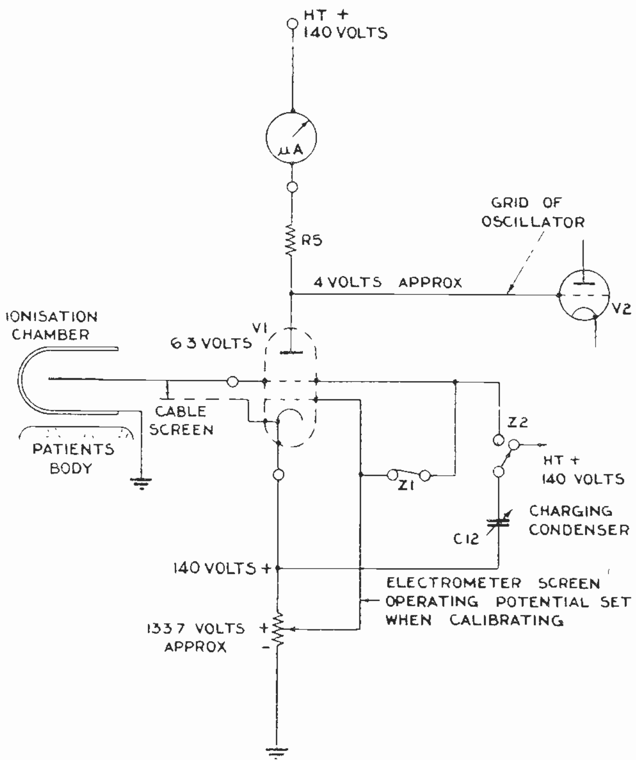


FIG. 4

Associated with the discharge meter is the valve V_3, and this system virtually constitutes a valve voltmeter for giving an indication of the relative potential of the ionisation chamber over the 5·0 roentgen increments of X-radiation.

The central electrode of the chamber and the surrounding conducting wall thus constitutes a cylindrical condenser, with an air insulating medium, across which there is a potential of 133·7 volts approximately. This is the condition of the chamber when the X-radiation is first applied. A potential difference of 120 volts upwards is necessary to ensure ionic saturation of the air medium, which is essential for accuracy.

With the chamber and grid operating conditions so set, let it be supposed that the X-ray plant is switched on and the beam impinges on the chamber (see Fig. 5). Under the influence of the beam the air in the chamber is ionised, and positive ions travel from the central electrode to earth, and negative ions to that electrode, with the result that there

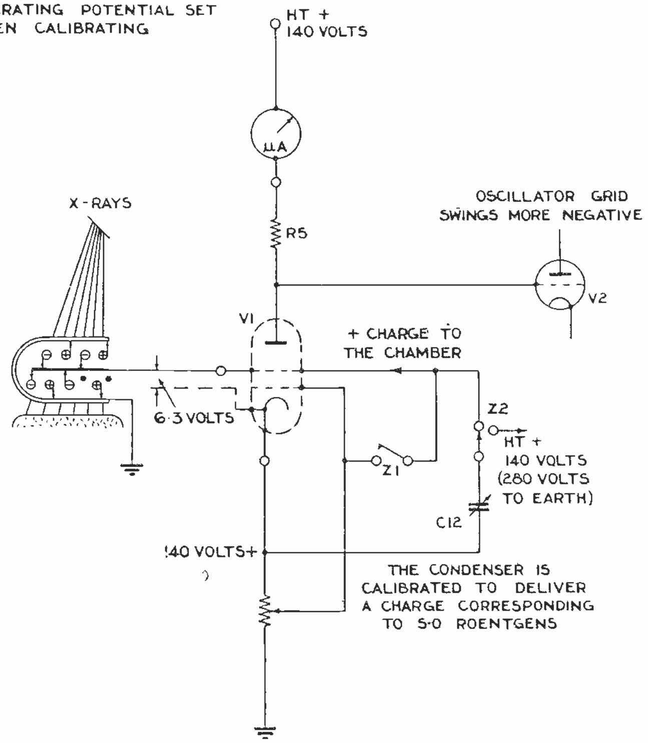


FIG. 5

is a leakage current across the chamber and the potential difference across it falls.

An important feature of the design is that the ionisation chamber may take the form of a head which may be used at a remote distance from the main electronic unit containing the electrometer valve. The connecting link between the chamber and the valve is a highly insulated and screened Telcothene cable. This has a capacity between the core and screen of 21·5 picofarads per foot. The total capacity due to this cable link is in parallel with the natural capacities of the chamber and the electrometer grid system.

It will be appreciated therefore that the length of the cable link is limited between the two extremes of being too short and too long, these being 8·0 and 16·0 feet respectively.

In the prototype model the length of the cable link was 11·5 feet, and its measured capacity was 260 picofarads. The capacity of the chamber and its body was 12·0 picofarads, and that of the electrometer grid system was 9·3 picofarads. This gives a total capacity of this system of approximately 282 picofarads.

Now from the definition of the roentgen

$$\text{we have r (in roentgens)} = \frac{CV}{v} = \frac{CV}{v}$$

where C and V are in electrostatic units and v, the volume of the chamber, is in cubic centimetres.

After the dosemeter as a whole had been set and checked at a Hospital where a Victor X-ray installation was used, and using a Victoreen sub-standard dosemeter as a standard of reference, it was observed that, when a quantity of X-radiation of 5·0 roentgens had been applied to the chamber the potential of its central electrode and the electrometer grid had fallen to 130·5 volts positive with respect to earth, the volume of the chamber being 0·555 ccs.

Converting voltages and capacities to E.S.U.'s and substituting these experimentally measured values in the above equation, we have

$$r = \frac{3\cdot 2}{300} \times \frac{2\cdot 82 \times 9 \times 10}{0\cdot 555} = 4\cdot 89 \text{ roentgens.}$$

The slight difference between this and the empirical calibration is attributed to difficulty in measuring the total capacity of the system to a high degree of accuracy.

We have so far considered only the initial increment of 5·0 roentgens acting on the chamber. The effect of this was to lower the grid potential by 3·2 volts. From the characteristic curves for the valve, it will be seen that the effect of this is to reduce the current practically to zero and thus to cause a positive rise of potential on its anode. It is obvious that this positive pulse is passed on to the grid of the oscillator valve V_2, whose anode circuit is closed. This valve has a steep anode current/grid voltage curve and it is set by means of the bias control R_{11} at a critical point which causes a rapid rise of current through the relay Z_2. This relay then acts to switch over the three contactors with which it is loaded.

It should be mentioned here that when the positive pulse is passed from the electrometer anode to the grid of the oscillator valve, V_2, the transient nature of the impulse in the circuits around the latter render the condenser C_9 necessary to ensure proper functioning of the oscillator.

Referring now to the charging condenser C_{12}, which is also a calibrating device, it will be seen that before the relay Z_2 is switched from its initial position this charging condenser is across 140 volts and accordingly charges up to that potential. When, however, the relay Z_2 acts to switch over, this condenser is switched from the common H.T. to the ionisation chamber, and also to the electrometer grid—which is now isolated to relay Z_1 from its initial bias supply down R_{10}.

It will be understood that as the condenser C_{12} is switched by relay Z_2 to the chamber, it shares its charge with the total capacity of the chamber-electrometer valve system. The effect of C_{12} sharing its charge is to restore the bias of the grid system to 6·3 volts negative to the cathode from the 9·5 negative to which it has fallen due to the discharge current across the chamber under the influence of the ionising X-radiation. Now that the negative bias on the electrometer valve has been reduced to 6·3 volts negative, it takes current and its anode potential drops; so also does that of the oscillator valve grid, and the current through this latter valve falls to the critical value for which it was originally set (Fig. 6).

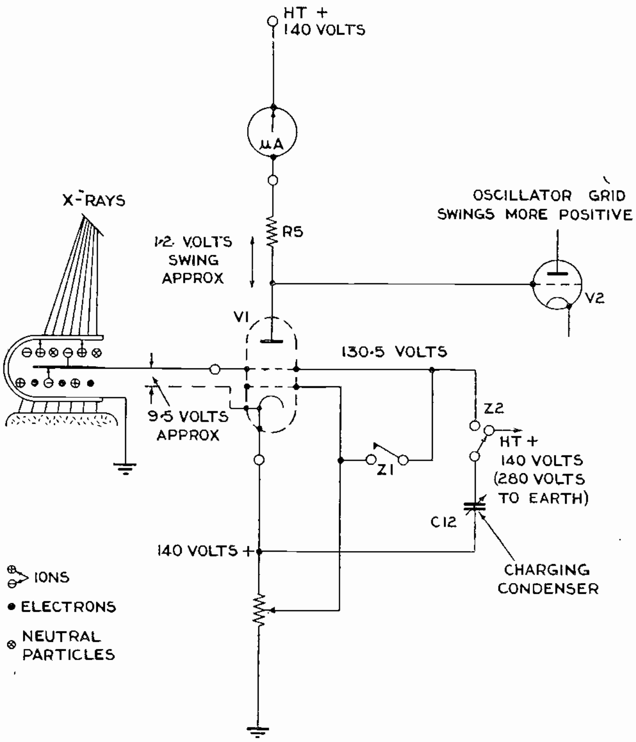


FIG. 6

The cycle of events now repeats itself whilst the chamber is subject to X-rays

It will be obvious that when Z_2 is energised and switches over, its middle contact short circuits the grid of the oscillator and thus rapidly damps down any spurious oscillation in this system. Its third contact closes the 12·0 volt circuits in the Integrating Unit which is housed in the cabinet.

This cabinet contains the mains switch, S_1, fuses FZ_{1-2}, H.T. switch S_2, charge indicator M.1, integrating mechanism Z_4, and its associated rectifier Rec_1, indicating buzzer buz_1, and relay Z_3 in electrical association with Z_4.

Returning to the relay Z_2, this has been caused to act due to the sequence of events following the application of the X-ray beam to the chamber. It will be remembered that relay Z_1 has closed to the left, looking at the diagram, and will remain so until the mains switch is broken at the end of a working session. Accordingly the circuit to the "signal" coils via the rectifier rec_1 is closed at that point, but until relay Z_2 switches to the left the signal circuit is broken here.

Therefore as Z_2 is closed, due indirectly to the influence of the X-ray beam, a pulse of current passes through the signal coils of Z_4, which represents in simple form an electro-mechanical integrating system. This is an application and improvement of a well-known impulse system used in horology. It consists of a spring loaded toothed wheel which a pawl engages to rotate against a spring.

The pawl is activated by an armature pulled magnetically towards the core of the coils of Z_4 when the pulsating current circuit is switched by Z_2 in the manner already explained. By means of a control on the panel of the integrating unit, the dose is set by the hands shown at Z_4. One is black and is set at zero on a dial calibrated from 0 to 550 roentgens. The other, coloured red, is set around the dial at a figure corresponding to the dose which has been prescribed for the treatment. A friction clutch device protects the setting mechanism from being strained and damaged by forcing past legitimate rotation.

In order to facilitate accurate zero setting by the hands, the contacts which they carry in rotation are cushioned by springs to give flexibility in positioning the hands around zero and take up any slight loose spacing due to the gear teeth and manufacturing discrepancies in the integrating mechanism as a whole.

The diagram shows that the buzzer (buz_1) and relay Z_1 are effectively in series with the two contacts carried by the hands, as indicated by Z_4. When these contacts are caused to meet by the rotation of the hands, they meet and close their contacts, and thus energise the buzzer and the relay Z_3. The buzzer thus gives an acoustic warning that the prescribed dose has been delivered.

It will be seen from the diagram that relay Z_3 is loaded with contacts connected by a pair of leads to the output sockets P_3. The purpose of this relay is to operate any electro-mechanical device which may be fitted on the X-ray installation to cut off the beam at the end of the specified dose and thus ensure that the patient does not receive an overdose.

Perhaps it should be mentioned that V_4 is a stabiliser for the H.T. supply system ; the other part of this needs no explanation.

At this point it should be repeated that the highest possible insulation—with due regard to the radiological requirements of compactness and convenience of application in body cavities—must be maintained. The insulation between the central electrode of the chamber and that of its conducting inner wall must be of the same order as the associated grid of the electrometer valve, that is 10^{17} ohms approximately. Similarly, the wiring around that valve must be of the same order.

This high insulation must be preserved throughout manufacture, which means that great care must be taken at each stage of assembly and wiring to guard insulating surfaces against contamination by conducting material. For example, the handling of the perspex insulating blocks on the relay by naturally damp hands has been the cause of much trouble in research work on the first model. Another cause of extraneous effects has been that of light falling on the grid of the electrometer valve when it is exposed. For this reason the cover should be in position on the electrometer unit when the instrument is working.

In order to protect the grid of the electrometer valve and its directly associated components, such as relays Z_1, Z_2, the charging condenser C_{12}, and the input from the cable connector between the valve grid and the ionisation chamber are all contained in a lead box with a good fitting lead cover.

Silica gel air driers are provided to maintain a dry atmosphere in the cabinets. This, and the maintenance of chemical cleanliness throughout the instrument, and in particular of the ionisation chamber and all material around the electrometer valve is of paramount importance.

MARCONI NEWS AND NOTES

INTERNATIONAL STUDY GROUP VISITS MARCONI'S

AFTER travelling through France, Holland, the U.S.A. and England, studying all the aspects of television in those countries, the Television Study Group of the International Radio Consultative Committee ended their extensive tour with a visit to the birthplace of the Radio Industry on Thursday, May 4th, 1950, when the delegates were the guests of Marconi's Wireless Telegraph Co., Ltd.

The delegates had an early demonstration of Marconi efficiency when they left London in three coaches. The leading coach had been specially fitted with V.H.F. radio and contact was made with Chelmsford when the coaches were at Stratford. Continuous two-way working was maintained, and the arrival of the coaches at Chelmsford was timed exactly.

Mr. F. N. Sutherland and Mr. F. S. Mockford talking to some of the delegates.

In the large club-room of the Marconi Athletic and Social Club, Mr. F. N. Sutherland, Mr. F. S. Mockford, and other hosts met the C.C.I.R. party and tea was served.

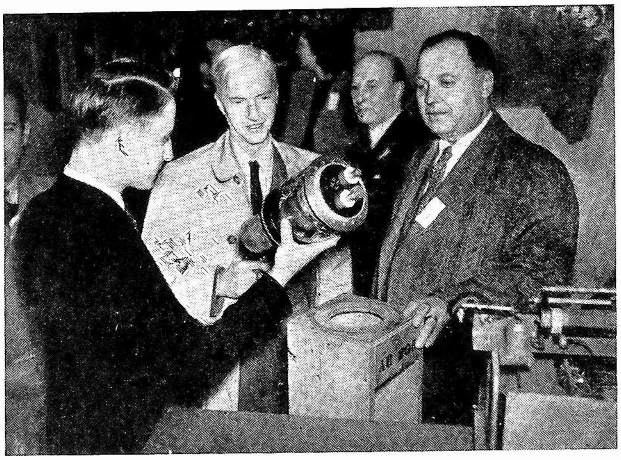
After a tour of the New Street Works the delegates went to Ingatestone for dinner, where they were met by Mr. H. G. Nelson, who later addressed the delegates in both English and French.

Television Garden Party

The delegates then travelled to Baddow where a " Television Garden Party " had been arranged. This Baddow show was brilliantly conceived and organised, not only was television, in all its aspects, fully displayed and explained but the seriousness of the evening's work was pleasantly tempered by a live television programme and excellent catering.

Of great importance to the delegates were the " side-shows " of the Garden Party. These included a lecture on " Evaluation of Picture Quality " and a comparison of 16 mm. cine film with 16 mm. television film recorded from 405 lines. Other " side-shows " which drew large audiences were the " Investigation of Scanning Standards, Monochrome and Colour," and the " Spot Wobble " demonstration.

A spectacular " live " event opened the Garden Party. On their arrival the delegates were shown into a large marquee erected on the lawn. In the marquee



Mr. E. B. Esping (Chairman of Study Group 11) and Mr. F. D. Heegard inspect a transmitter valve.

were 15-inch television monitors, and on the roof of the research laboratories was a Marconi Image Orthicon camera. The first demonstration of Marconi television seen by the delegates was a brilliant picture of the Dagenham Girl Pipers as they marched through the main gates and up the drive, counter-marching through the marquee they provided the touch of colour and lively music which was the keynote of the evening's entertainments.

A continuous television programme was provided from the Baddow television studio and relayed to receivers situated at many points throughout the building and in the marquee. This programme included musical items, a table-tennis display by members of the M.A.S.C., and an interesting " interview " on the history of wireless, illustrated with some of the unique historical exhibits which the Marconi Company have preserved. This item was given by Mr. W. T. Ditcham, who was interviewed by Mr. Barrie Edgar of the B.B.C. Another B.B.C. star, Miss Sylvia Peters, did the announcing, and later interviewed delegates before the cameras.

Mr. H. G. Nelson and Mr. F. N. Sutherland with the Dagenham Girl Pipers.

The whole programme was produced and directed by Mr. Stephen McCormack, the B.B.C. television producer.

The final item by the Dagenham Girl Pipers demonstrated the remarkable properties of the Marconi Image Orthicon cameras. Despite the fact that only a modicum of lighting was in use for the benefit of people moving between the laboratories and the marquee, the roof camera provided excellent pictures of the girls even while they marched along the lane in almost total darkness.

The Marconi " Television Garden Party " was a demonstration of television at its best, and will undoubtedly have done much to enhance the prestige of British television all over the world.

WILLIAM GEORGE RICHARDS

The late Mr. W. G. Richards, Publicity Manager, Marconi's Wireless Telegraph Co. Ltd.

IT is with deep regret that the death is announced of William George Richards, Publicity Manager of Marconi's Wireless Telegraph Co., Ltd., at his home in Chelmsford, on June 15th, at the age of sixty-one. His death brings to a close a long and active career in journalism and publicity.

Born in Cheltenham on March 6th, 1889, Mr. Richards began his journalistic career on being apprenticed to the *Stroud Journal*. In 1909 he joined the reporting staff of the *Citizen* (*Gloucester*), where he remained for the next five years.

As a member of the Territorial Army he was called to the colours at the outbreak of war in 1914, and went overseas with the Gloucester Hussars (Yeomanry). He saw service in the Middle East (Canal Zone) and Mesopotamia, and was Mentioned in Despatches.

After demobilisation Mr. Richards returned to journalism as a reporter on the *Yorkshire Evening Post* and, during the next two years, became keenly interested in the then young science of wireless and, despite much criticism from his associates, foretold a great future for Marconi's invention. His faith in it was so strong that, on December 1st, 1920, he joined the Marconi Company as an assistant in the Publicity Department under Mr. Arthur Burrows (later to become famous as " Uncle Arthur " of the B.B.C.). On January 1st, 1923, he succeeded Mr. Burrows as Chief of the Publicity Department.

Up to the death of the Marchese Marconi, in 1937, Mr. Richards was his close and intimate friend, and he was probably the world's greatest authority on Marconi, the man and scientist.

Mr. Richards was appointed Managing Director of Radio Intelligence, Ltd., where he was still responsible for initiating and controlling the publicity for all the Marconi Companies, on January 1st, 1932. When this Company was dissolved, he again took up the position of Publicity Manager of Marconi's Wireless Telegraph Co., Ltd. He also directed publicity for The Marconi International Marine Communication Co., Ltd.

For his work in advertising he was elected a Member of the Incorporated Society of Advertising Consultants.

The possessor of a keen mind which could strike straight to the heart of a problem, W.G. Richards's greatest asset was his ability to act as a guide, mentor, and personal friend, to all who worked for him : several former members of his staff have founded successful careers in publicity on his teaching.

His passing will be mourned all over the world, for his work was admired by all who knew him, and his friends were legion.

He leaves a widow and two daughters.

CHIEF ENGINEER OF MARCONI'S WIRELESS TELEGRAPH CO., LTD., AWARDED C.B.E. IN BIRTHDAY HONOURS

MR. G. M. WRIGHT, B. Eng., M.I.E.E., Engineer-in-Chief of Marconi's Wireless Telegraph Co., Ltd., has been made a C.B.E. in the Birthday Honours.

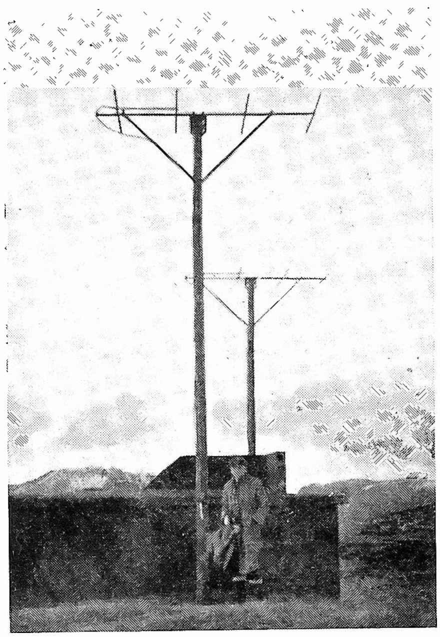
Mr. Wright originally joined the Marconi Company in 1912, and his work as a Research Engineer and Consultant, principally done in the Company's Chelmsford establishments, gained for him an international reputation.

At the outbreak of war he joined the Admiralty, becoming Assistant Director of Scientific Research and Chief Scientist at the Admiralty Signal Establishment. He returned to Marconi's as Engineer-in-Chief in 1946, and in November, 1948, was appointed a Member of the Radio Research Board of the Department of Scientific and Industrial Research.

V.H.F. LINKS THE FAROES

ALMOST every issue of the *Marconi Review* brings news of yet more uses and applications which have been discovered for Marconi V.H.F. equipment. The ubiquitous "Walkie-Talkie" has become almost as commonplace as the landline telephone, but the latest Marconi application illustrates how the two mediums—V.H.F. radio and telephones—can be successfully and economically wedded.

Some of the Faroe Islands have long been equipped with landline telephone systems, including some of the earliest examples of telephone instruments and all of them are of the manual type.



Situated on the top of a mountain on Torshavn in the Faroe Isles a Marconi Type H.16 V.H.F. transmitter-receiver and Yagi aerial array links the telephone system of the island with those of Suderoy and Sandoy isles.

Marconi Type H.16A V.H.F. transmitter-receivers now link the telephone systems of the islands of Torshavn, Suderoy, and Sandoy, and, for the first time, there is a universal inter-island telephone service for all telephone subscribers.

The V.H.F.-telephone link between Torshavn and Suderoy covers a range of 32 miles and the Marconi set is installed on the top of a mountain on each island. Petrol-driven generators supply the power for these two installations.

At Sandoy—which is 10 miles from Torshavn—the Marconi equipment is installed in the telephone exchange.

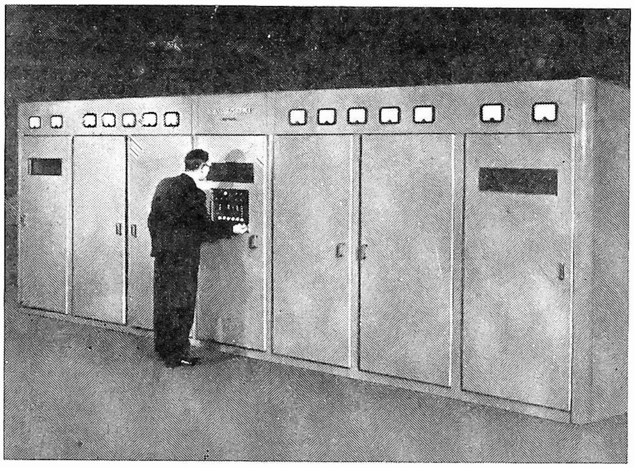
Climatic conditions in the Faroes are extremely severe. Telephone wires on the islands are made of steel, instead of the usual copper, to withstand the Arctic conditions which prevail over long periods. Such conditions are a severe test of equipment, but Marconi equipment is specially designed to operate successfully under all varieties of climate.

SUCCESS OF MARCONI AIR-COOLED BROADCASTING TRANSMITTERS

MUCH attention has been given in the world Press recently to the capture, by the Marconi Company, of an order of two 100 kW. air-cooled broadcasting transmitters for the Argentine.

This is the latest order for this model transmitter and there are, at present, orders placed for a dozen of them from Finland, Denmark, Egypt, India, and the British Broadcasting Corporation.

It is the intention of the Argentine Government to work their two transmitters in parallel (the Marconi Company are arranging the installation for this purpose)



A typical Marconi 100 kW broadcasting transmitter. Similar transmitters are to be supplied to the Argentine Government.

to give an output of 200 kW. This will mean that the station, to be sited at Gral Pacheco some 15 miles North of Buenos Aires, will be the most powerful in South America.

Once again the unique Marconi High Constancy Crystal Drive has been chosen for these transmitters to ensure a very high degree of wavelength accuracy.

The day-to-day frequency stability of a Marconi High Constancy Crystal Drive is one cycle in 100 million (1 in 10^8).

Prior to placing this order the Argentine Government had ordered from the Marconi Company two 20 kW. transmitters, for local broadcasting, one to be installed at Gral Pacheco and the other at Santa Rosa.

TELEVISION DEMONSTRATIONS IN SOUTH AFRICA

ELABORATE arrangements were made to show television to the people of South Africa when a demonstration team, engineers and equipment were specially flown from England to Johannesburg to present what must have been the most comprehensive television working display that has ever been taken from one country to another.

This television show was one of the most outstanding attractions of the Witwatersrand Easter Show which ran from April 1st to 10th inclusive.

The two British firms who made this project possible were Marconi's Wireless Telegraph Co., Ltd., and Cinema Television, Ltd. who co-operated so successfully at the Milan Television Congress and Exhibition last autumn.

South Africans visiting the Rand Show saw a Marconi mobile television unit working " in the field." It televised scenes in the riding arenas and various other parts of the show grounds, and transmitted pictures, either over cables or by the new Marconi 30-watt portable television " suitcase " transmitter, to a special Television Hall.

This Television Hall was divided into two sections. Visitors entered the first portion where they were able to walk around a glass-lined studio and watch indoor theatre programmes being televised. Simultaneously, above their heads, they saw the same programme reproduced on a row of domestic television receivers.

From this first half of the hall the people then passed into the next section which was a cinema especially designed to demonstrate large-screen television. Here they saw on the cinema screen the televised programme from the studio next door.

The idea of this television show was conceived by Mr. John Schlesinger, chairman of African Theatres.

A York aircraft was specially chartered to fly the Marconi and Cinema Television technicians and equipment to Johannesburg and back.

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Telegrams : Expanse, Chelmsford.

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London W.C.2.

Telephone : Temple Bar 4321.
Telegrams : Expanse, Estrand, London.

ARGENTINA.
Establecimientos Argentinos Marconi, Avenida Cordoba 645, Buenos Aires.

AUSTRALIA.
Amalgamated Wireless (Australasia) Ltd., 47, York Street, Sydney, N.S.W.

AUSTRIA.
Kapsch & Sohne, Wagenseilgasse 1, Vienna XII.

BELGIUM AND BELGIAN COLONIES.
Société Belge Radio-Electrique S.A., 66, Chaussee de Ruysbroeck, Forest-Bruxelles.

BOLIVIA.
Macdonald & Co. (Bolivia) S.A. P.O. Box 879, La Paz.

BRAZIL.
Companhia Marconi Brasileira, Caixa Postal No. 126, Rio de Janeiro.

BRITISH EAST AFRICA.
(Kenya, Uganda, Tanganyika, Zanzibar.) Kinleven Ltd., P.O. Box 35, Nairobi, Kenya.

BURMA.
William Jacks & Co., Ltd., 517, Merchant Street, Rangoon.

CANADA.
Canadian Marconi Co., Marconi Building, 211, St. Sacrament Street, Montreal.

CENTRAL AMERICA.
(Guatemala, San Salvador, Honduras, Costa Rica, Panama.) Keilhauer, Pagram & Co. Ltd., 20, Calle Oriente, No. 22, Guatemala.

CHILE.
Gibbs & Co., Casilla 67 D, Santiago.

CHINA.
Marconi (China) Ltd., Queens Building, Chater Road, Hong Kong.

DENMARK.
Sophus Berendsen Ltd., Post Box 372, Copenhagen V.d.

ECUADOR.
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Associated British Manufacturers (Egypt) Ltd., Building B, 11, Sharia Emad el Din, Cairo.

FAROE ISLANDS.
S. H. Jakobsen Radiohandil, Postbox 35, Torshavn.

FINLAND.
de Jersey & Co. (Finland) Ltd., Mikonkatu 9, Helsinki.

FRANCE AND FRENCH COLONIES.
Compagnie Générale de Télégraphie sans Fil, 79, Boulevard Haussmann, Paris, 8e.

GREECE.
P. C. Lycourezos, Kanari Street 5, Athens.

IRAQ.
C. A. Bekhor Ltd., P.O. Box 138, Baghdad.

ISRAEL.
Middle East Mercantile Corpn., Ltd., 5, Levontin St., Tel-Aviv.

ITALY.
Marconi Societa Industriale, Via Hermada 2, Genoa-Sestri.

LEBANON.
Mitchell, Cotts & Co. (Middle East) Ltd., P.O. Box 251, Beyrouth.

MALAYA ; SINGAPORE ; SARAWAK, & BR. NORTH BORNEO.
United Engineers Ltd., P.O. Box 41, Singapore.

MEXICO.
Representaciones Britanicas S.A., Avenida Madero 55, Mexico City.

NEW ZEALAND.
Amalgamated Wireless (Australasia) Ltd., P.O. Box 830, Wellington.

NORWAY.
Norsk Marconikompani, 35, Munkedamsveien, Oslo.

NYASALAND.
Lake Nyasa Development & Trading Co. Ltd., P.O. Box 112, Blantyre.

PARAGUAY.
Agroindustrial y Comercial Espinoza Lda., S.A., Casilla de Correos No. 651, Asuncion.

PERSIA.
Pasal Trading Company, Avenue Saadi, Teheran.

PERU.
Milne & Co., S.A., Lima.

POLAND.
J. Plebanski, Frascati 2 m 15, Warsaw.

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RUMANIA.
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SAUDI ARABIA.
Mitchell, Cotts & Co. (Sharqieh) Ltd., P.O. Box 31, Jedda.

SIAM.
The Borneo Co. Ltd., Bangkok.

SOUTH AFRICA (INCLUDING N. AND S. RHODESIA).
Marconi (South Africa) Ltd., 321-4 Union Corporation Bldg., Marshall Street, Johannesburg.

SPAIN AND SPANISH COLONIES.
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SWEDEN.
Svenska Radioaktiebolaget, Alstromergatan 12, Stockholm.

SWITZERLAND.
Hasler S.A., Belpstrasse, Berne.

SYRIA.
Mitchell, Cotts & Co. (Middle East) Ltd., P.O. Box 451, Damascus.

TURKEY.
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