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THE CALCULATION OF SEARCH AREAS RELATING TO D.F. FIXES

BY

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IMPORTANT
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SUMMARY

Formulas are deduced to enable the dimensions of a rectangular region which has a 90% probability that the target lies inside the region, to be calculated. For the special case in which N stations are equi-spaced along an arc at a constant distance, s, from the target and have the same variance, V, the length and breadth of the search area are proportional to \( \sin \theta \) and \( \sqrt{V} \).

If \( \phi \) is the angle subtended by the wing stations at the target then the length of the search region is proportional to

\[
P(N, \phi) = \left[ N - 1 \sin \left( \frac{\phi}{N-1} \right) \right]^\frac{1}{2}
\]

If \( \phi < 90^\circ \), the length of the search region is not decreased when the number of stations is increased from 2 to 3; \( P(N, \phi) \) decreases as \( N \) increases for \( N \) greater than 3. For small values of \( \phi \)

\[
P(N, \phi) \approx \frac{\sqrt{V}}{\phi} \left[ \frac{N-1}{N(N-1)} \right]^{\frac{1}{2}}
\]

Small values of \( \phi \) should thus be avoided if possible.

The width of the search region is proportional to

\[
G(N, \phi) = \left[ N + 1 \sin \left( \frac{\phi}{N-1} \right) \right]^{\frac{1}{2}}
\]

This function decreases as \( N \) increases for \( \phi < 120^\circ \); if \( \phi > 120^\circ \) \( G(N, \phi) \) decreases as \( N \) increases if \( N > 3 \) and \( G(2, \phi) = G(3, \phi) \).

The search region of least area and also the one with the smallest major axis for constant \( N \) occurs when \( \phi = \frac{(N-1)180^\circ}{N} \).
1. **INTRODUCTION**

When bearings on a target are taken from a number of stations it is not sufficient to plot the bearings and estimate the Best Point for the target. It is common practice to calculate the dimensions of a rectangular region which has a 90% probability that the target lies inside it, in order to estimate the precision of the fix. Various methods have been produced for doing this (of References 1, 2 and 3) and the method described in References 1 and 2 has been programmed for a number of computers. The method is extremely tedious to compute by hand and it is not clear from the formulae employed how the various parameters of the fix, namely, the number of stations, the variance of the bearings, the distance from the station and the angle subtended by the wing stations at the target, affect the size and shape of the region.

It is important, when the disposition of the stations and the requirements for new apparatus are being studied to consider the way in which various factors affect the size and shape of the region, since this vitally affects the performance of the system in practice. In this report formulae are produced to enable the size and shape of the search region for certain theoretical arrangements to be quickly deduced and the way in which each parameter affects the dimensions of this region is discussed. A comparison of the results obtained using the formulae given in this report with those obtained using the method described in References 1 and 2 is given in the Appendix.

2. **DERIVATION OF THE FUNDAMENTAL FORMULAE**

The form of the search area under consideration is a band of width \(W/2\) on either side of the arc of the great circle passing through the estimated position of the target and joining two points \(S_1\) and \(S_2\). The arc \(S_1S_2\) is called the major axis of the search area and the points \(S_1\) and \(S_2\) will be referred to as its "end points". In order to specify the search area completely it is necessary to find the angle which the major axis makes with the northerly direction at the estimated position of the target, the distances of \(S_1\) and \(S_2\) from this point and the half-width \(W/2\).

Let bearings be given from a number of stations \(A_n\).

Suppose that \(\delta_n(n)\) is the angle which the bearing from the station \(A_n\) makes with the great circle \(A_nS\); \(\delta_n(n)\) is called the angular error of the station \(A_n\) at the point \(S\). Suppose also that the station \(A_n\) has variance \(V_n\) measured in (degrees)\(^2\). The sum

\[ \sum \delta_n(n) / V_n \]

is called the weighted sum of the angular errors at the point \(S\) and has a value for every point \(S\) on the earth's surface. The estimated position of the target is the point \(P\) at which the weighted sum of the angular errors is a minimum, the major axis of the required region on the sphere is the 'major axis' of the contour on the sphere for which

\[ \sum_{P} + 4 \times \theta^2 / 180^2 \]

and the width of the region is determined as stated below. These definitions are in accordance with those used in References 1, 2 and 3.

It is therefore necessary to find the function \(E_S\). When this is known the form of the contour

\[ E_S = E_P + 4 \times \theta^2 / 180^2 \]

can be ascertained and the direction of its 'major axis' found. The points \(S_1\) and \(S_2\) are points on this great circle for which

\[ E_S = E_P + 4 \times \theta^2 / 180^2 \]

and thus the length of the search area can be computed. Similarly, the width of the search area can be calculated by finding two points \(S_b\) and \(S_e\) on the great circle which is orthogonal to the major axis at the point \(P\),

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and for which
\[ Z_p^+ = Z_p + \frac{\varphi}{180} \] also holds.

In Fig. 1 let \( P \) be the estimated position of the target, \( N \) be the North Pole (it is assumed that the target lies in the northern hemisphere) and \( A \) be a typical station contributing to the fix. Let the bearing from \( A \) meet the great circle through \( P \) and \( N \) in \( C \) and let \( S \) be a point such that the great circle \( SP \) makes an angle \( \gamma \) with the great circle \( PN \) and the angular distance \( SP = l \). Let the great circle through \( P \) which meets the great circle \( AC \) at right angles meet \( AC \) in \( D \).

Let angular distance \( AP = \Theta \)

\[
\begin{align*}
\theta &= 0, \\
\alpha &= \theta_s, \\
\beta &= \theta, \\
\gamma &= \theta_d
\end{align*}
\]

Let angle \( ACP = \beta \)
angle \( CAP = \beta_p \)
angle \( CAS = \delta \)

Using the sine formula in spherical triangle \( ACS \) we have

\[ \sin \delta = \frac{\sin \angle ACS \sin \angle CS}{\sin \delta_s} \quad (1) \]

Using the sine and cosine formulas in spherical triangle \( CEP \) we obtain

\[ \cos CS = \cos \alpha \cos \beta \sin \gamma + \sin \alpha \cos \gamma \cos (180 - \gamma) \quad (2) \]
\[ \sin \hat{S}P = \frac{\sin \gamma \sin \gamma}{\sin CS} \quad (3) \]

and

\[ \cos \hat{S} = \frac{\cos l - \cos \alpha \cos \gamma \cos CS}{\sin \alpha \sin CS} \]

\[ = \frac{\cos l \sin \alpha \cos \gamma \cos CS}{\sin CS} \quad (4) \]

using (3)

Now \( \sin \hat{A}CS = \sin (\beta - \hat{S}CP) \)

\[ = \sin \beta \cos \hat{S}CP - \cos \beta \sin \hat{S}CP \]

Thus using equations (3) and (4) we get

\[ \sin \hat{A}CS \sin CS = \sin l \left[ \sin \beta \cos \gamma \cos \gamma - \cos \beta \sin \gamma \right] + \cos l \sin \beta \sin \gamma \quad (5) \]

Using the cosine formula in spherical triangle \( APS \) we have
FIG. 1
\[ \cos \theta = \cos \theta \cos \psi + \sin \theta \sin \psi \cos \theta \] 
\[ \sin^2 \theta = 1 - (\cos \theta \cos \psi + \sin \theta \sin \psi \cos \theta)^2 \] 
\[ = \sin^2 \theta \left[ 1 - 2 \cot \theta \sin \psi + \cot^2 \theta \sin^2 \psi \right] + \sin \theta \sin \psi \] 
\[ \text{From equations (1), (5) and (6) we find} \] 
\[ \sin \theta = \frac{\sin \theta \left( \sin \beta \cos \psi + \cos \beta \sin \psi \right) + \cos \theta \sin \beta \sin \psi}{\sin^2 \theta \left[ 1 - 2 \cot \theta \sin \psi + \cot^2 \theta \sin^2 \psi \right]} \] 
\[ \text{If } l \text{ is small, we may replace } \sin \psi \text{ by } l \text{ and } \cos \psi \text{ by } (1-l^2) \text{ on the right-hand side and obtain} \] 
\[ \sin^2 \theta \approx \left( 1 - l^2 \right) \sin^2 \psi + 2 l \sin \beta \sin \psi \] 
\[ + \sin^2 \theta \left[ 1 - 2 \cot \theta \cos \theta \sin \psi + l^2 \left( \cot^2 \theta - \cos^2 \theta \right) \right] \] 
\[ + \frac{l^2}{\sin^2 \theta} \left( \sin^2 \beta \cos^2 \psi + \sin^2 \psi \cos \theta - 2 \cos \beta \cos \theta \sin \psi \right) \] 
\[ \sin^2 \theta \left[ 1 - 2 \cot \theta \cos \theta \sin \psi + l^2 \left( \cot^2 \theta - \cos^2 \theta \right) \right] \] 
\[ \approx \sin^2 \theta \sin \psi \] 
\[ + \frac{2l}{\sin^2 \theta} \left[ \sin \beta \sin \psi \left( \sin \beta \cos \psi + \cos \beta \sin \psi \right) \right] \] 
\[ + \frac{l^2}{\sin^2 \theta} \left[ \sin^2 \beta \cos^2 \psi + \sin^2 \psi \cos \theta - 2 \cos \beta \cos \theta \sin \psi \right] \] 
\[ \text{From equation (5)} \] 
\[ + \\sin^2 \beta \sin \psi \left( \cot^2 \theta - \cos^2 \theta \right) \] 
\[ + 4 \cot \theta \cos \theta \sin \beta \sin \psi \left( \sin \beta \cos \psi + \cos \beta \sin \psi \right) \] 
\[ + 4 \cot^2 \theta \cos^2 \theta \sin^2 \beta \sin \psi \]
Using the sine formula in spherical triangle DCP we have

$$\sin d = \frac{\sin \delta \sin \phi}{\sin 90^\circ} = \sin \delta \sin \phi$$

Substituting this in equation (8) we get

$$\sin^2 \delta = \frac{\sin^2 d}{\sin^2 \theta}$$

$$+ \frac{2l}{\sin^2 \theta} \left[ \sin d (\sin \beta \cos \omega - \cos \beta \sin \omega) + \sin^2 \delta \cot \theta \cos \lambda \right]$$

$$+ \frac{l^2}{\sin^2 \theta} \left[ \sin^2 \beta \cos^2 \psi + \sin^2 \psi \cos^2 \beta - 2 \cos \omega \sin \beta \cos \phi \sin \psi \cos \psi \right]$$

$$- \sin^2 d (1 + \cot^2 \theta - \cos^2 \lambda \phi)$$

$$+ 4 \sin d \cot \theta \cos \lambda \phi (\sin \beta \cos \omega - \cos \beta \sin \omega)$$

$$+ 4 \sin^2 d \cot^2 \theta \cos^2 \lambda \phi$$

(10)

If the bearing from \( \lambda \) is not a wild bearing (which must be excluded from the fix) \( \delta, d \) and \( e \) will be small. Expanding both sides of equation (10) in powers of \( \delta, d \) and \( e \) we obtain, to the second order of small quantities,

$$\delta^2 = \frac{d^2}{\sin^2 \theta} + \frac{2l d}{\sin^2 \theta} (\sin \beta \cos \psi - \cos \beta \sin \psi)$$

$$+ \frac{l^2}{\sin^2 \theta} \left[ \sin^2 \beta \cos^2 \psi + \sin^2 \psi \cos^2 \beta - 2 \sin \beta \cos \phi \sin \psi \cos \psi \right]$$

Suppose that \( N \) stations contribute to the fix under consideration and that the parameters defined above with suffix \( n \) refer to the \( n \)th station and that this station has variance \( V_n \). The weighted sum of the angular errors at \( S \) is given by

$$\sum_{n=1}^{N} \frac{\delta_n^2}{V_n}$$

$$\sum_{n=1}^{N} \frac{\delta_n^2}{V_n \sin^2 \theta_n} + 2l \left[ \cos \psi \sum_{n=1}^{N} \frac{\delta_n \sin \theta_n}{V_n \sin^2 \theta_n} - \sin \psi \sum_{n=1}^{N} \frac{\delta_n \cos \theta_n}{V_n \sin^2 \theta_n} \right]$$

$$+ l^2 \left[ \cos^2 \psi \sum_{n=1}^{N} \frac{\sin^2 \theta_n}{V_n \sin^2 \theta_n} + \sin^2 \psi \sum_{n=1}^{N} \frac{\cos^2 \theta_n}{V_n \sin^2 \theta_n} - 2 \sin \psi \cos \theta \sum_{n=1}^{N} \frac{\sin \theta_n \cos \theta_n}{V_n \sin \theta_n} \right]$$

(11)
Using the sine rule in spherical triangle \( \triangle \text{ABC} \) we have

\[
\sin \delta_p = \frac{\sin \alpha \sin \beta}{\sin \gamma} = \frac{\sin \delta}{\sin \delta}
\]

which becomes, if we ignore terms of order higher than \( \delta_p \) and \( d^2 \)

\[
\delta_p = \frac{\delta}{\sin \delta}
\]

and thus the weighted sum of the square of the angular errors at the
Best Point \( P \) is given by

\[
\sum_{n=1}^{N} \frac{\delta_{P_n}^2}{v_n} = \sum_{n=1}^{N} \frac{d_n^2}{v_n \sin^2 \theta_n}
\]

Since \( P \) is the Best Point corresponding to the fix the weighted sum
of the square of the angular errors is a minimum there and thus the
coefficients of the first power of \( L \) in equation (ii) must vanish.

We have therefore

\[
\sum_{n=1}^{N} \delta_{P_n}^2 = \sum_{n=1}^{N} \frac{d_n^2}{v_n \sin^2 \theta_n} - 2 \sin \psi \cos \psi \sum_{n=1}^{N} \frac{\sin \beta \cos \beta}{v_n \sin^2 \theta_n}
\]

Since, by Schwarz's inequality

\[
\left( \sum_{n=1}^{N} \frac{\sin \beta}{v_n \sin \theta_n} \right) \left( \sum_{n=1}^{N} \frac{\cos \theta}{v_n \sin \theta_n} \right) \left( \sum_{n=1}^{N} \frac{\sin \theta \cos \theta}{v_n \sin \theta_n} \right) > 0
\]

unless \( \tan \theta_n \) is constant for all the stations, that is, unless all the
bearings are parallel when they cross the great circle \( \varphi \), the curves \( L = \) constant are in general ellipses for small values of \( L \). If \( \tan \theta_n \)
is constant for all the stations, the curves \( L = \) constant are parabolas.
In either case the bearing \( \varphi \) of the search area is that of the major axis
of these ellipses and is given by

\[
tan 2 \varphi = \left[ -2 \sum_{n=1}^{N} \frac{\sin \beta \cos \beta}{v_n \sin \theta_n} \right] \left( \sum_{n=1}^{N} \frac{\sin \theta \\cos \theta}{v_n \sin \theta_n} \right) - \left( \sum_{n=1}^{N} \frac{\sin \theta \cos \theta}{v_n \sin \theta_n} \right)
\]

\[
= \left[ \sum_{n=1}^{N} \frac{\sin 2 \beta}{v_n \sin \theta_n} \right] / \left[ \sum_{n=1}^{N} \frac{\cos 2 \beta}{v_n \sin \theta_n} \right]
\]

(13)
The four end points of the axes of the search region are points at which
\[ \psi = \psi_r, \] where \( \psi_r \) is one of the four angles given by equation (13), and
\[ t = t_r \] where \( t_r \) is given by the equation
\[ \sum a - \sum b = \frac{4 \pi^2}{180^2} \]
if the variances are measured in \((\text{degrees})^2\).

We thus have
\[ t_r^2 \left[ \cos^2 \psi_r \sum_{n=1}^{N} \frac{\sin^2 \beta_n}{V_n \sin^2 \theta_n} - 2 \sin \psi_r \cos \psi_r \sum_{n=1}^{N} \frac{\sin \beta_n \cos \beta_n}{V_n \sin^2 \theta_n} \right. \]
\[ + \sin^2 \psi_r \sum_{n=1}^{N} \frac{\cos^2 \beta_n}{V_n \sin^2 \theta_n} \right] = \frac{4 \pi^2}{180^2}, \]
where \( r = 1, 2, 3, 4 \).

or
\[ t_r^2 \left[ \left( \frac{1}{2} + \frac{1}{2} \cos 2 \psi_r \right) \sum_{n=1}^{N} \frac{\sin^2 \beta_n}{V_n \sin^2 \theta_n} - \frac{1}{2} \sin 2 \psi_r \sum_{n=1}^{N} \frac{\sin \beta_n}{V_n \sin^2 \theta_n} \right. \]
\[ + \left( \frac{1}{2} - \frac{1}{2} \cos 2 \psi_r \right) \sum_{n=1}^{N} \frac{\sin^2 \beta_n}{V_n \sin^2 \theta_n} \right] = \frac{4 \pi^2}{180^2} \]

\[ t_r^2 \left[ \frac{1}{2} \sum_{n=1}^{N} \frac{1}{V_n \sin^2 \theta_n} - \frac{1}{2} \cos 2 \psi_r \sum_{n=1}^{N} \frac{\cos \beta_n}{V_n \sin^2 \theta_n} \left[ \sec 2 \psi_r \sum_{n=1}^{N} \frac{\sin 2 \beta_n}{V_n \sin^2 \theta_n} \right] \right. \]
\[ = \frac{4 \pi^2}{180^2} \]

Thus \[ t_r = \sqrt{\frac{2 \pi^2}{180^2} \left[ \sum_{n=1}^{N} \frac{1}{V_n \sin^2 \theta_n} - \sec 2 \psi_r \sum_{n=1}^{N} \frac{\cos 2 \beta_n}{V_n \sin^2 \theta_n} \right]} \]

\( t_r \) being measured in radians. The length of the search region \( L \) is given by
\[ L = t_1 + t_2 \] where \( t_1 \) and \( t_2 \) are the values of \( t_r \) given by equation (13) for which \( \cos 2 \psi_r \) and
\[ \sum_{n=1}^{N} \frac{\cos 2 \beta_n}{V_n \sin^2 \theta_n} \]
have the same sign and thus
Similarly the width of the search region, \( W \), is

\[
W = \frac{240 \sqrt{2}}{\left[ \sum_{n=1}^{N} \frac{1}{V_n \sin^2 \theta_n} + \left| \sec 2 \gamma \left( \sum_{n=1}^{N} \frac{\cos 2 \beta_n}{V_n \sin^2 \theta_n} \right) \right| \right]^{\frac{1}{2}}} \text{ nautical miles}
\]

3. DERIVATION OF FORMULA FOR SYMMETRICAL ARRANGEMENTS OF STATIONS

Consider the theoretical case in which all the stations are equispaced along an arc at the same angular distance \( \theta \) from the target and have the same variance \( V \). The practical case frequently approximates to this when all the stations are using similar equipment and the target is a long way away. Assume further that all the bearings pass through the point \( P \). The bearing of the search region \( V \) is given by the equation,

\[
\tan 2V = \left[ \sum_{n=1}^{N} \frac{\sin 2 \beta_n}{V_n \sin^2 \theta_n} \right] / \left[ \sum_{n=1}^{N} \frac{\cos 2 \beta_n}{V_n \sin^2 \theta_n} \right]
\]

and the length and breadth of the search region in nautical miles are given by the formula

\[
L = \frac{240 \sqrt{2}}{\left[ \sum_{n=1}^{N} \frac{1}{V_n \sin^2 \theta_n} - \left| \sec 2 \gamma \left( \sum_{n=1}^{N} \frac{\cos 2 \beta_n}{V_n \sin^2 \theta_n} \right) \right| \right]^{\frac{1}{2}}}
\]

Suppose that the stations \( A_1, A_2, \ldots, A_N \) are arranged as in Fig. 2 so that

\[
A_1 \hat{A} A_2 = A_2 \hat{A} A_3 = A_3 \hat{A} A_4 = \ldots = A_{N-1} \hat{A} A_N = \gamma
\]
and that the bearing from \( A_i \) to \( P \) makes an angle \( \eta \) with \( FN \). Then

\[
\beta_n = 180^\circ - \widehat{PA}_n = 180^\circ - \left(180^\circ - \eta + (n-1)\gamma \right)
\]

or

\[
\beta_n = \eta - (n-1)\gamma 
\]

\( n = 1, 2 \ldots N \)

Thus

\[
\sum_{n=1}^{N} \sin 2\beta_n = \sum_{n=1}^{N} \sin \left[ 2\eta - 2(n-1)\gamma \right]
\]

\[
= \sin \left[ 2\eta - (N-1)\gamma \right] \sin N\gamma \csc \gamma 
\]

and

\[
\sum_{n=1}^{N} \cos 2\beta_n = \sum_{n=1}^{N} \cos \left[ 2\eta - 2(n-1)\gamma \right]
\]

\[
= \cos \left[ 2\eta - (N-1)\gamma \right] \sin N\gamma \csc \gamma 
\]

Thus if \( \sin N\gamma \neq 0 \) the bearing of the search region is given by the equation

\[
\tan 2\psi = \tan \left[ 2\eta - (N-1)\gamma \right]
\]

and

\[
| \sec 2\psi | = | \sec \left[ 2\eta - (N-1)\gamma \right] |
\]

The length and breadth of the search area in nautical miles are thus given by the formula

\[
\frac{240 \sqrt{2} \psi \sin \theta}{\left[ N \frac{\theta}{\psi} \sec \left[ 2\eta - (N-1)\gamma \right] \cos \left[ 2\eta - (N-1)\gamma \right] \sin N\gamma \csc \gamma \right]^x}
\]

or

\[
= \frac{240 \sqrt{2} \psi \sin \theta}{\left[ N \frac{\theta}{\psi} \sin N\gamma \csc \gamma \right]^x}
\]

If \( A_i \neq A_m \neq \psi \) then \( \gamma = \phi(N-1) \) and the bearings of the axes of the search region are given by

\[
\psi = \eta - \phi/2 
\]

and

\[
\psi = \eta - \phi/2 + 90^\circ
\]
FIG. 2
the bearing of the major axis being that value of \( \psi \) for which \( \cos 2\psi \) and 
\( \cos (2\pi - \psi) \sin (\pi/\psi - 1) \cos \sec (\pi/\psi - 1) \) have the same sign. The length
and breadth of the search region in nautical miles are given by the formula

\[
\frac{240 \sqrt{2} \sqrt{V} \sin \theta}{\left| N \sin (\pi/N - 1) \sin \left( \frac{\pi}{N - 1} \right) \right|^{1/2}}
\]

If \( \sin Ny = 0 \) then \( \gamma = \pi/2 \). In this case the stations are symmetr-
ically placed with respect to \( P \) and the elliptical contours become circles. The length and breadth of the search region may be obtained directly from equation (14) since

\[
\sum_{n=1}^{N} \sin 2\theta_n = \sum_{n=1}^{N} \cos 2\theta_n = 0
\]

and thus

\[
L = W = 240 \sqrt{2} \sqrt{V} \sin \theta/\pi \text{ nautical miles.}
\]


The formulae derived in the previous sections assume that powers of \( l \) higher than \( l^2 \), where \( l \) is the arc length of the axis under consideration measured in radians, may be neglected. Thus, the longer the axis the greater the error becomes. Since powers of \( \delta \), \( d \) and \( e \) higher than the second and products of these terms are also neglected, the calculated values of the lengths of the axes of the search region are more in error if the fix contains inaccurate bearings. Since in general, a fix containing inaccurate bearings will also have a large search area, the length of the axis can be used as a guide in all cases.

A number of calculations have been made comparing the results obtained using formula (15) for stations arranged in the asymmetrical way described in section 3 with the results obtained using the analysis described in References 1 and 2. In all cases the values obtained for the length of the search region agreed exactly. When \( V = 1 \) (degree)\(^2\) no error in the length of the search region exceeded 2% and when the angle subtended at the target by the wing stations was 40° or more no length differed from that computed by the method described in References 1 and 2 by more than 1 nautical mile. When \( V = 5 \) (degrees)\(^2\), the angle subtended at the target by the wing stations = 20°, the distance of the stations from the target = 15° and three stations contribute to the fix there is a discrepancy of 10%. The method used for comparison is not accurate for fixes of this nature which increases the difficulty in assessing the situation. All the computed results are given in the Appendix.

If terms of higher power than \( l^2 \) are ignored the resulting equation gives values of \( l \) which are equal in modulus but differ in sign for the two ends of the search region. It is known that in fact the estimated position of the target is nearer to the stations than the mid-point of the major axis of the search area. If the position of the end points of the axes of the search region are required, additional powers of \( l \) must be included in the expression for \( L \). Let us assume that
and that

\[
L = \frac{2\pi b}{180} \left[ \sum_{n=1}^{N} \frac{1}{V_n \sin^2 \theta_n} - \sec 2\beta \sum_{n=1}^{N} \frac{\cos 2\beta_n}{V_n \sin^2 \theta_n} \right]^{1/2}
\]

is the first approximation to the value of \( L \) for one end of the search region, obtained by putting \( \beta \) and \( \gamma \) equal to zero. Suppose also that the true value of the weighted sum of the squares of the angular errors obtained by using equation (7), which is exact, to compute \( \beta \) for each station at the point on the axis of the search region for which \( L = \tilde{L} \) is \( L \) whilst the value of this function at the point on the axis of the search region for which \( L = -\tilde{L} \) is \( L \). We thus have

\[
\alpha L^3 = \frac{\omega^3}{180^3}
\]

from equation (14)

\[
\hat{L} = L_p + \alpha L^3 + \beta L^4 + \gamma L^5
\]

and

\[
\hat{L}_n = L_p + \alpha L^3 - \beta L^4 + \gamma L^5
\]

Adding (16) and (17) we obtain

\[
\gamma L^5 = \frac{1}{2} \left( \hat{L} + L_n \right) - L_p - \frac{\omega^3}{180^3}
\]

and subtracting (17) from (16) we get

\[
\beta L^4 = \frac{1}{2} \left( \hat{L} - L_n \right)
\]

and thus

\[
\hat{L} = L_p + \frac{\omega^3}{180^3} \left( \frac{1}{L} \right)^3 + \frac{1}{2} \left( \hat{L} \right) \left( \frac{1}{L} \right)^3 + \left[ \frac{1}{2} \left( \hat{L} - L_n \right) \right] \left( \frac{1}{L} \right)^4
\]

A better approximation to the positive value of \( L \) for which \( \hat{L} = L_p + \frac{\omega^3}{180^3} \) is given by
by using Newton's formula. Similarly a better approximation to the negative value of $l$ for which

$$Z_s = Z_p + 4 \theta^2/180^2$$

is given by

$$I_s = I[\frac{5 Z_s^2 E - 5 Z_p^2 E - 8 \theta^2/180^2}{7 Z_s^2 E - 8 Z_p^2 E - 16 \theta^2/180^2}]$$

The accuracy of the new values of $I_s$ and $I_s$ should be tested by substituting them in equation (18) and checking that $Z_s$ is equal to $Z_p + 4 \theta^2/180^2$.

The values of $l_s$ and $l_s$ may be improved by further application of Newton's formula using the equation

$$I'_s = I_s - \frac{\alpha \theta^2 + \beta \theta^2 + \gamma \theta^2 - 4 \theta^2/180^2}{2 \alpha \theta^2 + 3 \beta \theta^2 + 4 \gamma \theta^2}$$

As a final check the value of $Z_s$ at the end points should be computed using equation (7). If these are not satisfactory more terms must be taken in the series for $Z_s$ and a procedure similar to that outlined above adopted.

5. **THE EFFECT OF THE PARAMETERS OF A FIX ON THE SIZE OF THE SEARCH AREA**

It will be seen from the Appendix that formula (15) is sufficiently accurate to enable it to be used to study the way in which the various parameters of a fix namely, the number of stations, the variance of the stations, the distance from the target and the angle which the wing stations subtend at the target affect the size of the search area. A few salient points are given below:

5.1. The length and breadth of the search area are both proportional to the sine of the angular distance of the stations from the target. For small distances the dimensions of the search area are proportional to the distance from the target.

5.2. The length and breadth of the search area are both proportional to the square root of the variance of the stations. If the variance is not known precisely, as is usually the case since it often depends on physical factors such as propagation conditions which cannot be controlled, then the percentage error in the dimensions of the search area due to this inexactness is approximately half the percentage error in the variance. In practice it is not usually possible to obtain the dimensions of the search area correct to more than two significant figures; this corresponds to a $2\%$ error in estimating the variance.
5.3. The length of the search area is proportional to

\[ F(N, \phi) = \left[ N - \left| \frac{\sin \frac{N\phi}{2}}{\sin \phi} \right| \right]^{-\frac{1}{2}} \]

where \( N \) is the number of stations and \( \phi \) is the angle subtended at the target by the wing stations. If \( \phi < 90^\circ \)

\[ F(2, \phi) = \left[ 2 - \sin \frac{2\phi}{\sin \phi} \right]^{-\frac{1}{2}} = \frac{1}{\sqrt{2}} \cos \frac{\phi}{2} \]

\[ F(3, \phi) = \left[ 3 - \sin \frac{3\phi}{2} \cos \frac{\phi}{2} \right]^{-\frac{1}{2}} = \frac{1}{\sqrt{2}} \cos \frac{\phi}{2} \]

Thus, if all the other parameters of the system remain the same, the length of the search area is not reduced by increasing the number of stations from 2 to 3. It is obvious from physical considerations that this must be the case since, if the system is symmetrical about the middle bearing, the axis of the search area must lie along it and the middle bearing therefore makes no contribution to the weighted sum of the angular errors at any point along the major axis of the search area. For values of \( N \) greater than 3 the function \( F(N, \phi) \) decreases as \( N \) increases provided that \( \phi \) remains constant. This is shown in the table of the dimensions of search areas for various values given in the Appendix.

5.4. The width of the search area is proportional to

\[ G(N, \phi) = \left[ N + \left| \frac{\sin \frac{N\phi}{2}}{\sin \phi} \right| \right]^{-\frac{1}{2}} \]

This function decreases as \( N \) increases for values of \( \phi < 180^\circ \). If \( 180^\circ > \phi > 120^\circ \), \( G(2, \phi) = G(3, \phi) \)

5.5. For small values of \( \phi \)

\[ F(N, \phi) = \left[ N - \frac{\left( N\phi/(N-1) - \frac{1}{6} (N\phi/(N-1))^2 \right)}{\left( \phi/(N-1) - \frac{1}{6} (\phi/(N-1))^2 \right)} \right]^{-\frac{1}{2}} \]

Thus \( F(N, \phi) \) increases as \( \phi \) tends to zero. For this reason a small value of \( \phi \) (which is equivalent to a narrow base line) should be avoided if possible since it is not easy to mitigate its effects by varying the other parameters of the system. It is necessary to increase \( N \) from 2 to 22, or to
reduce the variance to one quarter of its original value or to halve the distance to the target to achieve the same effect as that obtained by doubling \( \phi \), that is, by doubling the base line, if \( \phi \) is small. It will be seen from the Appendix that the formula for the length of the search area is not very accurate when \( \phi \) is small and that the situation is even worse than that predicted from formula (45). It is therefore of great importance to extend the base line as far as possible if \( \phi \) is likely to be small if the best possible results are to be obtained.

5.6. The search area of least area and also the one with the smallest major axis for a given number of stations occurs when \( \phi = (N-1) \times 180/\pi \). This arrangement gives the best results for a given amount of equipment but the length of the resulting base line is usually greater than can be tolerated in practice.
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<td>2.</td>
<td>E. M. L. Biale</td>
<td>On probability regions in DP analysis</td>
<td>AEL/R4/M2.5 - SECRET</td>
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<td>3.</td>
<td>K. Humphreys and G. F. M. Reekden</td>
<td>Methods of Rapid Analysis of DP Observations</td>
<td>AEL/R1/Maths 2.5 - March, 1951 - SECRET</td>
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APPENDIX

In the following tables let

\( \theta \) = angular distance of the stations from the target

\( \phi \) = angle subtended at the target by the wing stations

\( N \) = number of stations

\( V \) = variance of the bearings

\( L_k \) = length of search area as calculated by formula (15)

\( L_s \) = length of search area as calculated by the method described in References 1 and 2

\( W_s \) = width of search area as calculated by formula (15)

\( W_s \) = width of search area as calculated by the method described in References 1 and 2
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