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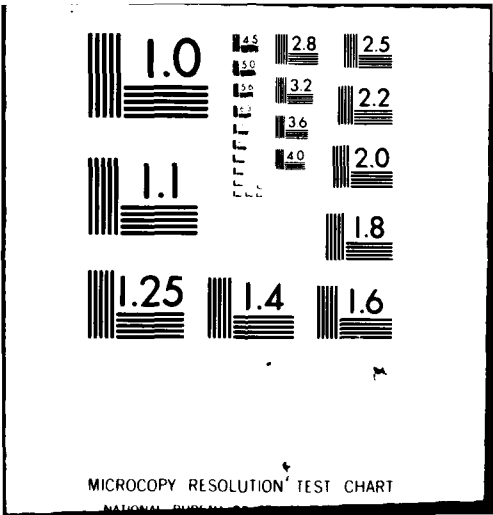
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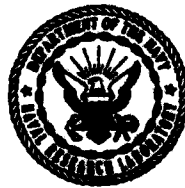
**Maximum Likelihood Angle Estimates  
of Two Signals Using Three Squinted Beams  
(Symmetric Solution)**

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*Radar Analysis Branch  
Radar Division*

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## MAXIMUM LIKELIHOOD ANGLE ESTIMATES OF TWO SIGNALS USING THREE SQUINTED BEAMS (SYMMETRIC SOLUTION)

### INTRODUCTION

The problem of estimating the angle of arrival of closely spaced targets has received considerable attention [1-19]. Two solution methods, the maximum likelihood estimate (MLE) and the maximum entropy method (MEM) have been used extensively for many problems. For array antennas, White [1] calculated the mean-square error for the two-target case when the signal-to-noise ratio (SNR) was large, a case which provides small errors. This calculation was made for both the case in which the plane of symmetry between the targets was known and the case in which it was not known. Lang [2] compared the MLE with the MEM for the two-target nonsymmetric case. He found that the MLE was only slightly better than the MEM; at most the difference was approximately  $\sqrt{2}$ . In addition to comparing the accuracy of the MLE and MEM for the two-target case, Trunk et al. [3] compared the MLE accuracy to the Cramer-Rao bound for unbiased estimators. They showed that the MLE can achieve better accuracy than the bound for the lower signal-to-noise ratios because it is a biased estimator.

Besides the accuracy of the estimates, a number of implementations have been studied. White [1] describes a double-null tracking system which approximates the MLE estimate using an array antenna. He also discusses a tempered double-null tracker using multiple beams. Neither of these implementations estimate the angle of arrival on a single pulse; they search for a solution through a tracking loop. Howard [4] uses the MLE method to obtain the angle estimate on a single pulse by a search technique.

Some closed-form solutions for the angle of arrival of two targets under special conditions have been obtained. Peebles and Berkowitz [5] obtained a noise-free solution for two targets and three squinted beams when the antenna patterns could be approximated by polynomials. White [1] obtained a fixed-beam solution under the special conditions of symmetric antenna patterns pointed directly at the plane of symmetry between two targets. Recently a closed-form MLE using three subapertures was obtained for two targets both when the plane of symmetry between them was known and when it was unknown [6]. The accuracy was nearly as good as if all the elements of an array had been used. Since a closed-form MLE using three subapertures had been obtained, we addressed the analogous problem of obtaining a closed-form MLE using three squinted beams. We first reduced the mean square error cost function found in the MLE formulation into as simple a form as possible in terms of the unknown angles of arrival. We then found the angles that minimized the cost and evaluated the accuracy of the estimates. We investigated only the case in which the plane of symmetry separating the sources or targets is known.

**MLE FORMULATION FOR THREE SQUINTED BEAMS AND TWO TARGETS**

We begin by defining the geometry and antenna system with the aid of Fig. 1. The antenna lies in the  $z$ - $y$  plane with the principal axes of the antenna defined along the  $z$  and  $y$  axes. This implies that the aperture illumination is factorable in the  $z$  and  $y$  directions. The antenna patterns can then be written in terms of the product of two individual antenna patterns which are functions of the direction cosines. For large apertures and narrow beams pointed near the bore site axis  $x$ , the direction cosine can be approximated by the elevation and azimuth angles  $\theta$  and  $\psi$ , respectively, as shown in Fig. 1. The angles of arrival of the radiation from source 1 and source 2 are defined to be  $(\theta_1, \psi_0)$  and  $(\theta_2, \psi_0)$ , respectively. We have defined the azimuth  $\psi_0$  of the two sources to be the same and, consequently, there is no cross-leveling of the array with respect to a line connecting the sources.

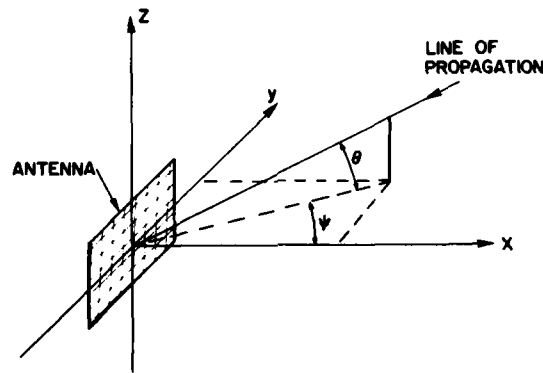


Fig. 1 - Coordinate system

The antenna is constructed so that three squinted beams are formed. The beams are symmetric about the  $x$ - $z$  plane and are squinted in the elevation direction  $\theta$ . Using representative antenna pattern shapes, their antenna pattern factors in the  $\theta$  direction are shown in Fig. 2.

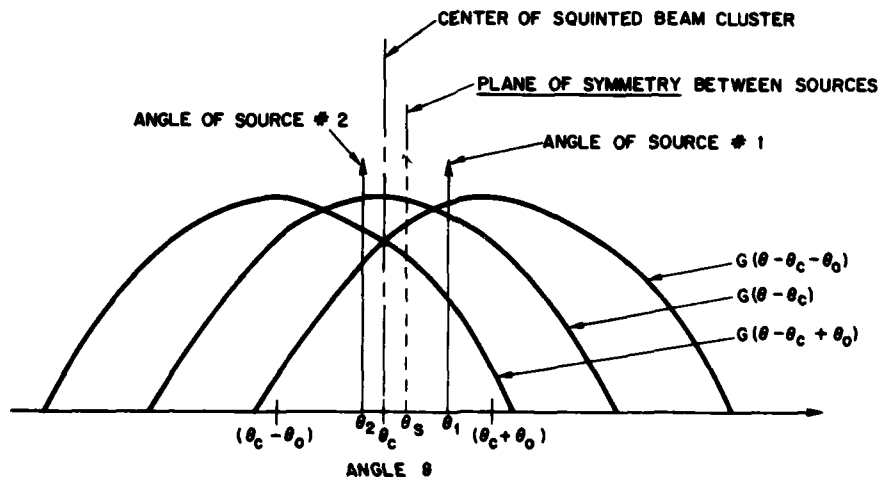


Fig. 2 - Antenna patterns for three squinted beams in  $\theta$  direction for a fixed angle  $\psi$

The three beams are identical and the separation in angle of adjacent beam centers is denoted by  $\theta_0$ . The pointing of the three squinted beams is specified by the pointing angle  $\theta_c$  of the center of the middle beam. The plane of symmetry between the two sources is specified by angle  $\theta_s = (\theta_1 - \theta_2)/2$ . The antenna pattern factors for the three beams in the  $\theta$  coordinate are given in terms of the angle of arrival  $\theta$  of a source by  $G(\theta - \theta_c - \theta_0)$ ,  $G(\theta - \theta_c)$ , and  $G(\theta - \theta_c + \theta_0)$ , respectively. The antenna pattern factors in the  $\psi$  direction are given by  $H(\psi)$  for all three beams. The antenna patterns for the three beams are then given by

$$\begin{aligned} F(\theta - \theta_c - \theta_0, \psi) &= H(\psi) G(\theta - \theta_c - \theta_0), \\ F(\theta - \theta_c, \psi) &= H(\psi) G(\theta - \theta_c), \end{aligned}$$

and

$$F(\theta - \theta_c + \theta_0, \psi) = H(\psi) G(\theta - \theta_c + \theta_0).$$

The antenna is also constructed with the property that when a plane wave sweeps across the aperture, signals will be produced at the output ports of the beamforming devices that are all in phase. These signals after conversion to baseband are denoted by the complex numbers  $s_1$ ,  $s_2$ , and  $s_3$ , where the real and the imaginary parts are the time-coincident samples of the in-phase and the quadrature channels of the synchronous detector, respectively. The signals  $s_1$ ,  $s_2$ , and  $s_3$  out of the three beamforming ports can be expressed as the summation of the excitation produced by the plane-wave signals sweeping across the antenna and the additive thermal noise. For two sources in the far field, the received signals are written as

$$\begin{aligned} s_1 &= a_1 F(\theta_1 - \theta_c - \theta_0, \psi) + a_2 F(\theta_2 - \theta_c - \theta_0, \psi) + n_1, \\ s_2 &= a_1 F(\theta_1 - \theta_c, \psi) + a_2 F(\theta_2 - \theta_c, \psi) + n_2, \end{aligned}$$

and

$$s_3 = a_1 F(\theta_1 - \theta_c + \theta_0, \psi) + a_2 F(\theta_2 - \theta_c + \theta_0, \psi) + n_3, \quad (2)$$

where  $a_1$  and  $a_2$  are the strengths of the sources 1 and 2, respectively, and  $n_1$ ,  $n_2$ , and  $n_3$  are the thermal noise in each of the channels associated with a beamforming device. The noise is assumed to be uncorrelated and Gaussian distributed with a mean of zero and a standard deviation of  $\sigma$ . Equations (2) can be written in vector form

$$\mathbf{S} = \mathbf{W}\mathbf{A} + \mathbf{N}, \quad (3)$$

where

$$\mathbf{S} = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \quad \mathbf{N} = \begin{bmatrix} n_1 \\ n_2 \\ n_3 \end{bmatrix},$$

and

$$\mathbf{W} = \begin{bmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \\ w_{31} & w_{32} \end{bmatrix}.$$

The coefficients of the matrix  $\mathbf{W}$  are the antenna gains of each of the beams in the direction of each of the sources, as described in Eq. (2), and are given by

$$\begin{aligned} w_{11} &= F(\theta_1 - \theta_c - \theta_0, \psi), & w_{12} &= F(\theta_2 - \theta_c - \theta_0, \psi), \\ w_{21} &= F(\theta_1 - \theta_c, \psi), & w_{22} &= F(\theta_2 - \theta_c, \psi), \\ w_{31} &= F(\theta_1 - \theta_c + \theta_0, \psi), & w_{32} &= F(\theta_2 - \theta_c + \theta_0, \psi). \end{aligned} \quad (4)$$



We have now constructed a model of the signals received by an antenna using three squinted beams, excited by two distant sources at different angles. We would now like to estimate the unknown parameters  $\mathbf{A}$  and the angles of arrival  $\theta_1$  and  $\theta_2$  using the noisy measurements  $\mathbf{S}$ . The estimation technique we will use is the maximum likelihood procedure.

Since  $\mathbf{N}$  is a Gaussian random vector with uncorrelated but equal variance components, maximizing the likelihood function is equivalent to minimizing the square error

$$L = (\mathbf{S} - \mathbf{W}\mathbf{A})^* (\mathbf{S} - \mathbf{W}\mathbf{A}), \quad (5)$$

where the asterisk represents the conjugate transpose. The value of  $\mathbf{A}$  which minimizes  $L$  is

$$\mathbf{A} = (\mathbf{W}^*\mathbf{W})^{-1} \mathbf{W}^*\mathbf{S},$$

which expands to

$$\mathbf{A} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = E^{-1} \begin{array}{c} \left[ \begin{array}{c} \frac{(p_1 - q_1) + p_2(p_1 p_2 - q_1 q_2)}{w_{21}} \\ \dots \\ \frac{-(p_1 - q_1) - q_2(p_1 p_2 - q_1 q_2)}{w_{22}} \end{array} \right] \\ \left[ \begin{array}{c} \frac{p_2(p_2 - q_2) - q_1(p_1 - q_1)}{w_{21}} \\ \dots \\ \frac{p_1(p_1 - q_1) - q_2(p_2 - q_2)}{w_{22}} \end{array} \right] \\ \left[ \begin{array}{c} \frac{-(p_2 - q_2) - q_1(p_1 p_2 - q_1 q_2)}{w_{21}} \\ \dots \\ \frac{(p_2 - q_2) + p_1(p_1 p_2 - q_1 q_2)}{w_{22}} \end{array} \right] \end{array} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} \quad (6)$$

where

$$E = (p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_1 p_2 - q_1 q_2)^2,$$

$$p_1 = \frac{w_{11}}{w_{21}}, \quad q_1 = \frac{w_{12}}{w_{22}},$$

$$q_2 = \frac{w_{31}}{w_{21}}, \quad p_2 = \frac{w_{32}}{w_{22}}.$$

Equation (5) for the mean-square error  $L$  can be written as

$$L = \sum_{i=1}^3 \|f_i\|^2 = \sum_{i=1}^3 f_i f_i^*, \quad (7)$$

where

$$f_i = s_i - w_{i1} a_1 - w_{i2} a_2 \quad (8)$$

for  $i = 1, 2$ , and  $3$ . Substituting the values  $a_1$  and  $a_2$  found in (6) into (8) we obtain

$$\begin{aligned} f_1 &= \frac{(p_2 - q_2) [(p_2 - q_2)s_1 - (p_1 p_2 - q_1 q_2)s_2 + (p_1 - q_1)s_3]}{(p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_1 p_2 - q_1 q_2)^2}, \\ f_2 &= \frac{-(p_1 p_2 - q_1 q_2) [(p_2 - q_2)s_1 - (p_1 p_2 - q_1 q_2)s_2 + (p_1 - q_1)s_3]}{(p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_1 p_2 - q_1 q_2)^2}, \\ f_3 &= \frac{(p_1 - q_1) [(p_2 - q_2)s_1 - (p_1 p_2 - q_1 q_2)s_2 + (p_1 - q_1)s_3]}{(p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_1 p_2 - q_1 q_2)^2}. \end{aligned} \quad (9)$$

Using Eqs. (9) in (5), the mean square error becomes

$$L = \frac{|| (p_2 - q_2)s_1 - (p_1 p_2 - q_1 q_2)s_2 + (p_1 - q_1)s_3 ||^2}{(p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_1 p_2 - q_1 q_2)^2} \quad (10)$$

The coefficients  $p_1$ ,  $q_1$ ,  $p_2$ , and  $q_2$  in (9) are complicated nonlinear functions of the angles of arrival and the geometry. Finding the parameters which minimize the error would be difficult in most cases. However, a special case is examined which is of a simpler form than (10).

### SOLUTION UNDER SYMMETRY CONDITIONS

We investigate the solution for the angles of arrival of signals when the angular bisecting plane between them is known and both emitters are at the same azimuth  $\psi$ . The peak of the center beam in elevation is pointed directly at the bisecting angle between the two sources. In the three squinted beam cluster, the squint all appears in elevation. For these conditions  $\theta_c = 0^\circ$ ,  $\theta_1 = -\theta_2$ , and the weights become

$$\begin{aligned} w_{11} &= F(\theta_1 - \theta_0, \psi), & w_{12} &= F(-\theta_1 - \theta_0, \psi), \\ w_{21} &= F(\theta_1, \psi), & w_{22} &= F(-\theta_1, \psi), \\ w_{31} &= F(\theta_1 + \theta_0, \psi), & w_{32} &= F(-\theta_1 + \theta_0, \psi). \end{aligned} \quad (11)$$

Using the fact that the antenna patterns are factorable under certain conditions as expressed by Eq. (1), Eq. (11) can be rewritten as

$$\begin{aligned} w_{11} &= H(\psi) G(\theta_1 - \theta_0), & w_{12} &= H(\psi) G(-\theta_1 - \theta_0), \\ w_{21} &= H(\psi) G(\theta_1), & w_{22} &= H(\psi) G(-\theta_1), \\ w_{31} &= H(\psi) G(\theta_1 + \theta_0), & w_{32} &= H(\psi) G(-\theta_1 + \theta_0). \end{aligned} \quad (12)$$

Using the definition of  $p_1$ ,  $q_1$ ,  $p_2$ , and  $q_2$  we find

$$\begin{aligned} p_1 &= \frac{w_{11}}{w_{21}} = \frac{H(\psi) G(\theta_1 - \theta_0)}{H(\psi) G(\theta_1)} = \frac{G(\theta_1 - \theta_0)}{G(\theta_1)}, \\ q_2 &= \frac{w_{31}}{w_{21}} = \frac{H(\psi) G(\theta_1 + \theta_0)}{H(\psi) G(\theta_1)} = \frac{G(\theta_1 + \theta_0)}{G(\theta_1)}, \\ q_1 &= \frac{w_{12}}{w_{22}} = \frac{H(\psi) G(-\theta_1 - \theta_0)}{H(\psi) G(-\theta_1)} = \frac{G(-\theta_1 - \theta_0)}{G(-\theta_1)}, \end{aligned}$$

and

$$p_2 = \frac{w_{32}}{w_{22}} = \frac{H(\psi) G(-\theta_1 + \theta_0)}{H(\psi) G(-\theta_1)} = \frac{G(-\theta_1 + \theta_0)}{G(-\theta_1)}.$$

Using the fact that the antenna patterns for the beams have even symmetry,  $G(\theta) = G(-\theta)$ , we find that  $p_1 = p_2$  and  $q_1 = q_2$  and define

$$p = p_1 = p_2$$

and

$$q = q_1 = q_2.$$

Using the symmetry conditions in the expression for the mean square error  $L$  in Eq. (10), we find

$$L = \frac{||s_1 - Xs_2 + s_3||^2}{2 + X^2} \quad (13)$$

where

$$X = p + q = \frac{G(\theta_1 - \theta_0) + G[-(\theta_1 + \theta_0)]}{G(\theta_1)}$$

To minimize the mean square error  $L$  with respect to the angle of arrival  $\theta_1$  in (13) is equivalent to minimizing  $L$  with respect to  $X$  and then relating  $X$  to  $\theta_1$  through a table look up. The minimum value of  $L$  is found by finding its stationary points with respect to the real variable  $X$  in terms of the complex numbers  $s_1$ ,  $s_2$ , and  $s_3$ . The stationary points are found by differentiating the mean square error  $L$  with respect to  $X$ , setting the result equal to zero, and solving for  $X$ . The result is

$$X = \frac{(\eta - 2\gamma)}{\alpha + \beta} \pm \sqrt{\frac{(\eta - 2\gamma)}{\alpha + \beta} + 2}, \quad (14)$$

where

$$\alpha = s_1^* s_2 + s_2^* s_1,$$

$$\beta = s_2^* s_3 + s_3^* s_2,$$

$$\gamma = s_2^* s_2, \text{ and}$$

$$\eta = s_1 s_1^* + s_3 s_3^* + s_1 s_3^* + s_3 s_1^*.$$

Because of the geometry,  $\theta_1$  cannot be less than zero degrees, and consequently

$$X \geq \frac{G(-\theta_0) + G(-\theta_0)}{G(0)},$$

or

$$X \geq \frac{2G(\theta_0)}{G(0)},$$

where  $G(\theta_0) = G(-\theta_0)$ . If  $X$  is less than this zero-angle value due to noise, we limit  $X$  to

$$X = \frac{2G(\theta_0)}{G(0)}. \quad (15)$$

The solution is that value of  $X$  given by (14) or (15) which makes  $L$  in (13) a minimum.

Not only can the angle of arrival  $\theta_1$  be estimated, but the estimates of the complex amplitudes can be made using (6). For the special case under consideration,  $a_1$  and  $a_2$  are estimated in terms of  $p$  and  $q$  by

$$a_1 = \frac{1}{w_{32}} \frac{[1 + p(p + q)] s_1 + (p - q)s_2 - [1 + q(p + q)] s_3}{(p - q) [(p + q)^2 + 2]}$$

and

$$a_2 = \frac{1}{w_{32}} \frac{-[1 + q(p + q)] s_1 + (p - q)s_2 + [1 + p(p + q)] s_3}{(p - q) [(p + q)^2 + 2]}.$$

To compare the results to previous work, we define a reflection coefficient by

$$\rho = \frac{a_2}{a_1} = \frac{-[1 + q(p + q)]s_1 + (p - q)s_2 + [1 + p(p + q)]s_3}{[1 + p(p + q)]s_1 + (p - q)s_2 - [1 + q(p + q)]s_3}. \quad (16)$$

If the angle of arrival and stored antenna patterns are known,  $p$  and  $q$  can be found. Consequently, the reflection coefficient can be estimated. For the latter purposes we define the magnitude  $|\rho|$  and phase  $\phi$  of the reflection coefficient  $\rho$ .

For a system to be put in operation, a calibration curve of  $X$  vs the angle of arrival  $\theta_1$  would be found experimentally and stored for reference in a table. For our purposes here, we wish to illustrate the nature of this curve and use it later to indicate the system's expected performance. The normalized antenna patterns chosen are

$$G(\theta \pm \theta_0) = \frac{\sin \pi d(\theta \pm \theta_0)/\lambda}{\pi d(\theta \pm \theta_0)/\lambda} \cdot \frac{\pi^2}{\pi^2 - [\pi d(\theta \pm \theta_0)/\lambda]^2}, \quad (17)$$

where  $d$  is the aperture width and  $\lambda$  is the wavelength. The beamwidth  $B_\theta$  for this antenna pattern is

$$B_\theta = 82.5\lambda/d$$

in degrees. For an antenna aperture width of 2.5 wavelengths and a squint angle of 0.8 beamwidth, the calibration curve of the parameter  $X$  vs angle of arrival  $\theta_1$  using the postulated antenna pattern (17) is shown in Fig. 3. We find that the curve is very flat for small angles, which indicates that large signal-to-noise ratios will be required to obtain descent-angle estimates for closely spaced targets. We next evaluate quantitatively the performance of the angle-measurement procedure.

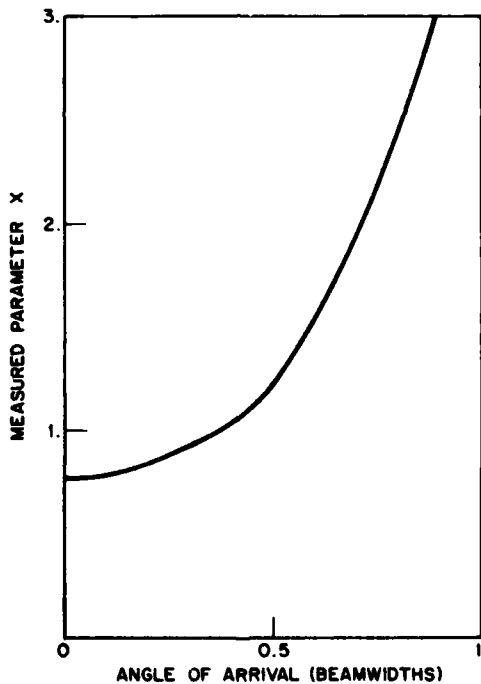


Fig. 3 - Calibration curve

**ANGLE ESTIMATE PERFORMANCE**

The performance of the MLE angle estimates has been evaluated using a simulation technique. To compare the results to previous work, the signal-to-noise ratio is defined to be

$$\frac{S}{N} = 10 \log \frac{|a_1|^2}{2\sigma^2}$$

This is the signal-to-noise ratio of one source (the strongest) at the center of the center beam. Using this signal-to-noise ratio, noisy signals are generated using (3), and the angle of arrival  $\theta_1$  is estimated. This process is repeated 400 times and the root mean square (RMS) error in the estimates of  $\theta_1$ ,  $|\rho|$ , and  $\phi$  is computed.

For a 30-dB signal-to-noise ratio, a magnitude of the reflection coefficient of 0.9 and three values of  $\theta_1$ , the RMS error in estimating  $\theta_1$  is plotted vs the relative phase shift  $\phi$  between the sources in Fig. 4. We find that the error is smallest when the effective signal-to-noise ratio is largest (i.e., signals  $a_1$  and  $a_2$  are in phase) and largest when the signals are out of phase. Also, Fig. 4 shows that the closer the signal spacing, the more difficult it is to measure the angle of arrival. The RMS error in estimating the angle of arrival is also shown in Fig. 5 using the same conditions as used in Fig. 4, except that  $|\rho| = 0.2$ . The effective  $S/N$  is more constant with relative phase between the sources, and so the curves are flatter. Again, Fig. 5 shows that it is easier to estimate the angle of widely separated signals.

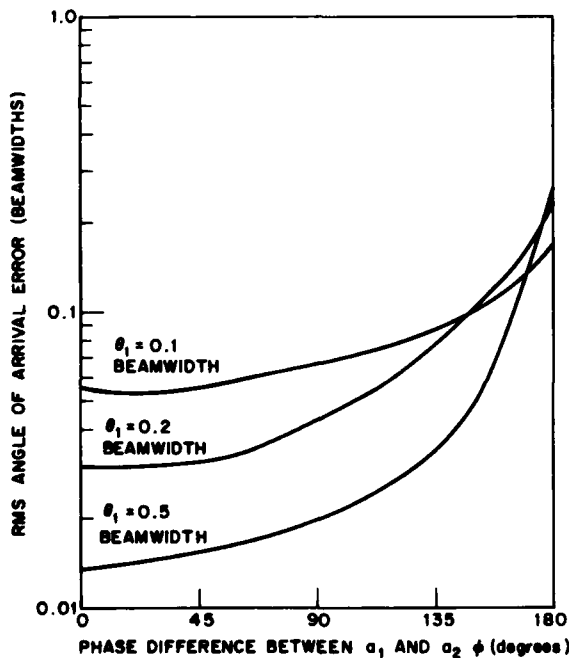


Fig. 4 — RMS error in angle of arrival for  $|\rho| = 0.9$  and  $S/N = 30$  dB

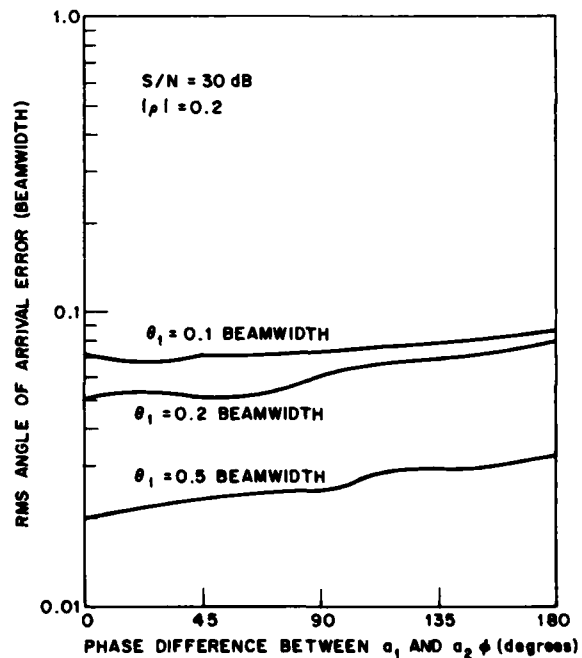


Fig. 5 — RMS error in angle of arrival for  $|\rho| = 0.2$  and  $S/N = 30$  dB

Besides estimating the angle of arrivals, we estimated the relative amplitude and phase between the two signals. Using a 30-dB signal-to-noise ratio and a reflection coefficient magnitude of 0.9, the RMS error for  $|\rho|$  and  $\phi$  is shown in Figs. 6 and 7, respectively, for three angles of arrival. Again we find that the estimates are better for the more widely separated sources.

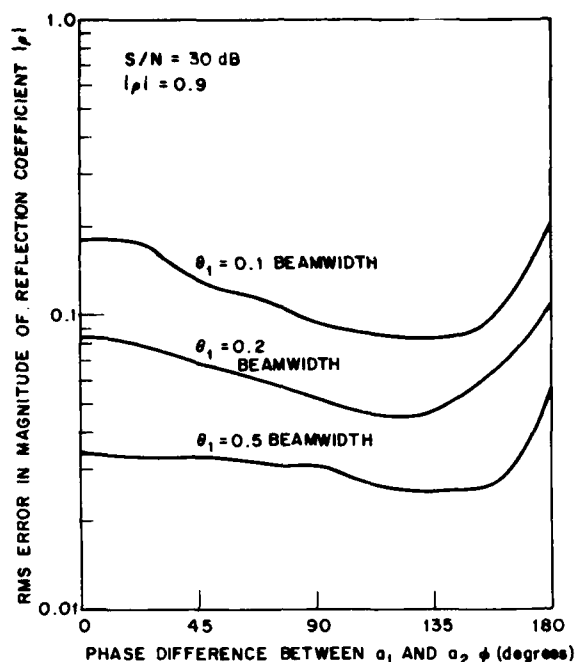


Fig. 6 — RMS error in the magnitude of the reflection coefficient for  $|\rho| = 0.9$  and  $S/N = 30$  dB

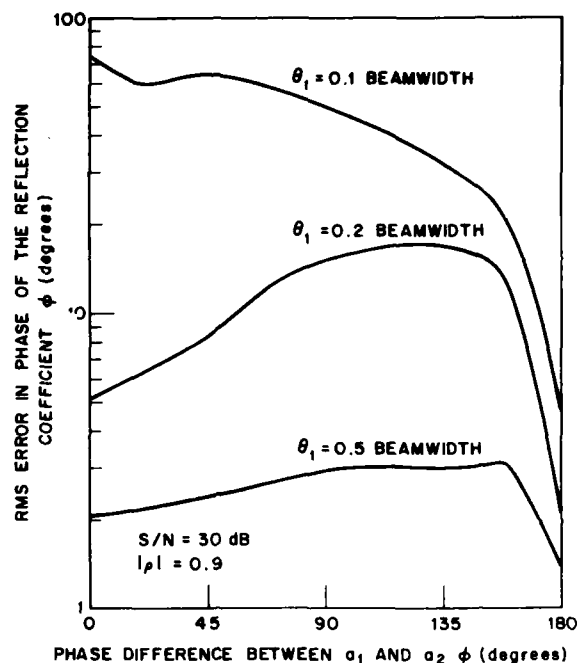


Fig. 7 — RMS error in the phase of the reflection coefficient for  $|\rho| = 0.9$  and  $S/N = 30$  dB

We next compare the performance of the MLE solution using three squinted beams to the Cramer-Rao bound results found in Ref. 3 and to the MLE solution using three subapertures [6]. This comparison is shown in Fig. 8, where a 30-dB signal-to-noise ratio,  $|\rho| = 0.9$ , and two different angles of arrival are used. We find the errors in the MLE solutions using either subaperture or squinted beams are not very different. Sometimes better results than predicted by the Cramer-Rao bound for unbiased estimators can be achieved with biased estimators than with unbiased ones. Although not shown, the estimates for  $|\rho|$  and  $\phi$  are about the same for the MLE estimates using subapertures [6] or using squinted beams as described in this paper.

## SUMMARY

The estimation of the angle of arrival of two closely spaced sources is studied using an antenna constructed to form three identical squinted beams. A simple closed-form solution for the angle of arrival is found under certain restrictions. The restrictions are that the center of the middle beam is directed toward the bisecting line between the targets and that the principal axes of the antenna are parallel to and perpendicular to the line connecting the targets. This condition can be obtained with an antenna viewing an emission or reflection over a smooth reflecting sea.

The accuracy of the estimates of the angle of arrival and the reflection coefficient was studied using simulation procedures. The best angle estimates, especially for reflection coefficients near 1, were obtained when the signals were in phase and the worst when the signals were out of phase. This can be explained by the high and low effective signal-to-noise ratios under these conditions. The results showed the estimates became better as the target separation increased. Finally, the MLE estimates for three squinted beams were comparable to the MLE estimates for three subapertures; only minor differences were noted.

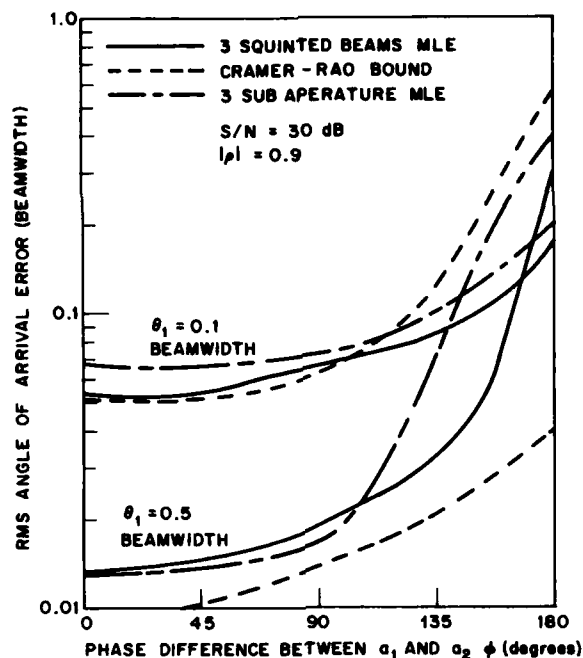


Fig. 8 — Comparison of RMS angle of arrival errors for  $|\rho| = 0.9$  and  $30 \text{ dB S/N}$

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