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MEASUREMENT AND ANALYSES OF ASR-4
SYSTEM ERROR. PART I. OVERVIEW

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National Aviation Facilities Experimental
Center
Atlantic City, New Jersey

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| 16. Abstract <p>The positional accuracy of aircraft radar targets as displayed in an air traffic control airport surveillance radar system (ASR-4) was sought as one of the inputs essential for determining aircraft separation standards. Using radar track input from the Atlantic City, New Jersey, ASR-4, the radar targets of two test aircraft executing flight patterns of varying relative spacing were photographed as displayed in both beacon and primary radar modes on scan-converted and PPI displays. The displayed positions were related to simultaneous precision track from single-target instrumentation radars (EAIR and TAIR) to derive error measures for range, azimuth, and separation. The extensive analysis program employed a "least-squares" analysis of variance. The data clearly demonstrated the strong interdependency of the individual components that contribute to radar system separation error. Further, it was noted that the tails of the distribution of the radar separation error response measure were not normally distributed.</p> <p>This Part I report presents a general, abbreviated, nontechnical description of a limited set of results to describe basic trends with maximum simplification; and it includes a minimum of statistical data. More detailed treatments of the large-sample, multidimensional, multivariate experimentations are presented in the associated reports, "Part II: Analyses" and "Part III: Summary."</p> | | | | | |
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PREFACE

Technical reporting of the measurements and analyses of ASR-4 terminal radar system error under Project 142-177-010 is organized into three parts. To facilitate independent or exclusive use of either report, each contains a sufficient description of methodology, data bank development, and the analyses which are reported.

PART I: OVERVIEW

This report is intended to present a general, nontechnical description of a limited set of the results which were developed in multivariate, multidimensional experiments using a large data sample. To achieve maximum clarity and simplify reader understanding of the overall effort, a very minimum of statistical data is presented in this report, and basic trends are described without expansion to describe or explain anomalies. More detailed treatments are presented in the associated reports.

PART II: ANALYSES

This is the main study, and it consists of three independent data collection programs and independent analyses. The report describes in detail the results of extensive data analysis and presents tables of summary statistical values for the two major data sets, which are categorized as "Phase I Data" and "Phase II Data."

PART III: SUMMARY

The summary is a compendium and consolidation of the numerous analyses and subsets of data appearing in the main report, "Part II: Analyses." To relieve the reader of nonsignificant differences that result in three independent studies on a common problem, all similar system response measures were pooled and combined into a single expression, and analysis of variance was then performed for the pooled expressions. The general effect is that the data thus becomes more homogeneous, and less subject to extraneous effects.

The extensive and complex nature of data collection and data analysis for these studies involved many participants whose individual contributions merit commendation, which can be made only generally. However, a few individuals must be specially cited.

We appreciate the direction and consultation provided by Mr. Walter Faison, for Systems Research and Development Service, and Mr. William Broadwater, Air Traffic Service, who largely developed the program's conceptual approach. We are very pleased to acknowledge the guidance and technical assistance of Dr. J. Stuart Hunter, of the Princeton University School of Engineering, for his painstaking and enthusiastic support in the statistical analysis and modeling effort.

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INTRODUCTION

At the request of Air Traffic Service (ATS), a study was conducted to determine quantitatively certain system error characteristics of an airport surveillance radar system (ASR). The measurements were specified to include the nominal operating environment of a "typical" terminal radar system up to the point of service, that is, the radar displays used in air traffic control. As a source of representative radar data, the Atlantic City ASR-4 was selected because of its proximity to precision tracking radar capability at the National Aviation Facilities Experimental Center (NAFEC) and because it was a field-operational radar currently in service.

CONTROL VARIABLES

The typical operating parameters for a terminal radar system were defined as being (1) a range extending from the radar main bang, or minimum range, to 50 nautical miles; (2) altitude from ground level to 20 thousand feet; (3) both raw radar and beacon, primary and secondary radar modes respectively; (4) all azimuths of the radar antenna; (5) two types of radar displays currently in use in the ATC system, PPI and RBDE; and (6) target aircraft pairs in angular proximity varying from 7 nautical miles apart down to loss of radar resolution when their radar targets merge.

RESPONSE VARIABLES

The primary responses of the radar system selected for investigation were (1) slant range error, (2) azimuth error, (3) position error, which is the vector derived from the range error and the azimuth error, and (4) relative separation error. Measures of these responses were to be used to provide a series of statistical estimates showing the effect of various operating parameters on the primary system response measures.

SYSTEM PERFORMANCE MEASURES

The basic measurement sought was the difference between the displayed aircraft range, azimuth, position, and separation, and the actual, or real, aircraft range, azimuth, position, and separation. These differences were considered to comprise the system errors.

PROJECT METHODOLOGY

To treat the system errors thus defined, it was necessary (1) to acquire an adequate data sample of displayed aircraft radar position, (2) to acquire a corresponding sample of aircraft true position, (3) to compute the statistical characteristics of the differences between them, that is, the displayed position minus the true position, and (4) to develop the population error parameter estimates relating to the six operating parameters.

DATA COLLECTION

To accomplish this, two aircraft, usually Grumman Gulfstreams, were flown in converging/diverging flight patterns on four radial courses from the radar antenna site separated by 90° , at four altitudes (20, 14, 8, and 3 thousand feet), and from about 45 nautical miles from the radar site to within 5 nautical miles of the radar antenna. These aircraft positions were monitored simultaneously by two precision-tracking instrumentation radars as well as by the ASR-4. Displays of the ASR-4 radar, in both radar modes, were photographed on a scan-by-scan basis, while simultaneously the precision-tracking radars acquired track data for a scan-by-scan determination of true aircraft position. The observation data from these three sources, and computed data of their relationships, then provided the basic data for analysis. There resulted about 30,000 observations for determining range, azimuth, and position error, and about 15,000 observations for determining separation error.

ANALYSIS

The analytical scheme employed here was an analysis of variance approach using each of the primary system response variables and all of their cross-correlation coefficients as responses for the analysis.

KEY RESULTS

The technical report, "Measurement and Analyses of ASR-4 System Error, Part II: Analyses," describes in detail the data collection and analysis methods and results. For purposes of discussion in this paper, a very minimum of statistical data is presented. This report is intended to present a general, non-technical summary of a limited set of the overall results; and as such, a few liberties are taken in explaining the results in an effort to achieve clarity.

Since the primary concern of this study has been the radar system error associated with two aircraft in geographical (lateral) proximity, only those response variables most directly impinging on radar separation error are herein presented.

Table 1 presents the mean and standard deviation of the range error, azimuth error, position error, and separation error as functions of their radar mode, that is, whether the targets were displayed as primary radar targets or as secondary radar targets. Furthermore, the table blocks the data according to whether the target was in range block 1 (from about 25 nautical miles to 5 nautical miles in range from the radar antenna site and center of the radar display) or in range block 2 (from about 45 nautical miles to 25 nautical miles in range from the radar antenna and display center).

TABLE 1. ESTIMATES OF THE RESPONSE PARAMETERS (IN NAUTICAL MILES)

| | <u>Primary Radar</u> | | <u>Secondary Radar</u> | |
|--------------------------|----------------------|----------------------|------------------------|----------------------|
| | <u>Range Block 1</u> | <u>Range Block 2</u> | <u>Range Block 1</u> | <u>Range Block 2</u> |
| Separation Error: | | | | |
| mean | .0387 | .0651 | .0470 | .1130 |
| s.d.* | .1249 | .1588 | .1526 | .2309 |
| Range Error: | | | | |
| mean | .0871 | .4684 | .0270 | .5148 |
| s.d.* | .2977 | .3143 | .3214 | .2970 |
| Azimuth Error: | | | | |
| mean | .0895 | .2967 | .0198 | .1272 |
| s.d.* | .1435 | .1764 | .1483 | .2126 |
| Position Error: | | | | |
| mean | .5083 | .9182 | .5414 | .9152 |
| s.d.* | .2902 | .4613 | .3219 | .4397 |

* = standard deviation

The analysis performed always subtracted the true estimate of the response parameter from the displayed estimate of the response parameter. Since all of the estimates presented in table 1 are positive values, this indicates that the displayed value was greater than the true value.

Figures 1, 2, 3, and 4 depict the estimates of mean range error, mean azimuth error, mean position error, and mean separation error and the 95-percent confidence intervals as a function of the range of the target, and categorized by primary radar and secondary radar respectively. These figures show the best estimate of the "true" range, azimuth, position, and separation of aircraft targets compared to their displayed positions. For example, in looking at figure 4a, "Separation Error (Primary Radar)," you see that the expected separation error when aircraft are, on the average, at a range of 15 nautical miles is .039 nautical miles, with the 95-percent confidence interval being between +0.284 to -0.206 nautical miles. Whereas, when the aircraft are on the average at a range of 35 nautical miles, the expected separation error is 0.065 nautical miles, with the 95-percent confidence interval being between +0.370 and -0.240 nautical miles.

Figure 5, labeled "Aircraft Separation," depicts the estimate of "given that two aircraft are displayed on an air traffic controller's radar display at 3 nautical miles apart, what is the best estimate of their true relative separation?" Generally, the scale on the ordinate (vertical axis) could be changed to center around 2 nautical miles or 4 nautical miles, rather than (as depicted) around 3 nautical miles, and the same relative relationship would exist. The "mean" line represents the best estimate of the true aircraft separation, given that the displayed separation was 3 nautical miles. The other two sets of lines indicate the 95-percent and 99-percent confidence intervals around that true position relative to the 3-nautical mile displayed position.

Figures 6 and 7 are presented to depict the relative position error of an aircraft as a function of range block 1 and range block 2. These graphic figures clearly show that the probable position error is not circular. This is due to the fact that range error and azimuth error are not independent of each other, and thus are correlated. This means that, as the absolute value of range error increased, the azimuth error had a significant tendency to increase also. The center of the ellipses was established as the mean range error and the mean azimuth error. The contours of the ellipses are the 95-percent and 99-percent confidence boundaries of the mean deviations of the range error and the azimuth error. The tilting of the ellipses is due to the fact that the scan-by-scan range error and azimuth error values were significantly correlated with each other.

The reader should be cautioned that these ellipses are representative of the described position error terms for a single aircraft, and are not appropriate for inferring any expected overlap of one adjacent aircraft on another, since that would involve a third and a fourth function not depicted here. The range error and azimuth error of two aircraft in proximity are also each correlated; however, graphic depiction of these functions would require a three-dimensional figure. The best estimate of the probable overlap, or separation error, should be gotten from figure 5, labeled "Aircraft Separation."

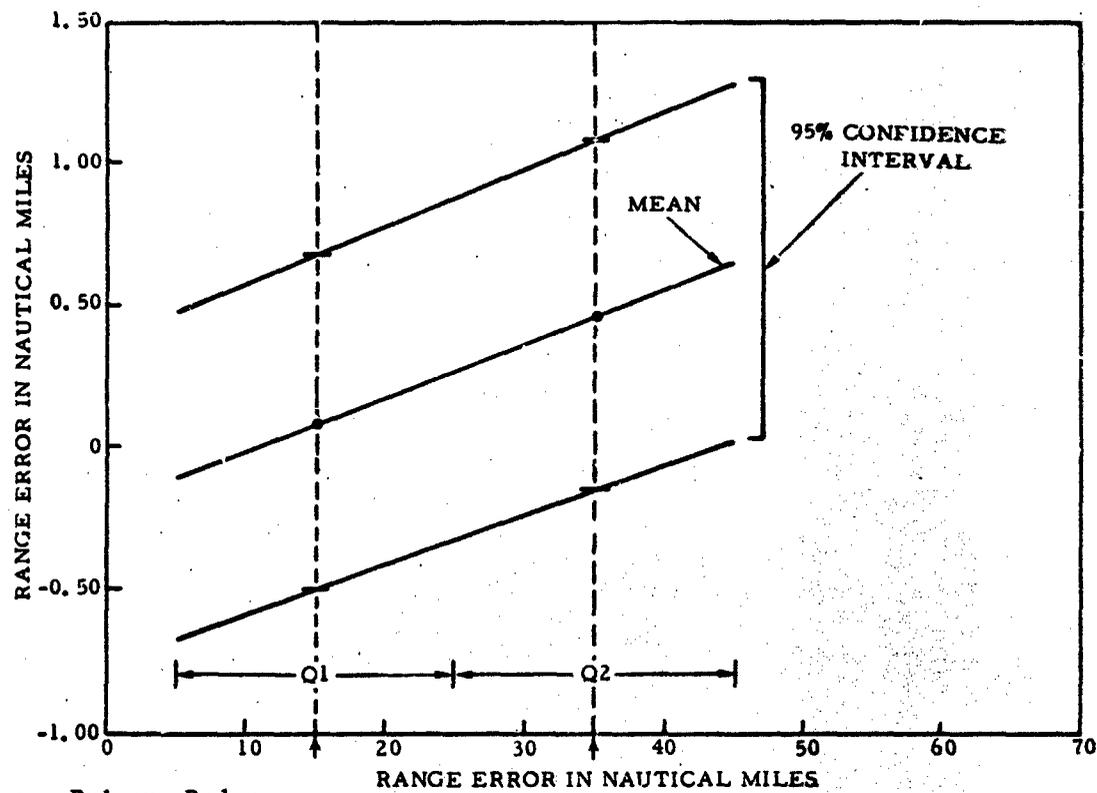
In general, there was no statistically significant difference between the numerical values presented for the primary radar and those presented for the secondary radar. That is to say, these two radar modes performed comparably as far as these positional errors were concerned. For illustrative purposes, the results for each of the radar modes are presented separately. If one were to compare the corresponding data in the table and the graphic presentations, the conclusion emerges that the absolute values vary between the radar modes; however, there is no statistically significant difference between the corresponding values and the graphed presentations for differing radar modes.

In general, and consistently throughout, there was a statistically significant difference between the magnitude of the estimates for range block 1 versus range block 2. In every case, the mean and standard deviation are smaller for range block 1, which was the range block closer to the radar antenna site and center of the display. In figures 6 and 7, the mean values for range block 1 and range block 2 are presented. The estimate of the standard deviation for that point on the graph was calculated, and then the 95-percent confidence interval was estimated and shown on the related graphs. These corresponding points were then connected with a straight line.

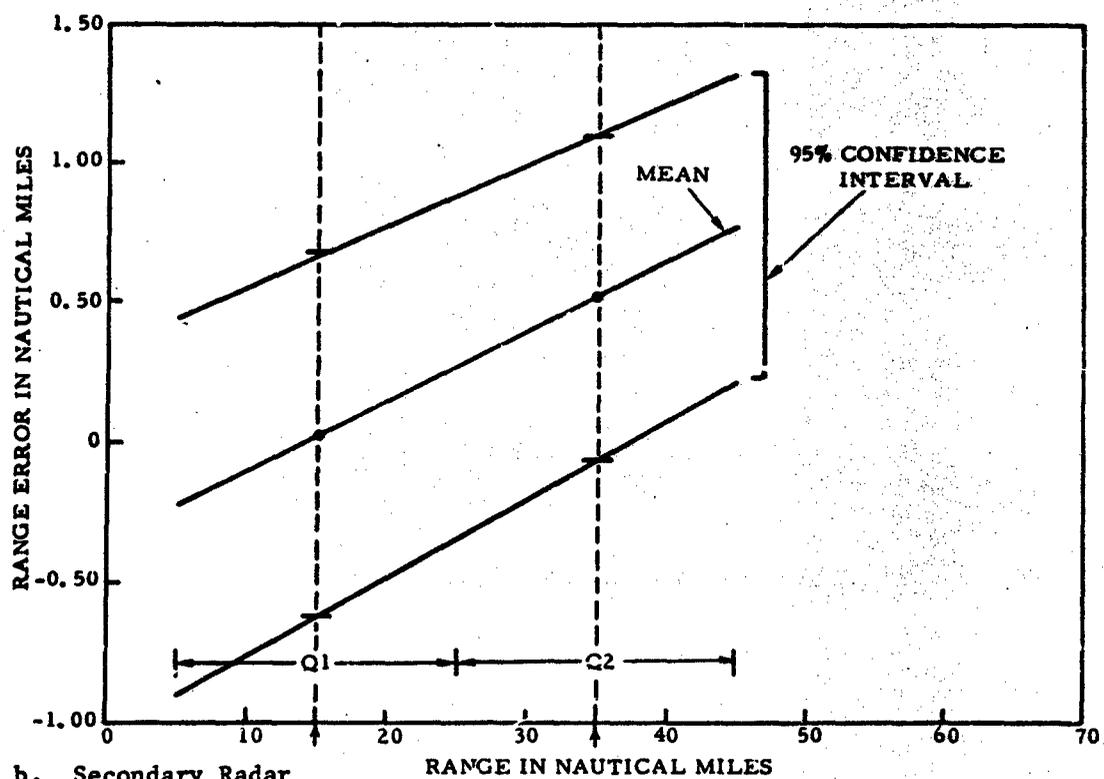
The resulting linearity of the presentation contributes to the clarity of the graphic message at the expense of minor departure, chiefly at each end of the plots, from strictures of precise data plotting. While the plot extends from 5 to 45 nautical miles in range from the radar antenna, a linear representation of the range, azimuth, position, and separation errors is supported by the subject data within a range from 10 to 40 nautical miles. Beyond these limits, both the mean and variance can be expected to depart significantly from a straight line, or linear projection.

Finally, NO extrapolation of these plots should be considered, since neither the data from this study nor the linearity exceeded the boundaries at 5 nautical miles and 45 nautical miles.

Assuming that the corresponding function is a linear function, the figures herein present a reasonable approximation of the data. What these graphic presentations show is the estimated mean error as a function of range from the radar antenna and center of the radar display, along with an estimate of the 95-percent confidence interval. This means that 95-percent of the time (95 times out of a hundred) you can expect the true value of (1) the range error, (2) the azimuth error, (3) the position error, or (4) the separation error to lie between the upper and lower lines in the figures. It is not a statistical or analytical question as to whether the magnitudes of these values are operationally significant.

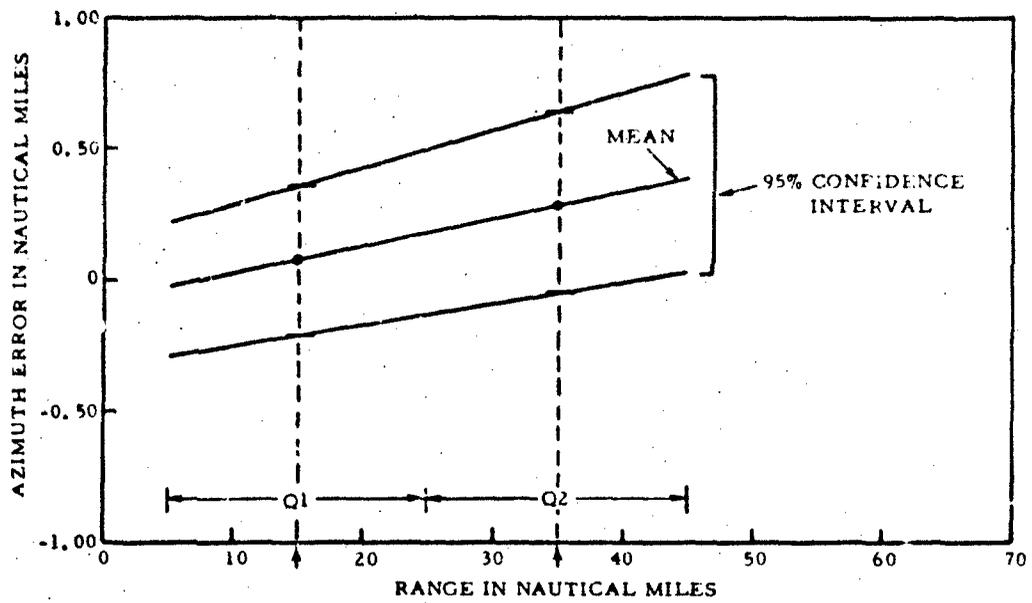


a. Primary Radar

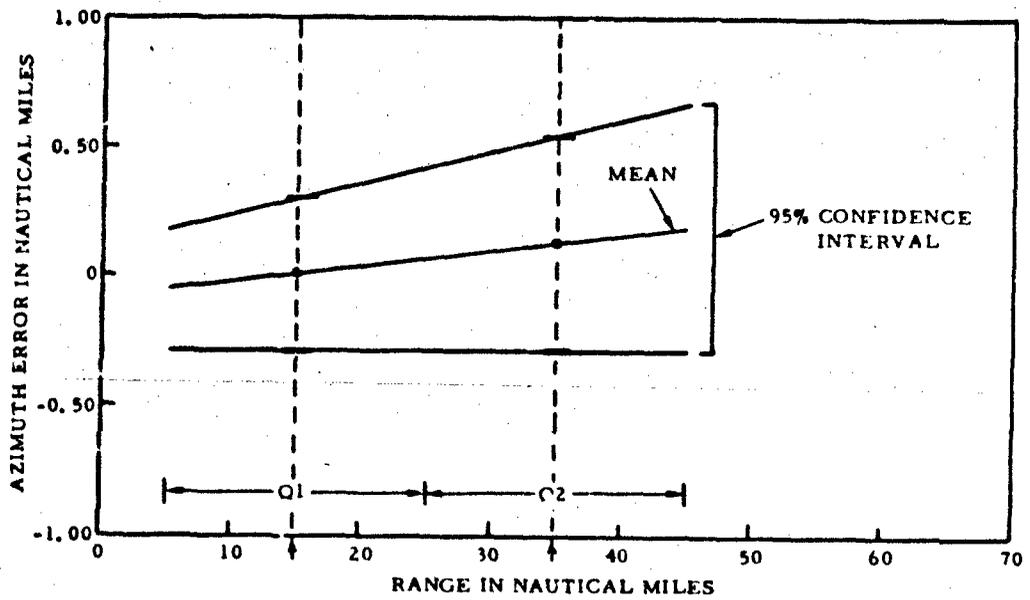


b. Secondary Radar

FIGURE 1. RANGE ERROR

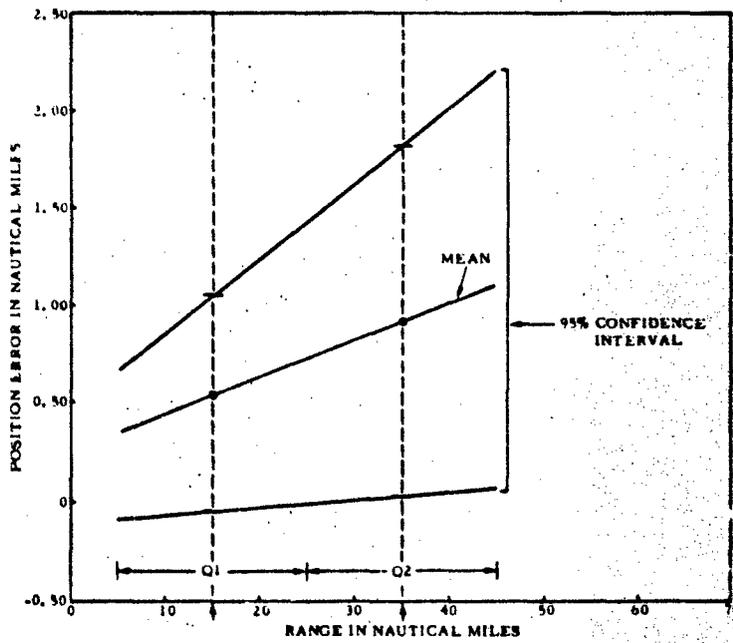


a. Primary Radar

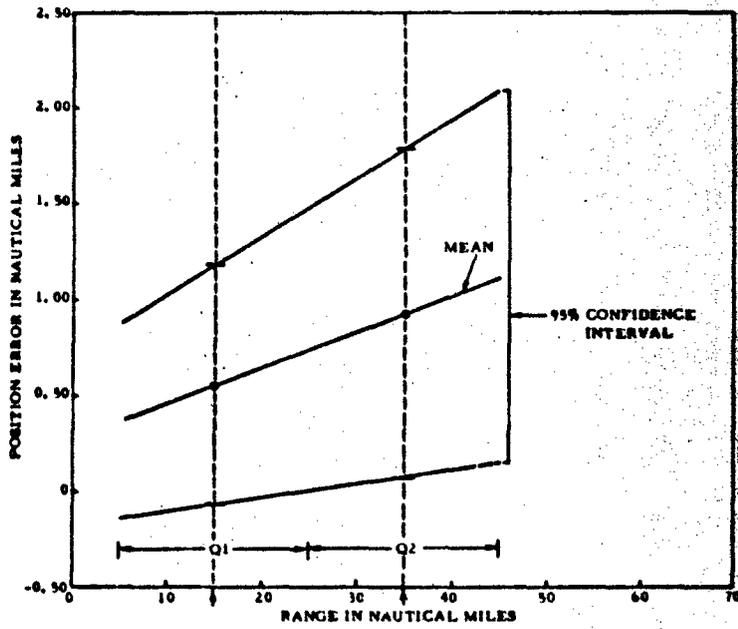


b. Secondary Radar

FIGURE 2. AZIMUTH ERROR

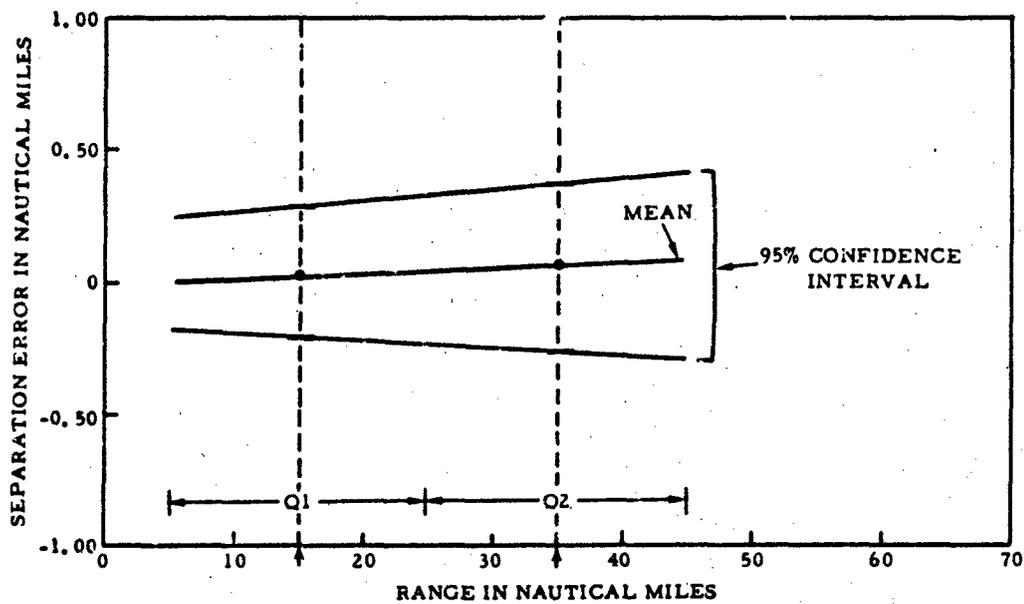


a. Primary Radar

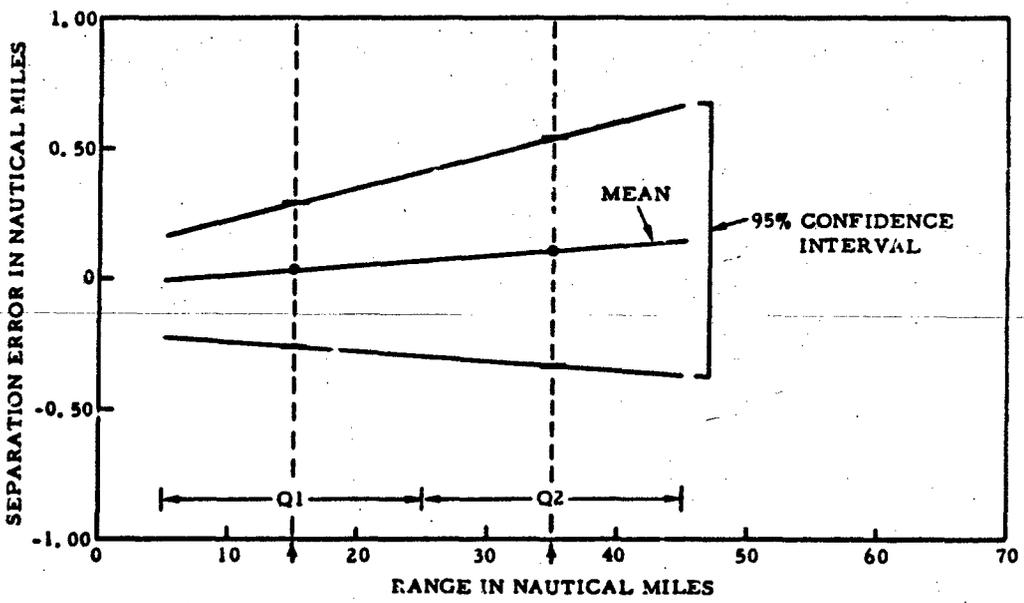


b. Secondary Radar

FIGURE 3. POSITION ERROR

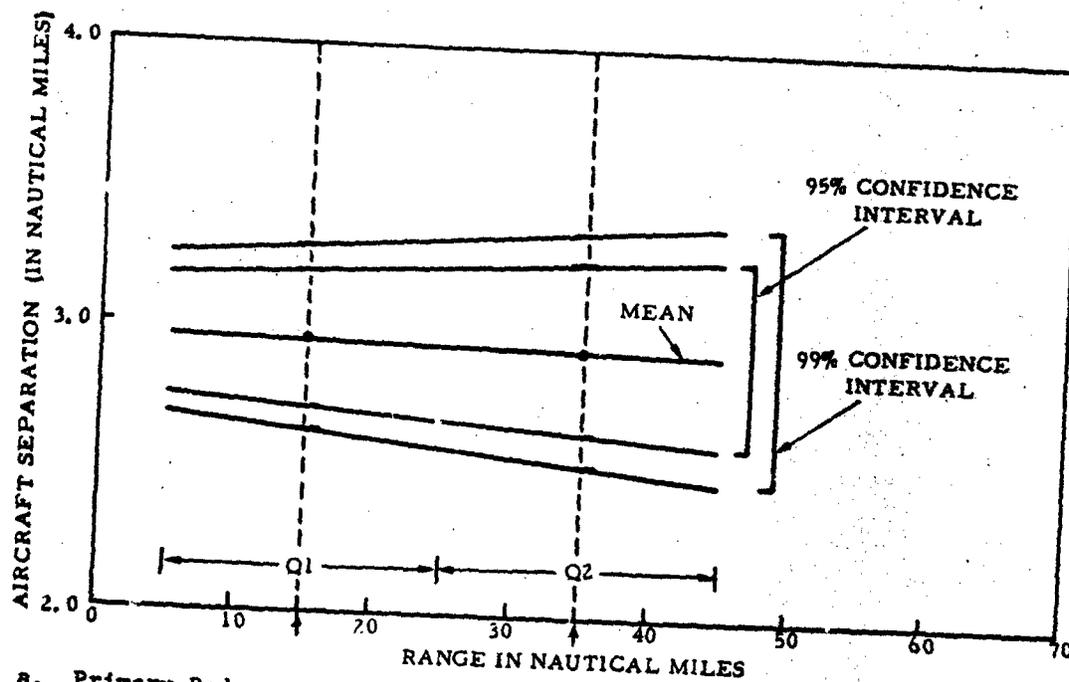


a. Primary Radar

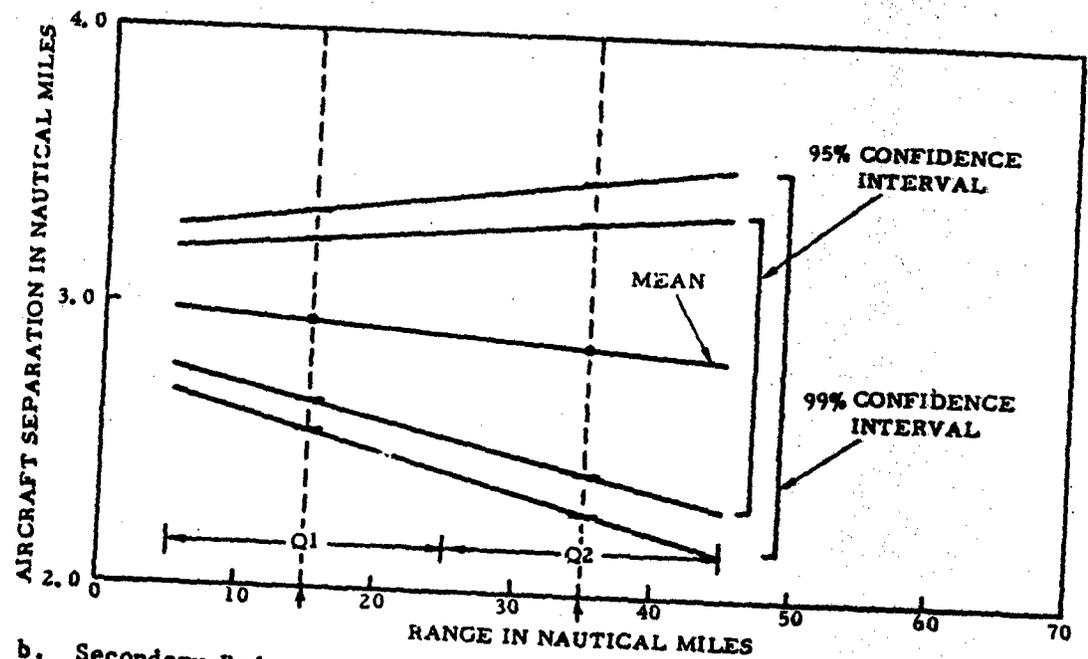


b. Secondary Radar

FIGURE 4. SEPARATION ERROR

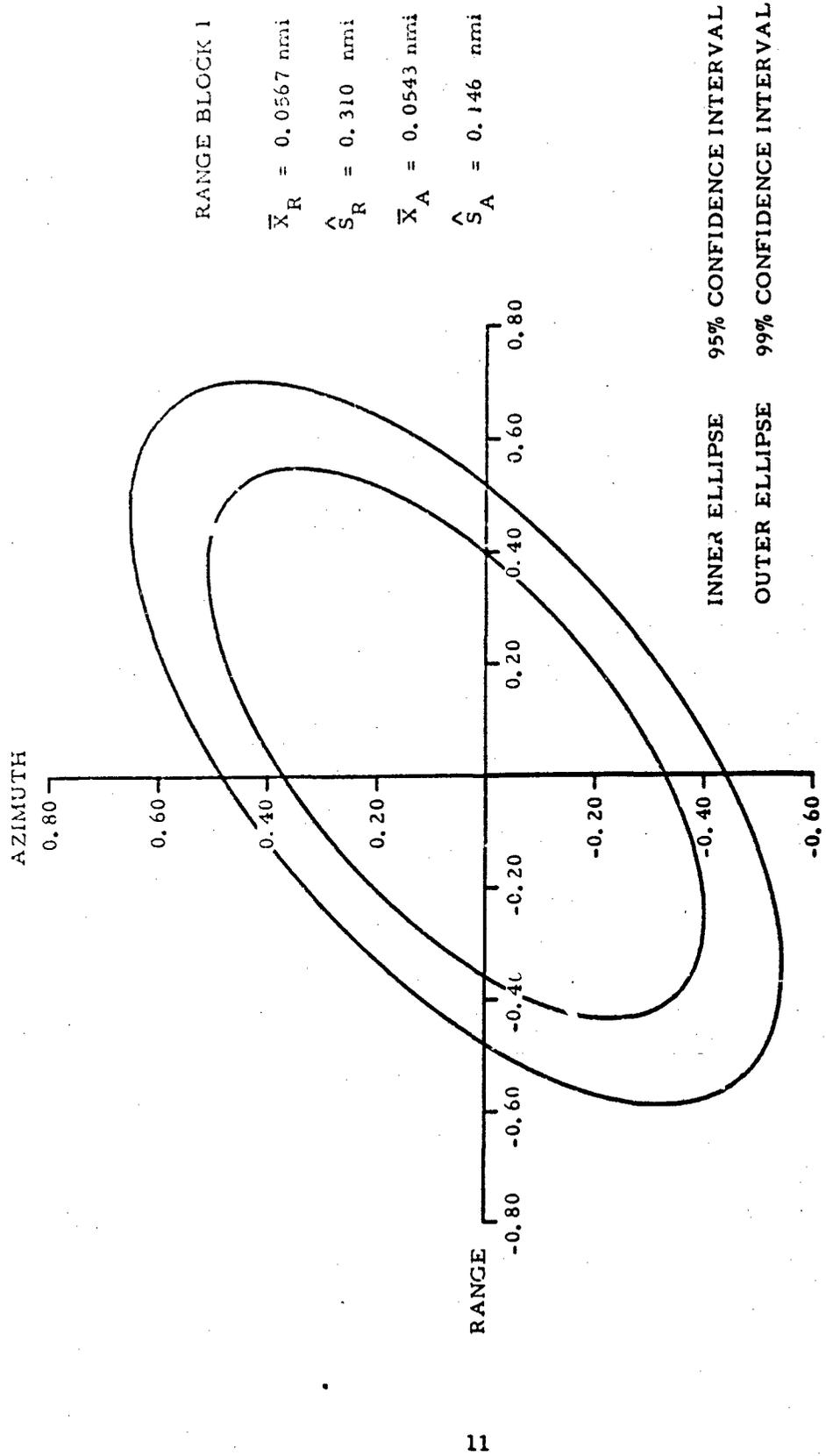


a. Primary Radar



b. Secondary Radar

FIGURE 5. AIRCRAFT SEPARATION



RANGE BLOCK 1

$$\bar{X}_R = 0.0567 \text{ nmi}$$

$$\hat{S}_R = 0.310 \text{ nmi}$$

$$\bar{X}_A = 0.0543 \text{ nmi}$$

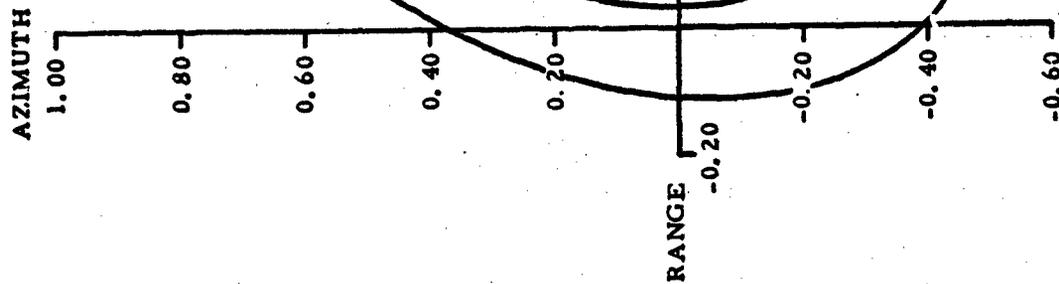
$$\hat{S}_A = 0.146 \text{ nmi}$$

INNER ELLIPSE 95% CONFIDENCE INTERVAL

OUTER ELLIPSE 99% CONFIDENCE INTERVAL

74-8-10

FIGURE 6. PROBABLE ERROR DISTRIBUTION FOR RELATIVE POSITION ERROR
 -- RANGE BLOCK 1



RANGE BLOCK 2

$$\bar{X}_R = 0.4907 \text{ nmi}$$

$$\hat{S}_R = 0.306 \text{ nmi}$$

$$\bar{X}_A = 0.2156 \text{ nmi}$$

$$\hat{S}_A = 0.195 \text{ nmi}$$

INNER ELLIPSE 95% CONFIDENCE INTERVAL
 OUTER ELLIPSE 99% CONFIDENCE INTERVAL

74-8-11

FIGURE 7. PROBABLE ERROR DISTRIBUTION FOR RELATIVE POSITION ERROR
 -- RANGE BLOCK 2