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AN ANALYSIS OF RADIO NAVIGATION SENSOR ACCURACIES ASSOCIATED WI--ETC(U)
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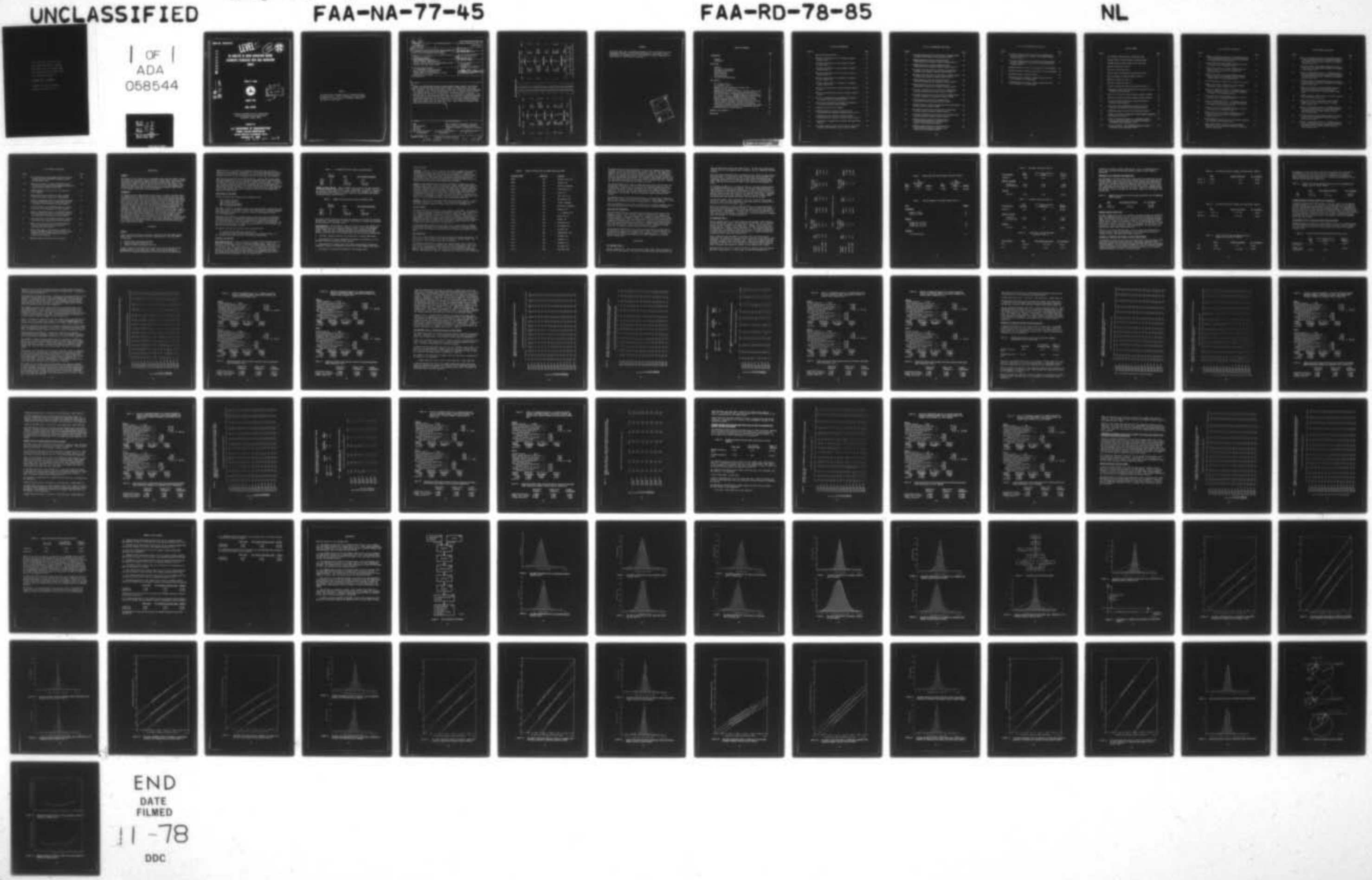

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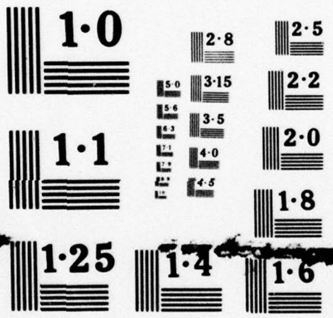
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Report No. FAA-RD-78-85

# AN ANALYSIS OF RADIO NAVIGATION SENSOR ACCURACIES ASSOCIATED WITH AREA NAVIGATION (RNAV)

Thomas V. Logue

AUGUST 1978

FINAL REPORT

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16. Abstract

Flight test data gathered during a series of RNAV flight tests, at the National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, New Jersey, are presented. The report concentrates on the radio navigation sensor errors and the resulting errors in position determination that are inherent in area navigation (RNAV) operation in the terminal area. Statistical data, as well as distributions of the errors, are presented. Also included is a comparison of the Advisory Circular 90-45A tangent point table calculated from regression equations. One standard deviation of 1.4 nautical miles for very high frequency omnidirectional radio range (VOR) and 0.11 nautical mile for distance measuring equipment (DME) were computed from the flight test data. These statistics represent combined ground and airborne sensor errors.

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# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

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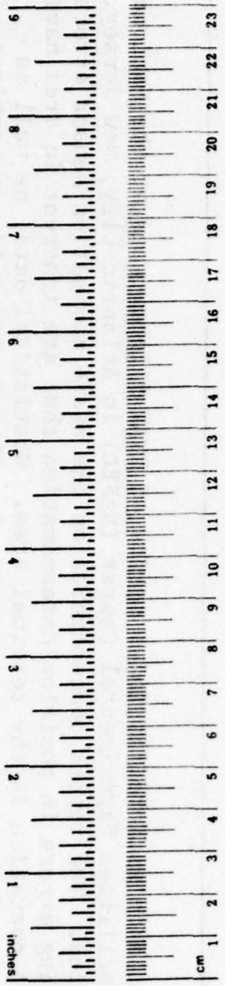
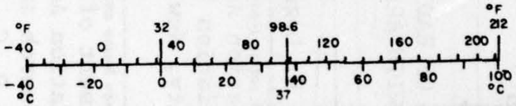
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



# PREFACE

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## INTRODUCTION

### PURPOSE.

The purpose of this project was to investigate area navigation (RNAV) concepts, procedures, and accuracies through a series of flight tests. The data derived may be used to establish minimum operational characteristics (MOC), and to determine the impact of RNAV on the air traffic control (ATC) system. This report concentrates on the raw sensor errors (i.e., very high frequency omnidirecional radio range (VOR) and distance measuring equipment (DME) errors) of air transport and general aviation equipment.

### BACKGROUND.

The Federal Aviation Administration (FAA) interest in RNAV is directed toward the implementation of RNAV routes and operational procedures that will permit navigation in any area within the radiation volume of ground-based VOR navigation facilities rather than only VOR inbound and outbound radial flight procedures as are now used in the present navigation system. In January 1972, the FAA sponsored an RNAV symposium which highlighted the major operational and technical problem areas that were affecting the immediate implementation and acceptance of RNAV. Based on the intense interest evidenced during the symposium, an FAA/Industry Task Force was established to define how to implement RNAV in the National Airspace System (NAS) in an orderly manner, while at the same time, identifying the payoffs to the ATC system and users. A report entitled "Application of Area Navigation in the National Airspace System" was published in February 1973 and defined the way in which RNAV would be implemented in the NAS. It also detailed an action plan which included substantial research and development efforts. This report responds to a portion of this action plan, and deals in detail with airborne VOR and DME radio sensor errors associated with RNAV.

## DISCUSSION

### GENERAL.

Flight tests were conducted using three commercially available RNAV systems which represent three distinct levels of sophistication. The three RNAV systems were:

1. Collins Radio Corporation--ANS-70A,
2. EDO Air Corporation--TCE-71A, and
3. FOSTER AIR DATA Incorporated--AD 611/D.

To date, reports on the flight tests utilizing the Collins ANS-70A and the FOSTER AIR DATA AD 611/D have been issued. These are, respectively, FAA-RD-76-32, "A Flight Investigation of System Accuracies and Operational

Capabilities of an Air Transport Navigation System," May 1976, by Robert H. Pursel and Jack D. Edmonds, and FAA-RD-77-43, "A Flight Investigation of System Accuracies and Operational Capabilities of a General Aviation Area Navigation System," June 1977, by Jack D. Edmonds, Robert H. Pursel, and John Gallagher.

Both the Collins ANS-70A and the EDO AIR TCE-71A represent RNAV systems which would find application in the air transport/commercial fleet, while the FOSTER AIR DATA AD 611/D could be classified as a general aviation system. Accordingly, air transport category airborne radio navigation sensors (VOR and DME) were used to provide position data to the Collins ANS-70A and the EDO AIR Corporation TCE-71A RNAV systems, while general aviation category airborne radio navigation sensors (VOR and DME) were used to provide position data to the FOSTER AIR DATA AD 611/D RNAV system.

## DESCRIPTION OF EQUIPMENT.

The air transport type airborne sensor equipments were:

VOR 1--Collins 51RV-2B
VOR 2--Bendix RNA-26C
DME 1--Collins Radio 860E-3
DME 2--King Radio KDM-7000

Both DME's conform to Aeronautical Radio Incorporated (ARINC) characteristic 568. The analog outputs of the DME's provided range information to the RNAV equipment, while the digital outputs were routed to a digital instrumentation system for recording purposes.

Both VOR's were modified to provide continuous bearing-to-station information. The modification was a standard field modification to provide four-wire sine-cosine bearing outputs. Work was accomplished per Collins Service Bulletin No. 22 for the 51RV-2B and per Bendix Mod. 6 (preliminary) for the RNA-26C. The sine-cosine bearing outputs provided bearing information to both the RNAV equipment and the instrumentation system.

The general aviation type airborne sensor equipments were:

(1) Collins VIR-30 (VOR)--Dual installation.
(2) King KN-65 (DME)--modified with range block interface adapter as per AIR DATA Installation Bulletin IB-73006--Dual installation.

## EQUIPMENT CALIBRATIONS.

AIR TRANSPORT QUALITY. Prior to the start of flight tests, both VOR's and both DME's were calibrated to establish airborne equipment errors. VOR's were checked at 30° intervals from 0° to 330° with a radiofrequency (RF) input level of 100 microvolts. DME's were checked at 5 nautical mile (nmi) intervals from 0 to 150 nmi. Table 1 summarizes the results. No correction factors were applied to the data because the checks indicated the equipments were within the manufacturers' specifications and therefore represented typical errors in VOR and DME airborne equipment of the air transport type.

TABLE 1. AIR TRANSPORT QUALITY SENSOR CALIBRATION DATA

| | No. of Samples | Mean | One Standard Deviation |
|---|---|---|---|
| VOR 1 | 12 | -0.2° | 0.4° |
| VOR 2 | 12 | 0.04° | 0.3° |
| DME 1 | 31 | 0.01 nmi | 0.02 nmi |
| DME 2 | 31 | -0.06 nmi | 0.02 nmi |

**GENERAL AVIATION QUALITY.** VOR's and DME's were checked at the same intervals as the air transport type sensors. Table 2 summarizes the results. As with the air transport type sensors, no correction factors were applied to the general aviation sensor data because the checks indicated the equipments were within the manufacturers' specifications.

TABLE 2. GENERAL AVIATION QUALITY SENSOR CALIBRATION DATA

| | No. of Samples | Mean | One Standard Deviation |
|---|---|---|---|
| VOR 1 | 12 | -0.4° | 0.2° |
| VOR 2 | 12 | -0.3° | 0.2° |
| DME 1 | 31 | 0.004 nmi | 0.004 nmi |
| DME 2 | 31 | 0.006 nmi | 0.007 nmi |

Once these initial checks were made and all sensors were verified to be within manufacturers' specifications, no further calibrations or checks were performed for the duration of the flight tests.

**TEST OBJECTIVES.** The objectives of each of the flight tests were defined and identified in each of the reports published to date. One of the objectives in each flight test was to quantify the sensor error associated with RNAV flight. Since this report deals specifically with the sensor error data derived from those tests, the following areas were given careful consideration:

1. The mean, standard deviation, and distribution of VOR and DME errors.

2. The accuracies of the two categories of navigation receivers; i.e., air transport quality and general aviation quality.

3. The generation of tangent point (TP) tables from measured errors and a comparison of these to the Advisory Circular (AC) 90-45A tangent point table.

4. The effects of altitude and distance on VOR and DME errors.

## DATA COLLECTION

AIRBORNE. A mixture of analog, digital, and discrete signals was recorded on time-referenced, seven-track 200 bit per inch (bpi) digital incremental recorders at a 2-hertz (Hz) rate throughout the flights. A complete list of the parameters recorded is presented in reports FAA-RD-76-32, FAA-RD-76-113, and FAA-RD-77-43. The signals were conditioned and multiplexed by data acquisition systems. All of the systems were designed and fabricated at the National Aviation Facilities Experimental Center (NAFEC).

GROUND. Ground-based data were obtained from NAFEC's Extended Area Instrumentation Radar (EAIR). EAIR is a precision, C-band tracking radar which has a maximum tracking distance of 190 nmi when operated in the beacon tracking mode (all flights were tracked in beacon tracking mode). Digital output data consisting of slant range, azimuth angle, elevation angle, and realtime are recorded on magnetic tape at a 10-Hz rate. Analog track data in z-y, x-y coordinates are recorded in realtime on 30-inch plot paper. Accuracy of the system is 0.2 milliradian in azimuth and elevation and a root-mean-square (rms) range error not exceeding 20 yards at 3,000 yard/second range rate.

OBSERVER. Observer data logs were used by the flight test observer to record information pertinent to the flight. The observer also monitored the data acquisition display during the flights and recorded any abnormalities.

## FLIGHT PATTERNS.

All flight tests were conducted in local airspace around NAFEC. The majority of routes were designed by Champlain Technology Industries. The routes consist of a standard instrument departure (SID) and a standard terminal arrival route (STAR) which were connected by a transition segment. Three basic routes were modified slightly for each of the tests, but the routes retained basic commonality for all the flight tests as well as for simulation tests conducted using the NAFEC Digital Simulator Facility (DSF). These patterns are fully documented in reports FAA-RD-76-32 and FAA-RD-77-43.

By utilizing these patterns for the flight tests, a large number of VOR/DME stations were available for providing sensor information to the RNAV systems. Table 3 lists the stations that were used for the sensor data analyzed in this report.

## DATA PROCESSING.

Figure 1 is a block diagram of the general aviation processing procedures. The air transport quality sensor errors are processed in a similar manner. The following is a brief description of the flow diagram.

The EAIR data tapes (B) are a seven-track, 556-bpi format tape of actual aircraft position in latitude, longitude, and altitude referenced to time. This tape is then time-merged every 0.5 seconds with the airborne data tape (A), which is also time referenced. The result is a time-correlated, nine-track, 800-bpi, time-merged data tape (C) containing both airborne and EAIR information.

## TABLE 3. VOR/DME STATIONS USED IN SENSOR ERROR DATA BASE

| Frequency (MHz) | Identifier | Location |
|---|---|---|
| 108.6 | ACY | Atlantic City, N.J. |
| 108.2 | ARD | Yardley, Pa. |
| 112.6 | ATR | Waterloo, Delaware |
| 115.4 | COL | Colts Neck, N.J. |
| 113.4 | CYN | Coyle, N.J. |
| 111.2 | DPK | Deer Park, N.Y. |
| 117.9 | EMI | Westminster, Md. |
| 111.4 | ENO | Kenton, Delaware |
| 114.0 | EWT | New Castle, Delaware |
| 113.6 | HTO | Hampton, N.Y. |
| 115.9 | JFK | J. F. Kennedy, N.Y. |
| 115.2 | MIV | Millville, N.J. |
| 113.2 | MXE | Modena, Pa. |
| 112.8 | OOD | Woodstown, N.J. |
| 113.7 | OTT | Nottingham, Md. |
| 117.6 | PXT | Patuxent, Md. |
| 113.8 | RBV | Robbinsville, N.J. |
| 114.1 | RIC | Richmond, Va. |
| 112.9 | SBJ | Solberg, N.J. |
| 114.5 | SBY | Salisbury, Md. |
| 114.8 | SIE | Sea Isle, N.J. |
| 112.4 | SWL | Snow Hill, Md. |

The merged tapes were then examined by the search (D) program which checked pertinent aircraft parameters and flags, defined start and stop times for the segments, and recorded any detected changes on a printout. The information garnered from the search program along with the merged tapes constituted the input to the parameter tape program. The parameter tape program calculates all the error values from the raw data. The parameter tapes contain all data plus all calculated error values in increments of 0.1 nmi along the route. Information may then be recovered from any point on the run.

The outlier program (F) is used to remove any gross errors that may have been precipitated by glitches in the data collection equipment and/or the radar tracking data. Gross errors are defined as any error magnitude greater than 1 nmi for DME and 10° for VOR. The histograms justify using these error magnitudes, as VOR and DME 3-sigma values are ±5° and ±0.5 nmi, respectively. The parameter outlier (POL) (G) are the parameter tapes with gross errors removed.

The VOR/DME tapes (H) contain the sensor errors which have been stripped from the POL tapes. DME error is defined as: DME Error = Sensed Range - Actual Range. VOR Error is defined as: VOR Error = Sensed Bearing - Actual Bearing.

Once the VOR/DME errors have been stripped from the outliered parameter tapes, the resulting tapes can be used for all subsequent statistical processing.

## DATA ANALYSIS METHODOLOGY.

Since the sensor data were derived from three separate flight tests, it was decided to treat the data from each flight test separately to determine if differences exist. Also, the data from each flight test were further classified according to the phase of flight; i.e., terminal, approach, and enroute. A further separation of the data was dictated by the fact that there were two categories of sensors used for the tests, air transport and general aviation. The data analysis methodology was therefore to compute means, standard deviations, and distributions of the data in these specific categories; examine them; and, if possible, combine these data across categories.

For purposes of identification, the data associated with the Collins ANS-70 flights will be known as air transport test I, while the data associated with the EDO TCE-71A flights will be known as air transport test II. The data associated with the Foster AIR DATA AD 611/D RNAV flights will be known as general aviation data.

# TEST RESULTS

## AIR TRANSPORT TEST I.

The air transport test I data were collected during flight tests utilizing the Collins ANS-70 RNAV system. Two VOR'S and two DME's were used during this test since the ANS-70 can utilize dual sensor inputs. The data were classified as terminal area data with approach data included in the 0 to 5,000-foot altitude interval.

Means and standard deviations were calculated for each sensor in each of three altitude bands; 0 to 5,000 feet, 5,000 to 10,000 feet, and above 10,000 feet. The purpose was to examine the data for receiver biases and determine any significant difference in the errors associated with the different altitude bands. DME data are presented in table 4, while VOR data are presented in table 5.

In examining the DME data, it can be seen that for the same altitude interval, the standard deviations are very similar, and the differences approach the range resolution of the airborne DME sensor (0.01 nmi). Within the same altitude interval, the differences in means indicate the small bias error on the number 2 receiver, which was evident in the equipment calibration. Examining the DME data across the three altitude intervals, a slight tendency toward increasing means and standard deviations with altitude can be seen.

The VOR data exhibit similar uniformity across both receivers and altitude intervals. There are some differences in the means which are attributable to the bias errors of the individual stations.

Based on the uniformity of both the DME and VOR data, the data were pooled both across receivers and altitude intervals. Table 6 presents the results of the pooled data. Histograms of the pooled DME and VOR data are presented in figures 2 and 3, respectively. A normal curve is fitted to the data in each case. Each of the discriptions is leptokurtic, since they exhibit a relatively high peak compared to a normal distribution.

## AIR TRANSPORT TEST II.

The air transport test II data were collected during flight tests utilizing the EDO TCE-71A RNAV system. Only one VOR and one DME were used on this test because the TCE-71A accepts only single-sensor inputs. Data in this group include approach, terminal, and enroute data. SID/STAR configurations were incorporated into a flight pattern, designated A2. This pattern, along with its variations, is explained in detail in the report "A Flight Investigation of System Accuracies and Operational Capabilities of a General Aviation Area Navigation System," report No. FAA-RD-77-43.

Table 7 shows the type and number of patterns flown, and tables 8 and 9 demonstrate the results with mean and standard deviations of the specific data categories. As with the air transport test I data, both the DME and the VOR data show uniformity across data categories. Comparing the DME and VOR data across test I and test II, it can be seen that the data are nearly identical. Table 10 presents the statistical summary for the combined test II data.

Distributions for the test II data are plotted in figures 4 and 5 for VOR and DME error, respectively. As can be seen, the DME data distribution is

TABLE 4. DME ERROR STATISTICS--TEST I

| Altitude (feet) | Mean (nmi) | DME 1 Sensor One Standard Deviation (nmi) | Samples | Mean (nmi) | DME 2 Sensor One Standard Deviation (nmi) | Samples |
|---|---|---|---|---|---|---|
| 0-5,000 | -0.05 | 0.07 | 13,295 | -0.09 | 0.06 | 12,855 |
| 5,000-10,000 | -0.05 | 0.07 | 25,051 | -0.09 | 0.08 | 24,476 |
| Above 10,000 | -0.09 | 0.11 | 46,006 | -0.14 | 0.09 | 37,117 |

TABLE 5. VOR ERROR STATISTICS--TEST I

| Altitude (feet) | Mean (deg) | VOR 1 Sensor One Standard Deviation (deg) | Samples | Mean (deg) | VOR 2 Sensor One Standard Deviation (deg) | Samples |
|---|---|---|---|---|---|---|
| 0-5,000 | -0.3 | 1.4 | 4,451 | 0.3 | 1.6 | 4,380 |
| 5,000-10,000 | 0.2 | 1.3 | 11,726 | 0.4 | 1.3 | 11,488 |
| Above 10,000 | -0.3 | 1.4 | 26,937 | 0.1 | 1.6 | 20,302 |

TABLE 6. POOLED TOTAL VOR AND DME ERROR STATISTICS--TEST I

| VOR | | | DME | | |
|---|---|---|---|---|---|
| Mean (deg) | One Standard Deviation (deg) | Samples | Mean (nmi) | One Standard Deviation (nmi) | Samples |
| 0.01 | 1.5 | 79,284 | -0.092 | 0.094 | 158,800 |

TABLE 7. TYPE AND NUMBER OF PATTERNS FLOWN IN TEST II

| Type | Number |
|---|---|
| APPROACHES | |
| Runway 4, NAFEC | 31 |
| Runway 13, NAFEC | 31 |
| ENROUTE | |
| 10,000 feet altitude | 6 |
| 20,000 feet altitude | 9 |
| 25,000 feet altitude | 9 |
| TERMINAL | |
| SID-STAR Patterns | 31 |

TABLE 8. DME ERROR STATISTICS--TEST II

| Data Category | Mean (nmi) | One Standard Deviation (nmi) | No. of Samples |
|---|---|---|---|
| APPROACH | -0.007 | 0.12 | 10,552 |
| ENROUTE ALTITUDE | | | |
| 10,000 feet | -0.09 | 0.08 | 3,990 |
| 20-25,000 feet | -0.14 | 0.16 | 12,849 |
| TERMINAL | | | |
| SID-STAR | -0.05 | 0.08 | 29,983 |

TABLE 9. VOR ERROR STATISTICS--TEST II

| Data Category | Mean (degrees) | One Standard Deviation (degrees) | No. of Samples |
|---|---|---|---|
| APPROACH | -0.38 | 1.5 | 10,649 |
| ENROUTE ALTITUDE | | | |
| 10,000 feet | -1.07 | 1.01 | 4,018 |
| 20-25,000 feet | -0.77 | 1.6 | 13,026 |
| TERMINAL | | | |
| SID-STAR | -0.89 | 1.7 | 29,983 |

TABLE 10. POOLED TOTAL DME AND VOR ERROR STATISTICS--TEST II

| Data Category | Mean | One Standard Deviation | No. of Samples |
|---|---|---|---|
| DME | -0.06 nmi | 0.12 nmi | 57,374 |
| VOR | -0.78° | 1.62° | 57,676 |

leptokurtic and shows a slight negative bias. This is consistent with the test I data. The VOR data are also slightly biased, but only slightly leptokurtic.

## SUMMATION OF AIR TRANSPORT TYPE SENSOR DATA.

The histograms of the VOR and DME error distributions associated with the two separate flight tests where air transport quality sensors were used show that the data exhibit similar uniformity and all distributions tend toward being leptokurtic. Likewise, statistical similarity exists between the two sets of data. Therefore, the data from these two tests were pooled. Figure 6 shows the combined DME error distribution, and figure 7 shows the combined VOR error distribution. Table 11 provides the statistical summary for the combined VOR and DME data.

TABLE 11. SUMMATION OF POOLED VOR AND DME ERROR STATISTICS FOR AIR TRANSPORT QUALITY SENSORS

| | Mean | One Standard Deviation | No. of Samples |
|---|---|---|---|
| VOR | -0.3° | 1.5° | 136,960 |
| DME | -0.08 nmi | 0.1 nmi | 216,174 |

## GENERAL AVIATION SENSOR DATA.

All data flights were in the 0 to 5,000 feet altitude interval and, therefore, would be considered terminal area data with approaches included in the data. Again, VOR and DME errors were used to calculate mean and standard deviations. Tables 12 and 13 show the statistical results of the individual VOR and DME sensor errors. Based on the uniformity of both the VOR and DME data, the data were pooled across the receivers. Table 14 enumerates the statistics for the pooled data. Figure 8 shows the pooled VOR histogram. As can be seen, the distribution tends toward being leptokurtic.

Figure 9 is the pooled DME histogram. As can be seen, the distribution is almost Gaussian. This contrasts markedly to the distributions of the air transport quality DME sensors which were leptokurtic.

## COMBINED AIR TRANSPORT AND GENERAL AVIATION SENSOR ERRORS.

A comparison of tables 11 and 14 for the statistical results of the air transport type and general aviation type data, respectively, indicates almost identical results. The one marked difference between these data is the shape of the distribution of the two types of DME data. The air transport type data exhibits a leptokurtic distribution, while the distribution for the general aviation DME sensor error data is nearly Gaussian.

TABLE 12. VOR ERROR STATISTICS--GENERAL AVIATION QUALITY SENSORS

| | Mean | Standard Deviation | No. of Samples |
|---|---|---|---|
| VOR No. 1 | 0.004° | 1.0° | 38,003 |
| VOR No. 2 | 0.12° | 1.15° | 38,339 |

TABLE 13. DME ERROR STATISTICS--GENERAL AVIATION QUALITY SENSORS

| | Mean | Standard Deviation | No. of Samples |
|---|---|---|---|
| DME No. 1 | -0.017 nmi | 0.121 nmi | 38,452 |
| DME No. 2 | -0.043 nmi | 0.151 nmi | 39,305 |

TABLE 14. POOLED TOTAL VOR AND DME ERROR STATISTICS--GENERAL AVIATION QUALITY SENSORS

| | Mean | Standard Deviation | No. of Samples |
|---|---|---|---|
| VOR | 0.06° | 1.1° | 76,342 |
| DME | -0.03 nmi | 0.14 nmi | 76,757 |

Nevertheless, in the real world, both types of equipment will be present in an intermix, and therefore the data will be combined in this analysis. Table 15 presents the statistical data for the combined air transport and general aviation data, and figures 10 and 11 present the distribution for the combined VOR and DME data, respectively.

TABLE 15. POOLED TOTAL VOR AND DME ERROR STATISTICS FOR AIR TRANSPORT AND GENERAL AVIATION QUALITY SENSORS

| | Mean | One Standard Deviation | No. of Samples |
|---|---|---|---|
| VOR | -0.17° | 1.4° | 213,302 |
| DME | -0.07 nmi | 0.11 nmi | 292,951 |

## VOR/DME NAVIGATION SOLUTION ERRORS AND DISTRIBUTIONS.

A latitude/longitude positional solution, as derived solely from the measured VOR/DME information (i.e., not processed by the RNAV computer), was compared with the latitude/longitude information supplied by EAIR. The resulting error was then resolved into crosstrack and along-track components. Statistical computations were done on these components to determine sensor error distributions. Figure 12 shows the navigation solutions flow diagram. These data were processed in a manner similar to the sensor error data, with the navigation solutions associated with each individual flight test examined, first on an individual basis, and then combined.

## AIR TRANSPORT TEST I, VOR/DME NAVIGATION SOLUTION ERRORS.

VOR/DME navigation solution errors were computed from the data collected during the first flight tests using air transport quality sensors. Table 16 enumerates the statistical results for both crosstrack and along-track navigation solution errors.

TABLE 16. VOR/DME NAVIGATION SOLUTION ERROR STATISTICS--TEST I

| | Mean (nmi) | One Standard Deviation (nmi) | Number of Samples |
|---|---|---|---|
| VOR/DME Crosstrack Error | 0.030 | 0.940 | 84,672 |
| VOR/DME Along-track Error | - 0.078 | 0.788 | 84,672 |

Figures 13 and 14 present the distributions for VOR/DME navigation solution errors for crosstrack and along-track conditions, respectively. Distributions in both cases are leptokurtic.

Since VOR error is angular in nature. Crosstrack and along-track errors in any navigation solution where VOR is used are dependent upon distance from the station. A convenient method to show this relationship is the FAA Advisory Circular 90-45A "tangent point table," in which VOR/DME navigation system errors are broken out as a function of perpendicular tangent point distance (TPD) and along-track distance (ATD) (figure 15).

The VOR/DME navigational error data obtained from these RNAV flight tests were organized into intervals defined by the tangent point distance and the along-track distance. This table includes both terminal and enroute data collected on these flights. Two-sigma (2 standard deviation) values for crosstrack and along-track errors were then calculated from the data entered into an error table of measured 2-sigma accuracies (table 17).

Table 17 is similar in structure to the error tables used in Advisory Circular 90-45A. The values, however, are based on the measured VOR/DME positional errors and do not include flight technical error (FTE) or RNAV computer error.

There are considerable data missing (indicated by dashes) at the longer tangent point and along-track distances. In an attempt to extrapolate and refine this table, a stepwise multiple regression was run on the data contained in table 17.

Stepwise multiple regression is a statistical technique for analyzing a relationship between a dependent variable and a set of independent variables, and for selecting the independent variables in the order of their importance.

The dependent variable was the 2-sigma value for crosstrack or along-track sensor error, while the independent variables were the tangent point distance and the along-track distance. Tangent point distance is defined as a perpendicular line from the route to the subject VOR/DME ground station (VORTAC) (figure 15). The point where the line intercepts the route is the tangent point.

The results of the regression for the 2-sigma crosstrack values are presented in table 18, while the resulting correlation matrix is presented in table 19. As can be seen, along-track distance contributes the largest proportion to the 2-sigma crosstrack error. The contribution of the tangent point distance is very negligible. The resulting equation: 2-sigma crosstrack error = -0.187 nmi + 0.044 (ATD) nmi + 0.002 (TPD) nmi, describes the 2-sigma crosstrack error with a standard error of estimate of 0.832 nmi.

The results for the 2-sigma along-track regression are similarly presented in table 20, while the resulting correlation matrix is presented in table 21. In this regression, the tangent point distance contributes the largest source of error, while the along-track distance contribution is nearly negligible. The resulting equation: 2-sigma along-track error = 0.551 nmi + 0.066 (TPD) nmi - 0.004 (ATD) nmi, describes the 2-sigma along-track error with a standard error of estimate of 0.997 nmi.

## TABLE 17. TANGENT POINT TABLE OF MEASURED 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS--TEST I

**Distance in Nautical Miles Along Track from Tangent Point**

| **Perpendicular Distance in Nautical Miles from Tangent Point to VOR** | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 | 120-130 | 130-140 | 140-150 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-10(x trk) | 0.3 | 0.6 | 1.0 | 1.5 | 2.3 | 1.5 | 2.1 | 3.2 | 3.7 | 4.6 | 4.3 | 5.2 | 3.9 | ----- | ----- |
| (alg trk) | 0.3 | 0.3 | 0.3 | 0.3 | 0.5 | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 | 0.4 | 0.1 | 0.2 | ----- | ----- |
| 10-20(x trk) | 0.3 | 0.6 | 1.1 | 2.2 | 3.1 | 2.9 | 2.6 | 2.7 | 3.4 | 3.3 | 4.4 | 9.1 | --- | ----- | ----- |
| (alg trk) | 0.6 | 0.6 | 0.6 | 0.8 | 0.9 | 0.7 | 0.6 | 0.5 | 0.6 | 0.6 | 0.6 | 1.2 | --- | ----- | ----- |
| 20-30(x trk) | 0.3 | 1.0 | 1.2 | 2.2 | 2.5 | 2.7 | 3.4 | 4.0 | --- | --- | 6.5 | 7.0 | --- | ----- | ----- |
| (alg trk) | 1.2 | 1.5 | 1.4 | 1.6 | 1.4 | 1.1 | 1.5 | 1.6 | --- | --- | 1.3 | 1.3 | --- | ----- | ----- |
| 30-40(x trk) | 0.3 | 0.7 | 1.5 | 1.8 | 1.7 | 2.0 | 3.2 | 2.9 | 3.3 | 5.1 | --- | --- | --- | ----- | ----- |
| (alg trk) | 1.7 | 1.6 | 2.0 | 1.7 | 1.3 | 1.2 | 1.5 | 1.6 | 1.3 | 1.9 | --- | --- | --- | ----- | ----- |
| 40-50(x trk) | 0.3 | 0.9 | 2.0 | 2.5 | 3.1 | 2.0 | 2.3 | 2.2 | 2.7 | 5.4 | 3.3 | --- | --- | ----- | ----- |
| (alg trk) | 2.2 | 2.5 | 3.4 | 2.8 | 2.4 | 1.8 | 1.6 | 1.4 | 1.5 | 3.3 | 1.6 | --- | --- | ----- | ----- |
| 50-60(x trk) | 0.5 | 0.7 | 1.2 | 0.6 | 1.4 | 1.7 | --- | 4.3 | 5.6 | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | 3.3 | 2.1 | 2.7 | 1.0 | 1.8 | 1.7 | --- | 3.2 | 3.5 | --- | --- | --- | --- | ----- | ----- |
| 60-70(x trk) | --- | --- | --- | --- | --- | --- | 2.3 | 1.9 | 2.5 | 4.5 | 5.0 | --- | --- | ----- | ----- |
| (alg trk) | --- | --- | --- | --- | --- | --- | 2.3 | 1.7 | 2.1 | 3.5 | 3.4 | --- | --- | ----- | ----- |
| 70-80(x trk) | 0.3 | 1.1 | 1.6 | 1.6 | 1.7 | 1.6 | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | 4.4 | 4.6 | 4.5 | 3.3 | 2.9 | 2.7 | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| 80-90(x trk) | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| 90-100(x trk) | 0.6 | 1.1 | 1.9 | 2.9 | 2.6 | 2.6 | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | 6.5 | 5.7 | 6.4 | 8.9 | 6.6 | 4.7 | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| 100-110(x trk) | 0.2 | --- | --- | 2.4 | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | 6.1 | --- | --- | 7.9 | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| 110-120(x trk) | 0.7 | 0.7 | 1.5 | 2.1 | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | 11.2 | 7.6 | 10.1 | 8.7 | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| 120-130(x trk) | --- | 0.9 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | --- | 5.9 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| 130-140(x trk) | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| 140-150(x trk) | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |
| (alg trk) | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ----- | ----- |

TABLE 18. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION CROSSTRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--TEST I

```
Step 1
Variable Entered ..... 1 (ATD)
Sum of Squares Reduced in this Step .....              185.171
 Proportion Reduced in this Step ........                0.760
Cumulative Sum of Squares Reduced .......              185.171
 Cumulative Proportion Reduced ..........                0.760   of   243.652
For 1 Variable Entered
 Multiple Correlation Coefficient .......    0.872
     (Adjusted for D.F.) ................    0.872
F-Value for Analysis of Variance   .......  272.309
 Standard Error of Estimate ............     0.825
     (Adjusted for D. F.) ...............    0.825
Variable        Regression      Std. Error of      Computed
 Number         Coefficient      Reg. Coeff.       T-Value
   1             0.04361          0.00264          16.502
Intercept       -0.04575

Step 2
Variable Entered ..... 2  (TPD)
Sum of Squares Reduced in this Step .....                0.343
 Proportion Reduced in this Step ........                0.001
Cumulative Sum of Squares Reduced .......              185.514
 Cumulative Proportion Reduced ..........                0.761   of   243.652
For 2 Variables Entered
 Multiple Correlation Coefficient .......    0.873
     (Adjusted for D. F.) ...............    0.871
 F-Value for Analysis of Variance  ......   135.617
 Standard Error of Estimate ............     0.827
     (Adjusted for D. F.) ...............    0.832
Variable        Regression      Std. Error of      Computed
 Number         Coefficient      Reg. Coeff.       T-Value
   1 (ATD)       0.04432           0.00283          15.640
   2 (TPD)       0.00205           0.00290           0.708
Intercept       -0.18716
```

TABLE 19. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR REGRESSION--TEST I

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Crosstrack |
|---|---|---|---|
| Along-Track Distance | 1.00000 | -0.35389 | 0.87177 |
| Tangent Point Distance | -0.35389 | 1.00000 | -0.27341 |
| 2-Sigma Crosstrack | 0.87177 | -0.27341 | 1.00000 |

TABLE 20. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--TEST I

Step 1

| | | |
|---|---|---|
| Variable Entered ..... 2 (TPD) | | |
| Sum of Squares Reduced in this Step ..... | | 420.908 |
| Proportion Reduced in this Step ........ | | 0.832 |
| Cumulative Sum of Squares Reduced ....... | | 420.908 |
| Cumulative Proportion Reduced .......... | | 0.832 of 505.926 |
| For 1 Variable Entered | | |
| Multiple Correlation Coefficient ....... | 0.912 | |
| (Adjusted for D. F.) ............... | 0.912 | |
| F-Value for Analysis of Variance ...... | 425.770 | |
| Standard Error of Estimate ............ | 0.994 | |
| (Adjusted for D. F.) ............... | 0.994 | |

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2(TPD) | 0.06728 | 0.00326 | 20.634 |
| Intercept | -0.86342 | | |

Step 2

| | | |
|---|---|---|
| Variable Entered ..... 1 (ATD) | | |
| Sum of Squares Reduced in this Step ..... | | 1.524 |
| Proportion Reduced in this Step ........ | | 0.003 |
| Cumulative Sum of Squares Reduced ....... | | 422.432 |
| Cumulative Proportion Reduced .......... | | 0.835 of 505.926 |
| For 2 Variables Entered | | |
| Multiple Correlation Coefficient ....... | 0.914 | |
| (Adjusted for D. F.) ............... | 0.913 | |
| F-Value for Analysis of Variance ...... | 215.027 | |
| Standard Error of Estimate ............ | 0.991 | |
| (Adjusted for D. F.) ............... | 0.997 | |

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.06575 | 0.00348 | 18.920 |
| 1 (ATD) | -0.00423 | 0.00340 | -1.246 |
| Intercept | -0.55146 | | |

TABLE 21. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR REGRESSION--TEST I

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Along-Track |
|---|---|---|---|
| Along-Track Distance | 1.00000 | -0.35389 | -0.37412 |
| Tangent Point Distance | -0.35389 | 1.00000 | 0.91212 |
| 2-Sigma Along-Track | -0.37412 | 0.91212 | 1.00000 |

These two equations were then used to generate a tangent point error table (table 22), for tangent point distance and along-track distance out to 150 nmi. Some negative values resulted in the first row of the table for along-track values. This was due to the negative intercept in the along-track regression equation. Obviously, 2-sigma error values cannot be negative. These negative values are underlined in table 22. The table also shows a slightly decreasing 2-sigma along-track error as a function of along-track distance. For comparison purposes, a theoretical error table was computed using the error values for VOR and DME that were used in Advisory Circular 90-45A. These are: VOR ground station, 1.9°; VOR airborne sensor, 3.0°; DME ground station, 0.1 nmi; and DME airborne sensor, 3 percent or 0.5 nmi. These error elements are 2-sigma values. The results are presented in table 23. Note again that this table does not include FTE or RNAV computer errors. Also, the error elements are combined using the Advisory Circular 90-45A root-sum-square method.

Figures 16 and 17 illustrate the crosstrack and along-track 2-sigma error, respectively, as generated from the regression equation. Also included are the limits set by the standard error of estimate. Looking at figure 16, the crosstrack errors are plotted with respect to along-track distance. The tangent point distance is disregarded because of its small value. In figure 17, the low-value along-track distance is disregarded, and along-track error is plotted with respect to tangent point distance. These two graphs depict the results portrayed in the tangent point table of table 22.

## AIR TRANSPORT TEST II, VOR/DME NAVIGATION SOLUTION ERRORS.

The summary statistics for VOR/DME navigation position errors are presented in table 24. Figures 18 and 19 are the distributions for crosstrack and along-track errors, respectively. Distributions in both cases are leptokurtic.

Table 25 is the tangent point table of 2-sigma crosstrack and along-track error values calculated from measured error values from the air transport test II data. As before, missing data are indicated by dashes.

A stepwise multiple regression was run on the air transport test II data. The results of the regression for 2-sigma crosstrack error as a function of tangent point distance and along-track distance are contained in table 26, while the resulting correlation matrix is presented in table 27.

The equation for predicting the 2-sigma crosstrack error can be obtained from the results of the regression:

$$\text{2-sigma crosstrack error} = 0.271 + 0.038\ (\text{ATD})\ \text{nmi} - 0.007\ (\text{TPD})\ \text{nmi}$$

A similar regression was run on the 2-sigma along-track errors values with along-track distance and tangent point distance as the independent variables. Table 28 presents the results of the regression, while table 29 presents the correlation matrix from the regression.

TABLE 22. TANGENT POINT TABLE OF 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS GENERATED FROM REGRESSION EQUATIONS--TEST I

| Perpendicular Distance in Nautical Miles from Tangent Point to VOR | Distance in Nautical Miles Along Track from Tangent Point | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 | 120-130 | 130-140 | 140-150 |
| 0-10(x trk) | 0.3 | 0.7 | 1.2 | 1.6 | 2.0 | 2.5 | 2.9 | 3.4 | 3.8 | 4.3 | 4.7 | 5.2 | 5.6 | 6.0 | 6.5 |
| (alg trk) | 0.1 | 0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.2 | -0.2 | -0.3 | -0.3 | -0.4 | -0.4 | -0.4 | -0.5 | -0.5 |
| 10-20(x trk) | 0.3 | 0.7 | 1.2 | 1.6 | 2.1 | 2.5 | 3.0 | 3.4 | 3.8 | 4.3 | 4.7 | 5.2 | 5.6 | 6.1 | 6.5 |
| (alg trk) | 0.7 | 0.7 | 0.6 | 0.6 | 0.6 | 0.5 | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 | 0.1 |
| 20-30(x trk) | 0.3 | 0.8 | 1.2 | 1.6 | 2.1 | 2.5 | 3.0 | 3.4 | 3.9 | 4.3 | 4.7 | 5.2 | 5.6 | 6.1 | 6.5 |
| (alg trk) | 1.4 | 1.3 | 1.3 | 1.3 | 1.2 | 1.2 | 1.1 | 1.1 | 1.0 | 1.0 | 1.0 | 0.9 | 0.9 | 0.8 | 0.8 |
| 30-40(x trk) | 0.3 | 0.8 | 1.2 | 1.7 | 2.1 | 2.6 | 3.0 | 3.4 | 3.9 | 4.3 | 4.8 | 5.2 | 5.7 | 6.1 | 6.5 |
| (alg trk) | 2.0 | 2.0 | 2.0 | 1.9 | 1.9 | 1.8 | 1.8 | 1.7 | 1.7 | 1.7 | 1.6 | 1.6 | 1.5 | 1.5 | 1.4 |
| 40-50(x trk) | 0.4 | 0.8 | 1.2 | 1.7 | 2.1 | 2.6 | 3.0 | 3.5 | 3.9 | 4.3 | 4.8 | 5.2 | 5.7 | 6.1 | 6.6 |
| (alg trk) | 2.7 | 2.7 | 2.6 | 2.6 | 2.5 | 2.5 | 2.4 | 2.4 | 2.4 | 2.3 | 2.3 | 2.2 | 2.3 | 2.1 | 2.1 |
| 50-60(x trk) | 0.4 | 0.8 | 1.3 | 1.7 | 2.2 | 2.6 | 3.0 | 3.5 | 3.9 | 4.4 | 4.8 | 5.3 | 5.7 | 6.1 | 6.6 |
| (alg trk) | 3.4 | 3.3 | 3.3 | 3.2 | 3.2 | 3.1 | 3.1 | 3.1 | 3.0 | 3.0 | 2.9 | 2.9 | 2.8 | 2.8 | 2.8 |
| 60-70(x trk) | 0.4 | 0.8 | 1.3 | 1.7 | 2.2 | 2.6 | 3.1 | 3.5 | 3.9 | 4.4 | 4.8 | 5.3 | 5.7 | 6.2 | 6.6 |
| (alg trk) | 4.0 | 4.0 | 3.9 | 3.9 | 3.8 | 3.8 | 3.8 | 3.7 | 3.7 | 3.6 | 3.6 | 3.5 | 3.5 | 3.5 | 3.4 |
| 70-80(x trk) | 0.4 | 0.9 | 1.3 | 1.7 | 2.2 | 2.6 | 3.1 | 3.5 | 4.0 | 4.4 | 4.9 | 5.3 | 5.7 | 6.2 | 6.6 |
| (alg trk) | 4.7 | 4.6 | 3.6 | 4.5 | 4.5 | 4.5 | 4.4 | 4.4 | 4.3 | 4.3 | 4.2 | 4.2 | 4.2 | 4.1 | 4.1 |
| 80-90(x trk) | 0.4 | 0.9 | 1.3 | 1.8 | 2.2 | 2.7 | 3.1 | 3.5 | 4.0 | 4.4 | 4.9 | 5.3 | 5.8 | 6.2 | 6.6 |
| (alg trk) | 5.3 | 5.3 | 5.2 | 5.2 | 5.2 | 5.1 | 5.1 | 5.0 | 5.0 | 4.9 | 4.9 | 4.9 | 4.8 | 4.8 | 4.7 |
| 90-100(x trk) | 0.5 | 0.9 | 1.3 | 1.8 | 2.2 | 2.7 | 3.1 | 3.6 | 4.0 | 4.4 | 4.9 | 5.3 | 5.8 | 6.2 | 6.7 |
| (alg trk) | 6.0 | 5.9 | 5.9 | 5.9 | 5.8 | 5.8 | 5.7 | 5.7 | 5.6 | 5.6 | 5.6 | 5.5 | 5.5 | 5.4 | 5.4 |
| 100-110(x trk) | 0.5 | 0.9 | 1.4 | 1.8 | 2.3 | 2.7 | 3.1 | 3.6 | 4.0 | 4.5 | 4.9 | 5.4 | 5.8 | 6.2 | 6.7 |
| (alg trk) | 6.6 | 6.6 | 6.6 | 6.5 | 6.5 | 6.4 | 6.4 | 6.3 | 6.3 | 6.3 | 6.2 | 6.2 | 6.1 | 6.1 | 6.0 |
| 110-120(x trk) | 0.5 | 0.9 | 1.4 | 1.8 | 2.3 | 2.7 | 3.2 | 3.6 | 4.0 | 4.5 | 4.9 | 5.4 | 5.8 | 6.2 | 6.7 |
| (alg trk) | 7.3 | 7.3 | 7.2 | 7.2 | 7.1 | 7.1 | 7.0 | 7.0 | 7.0 | 6.9 | 6.9 | 6.8 | 6.8 | 6.7 | 6.7 |
| 120-130(x trk) | 0.5 | 1.0 | 1.4 | 1.9 | 2.3 | 2.7 | 3.2 | 3.6 | 4.1 | 4.5 | 5.0 | 5.4 | 5.8 | 6.3 | 6.7 |
| (alg trk) | 8.0 | 7.9 | 7.9 | 7.8 | 7.8 | 7.7 | 7.7 | 7.7 | 7.6 | 7.6 | 7.5 | 7.5 | 7.4 | 7.4 | 7.4 |
| 130-140(x trk) | 0.5 | 1.0 | 1.4 | 1.9 | 2.3 | 2.8 | 3.2 | 3.6 | 4.1 | 4.5 | 5.0 | 5.4 | 5.9 | 6.3 | 6.7 |
| (alg trk) | 8.6 | 8.6 | 8.5 | 8.5 | 8.4 | 8.4 | 8.4 | 8.3 | 8.3 | 8.2 | 8.2 | 8.1 | 8.1 | 8.1 | 8.0 |
| 140-150(x trk) | 0.6 | 1.0 | 1.5 | 1.9 | 2.3 | 2.8 | 3.2 | 3.7 | 4.1 | 4.6 | 5.0 | 5.4 | 5.9 | 6.3 | 6.8 |
| (alg trk) | 9.3 | 9.2 | 9.2 | 9.1 | 9.1 | 9.1 | 9.0 | 9.0 | 8.9 | 8.9 | 8.8 | 8.8 | 8.8 | 8.7 | 8.7 |

TABLE 23. TANGENT POINT TABLE OF 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS USING ADVISORY CIRCULAR 90-45A 2-SIGMA VALUES FOR VOR AND DME ERRORS

| Perpendicular Distance in Nautical Miles from Tangent Point to VOR | DISTANCE IN NAUTICAL MILES ALONG TRACK FROM TANGENT POINT | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150 |
| 10(x trk) | 0.7 | 1.3 | 1.9 | 2.5 | 3.1 | 3.7 | 4.4 | 5.0 | 5.6 | 6.2 | 6.8 | 7.4 | 8.1 | 8.7 | 9.3 |
| (alg trk) | 0.7 | 0.9 | 1.1 | 1.4 | 1.6 | 1.9 | 2.2 | 2.5 | 2.8 | 3.1 | 3.4 | 3.7 | 4.0 | 4.2 | 4.5 |
| 20(x trk) | 0.9 | 1.4 | 2.0 | 2.6 | 3.2 | 3.8 | 4.4 | 5.0 | 5.6 | 6.2 | 6.8 | 7.5 | 8.1 | 8.7 | 9.3 |
| (alg trk) | 1.3 | 1.4 | 1.5 | 1.7 | 1.9 | 2.2 | 2.4 | 2.7 | 3.0 | 3.2 | 3.5 | 3.8 | 4.1 | 4.4 | 4.7 |
| 30(x trk) | 1.1 | 1.5 | 2.1 | 2.6 | 3.2 | 3.8 | 4.4 | 5.0 | 5.7 | 6.3 | 6.9 | 7.5 | 8.1 | 8.7 | 9.3 |
| (alg trk) | 1.9 | 2.0 | 2.1 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 | 3.3 | 3.5 | 3.8 | 4.1 | 4.3 | 4.6 | 4.9 |
| 40(x trk) | 1.4 | 1.7 | 2.2 | 2.8 | 3.3 | 3.9 | 4.5 | 5.1 | 5.7 | 6.3 | 6.9 | 7.5 | 8.2 | 8.8 | 9.4 |
| (alg trk) | 2.5 | 2.6 | 2.6 | 2.8 | 2.9 | 3.1 | 3.3 | 3.5 | 3.7 | 3.9 | 4.1 | 4.4 | 4.6 | 4.9 | 5.1 |
| 50(x trk) | 1.6 | 1.9 | 2.4 | 2.9 | 3.4 | 4.0 | 4.6 | 5.2 | 5.8 | 6.4 | 7.0 | 7.6 | 8.2 | 8.8 | 9.4 |
| (alg trk) | 3.1 | 3.2 | 3.2 | 3.3 | 3.4 | 3.6 | 3.7 | 3.9 | 4.1 | 4.3 | 4.5 | 4.8 | 5.0 | 5.2 | 5.5 |
| 60(x trk) | 1.9 | 2.2 | 2.6 | 3.1 | 3.6 | 4.1 | 4.7 | 5.3 | 5.9 | 6.5 | 7.1 | 7.7 | 8.3 | 8.9 | 9.5 |
| (alg trk) | 3.7 | 3.8 | 3.8 | 3.9 | 4.0 | 4.1 | 4.3 | 4.4 | 4.6 | 4.8 | 5.0 | 5.2 | 5.4 | 5.6 | 5.8 |
| 70(x trk) | 2.2 | 2.4 | 2.8 | 3.3 | 3.7 | 4.3 | 4.8 | 5.4 | 6.0 | 6.5 | 7.1 | 7.7 | 8.3 | 8.9 | 9.5 |
| (alg trk) | 4.4 | 4.4 | 4.4 | 4.5 | 4.6 | 4.7 | 4.8 | 5.0 | 5.1 | 5.3 | 5.5 | 5.6 | 5.8 | 6.0 | 6.3 |
| 80(x trk) | 2.5 | 2.7 | 3.0 | 3.5 | 3.9 | 4.4 | 5.0 | 5.5 | 6.1 | 6.7 | 7.2 | 7.8 | 8.4 | 9.0 | 9.6 |
| (alg trk) | 5.0 | 5.0 | 5.0 | 5.1 | 5.2 | 5.3 | 5.4 | 5.5 | 5.6 | 5.8 | 6.0 | 6.1 | 6.3 | 6.5 | 6.7 |
| 90(x trk) | 2.8 | 3.0 | 3.3 | 3.7 | 4.1 | 4.6 | 5.1 | 5.6 | 6.2 | 6.8 | 7.3 | 7.9 | 8.5 | 9.1 | 9.7 |
| (alg trk) | 5.6 | 5.6 | 5.7 | 5.7 | 5.8 | 5.9 | 6.0 | 6.1 | 6.2 | 6.3 | 6.5 | 6.6 | 6.8 | 7.0 | 7.2 |
| 100(x trk) | 3.1 | 3.2 | 3.5 | 3.9 | 4.3 | 4.8 | 5.3 | 5.8 | 6.3 | 6.9 | 7.5 | 8.0 | 8.6 | 9.2 | 9.8 |
| (alg trk) | 6.2 | 6.2 | 6.3 | 6.3 | 6.4 | 6.5 | 6.5 | 6.7 | 6.8 | 6.9 | 7.0 | 7.2 | 7.3 | 7.5 | 7.7 |
| 110(x trk) | 3.4 | 3.5 | 3.8 | 4.1 | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.6 | 8.1 | 8.7 | 9.3 | 9.9 |
| (alg trk) | 6.8 | 6.8 | 6.9 | 6.9 | 7.0 | 7.1 | 7.1 | 7.2 | 7.3 | 7.5 | 7.6 | 7.7 | 7.9 | 8.0 | 8.2 |
| 120(x trk) | 3.7 | 3.8 | 4.1 | 4.4 | 4.8 | 5.2 | 5.6 | 6.1 | 6.6 | 7.2 | 7.7 | 8.3 | 8.8 | 9.4 | 10.0 |
| (alg trk) | 7.4 | 7.5 | 7.5 | 7.5 | 7.6 | 7.7 | 7.7 | 7.8 | 7.9 | 8.0 | 8.1 | 8.3 | 8.4 | 8.5 | 8.7 |
| 130(x trk) | 4.0 | 4.1 | 4.3 | 4.6 | 5.0 | 5.4 | 5.8 | 6.3 | 6.8 | 7.3 | 7.9 | 8.4 | 9.0 | 9.5 | 10.1 |
| (alg trk) | 8.1 | 8.1 | 8.1 | 8.2 | 8.2 | 8.3 | 8.3 | 8.4 | 8.5 | 8.6 | 8.7 | 8.8 | 9.0 | 9.1 | 9.2 |
| 140(x trk) | 4.2 | 4.4 | 4.6 | 4.9 | 5.2 | 5.6 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.1 | 9.6 | 10.2 |
| (alg trk) | 8.7 | 8.7 | 8.7 | 8.8 | 8.8 | 8.9 | 8.9 | 9.0 | 9.1 | 9.2 | 9.3 | 9.4 | 9.5 | 9.6 | 9.8 |
| 150(x trk) | 4.5 | 4.7 | 4.9 | 5.1 | 5.5 | 5.8 | 6.3 | 6.7 | 7.2 | 7.7 | 8.2 | 8.7 | 9.2 | 9.8 | 10.3 |
| (alg trk) | 9.3 | 9.3 | 9.3 | 9.4 | 9.4 | 9.5 | 9.5 | 9.6 | 9.7 | 9.8 | 9.9 | 10.0 | 10.1 | 10.2 | 10.3 |

## TABLE 24. VOR/DME NAVIGATION SOLUTION ERROR STATISTICS--TEST II

| | Mean (nmi) | One Standard Deviation (nmi) | Number of Samples |
|---|---|---|---|
| VOR/DME Crosstrack Error | 0.05 | 0.90 | 57,106 |
| VOR/DME Along-Track Error | -0.16 | 0.61 | 57,106 |

## TABLE 25. TANGENT POINT TABLE OF MEASURED 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS--TEST II

Distance in Nautical Miles Along Track from Tangent Point

| Perpendicular Distance in Nautical Miles from Tangent Point to VOR | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-120 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-10(x trk) | 0.3 | 0.7 | 1.6 | 2.0 | 2.1 | 2.4 | 2.8 | 3.6 | ----- | ----- | ----- |
| (alg trk) | 0.2 | 0.3 | 0.4 | 0.4 | 0.2 | 0.2 | 0.2 | 0.4 | ----- | ----- | ----- |
| 10-20(x trk) | 0.4 | 0.9 | 0.8 | 1.7 | 1.1 | 2.6 | 1.9 | 1.0 | ----- | 4.2 | ----- |
| (alg trk) | 0.7 | 0.7 | 0.7 | 0.5 | 0.3 | 0.5 | 0.7 | .1 | ----- | 1.2 | ----- |
| 20-30(x trk) | 0.3 | 0.4 | 1.2 | 1.2 | ----- | ----- | 6.4 | 5.0 | ----- | 3.2 | ----- |
| (alg trk) | 1.3 | 0.9 | 1.2 | 1.0 | ----- | ----- | 2.0 | 1.7 | ----- | 0.6 | ----- |
| 30-40(x trk) | 0.4 | 0.5 | 1.0 | 1.5 | 2.6 | 3.8 | 3.6 | 2.4 | 3.2 | ----- | ----- |
| (alg trk) | 1.0 | 0.7 | 1.4 | 1.5 | 2.1 | 2.6 | 1.9 | 1.2 | 1.3 | ----- | ----- |
| 40-50(x trk) | ----- | 0.7 | 0.8 | 1.0 | 1.8 | 2.6 | 3.6 | 2.2 | 4.0 | ----- | ----- |
| (alg trk) | ----- | 1.4 | 1.6 | 1.3 | 1.9 | 2.3 | 2.8 | 1.7 | 2.4 | ----- | ----- |
| 50-60(x trk) | 0.3 | 0.2 | 0.8 | 1.5 | 1.2 | 1.6 | ----- | 2.5 | 1.7 | ----- | ----- |
| (alg trk) | 1.9 | 0.9 | 1.6 | 1.8 | 1.4 | 1.5 | ----- | 1.4 | 1.1 | ----- | ----- |
| 60-70(x trk) | 0.3 | 0.6 | 0.6 | ----- | ----- | 2.3 | 1.4 | ----- | ----- | ----- | ----- |
| (alg trk) | 3.2 | 3.8 | 1.9 | ----- | ----- | 2.4 | 1.4 | ----- | ----- | ----- | ----- |
| 70-80(x trk) | 0.3 | 0.6 | 1.2 | 1.1 | 1.4 | 1.8 | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | 2.8 | 2.6 | 3.6 | 2.1 | 2.1 | 2.3 | ----- | ----- | ----- | ----- | ----- |
| 80-90(x trk) | ----- | ----- | 1.2 | 1.1 | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | ----- | ----- | 3.6 | 3.0 | ----- | ----- | ----- | ----- | ----- | ----- | ----- |

TABLE 26. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION CROSSTRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--TEST II

Step 1

| | | | |
|---|---|---|---|
| Variable Entered ..... 1 (ATD) | | | |
| Sum of Squares Reduced in this Step ..... | | 62.820 | |
| Proportion Reduced in this Step ........ | | 0.620 | |
| Cumulative Sum of Squares Reduced ....... | | 62.820 | |
| Cumulative Proportion Reduced .......... | | 0.620 | of 101.381 |
| For 1 Variable Entered | | | |
| Multiple Correlation Coefficient ....... | 0.787 | | |
| (Adjusted for D. F.) ............... | 0.787 | | |
| F-Value for Analysis of Variance ...... | 97.747 | | |
| Standard Error of Estimate ............ | 0.802 | | |
| (Adjusted for D. F.) ............... | 0.802 | | |

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 1 | 0.03938 | 0.00398 | 9.887 |
| Intercept | -0.11450 | | |

Step 2

| | | | |
|---|---|---|---|
| Variable Entered ..... 2 (TPD) | | | |
| Sum of Squares Reduced in this Step ..... | | 1.974 | |
| Proportion Reduced in this Step ........ | | 0.019 | |
| Cumulative Sum of Squares Reduced ....... | | 64.794 | |
| Cumulative Proportion Reduced .......... | | 0.639 | of 101.381 |
| For 2 Variables Entered | | | |
| Multiple Correlation Coefficient ....... | 0.799 | | |
| (Adjusted for D. F.) ............... | 0.796 | | |
| F-Value for Analysis of Variance ...... | 52.244 | | |
| Standard Error of Estimate ............ | 0.787 | | |
| (Adjusted for D. F.) ............... | 0.794 | | |

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 1 (ATD) | 0.03839 | 0.00395 | 9.717 |
| 2 (TPD) | -0.00773 | 0.00433 | -1.784 |
| Intercept | 0.27101 | | |

TABLE 27. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR REGRESSION--TEST II

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Crosstrack |
|---|---|---|---|
| Along-Track Distance | 1.0000 | -0.1398 | 0.7872 |
| Tangent Point Distance | -0.1398 | 1.0000 | -0.2482 |
| 2-Sigma Crosstrack | 0.7872 | -0.2482 | 1.0000 |

### TABLE 28. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--TEST II

**Step 1**

Variable Entered ..... 2 (TPD)
Sum of Squares Reduced in this Step ..... 39.125
Proportion Reduced in this Step ........ 0.670
Cumulative Sum of Squares Reduced ....... 39.125
Cumulative Proportion Reduced .......... 0.670 of 58.352
For 1 Variable Entered
Multiple Correlation Coefficient ....... 0.819
(Adjusted for D. F.) ............... 0.819
F-Value for Analysis of Variance ...... 122.094
Standard Error of Estimate ............ 0.566
(Adjusted for D. F.) ............... 0.566

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.00409 | 0.00308 | 11.050 |
| Intercept | -0.00569 | | |

**Step 2**

Variable Entered ..... 1 (ATD)
Sum of Squares Reduced in this Step ..... 0.010
Proportion Reduced in this Step ........ 0.000
Cumulative Sum of Squares Reduced ....... 39.134
Cumulative Proportion Reduced .......... 0.671 of 58.352
For 2 Variables Entered
Multiple Correlation Coefficient ....... 0.819
(Adjusted for D. F.) ............... 0.816
F-Value for Analysis of Variance ...... 60.074
Standard Error of Estimate ............ 0.571
(Adjusted for D. F.) ............... 0.575

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.03401 | 0.00314 | 10.828 |
| 1 (ATD) | -0.00049 | 0.00286 | - 0.172 |
| Intercept | 0.02080 | | |

### TABLE 29. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR REGRESSION--TEST II

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Along-Track |
|---|---|---|---|
| Along-Track Distance | 1.0000 | -0.1398 | -0.1272 |
| Tangent Point Distance | -0.1398 | 1.0000 | 0.8188 |
| 2-Sigma Along-Track | -0.1272 | 0.8188 | 1.0000 |

The equation for predicting the 2-sigma along-track error is again derived from the results of the regression on along-track data:

2-sigma along-track error = 0.021 nmi + 0.034 (TPD) nmi - 0.0005 (ATD) nmi

These equations were then used to generate the tangent point table shown in table 30. This table again shows conservative results when compared to the Advisory Circular 90-45A theoretical tangent point table in table 23.

The two regression equations were used to generate figures 20 and 21. These figures portray the 2-sigma error as a function of the predominate variable. For 2-sigma crosstrack error, along-track distance contributes most of the error, and tangent point distance is disregarded. For 2-sigma along-track error, the tangent point distance contributes most of the error, and along-track distance is disregarded. The 2-sigma values for crosstrack and along-track distances are bounded by the standard error of estimate from the regression.

## COMBINED AIR TRANSPORT VOR/DME NAVIGATION SOLUTION.

As with the raw sensor data from tests I and II flight tests, the VOR/DME navigation solutions were also combined into one set of data. Figures 22 and 23 illustrate the distributions for crosstrack and along-track errors, respectively, for the combined air transport data. Table 31 enumerates the statistics for the combined data.

TABLE 31. VOR/DME NAVIGATION SOLUTION ERROR STATISTICS--COMBINED AIR TRANSPORT QUALITY SENSOR DATA

| | Mean (nmi) | One Standard Deviation (nmi) | Number of Samples |
|---|---|---|---|
| VOR/DME Crosstrack Error | 0.038 | 0.923 | 141,514 |
| VOR/DME Along-Track Error | -0.109 | 0.721 | 141,514 |

Table 32 is the tangent point table of the measured 2-sigma vlaues for crosstrack and along-track error from the combined data. A regression analysis was run on these data for both the crosstrack and the along-track errors.

Table 33 contains the results of the regression analysis with crosstrack error as the dependent variable and tangent point distance and along-track distance as the independent variables.

Table 34 contains the resulting correlation matrix. The equation for predicting the 2-sigma crosstrack error can be obtained from the results of the regression:

## TABLE 30. TANGENT POINT TABLE OF 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS GENERATED FROM REGRESSION EQUATIONS--TEST II

| Perpendicular Distance in Nautical Miles from Tangent Point to VOR | Distance in Nautical Miles Along-Track from Tangent Point | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 | 120-130 | 130-140 | 140-150 |
| 0-10(x trk) | 0.6 | 1.0 | 1.3 | 1.7 | 2.1 | 2.5 | 2.9 | 3.3 | 3.6 | 4.0 | 4.4 | 4.8 | 5.2 | 5.6 | 6.0 |
| (alg trk) | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| 10-20(x trk) | 0.5 | 0.9 | 1.3 | 1.7 | 2.0 | 2.4 | 2.8 | 3.2 | 3.6 | 4.0 | 4.3 | 4.7 | 5.1 | 5.5 | 5.9 |
| (alg trk) | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 |
| 20-30(x trk) | 0.4 | 0.8 | 1.2 | 1.6 | 2.0 | 2.3 | 2.7 | 3.1 | 3.5 | 3.9 | 4.3 | 4.7 | 5.0 | 5.4 | 5.8 |
| (alg trk) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 30-40(x trk) | 0.4 | 0.7 | 1.1 | 1.5 | 1.9 | 2.3 | 2.7 | 3.0 | 3.4 | 3.8 | 4.2 | 4.6 | 5.0 | 5.3 | 5.8 |
| (alg trk) | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| 40-50(x trk) | 0.3 | 0.7 | 1.0 | 1.4 | 1.8 | 2.2 | 2.6 | 3.0 | 3.3 | 3.7 | 4.1 | 4.5 | 4.9 | 5.5 | 5.6 |
| (alg trk) | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| 50-60(x trk) | 0.2 | 0.6 | 1.0 | 1.3 | 1.7 | 2.1 | 2.5 | 2.9 | 3.3 | 3.7 | 4.0 | 4.4 | 4.8 | 5.2 | 5.6 |
| (alg trk) | 2.0 | 2.1 | 2.1 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| 60-70(x trk) | 0.1 | 0.5 | 0.9 | 1.3 | 1.7 | 2.0 | 2.4 | 2.8 | 3.2 | 3.6 | 4.0 | 4.3 | 4.7 | 5.0 | 5.5 |
| (alg trk) | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.3 | 2.3 | 2.3 | 2.3 |
| 70-80(x trk) | 0.0 | 0.4 | 0.8 | 1.1 | 1.6 | 2.0 | 2.3 | 2.7 | 3.1 | 3.5 | 3.9 | 4.3 | 4.6 | 5.0 | 5.4 |
| (alg trk) | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| 80-90(x trk) | 0.0 | 0.3 | 0.7 | 1.1 | 1.5 | 1.9 | 2.3 | 2.7 | 3.0 | 3.4 | 3.8 | 4.2 | 4.6 | 5.0 | 5.3 |
| (alg trk) | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| 90-100(x trk) | -0.1 | 0.3 | 0.7 | 1.0 | 1.4 | 1.8 | 2.2 | 2.6 | 3.0 | 3.3 | 3.7 | 4.1 | 4.9 | 4.9 | 5.3 |
| (alg trk) | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 |
| 100-110(x trk) | 0.2 | 0.2 | 0.6 | 1.0 | 1.3 | 1.7 | 2.1 | 2.5 | 2.9 | 3.3 | 3.6 | 4.0 | 4.4 | 4.8 | 5.2 |
| (alg trk) | 3.8 | 3.8 | 3.8 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 |
| 110-120(x trk) | -0.3 | 0.1 | 0.5 | 0.9 | 1.3 | 1.7 | 2.0 | 2.4 | 2.8 | 3.2 | 3.6 | 4.0 | 4.3 | 4.7 | 5.1 |
| (alg trk) | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.1 | 4.0 | 4.0 | 4.0 | 4.0 |
| 120-130(x trk) | -0.4 | 0.0 | 0.4 | 0.8 | 1.2 | 1.6 | 2.0 | 2.3 | 2.7 | 3.1 | 3.5 | 3.9 | 4.3 | 4.6 | 5.0 |
| (alg trk) | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 |
| 130-140(xtrk) | -0.4 | 0.0 | 0.3 | 0.7 | 1.1 | 1.5 | 1.9 | 2.3 | 2.6 | 3.0 | 3.4 | 3.8 | 4.2 | 4.7 | 5.0 |
| (alg trk) | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.8 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 |
| 140-150(x trk) | -0.5 | -0.1 | 0.3 | 0.7 | 1.0 | 1.4 | 1.8 | 2.2 | 2.6 | 3.0 | 3.3 | 3.7 | 4.1 | 4.5 | 4.9 |
| (alg trk) | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 |

## TABLE 32. TANGENT POINT TABLE OF MEASURED 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS--COMBINED AIR TRANSPORT QUALITY SENSOR DATA

| Perpendicular Distance in Nautical Miles from Tangent Point to VOR | Distance in Nautical Miles Along Track from Tangent Point | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 | 120-130 | 130-140 | 140-150 |
| 0-10(x trk) | 0.3 | 0.7 | 1.4 | 1.8 | 2.2 | 2.0 | 2.5 | 3.2 | 3.7 | 4.6 | 4.3 | 5.3 | 3.9 | ----- | ----- |
| (alg trk) | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 3.0 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.2 | 0.2 | ----- | ----- |
| 10-20(x trk) | 0.3 | 0.7 | 1.1 | 2.2 | 3.0 | 2.8 | 3.1 | 2.8 | 3.4 | 7.6 | 4.4 | 9.1 | ----- | ----- | ----- |
| (alg trk) | 0.6 | 0.8 | 0.6 | 0.8 | 0.9 | 0.7 | 0.6 | 0.5 | 0.6 | 1.6 | 0.6 | 1.2 | ----- | ----- | ----- |
| 20-30(x trk) | 0.3 | 1.0 | 1.2 | 2.2 | 2.5 | 2.7 | 6.0 | 5.4 | ----- | 3.2 | 6.5 | 7.0 | ----- | ----- | ----- |
| (alg trk) | 1.3 | 1.5 | 1.4 | 1.6 | 1.4 | 1.1 | 2.0 | 1.7 | ----- | 0.5 | 1.3 | 1.3 | ----- | ----- | ----- |
| 30-40(x trk) | 0.3 | 0.6 | 1.3 | 1.7 | 2.4 | 3.5 | 5.0 | 5.5 | 6.3 | 5.1 | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | 1.5 | 1.4 | 1.8 | 1.6 | 1.8 | 2.1 | 2.3 | 2.4 | 2.3 | 2.0 | ----- | ----- | ----- | ----- | ----- |
| 40-50(x trk) | 0.3 | 0.9 | 1.9 | 2.4 | 2.9 | 2.4 | 3.2 | 2.2 | 3.5 | 5.4 | 3.3 | ----- | ----- | ----- | ----- |
| (alg trk) | 2.2 | 2.4 | 3.2 | 2.7 | 2.4 | 2.0 | 2.3 | 1.6 | 2.2 | 3.3 | 1.6 | ----- | ----- | ----- | ----- |
| 50-60(x trk) | 0.5 | 0.7 | 1.1 | 1.5 | 1.3 | 1.7 | ----- | 4.1 | 5.2 | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | 3.3 | 2.0 | 2.5 | 2.0 | 1.6 | 1.7 | ----- | 3.0 | 3.2 | ----- | ----- | ----- | ----- | ----- | ----- |
| 60-70(x trk) | 0.3 | 0.7 | 0.6 | 2.3 | 1.9 | 1.9 | 2.5 | 4.4 | 5.0 | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | 3.2 | 3.7 | 1.9 | 2.6 | 1.8 | 1.7 | 2.1 | 3.5 | 3.4 | ----- | ----- | ----- | ----- | ----- | ----- |
| 70-80(x trk) | 0.4 | 0.8 | 1.3 | 1.2 | 1.8 | 1.8 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | 3.2 | 3.3 | 4.0 | 2.9 | 2.5 | 2.3 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 80-90(x trk) | ----- | ----- | 1.2 | 1.1 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | ----- | ----- | 3.6 | 2.9 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 90-100(x trk) | 0.6 | 1.1 | 1.9 | 2.9 | 2.6 | 2.6 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | 6.5 | 5.7 | 6.4 | 8.9 | 6.6 | 4.7 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 100-110(x trk) | 0.2 | ----- | ----- | 2.2 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | 6.1 | ----- | ----- | 7.9 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 110-120(x trk) | 0.7 | 0.7 | 1.6 | 2.1 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | 11.2 | 7.6 | 10.2 | 8.7 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 120-130(x trk) | ----- | 0.9 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | ----- | 6.0 | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 130-140(x trk) | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| 140-150(x trk) | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |
| (alg trk) | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- | ----- |

TABLE 33. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION CROSSTRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--COMBINED AIR TRANSPORT QUALITY SENSOR DATA

**Step 1**

| | | |
|---|---|---|
| Variable Entered ..... 1 (ATD) | | |
| Sum of Squares Reduced in this Step ..... | | 264.013 |
| Proportion Reduced in this Step ........ | | 0.721 |
| Cumulative Sum of Squares Reduced ....... | | 264.013 |
| Cumulative Proportion Reduced .......... | | 0.721 of 366.305 |
| For 1 Variable Entered | | |
| Multiple Correlation Coefficient ....... | 0.849 | |
| (Adjusted for D. F.) ............... | 0.849 | |
| F-Value for Analysis of Variance ...... | 245.195 | |
| Standard Error of Estimate ............ | 1.038 | |
| (Adjusted for D. F.) ............... | 1.038 | |

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 1 (ATD) | 0.04958 | 0.00317 | 15.659 |
| Intercept | -0.14714 | | |

**Step 2**

| | | |
|---|---|---|
| Variable Entered ..... 2 (TPD) | | |
| Sum of Squares Reduced in this Step ..... | | 0.301 |
| Proportion Reduced in this Step ........ | | 0.001 |
| Cumulative Sum of Squares Reduced ....... | | 264.314 |
| Cumulative Proportion Reduced .......... | | 0.722 of 366.305 |
| For 2 Variables Entered | | |
| Multiple Correlation Coefficient ....... | 0.849 | |
| (Adjusted for D. F.) ............... | 0.848 | |
| F-Value for Analysis of Variance ...... | 121.803 | |
| Standard Error of Estimate ............ | 1.042 | |
| (Adjusted for D. F.) ............... | 1.047 | |

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 1 (ATD) | 0.04894 | 0.00340 | 14.373 |
| 2 (TPD) | -0.00186 | 0.00353 | - 0.526 |
| Intercept | -0.01631 | | |

TABLE 34. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR REGRESSION--COMBINED AIR TRANSPORT QUALITY SENSOR DATA

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Along-Track |
|---|---|---|---|
| Along-Track Distance | 1.0000 | -0.3586 | 0.8490 |
| Tangent Point Distance | -0.3586 | 1.0000 | -0.3311 |
| 2-Sigma Crosstrack | 0.8490 | -0.3311 | 1.0000 |

2-sigma crosstrack error = -0.016 nmi + 0.049 (ATD) nmi - 0.002 (TPD) nmi

A similar regression was run on the along-track error data in table 32. Table 35 contains the results of the along-track regression, while table 36 contains the resulting correlation matrix. The equation for predicting the 2-sigma along-track error can be obtained from the results of the regression:

2-sigma along-track error = -0.553 nmi + 0.061 (TPD) nmi - 0.001 (ATD) nmi

The equations were then used to generate another tangent point table shown in table 37. Figures 24 and 25 were generated from the regression equation, but as before, the least significant term in each regression equation is deleted. For the crosstrack equation, the tangent point distance term is deleted, while for the along-track equation, the along-track distance term is deleted. The boundaries, based on the standard error of estimate, are also depicted in the figures.

## GENERAL AVIATION VOR/DME NAVIGATION SOLUTION ERRORS.

Positional errors were calculated from the general aviation flight test sensor data and resolved into crosstrack and along-track components. Table 38 enumerates the statistics for the general aviation flights.

The distributions for these errors are presented in figures 26 and 27. Figure 26 is the distribution for the crosstrack error, while figure 27 is the distribution for the along-track error. Both distributions are leptokutic.

Table 39 is the tangent point table of the measured 2-sigma values for crosstrack and along-track error obtained from the general aviation RNAV flight tests. All of the data collected in these flight tests were collected in the terminal area, and the maximum altitude of the test patterns used for these flights was 5,000 feet. For this reason, the tangent point table of measured data was limited to short range data.

A regression analysis was run on these data. Table 40 contains the results of the regression, with crosstrack error as the dependent variable and tangent point distance and along-track distance as the independent variables. Table 41 contains the resulting correlation matrix.

The equation for predicting the 2-sigma crosstrack error can be obtained from the regression:

2-sigma crosstrack error = -0.059 nmi + 0.033 (ATD) nmi + 0.0003 (TPD) nmi

A similar regression was run on the along-track error data. Table 42 contains the results of the regression, while table 43 contains the resulting correlation matrix. The equation for predicting the 2-sigma along-track error can be obtained from the regression:

2-sigma along-track error = -0.234 nmi + 0.049 (TPD) nmi - 0.004 (ATD) nmi

TABLE 35. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--COMBINED AIR TRANSPORT QUALITY SENSOR DATA

<u>Step 1</u>

Variable Entered ..... 2 (TPD)
Sum of Squares Reduced in this Step ..... 384.102
Proportion Reduced in this Step ........ 0.777
Cumulative Sum of Squares Reduced ....... 384.102
Cumulative Proportion Reduced .......... 0.777 of 494.193
For 1 Variable Entered
Multiple Correlation Coefficient ....... 0.882
(Adjusted for D. F.) ............... 0.882
F-Value for Analysis of Variance ....... 331.450
Standard Error of Estimate ............ 1.077
(Adjusted for D. F.) .............. 1.077

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.06196 | 0.00340 | 18.206 |
| Intercept | -0.64358 | | |

Step 2

Variable Entered ..... 1 (ATD)
Sum of Squares Reduced in this Step ..... 0.139
Proportion Reduced in this Step ........ 0.000
Cumulative Sum of Squares Reduced ....... 384.241
Cumulative Proportion Reduced .......... 0.778 of 494.193
For 2 Variables Entered
Multiple Correlation Coefficient ....... 0.882
(Adjusted for D. F.) .............. 0.880
F-Value for Analysis of Variance ...... 164.247
Standard Error of Estimate ............ 1.082
(Adjusted for D. F.) .............. 1.087

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.06151 | 0.00366 | 16.793 |
| 1 (ATD) | -0.0122 | 0.00354 | - 0.345 |
| Intercept | -0.55266 | | |

TABLE 36. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR REGRESSION--COMBINED AIR TRANSPORT QUALITY SENSOR DATA

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Along-Track |
|---|---|---|---|
| Along-Track Distance | 1.0000 | -0.3586 | -0.3318 |
| Tangent Point Distance | -0.3586 | 1.0000 | 0.8816 |
| 2-Sigma Along-Track | -0.3318 | 0.8816 | 1.0000 |

## TABLE 37. TANGENT POINT TABLE OF 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS GENERATED FROM REGRESSION EQUATIONS--COMBINED AIR TRANSPORT QUALITY SENSOR DATA

| Perpendicular Distance in Nautical Miles from Tangent Point to VOR | Distance in Nautical Miles Along Track from Tangent Point | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 | 120-130 | 130-140 | 140-150 |
| 0-10(x trk) | 0.5 | 0.9 | 1.4 | 1.9 | 2.4 | 2.9 | 3.4 | 3.9 | 4.4 | 4.9 | 5.3 | 5.8 | 6.3 | 6.8 | 7.3 |
| (alg trk) | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 |
| 10-20(x trk) | 0.4 | 0.9 | 1.4 | 1.9 | 2.4 | 2.9 | 3.4 | 3.9 | 4.4 | 4.8 | 5.3 | 5.8 | 6.3 | 6.8 | 7.3 |
| (alg trk) | 0.7 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 20-30(x trk) | 0.4 | 0.9 | 1.4 | 1.9 | 2.4 | 2.9 | 3.4 | 3.8 | 4.3 | 4.8 | 5.3 | 5.8 | 6.3 | 6.8 | 7.3 |
| (alg trk) | 1.3 | 1.3 | 1.3 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 | 1.1 |
| 30-40(x trk) | 0.4 | 0.9 | 1.4 | 1.9 | 2.4 | 2.8 | 3.3 | 3.8 | 4.3 | 4.8 | 5.3 | 5.8 | 6.3 | 6.8 | 7.3 |
| (alg trk) | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.7 | 1.7 |
| 40-50(x trk) | 0.4 | 0.9 | 1.4 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.8 | 5.3 | 5.8 | 6.3 | 6.7 | 7.2 |
| (alg trk) | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.3 |
| 50-60(x trk) | 0.4 | 0.9 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.8 | 5.3 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| 60-70(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 |
| 70-80(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 4.4 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 |
| 80-90(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.2 | 3.7 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 5.0 | 5.0 | 5.0 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 4.8 | 4.8 | 4.8 | 4.8 |
| 90-100(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.2 | 2.7 | 3.2 | 3.7 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.6 | 7.1 |
| (alg trk) | 5.6 | 5.6 | 5.6 | 5.6 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 5.4 | 5.4 | 5.4 |
| 100-110(x trk) | 0.3 | 0.8 | 1.2 | 1.7 | 2.2 | 2.7 | 3.2 | 3.7 | 4.2 | 4.7 | 5.2 | 5.7 | 6.1 | 6.6 | 7.1 |
| (alg trk) | 6.2 | 6.2 | 6.2 | 6.2 | 6.2 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.1 | 6.0 | 6.0 |
| 110-120(x trk) | 0.3 | 0.7 | 1.2 | 1.7 | 2.2 | 2.7 | 3.2 | 3.7 | 4.2 | 4.7 | 5.1 | 5.6 | 6.1 | 6.6 | 7.1 |
| (alg trk) | 6.8 | 6.8 | 6.8 | 6.8 | 6.8 | 6.8 | 6.7 | 6.7 | 6.7 | 6.7 | 6.7 | 6.7 | 6.7 | 6.7 | 6.7 |
| 120-130(x trk) | 0.2 | 0.7 | 1.2 | 1.7 | 2.2 | 2.7 | 3.2 | 3.7 | 4.1 | 4.6 | 5.1 | 5.6 | 6.1 | 6.6 | 7.1 |
| (alg trk) | 7.4 | 7.4 | 7.4 | 7.4 | 7.4 | 7.4 | 7.4 | 7.4 | 7.3 | 7.3 | 7.3 | 7.3 | 7.3 | 7.3 | 7.3 |
| 130-140(x trk) | 0.2 | 0.7 | 1.2 | 1.7 | 2.2 | 2.7 | 3.1 | 3.6 | 4.1 | 4.6 | 5.1 | 5.6 | 6.1 | 6.6 | 7.1 |
| (alg trk) | 8.1 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 |
| 140-150(x trk) | 0.2 | 0.7 | 1.2 | 1.7 | 2.2 | 2.6 | 3.1 | 3.6 | 4.1 | 4.6 | 5.1 | 5.6 | 6.1 | 6.6 | 7.0 |
| (alg trk) | 8.7 | 8.7 | 8.6 | 8.6 | 8.6 | 8.6 | 8.6 | 8.6 | 8.6 | 8.6 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 |

TABLE 38. VOR/DME NAVIGATION SOLUTION ERROR STATISTICS--GENERAL AVIATION QUALITY SENSOR DATA

| | Mean (nmi) | One Standard Deviation (nmi) | Number of Samples |
|---|---|---|---|
| VOR/DME Crosstrack Error | -0.002 | 0.336 | 76,224 |
| VOR/DME Along-Track Error | -0.043 | 0.371 | 76,224 |

TABLE 39. TANGENT POINT TABLE OF MEASURED 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS--GENERAL AVIATION QUALITY SENSOR DATA.

| Perpindicular Distance in Nautical Miles from Tangent Point to VFR | Distance in Nautical Miles Along Track from Tangent Point | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 |
| 0-10(x trk) | 0.2 | 0.4 | 1.1 | 1.7 | --- | --- | --- |
| (alg trk) | 0.2 | 0.3 | 0.3 | 0.4 | --- | --- | --- |
| 10-20(x trk) | 0.3 | 0.4 | 0.7 | 0.9 | --- | --- | --- |
| (alg trk) | 0.6 | 0.5 | 0.5 | 0.4 | --- | --- | --- |
| 20-30(x trk) | 0.3 | 0.7 | 1.0 | 1.2 | --- | --- | --- |
| (alg trk) | 0.7 | 1.0 | 1.0 | 1.0 | --- | --- | --- |
| 30-40(x trk) | 0.4 | --- | --- | --- | --- | --- | --- |
| (alg trk) | 2.4 | --- | --- | --- | --- | --- | --- |
| 40-50(x trk) | --- | --- | --- | --- | --- | --- | --- |
| (alg trk) | --- | --- | --- | --- | --- | --- | --- |
| 50-60(x trk) | --- | --- | --- | --- | --- | --- | --- |
| (alg trk) | --- | --- | --- | --- | --- | --- | --- |
| 60-70(x trk) | --- | --- | --- | --- | --- | --- | --- |
| (alg trk) | --- | --- | --- | --- | --- | --- | --- |

## TABLE 40. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION CROSSTRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--GENERAL AVIATION QUALITY SENSOR DATA

Step 1

Variable Entered ..... 1 (ATD)
Sum of Squares Reduced in this Step ..... 1.830
Proportion Reduced in this Step ........ 0.801
Cumulative Sum of Squares Reduced ....... 1.830
Cumulative Proportion Reduced .......... 0.801 of 2.285
For 1 Variable Entered
Multiple Correlation Coefficient ....... 0.895
(Adjusted for D. F.) .............. 0.895
F-Value for Analysis of Variance ....... 44.144
Standard Error of Estimate ............ 0.204
(Adjusted for D. F.) .............. 0.204

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 1 (ATD) | 0.03273 | 0.00493 | 6.644 |
| Intercept | -0.05060 | | |

Step 2

Variable Entered ..... 2 (TPD)
Sum of Squares Reduced in this Step ..... 0.000
Proportion Reduced in this Step ........ 0.000
Cumulative Sum of Squares Reduced ....... 1.830
Cumulative Proportion Reduced .......... 0.801 of 2.285
For 2 Variables Entered
Multiple Correlation Coefficient ....... 0.895
(Adjusted for D. F.) .............. 0.885
F-Value for Analysis of Variance ...... 20.073
Standard Error of Estimate ............ 0.213
(Adjusted for D. F.) .............. 0.223

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 1 (ATD) | 0.03279 | 0.00527 | 6.224 |
| 2 (TPD) | 0.00035 | 0.00637 | 0.054 |
| Intercept | -0.05941 | | |

## TABLE 41. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR REGRESSION--GENERAL AVIATION QUALITY SENSOR DATA

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Crosstrack |
|---|---|---|---|
| Along-Track Distance | 1.0000 | -0.1960 | 0.8947 |
| Tangent Point Distance | -0.1960 | 1.0000 | -0.1678 |
| 2-Sigma Crosstrack | 0.8947 | -0.1678 | 1.0000 |

## TABLE 42. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--GENERAL AVIATION QUALITY SENSOR DATA

Step 1

Variable Entered ..... 2 (TPD)
Sum of Squares Reduced in this Step ..... 2.905
Proportion Reduced in this Step ........ 0.718
Cumulative Sum of Squares Reduced ....... 2.905
Cumulative Proportion Reduced .......... 0.718 of 4.046
For 1 Variable Entered
Multiple Correlation Coefficient ....... 0.847
(Adjusted for D. F.) .............. 0.847
F-Value for Analysis of Variance ...... 27.988
Standard Error of Estimate ............. 0.322
(Adjusted for D. F.) .............. 0.322

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.04984 | 0.00942 | 5.290 |
| Intercept | -0.36397 | | |

Step 2

Variable Entered ..... 1 (ATD)
Sum of Squares Reduced in this Step ..... 0.033
Proportion Reduced in this Step ........ 0.008
Cumulative Sum of Squares Reduced ....... 2.938
Cumulative Proportion Reduced .......... 0.726 of 4.046
For 2 Variables Entered
Multiple Correlation Coefficient ....... 0.852
(Adjusted for D. F.) .............. 0.837
F-Value for Analysis of Variance ...... 13.250
Standard Error of Estimate ............. 0.333
(Adjusted for D. F.) .............. 0.348

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.04878 | 0.00993 | 4.913 |
| 1 (ATD) | -0.00448 | 0.00822 | -0.546 |
| Intercept | -0.23417 | | |

## TABLE 43. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR REGRESSION--GENERAL AVIATION QUALITY SENSOR DATA

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Along-Track |
|---|---|---|---|
| Along-Track Distance | 1.00000 | -0.1960 | -0.2546 |
| Tangent Point Distance | -0.1960 | 1.0000 | 0.8473 |
| 2-Sigma Along-Track | -0.2546 | 0.8473 | 1.0000 |

TABLE 44. TANGENT POINT TABLE OF 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS GENERATED FROM REGRESSION EQUATIONS--GENERAL AVIATION QUALITY SENSOR DATA

| Perpendicular Distance in Nautical Miles from Tangent Point to VOR | Distance in Nautical Miles Along Track from Tangent Point | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 |
| 0-10(x trk) | 0.3 | 0.6 | 0.9 | 1.3 | 1.6 | 1.9 | 2.2 |
| (alg trk) | 0.2 | 0.2 | 0.1 | 0.1 | 0.0 | 0.0 | -0.1 |
| 10-20(x trk) | 0.3 | 0.6 | 0.9 | 1.3 | 1.6 | 1.9 | 2.2 |
| (alg trk) | 0.7 | 0.7 | 0.6 | 0.6 | 0.5 | 0.5 | 0.4 |
| 20-30(x trk) | 0.3 | 0.6 | 0.9 | 1.3 | 1.6 | 1.9 | 2.2 |
| (alg trk) | 1.2 | 1.1 | 1.1 | 1.1 | 1.0 | 1.0 | 0.9 |
| 30-40(x trk) | 0.3 | 0.6 | 0.9 | 1.3 | 1.6 | 1.9 | 2.2 |
| (alg trk) | 1.7 | 1.6 | 1.6 | 1.5 | 1.5 | 1.4 | 1.4 |
| 40-50(x trk) | 0.3 | 0.6 | 0.9 | 1.3 | 1.6 | 1.9 | 2.3 |
| (alg trk) | 2.2 | 2.1 | 2.1 | 2.0 | 2.0 | 1.9 | 1.9 |
| 50-60(x trk) | 0.3 | 0.6 | 0.9 | 1.3 | 1.6 | 1.9 | 2.3 |
| (alg trk) | 2.6 | 2.6 | 2.6 | 2.5 | 2.5 | 2.4 | 2.4 |
| 60-70(x trk) | 0.3 | 0.6 | 0.9 | 1.3 | 1.6 | 1.9 | 2.3 |
| (alg trk) | 3.1 | 3.1 | 3.0 | 3.0 | 3.0 | 2.9 | 2.9 |

These equations were then used to generate the tangent point table in table 44. The generated table was only carried out to 70 nmi because of the lack of measured data at the longer ranges.

Figures 28 and 29 were then generated to depict crosstrack error and along-track error, respectively, as a function of the predominant variable in the regression equation.

## COMBINED VOR/DME NAVIGATION SOLUTION ERROR DATA FOR BOTH AIR TRANSPORT AND GENERAL AVIATION TYPE SENSORS.

The navigation solution data from the three sets of flight tests were combined. Table 45 presents the statistics from the combined data, while figures 30 and 31 present the distributions for crosstrack and along-track errors. As can be seen, both of these distributions are leptokurtic.

TABLE 45. VOR/DME NAVIGATION SOLUTION ERROR STATISTICS--ALL DATA COMBINED

| | Mean (nmi) | One Standard Deviation (nmi) | Number of Samples |
|---|---|---|---|
| VOR/DME Crosstrack Error | 0.024 | 0.771 | 217,601 |
| VOR/DME Along-Track Error | -0.086 | 0.623 | 217,601 |

The combined measured data were entered into the tangent point table shown in table 46. A regression analysis was run on this combined data. The results of the regression on crosstrack error data are presented in table 47, while the resulting correlation matrix is presented in table 48.

The equation for predicting the 2-sigma crosstrack error can be obtained from the results of the regression:

$$-0.176 + 0.049\ (\mathrm{ATD}) + 0.003\ (\mathrm{TPD}).$$

A similar regression was run on the along-track data. Table 49 presents the results of the regression, while the resulting correlation matrix is presented in table 50.

The equation for predicting the 2-sigma along-track error can be obtained from the results of the regression:

$$-0.744\ \mathrm{nmi} + 0.065\ (\mathrm{TPD})\ \mathrm{nmi} + 0.001\ (\mathrm{ATD})\ \mathrm{nmi}$$

## TABLE 46. TANGENT POINT TABLE OF MEASURED 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS--ALL DATA COMBINED

Perpendicular Distance in Nautical Miles from Tangent Point to VOR

| | Distance in Nautical Miles Along Track from Tangent Point | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 | 120-130 | 130-140 | 140-150 |
| 0-10(x trk) | 0.3 | 0.6 | 1.3 | 1.7 | 2.1 | 2.0 | 2.5 | 3.2 | 3.7 | 4.6 | 4.3 | 5.3 | 3.9 | ---- | ---- |
| (alg trk) | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.1 | 0.2 | ---- | ---- |
| 10-20(x trk) | 0.3 | 0.6 | 1.0 | 1.8 | 2.8 | 2.8 | 3.0 | 2.8 | 3.4 | 8.4 | 4.4 | 9.1 | ---- | ---- | ---- |
| (alg trk) | 0.6 | 0.6 | 0.6 | 0.6 | 0.8 | 0.7 | 0.6 | 0.5 | 0.6 | 1.6 | 0.6 | 1.2 | ---- | ---- | ---- |
| 20-30(x trk) | 0.3 | 1.0 | 1.1 | 1.5 | 2.0 | 2.4 | 6.0 | 5.4 | ---- | 3.2 | 6.5 | 7.0 | ---- | ---- | ---- |
| (alg trk) | 1.3 | 1.4 | 1.1 | 1.2 | 1.1 | 1.0 | 2.0 | 1.7 | ---- | 0.6 | 1.3 | 1.3 | ---- | ---- | ---- |
| 30-40(x trk) | 0.4 | 0.7 | 1.3 | 1.7 | 2.3 | 3.4 | 5.0 | 5.5 | 6.3 | 5.0 | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | 2.1 | 1.6 | 1.7 | 1.6 | 1.8 | 2.1 | 2.3 | 2.4 | 2.3 | 1.9 | ---- | ---- | ---- | ---- | ---- |
| 40-50(x trk) | 0.4 | 0.9 | 1.8 | 2.4 | 2.9 | 2.4 | 3.2 | 2.2 | 3.5 | 5.4 | 3.3 | ---- | ---- | ---- | ---- |
| (alg trk) | 2.2 | 2.3 | 2.9 | 2.7 | 2.4 | 2.0 | 2.3 | 1.6 | 2.2 | 3.3 | 1.6 | ---- | ---- | ---- | ---- |
| 50-60(x trk) | 0.2 | 0.7 | 1.2 | 1.3 | 1.3 | 1.6 | ---- | 4.1 | 5.1 | ---- | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | 3.3 | 2.0 | 2.0 | 1.7 | 1.6 | 1.7 | ---- | 3.0 | 3.2 | ---- | ---- | ---- | ---- | ---- | ---- |
| 60-70(x trk) | 0.5 | 4.0 | 0.6 | 0.0 | 0.0 | 2.3 | 1.9 | 1.9 | 2.5 | 4.5 | 5.0 | ---- | ---- | ---- | ---- |
| (alg trk) | 0.7 | 4.6 | 1.9 | 0.0 | 0.0 | 2.6 | 1.8 | 1.7 | 2.1 | 3.4 | 3.4 | ---- | ---- | ---- | ---- |
| 70-80(x trk) | 0.4 | 0.8 | 1.3 | 1.2 | 1.8 | 1.8 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | 3.2 | 3.2 | 4.0 | 2.8 | 2.5 | 2.3 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 80-90(x trk) | ---- | ---- | 1.2 | 1.0 | ---- | ---- | ---- | ---- | ---- | 4.4 | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | ---- | ---- | 3.6 | 3.0 | ---- | ---- | ---- | ---- | ---- | 4.0 | ---- | ---- | ---- | ---- | ---- |
| 90-100(x trk) | 0.6 | 1.1 | 1.9 | 2.9 | 2.6 | 2.6 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | 0.6 | 3.8 | 6.4 | 8.8 | 6.6 | 4.6 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 100-110(x trk) | 0.2 | ---- | ---- | 2.4 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | 6.0 | ---- | ---- | 8.0 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 110-120(x trk) | 0.7 | 0.7 | 1.5 | 2.1 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | 11.2 | 7.6 | 10.1 | 8.6 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 120-130(x trk) | 0.9 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | 6.0 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 130-140(x trk) | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 140-150(x trk) | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| (alg trk) | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |

## TABLE 47. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION CROSSTRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--ALL DATA COMBINED

**Step 1**

Variable Entered ..... 1 (ATD)
Sum of Squares Reduced in this Step ..... 249.513
Proportion Reduced in this Step ........ 0.738
Cumulative Sum of Squares Reduced ....... 249.513
Cumulative Proportion Reduced .......... 0.738 of 338.086
For 1 Variable Entered
Multiple Correlation Coefficient ....... 0.859
(Adjusted for D. F.) ............... 0.859
F-Value for Analysis of Variance ....... 264.801
Standard Error of Estimate ............ 0.971
(Adjusted for D. F.) .............. 0.971

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 1 (ATD) | 0.04889 | 0.00300 | 16.273 |
| Intercept | -0.15712 | | |

**Step 2**

Variable Entered ..... 2 (TPD)
Sum of Squares Reduced in this Step ..... 0.006
Proportion Reduced in this Step ........ 0.000
Cumulative Sum of Squares Reduced ....... 249.519
Cumulative Proportion Reduced .......... 0.738 of 338.086
For 2 Variables Entered
Multiple Correlation Coefficient ....... 0.859
(Adjusted for D. F.) ............... 0.857
F-Value for Analysis of Variance ...... 131.004
Standard Error of Estimate ............ 0.976
(Adjusted for D. F.) .............. 0.981

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 1 (ATD) | 0.04898 | 0.00326 | 15.030 |
| 2 (TPD) | 0.00026 | 0.00336 | 0.079 |
| Intercept | -0.17594 | | |

## TABLE 48. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR REGRESSION--ALL DATA COMBINED

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Crosstrack |
|---|---|---|---|
| Along-Track Distance | 1.00000 | -0.37573 | 0.85908 |
| Tangent Point Distance | -0.37573 | 1.00000 | -0.31891 |
| 2-Sigma Crosstrack | 0.85908 | -0.31891 | 1.00000 |

## TABLE 49. RESULTS OF REGRESSION ANALYSIS OF VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERRORS, ALONG-TRACK DISTANCE, AND TANGENT POINT DISTANCE--ALL DATA COMBINED

Step 1

| | | |
|---|---|---|
| Variable Entered ..... 2 (TPD) | | |
| Sum of Squares Reduced in this Step ..... | 412.470 | |
| Proportion Reduced in this Step ........ | 0.577 | |
| Cumulative Sum of Squares Reduced ....... | 412.470 | |
| Cumulative Proportion Reduced .......... | 0.577 | of 714.729 |
| For 1 Variable Entered | | |
| Multiple Correlation Coefficient ....... | 0.760 | |
| (Adjusted for D. F.) ................ | 0.760 | |
| F-Value for Analysis of Variance ...... | 128.274 | |
| Standard Error of Estimate ............ | 1.793 | |
| (Adjusted for D. F.) ................ | 1.793 | |

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.06482 | 0.00572 | 11.326 |
| Intercept | -0.65789 | | |

Step 2

| | | |
|---|---|---|
| Variable Entered ..... 1 (ATD) | | |
| Sum of squares Reduced in this Step ..... | 0.120 | |
| Proportion Reduced in this Step ........ | 0.000 | |
| Cumulative Sum of Squares Reduced ....... | 412.590 | |
| Cumulative Proportion Reduced .......... | 0.577 | of 714.729 |
| For 2 Variables Entered | | |
| Multiple Correlation Coefficient ....... | 0.760 | |
| (Adjusted for D. F.) ................ | 0.757 | |
| F-Value for Analysis of Variance ...... | 63.498 | |
| Standard Error of Estimate ............ | 1.802 | |
| (Adjusted for D. F.) ................ | 1.812 | |

| Variable Number | Regression Coefficient | Std. Error of Reg. Coeff. | Computed T-Value |
|---|---|---|---|
| 2 (TPD) | 0.06527 | 0.00621 | 10.514 |
| 1 (ATD) | 0.00116 | 0.00602 | 0.192 |
| Intercept | -0.74434 | | |

## TABLE 50. CORRELATION MATRIX FROM VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR REGRESSION--ALL DATA COMBINED

| | Along-Track Distance | Tangent Point Distance | 2-Sigma Crosstrack |
|---|---|---|---|
| Along-Track Distance | 1.0000 | -0.3747 | -0.2734 |
| Tangent Point Distance | -0.3757 | 1.0000 | -0.7597 |
| 2-Sigma Crosstrack | -0.2734 | -0.7597 | 1.0000 |

These two equations were then used to generate the tangent point table in table 51. All the flight test data from the three different flight tests went into generating this table.

Figures 32 and 33 were also generated from the regression equations, but in each case, the factor which was the least significant term in the equation was eliminated. For figure 32, the least significant term was tangent point distance. For figure 33, along-track error, the least significant term was along-track distance.

## COMPARISON OF ADVISORY CIRCULAR 90-45A TANGENT POINT TABLE AND TANGENT POINT CALCULATED FROM REGRESSION EQUATION.

In order to compare the Advisory Circular 90-45A tangent point table to the tangent point table generated from a regression analysis of all data collected in the RNAV flight tests, a differential tangent point table was constructed. The table was constructed by taking a value in a discrete interval from the regression tangent point table and subtracting this value from the value in the corresponding interval in the Advisory Circular 90-45A tangent point table (Advisory Circular 90-45A TPT Value minus Regression TPT Value). The resulting table allows an immediate comparison of the differences between the Advisory Circular 90-45A and the regression tangent point tables.

The results are contained in table 52. As can be seen from the table, there are no negative values in this table. This means that in all cases, the Advisory Circular 90-45A tangent point table offers a more conservative figure than the table generated from the regression analysis.

## DME/DME NAVIGATION SOLUTION ERRORS.

A total of 28 RNAV flights were conducted with dual air transport quality DME used as the radio sensor inputs to the RNAV system. As part of the data analysis, a position was computed from the two DME ranges and was compared to the actual position derived from radar tracking. This provided quantitative data with respect to the DME/DME navigational solution errors.

Statistical data for crosstrack and along-track errors associated with a DME/DME position solution in the terminal area are shown in table 53. Figure 34 is a histogram of the DME/DME crosstrack errors, while figure 35 is a histogram of the DME/DME along-track errors. A normal curve is fitted to each of the histograms.

## TABLE 51. TANGENT POINT TABLE OF 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS GENERATED FROM REGRESSION EQUATIONS--ALL DATA COMBINED

| Perpendicular Distance in Nautical Miles from Tangent Point to VOR | Distance in Nautical Miles Along Track from Tangent Point | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 | 120-130 | 130-140 | 140-150 |
| 0-10(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.7 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | -0.1 | -0.1 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| 10-20(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.7 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| 20-30(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 1.2 | 1.2 | 1.2 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.4 | 1.4 | 1.4 | 1.4 |
| 30-40(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| 40-50(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 2.5 | 2.5 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.7 | 2.7 | 2.7 | 2.7 |
| 50-60(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.2 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 |
| 60-70(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 3.8 | 3.8 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 3.9 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| 70-80(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.5 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.6 | 4.7 |
| 80-90(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 5.1 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.2 | 5.3 | 5.3 | 5.3 | 5.3 |
| 90-100(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.7 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 5.8 | 5.8 | 5.8 | 5.8 | 5.8 | 5.9 | 5.9 | 5.9 | 5.9 | 5.9 | 5.9 | 5.9 | 5.9 | 5.9 | 6.0 |
| 100-110(x trk) | 0.3 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.2 | 4.8 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 6.4 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.6 | 6.6 | 6.6 | 6.6 | 6.6 |
| 110-120(x trk) | 0.4 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.8 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 7.1 | 7.1 | 7.1 | 7.1 | 7.1 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.3 | 7.3 |
| 120-130(x trk) | 0.4 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.8 | 4.8 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.8 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 | 7.9 |
| 130-140(x trk) | 0.4 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.8 | 5.2 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 8.4 | 8.4 | 8.4 | 8.4 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.5 | 8.6 | 8.6 |
| 140-150(x trk) | 0.4 | 0.8 | 1.3 | 1.8 | 2.3 | 2.8 | 3.3 | 3.8 | 4.3 | 4.8 | 5.3 | 5.7 | 6.2 | 6.7 | 7.2 |
| (alg trk) | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | 9.1 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 |

TABLE 52. TANGENT POINT TABLE OF THE DIFFERENCE BETWEEN THE 2-SIGMA VOR/DME NAVIGATION SOLUTION ERRORS OF THE ADVISORY CIRCULAR 90-45A TANGENT POINT TABLE (TABLE 23) AND TABLE 51

Distance in Nautical Miles Along-Track from Tangent Point

Perpendicular Distance in Nautical Miles from Tangent Point to VOR

| | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 | 70-80 | 80-90 | 90-100 | 100-110 | 110-120 | 120-130 | 130-140 | 140-150 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0-10(x trk) | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.1 | 1.3 | 1.4 | 1.5 | 1.6 | 1.7 | 1.9 | 2.0 | 2.1 |
| (alg trk) | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.9 | 2.2 | 2.5 | 2.8 | 3.1 | 3.4 | 3.7 | 3.9 | 4.1 | 4.4 |
| 10-20(x trk) | 0.6 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.3 | 1.4 | 1.5 | 1.6 | 1.8 | 1.9 | 2.0 | 2.1 |
| (alg trk) | 0.7 | 0.8 | 0.9 | 1.1 | 1.3 | 1.6 | 1.8 | 2.0 | 2.3 | 2.5 | 2.8 | 3.1 | 3.4 | 3.7 | 4.0 |
| 20-30(x trk) | 0.8 | 0.7 | 0.8 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 |
| (alg trk) | 0.7 | 0.8 | 0.9 | 0.9 | 1.1 | 1.3 | 1.5 | 1.7 | 2.0 | 2.2 | 2.5 | 2.7 | 2.9 | 3.2 | 3.5 |
| 30-40(x trk) | 1.1 | 0.9 | 0.9 | 1.0 | 1.0 | 1.1 | 1.2 | 1.3 | 1.5 | 1.6 | 1.7 | 1.8 | 2.0 | 2.1 | 2.2 |
| (alg trk) | 0.6 | 0.7 | 0.7 | 0.9 | 1.0 | 1.2 | 1.4 | 1.5 | 1.7 | 1.9 | 2.1 | 2.4 | 2.6 | 2.9 | 3.1 |
| 40-50(x trk) | 1.3 | 0.9 | 0.9 | 1.1 | 1.1 | 1.2 | 1.3 | 1.4 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 |
| (alg trk) | 0.6 | 0.7 | 0.6 | 0.7 | 0.8 | 1.0 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 | 2.8 |
| 50-60(x trk) | 1.6 | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.4 | 1.5 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 |
| (alg trk) | 0.5 | 0.6 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.3 | 1.5 | 1.7 | 1.9 | 2.1 | 2.3 | 2.5 |
| 60-70(x trk) | 1.8 | 1.6 | 1.5 | 1.5 | 1.4 | 1.5 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2.0 | 2.1 | 2.2 | 2.3 |
| (alg trk) | 0.6 | 0.6 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.1 | 1.2 | 1.4 | 1.5 | 1.6 | 1.8 | 2.0 | 2.3 |
| 70-80(x trk) | 2.2 | 1.9 | 1.7 | 1.7 | 1.6 | 1.6 | 1.7 | 1.7 | 1.8 | 2.0 | 2.0 | 2.1 | 2.2 | 2.3 | 2.4 |
| (alg trk) | 0.5 | 0.5 | 0.5 | 0.6 | 0.7 | 0.8 | 0.8 | 0.9 | 1.0 | 1.2 | 1.4 | 1.5 | 1.7 | 1.9 | 2.0 |
| 80-90(x trk) | 2.5 | 2.2 | 2.0 | 1.9 | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 | 2.1 | 2.1 | 2.2 | 2.3 | 2.4 | 2.6 |
| (alg trk) | 0.5 | 0.4 | 0.5 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.3 | 1.3 | 1.5 | 1.7 | 1.9 |
| 90-100(x trk) | 2.8 | 2.6 | 2.2 | 2.1 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.2 | 2.3 | 2.3 | 2.4 | 2.5 | 2.6 |
| (alg trk) | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 | 0.8 | 0.9 | 1.0 | 1.1 | 1.3 | 1.4 | 1.6 | 1.8 |
| 100-110(x trk) | 3.1 | 2.7 | 2.5 | 2.3 | 2.2 | 2.2 | 2.2 | 2.2 | 2.3 | 2.2 | 2.4 | 2.4 | 2.5 | 2.6 | 2.7 |
| (alg trk) | 0.4 | 0.3 | 0.4 | 0.4 | 0.5 | 0.6 | 0.6 | 0.7 | 0.8 | 1.0 | 1.0 | 1.1 | 1.3 | 1.4 | 1.6 |
| 110-120(x trk) | 3.3 | 3.0 | 2.8 | 2.6 | 2.5 | 2.4 | 2.3 | 2.3 | 2.3 | 2.4 | 2.5 | 2.6 | 2.6 | 2.7 | 2.8 |
| (alg trk) | 0.3 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.1 | 1.2 | 1.2 | 1.4 |
| 120-130(x trk) | 3.6 | 3.3 | 3.0 | 2.8 | 2.7 | 2.6 | 2.5 | 2.5 | 2.5 | 2.5 | 2.7 | 2.7 | 2.8 | 2.8 | 2.9 |
| (alg trk) | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 0.7 | 0.7 | 0.8 | 0.9 | 1.1 | 1.2 | 1.2 |
| 130-140(x trk) | 3.8 | 3.6 | 3.3 | 3.1 | 2.9 | 2.8 | 2.7 | 2.7 | 2.7 | 2.7 | 2.8 | 2.8 | 2.9 | 2.9 | 3.0 |
| (alg trk) | 0.3 | 0.3 | 0.3 | 0.4 | 0.3 | 0.4 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.0 | 1.2 |
| 140-150(x trk) | 4.1 | 3.9 | 3.6 | 3.3 | 3.3 | 3.0 | 3.0 | 2.9 | 2.9 | 2.9 | 2.9 | 3.0 | 3.0 | 3.1 | 3.1 |
| (alg trk) | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 |

TABLE 53. DME/DME NAVIGATION SOLUTION ERROR STATISTICS

| | Mean (nmi) | One Standard Deviation (nmi) | Number of *Samples* |
|---|---|---|---|
| Crosstrack | 0.023 | 0.126 | 38,693 |
| Along-Track | 0.005 | 0.155 | 38,693 |

Figure 36 is used to illustrate the geometry of the DME/DME solution and the effect of the included angle between the two DME stations and the aircraft. In these illustrations, the angle θ is formed by the intersection of the lines drawn from the DME stations to the aircraft position. In figure 36A, the angle θ is approximately 90°, and the positions defined by the intersection of the circles of DME range are sharply defined. The ambiguous solution is sufficiently distant from the primary solution so that the ambiguous solution can be discarded by utilizing a VOR bearing or by comparing the two solutions to the approximate position of the aircraft as derived through dead reckoning. Also, small errors in DME range have the least effect in terms of causing errors in the DME/DME solution.

In figure 36B, where the angle θ approaches 180°, and in figure 36C, where the angle θ approaches 0°, the situation is quite different. Neither of the two solutions are sharply defined, and they are close enough to each other so that it may be difficult to discriminate against the ambiguous solution. Also, DME errors will have the largest effect in terms of causing errors in the DME/DME solution.

The effects of the included angle on the solution error is illustrated by figures 37 and 38. These figures illustrate the error for crosstrack and along-track solutions, respectively, as a function of the included angle.

## SUMMARY OF TEST RESULTS

1. Combined ground and airborne sensor errors for air transport quality DME resulted in a mean of -0.08 nmi, with a one standard deviation of 0.1 nmi.

2. Combined ground and airborne sensor errors for air transport quality VOR resulted in a mean of -0.3° with a one standard deviation of 1.5°.

3. The error distributions from the air transport quality VOR and DME equipments are leptokurtic.

4. Combined ground and airborne sensor errors for general aviation quality DME resulted in a mean of -0.03 nmi with a one standard deviation of 0.14 nmi.

5. Combined ground and airborne sensor errors for general aviation quality VOR resulted in a mean of 0.06° with a one standard deviation of 1.1°.

6. The general aviation quality VOR error distribution is leptokurtic; the DME error distribution is normal.

7. The combined ground and airborne sensor errors for all combined DME data resulted in a mean of -0.07 nmi with a one standard deviation of 0.11 nmi.

8. The combined ground and airborne sensor errors for all combined VOR data resulted in a mean of -0.2° with a one standard deviation of 1.4°.

9. Navigation solutions in the terminal area using air transport quality sensors for VOR/DME radio information resulted in positional errors as follows:

| | Mean (nmi) | One Standard Deviation (nmi) | Samples |
|---|---|---|---|
| Crosstrack | 0.038 | 0.923 | 141,514 |
| Along-Track | -0.109 | 0.721 | 141,514 |

Distributions of both crosstrack and along-track VOR/DME navigation solution errors were leptokurtic.

10. Navigation solutions in the terminal area using general aviation quality sensors for VOR/DME radio information resulted in positional error as follows:

| | Mean (nmi) | One Standard Deviation (nmi) | Samples |
|---|---|---|---|
| Crosstrack | -0.002 | 0.336 | 76,224 |
| Along-Track | -0.043 | 0.371 | 76,224 |

Distributions of crosstrack and along-track VOR/DME navigation errors were leptokurtic.

11. Combined navigation solutions in the terminal area for all data resulted in positional errors as follows:

| | Mean (nmi) | One Standard Deviation (nmi) | Samples |
|---|---|---|---|
| Crosstrack | 0.024 | 0.771 | 217,601 |
| Along-Track | -0.086 | 0.623 | 217,601 |

12. Navigation solutions in the terminal area using DME/DME radio information resulted in positional errors as follows:

| | Mean (nmi) | One Standard Deviation (nmi) | Samples |
|---|---|---|---|
| Crosstrack | 0.023 | 0.126 | 38,693 |
| Along-Track | 0.005 | 0.155 | 38,693 |

# CONCLUSIONS

From the results, it is concluded that:

1. The combined ground station and airbone sensor errors for air transport type VOR sensors resulted in a 2-sigma value of 3.1°. This compares favorably with the 2-sigma value of 3.55° (±1.9° ground and ±3.0° airborne combined using root-sum-square) used in Advisory Circular 90-45A.

2. The combined ground station and airborne sensor errors for air transport type DME sensors resulted in a 2-sigma value of 0.2 nmi. This measured error is less than the Advisory Circular 90-45A budget of 0.51 nmi (±0.1 nmi ground and ±0.5 nmi maximum airborne).

3. The combined ground station and airborne sensor errors for general aviation type VOR sensors resulted in a 2-sigma value of 2.2° over the measured distance. This measured error is less than the Advisory Circular 90-45A budget of 3.55° (±1.9 ground and ±3.0° maximum airborne).

4. The combined ground station and airborne sensor errors for general aviation type DME sensors resulted in a 2-sigma value of 0.28 nmi over the measured distance. This measured error is less than Advisory Circular 90-45A budget of 0.41 nmi (±0.1 nmi ground and ±0.5 nmi maximum airborne).

5. The results of the comparison between the tangent point table generated from Advisory Circular 90-45A VOR and DME 2-sigma errors and the tangent point table generated from a regression of measured errors indicates in table 56 the measured crosstrack and along-track errors to be less than those in the tangent point table generated from the Advisory Circular 90-45A sensor error budget.

6. The VOR data as presented in tables 4 and 8 indicate that there is no significant degradation of shallow-angle signals in the terminal and approach areas. This conclusion is limited to approaches where the VOR is collocated at the field to which the approach is being made.

7. Comparisons between DME/DME and VOR/DME crosstrack and along-track navigation error solutions indicate the DME/VOR errors to be four times as great.

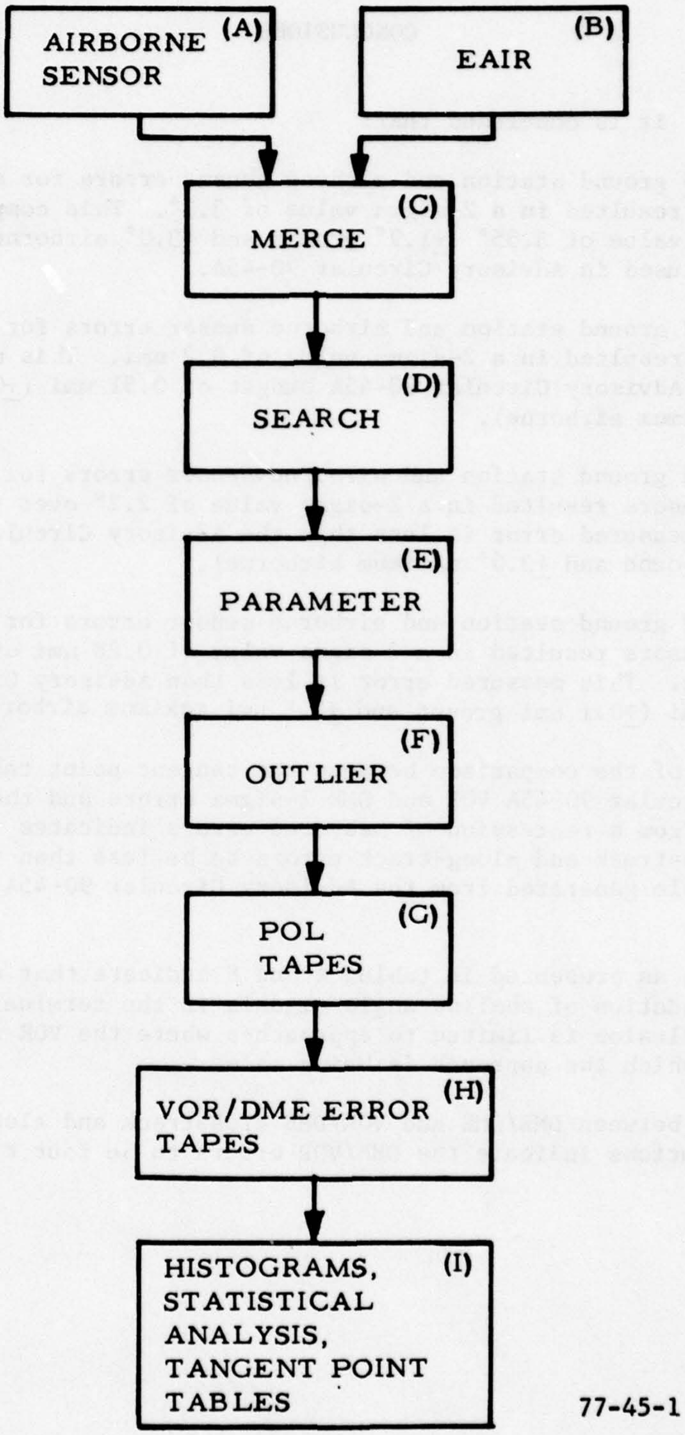

FIGURE 1. DATA PROCESSING PROCEDURES

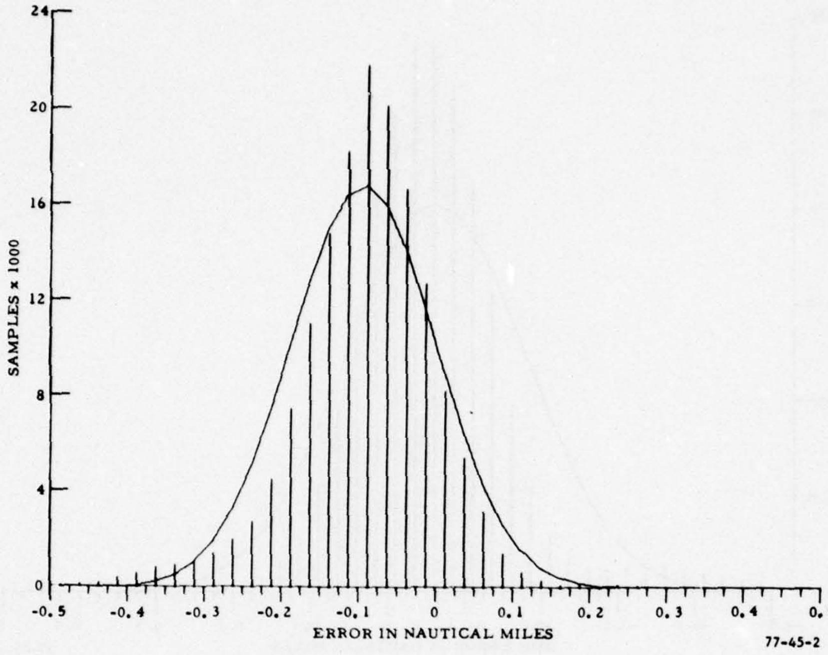

FIGURE 2. DME ERROR DISTRIBUTION FOR AIR TRANSPORT QUALITY SENSORS--TEST I

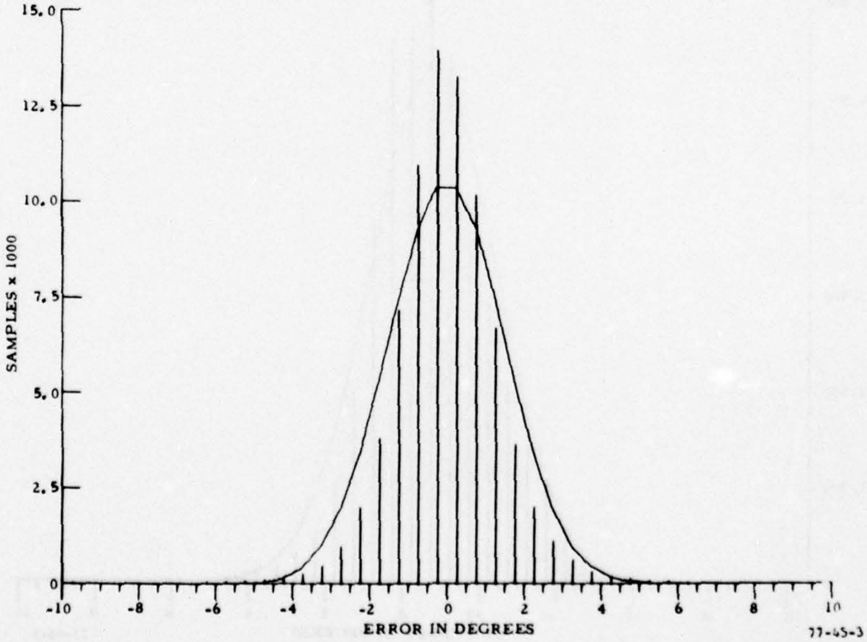

FIGURE 3. VOR ERROR DISTRIBUTION FOR AIR TRANSPORT QUALITY SENSORS--TEST I

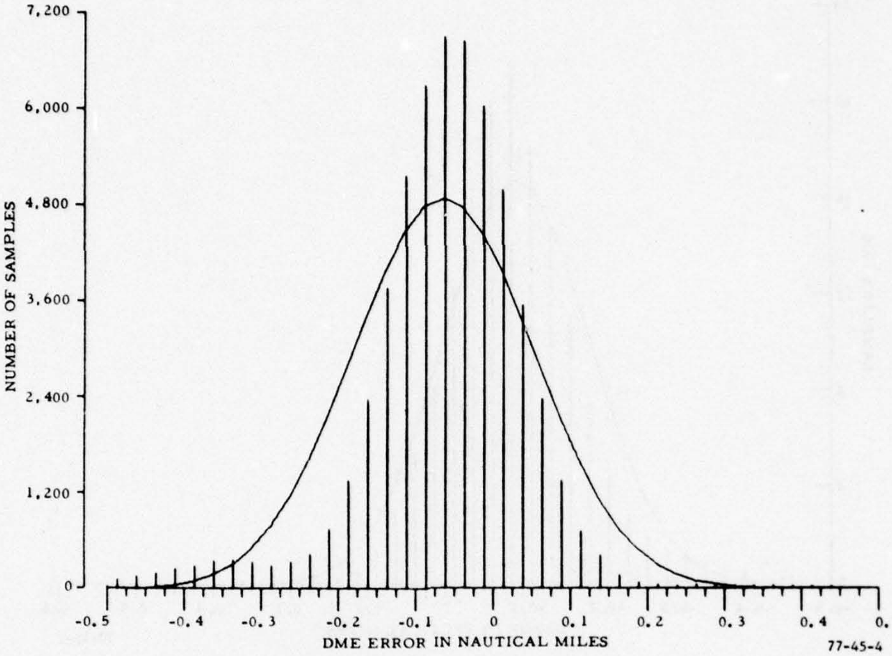

FIGURE 4. DME ERROR DISTRIBUTION FOR AIR TRANSPORT QUALITY SENSORS--TEST II

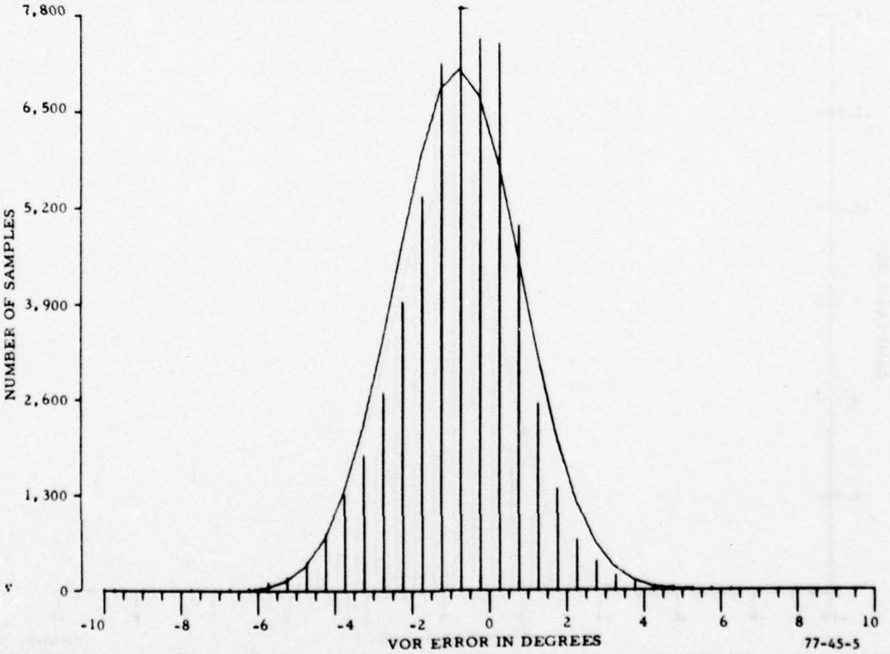

FIGURE 5. VOR ERROR DISTRIBUTION FOR AIR TRANSPORT QUALITY SENSORS--TEST II

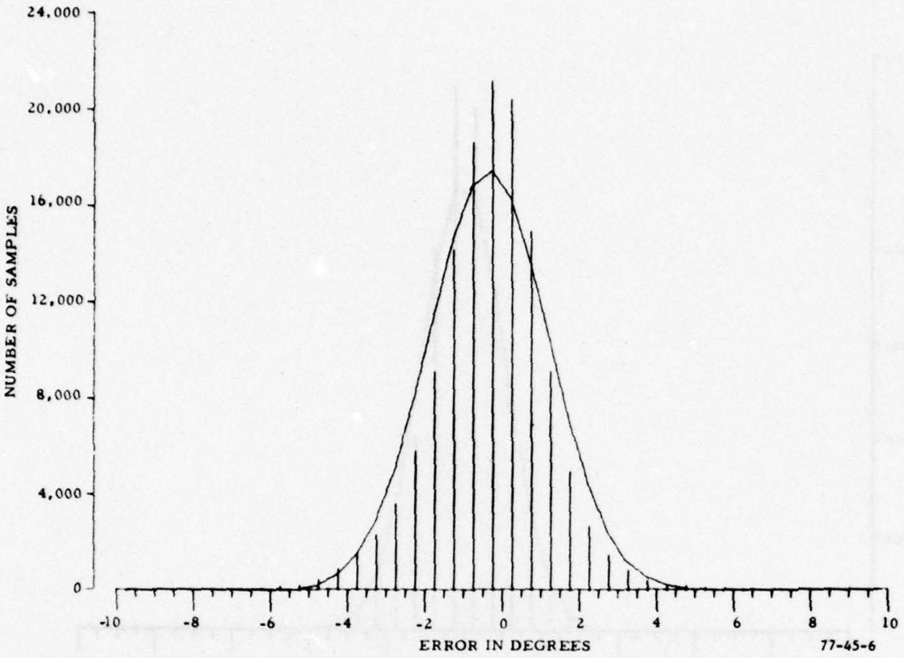

FIGURE 6. VOR ERROR DISTRIBUTION FOR COMBINED AIR TRANSPORT QUALITY SENSOR DATA

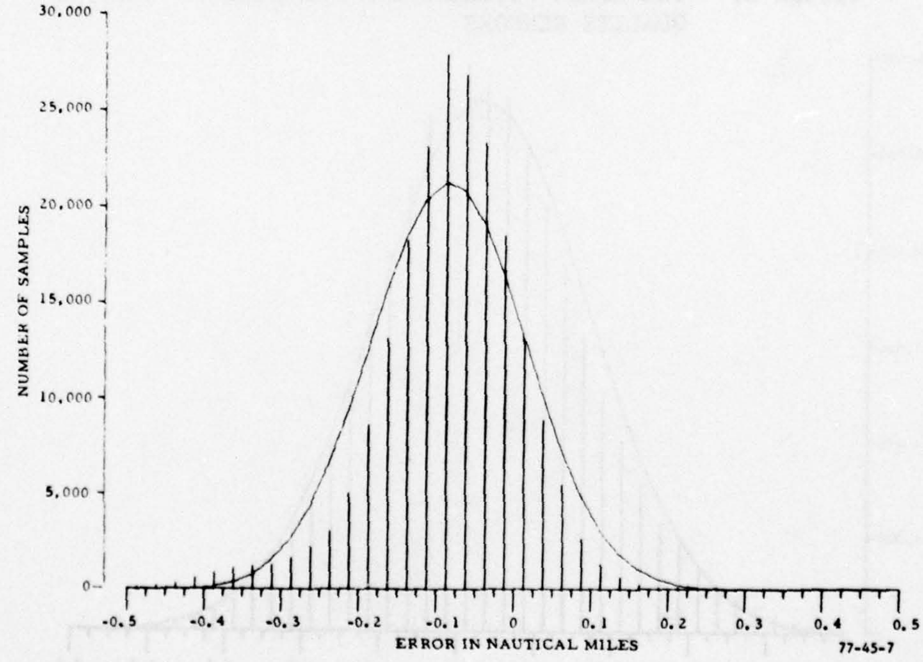

FIGURE 7. DME ERROR DISTRIBUTION FOR COMBINED AIR TRANSPORT QUALITY SENSOR DATA

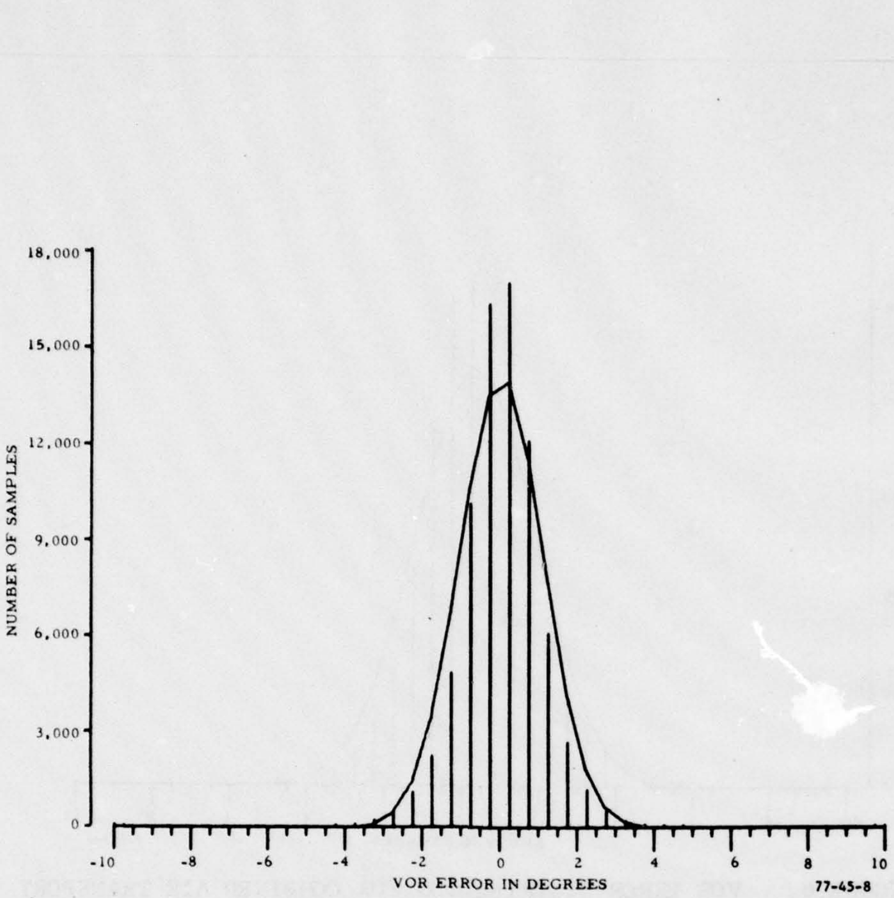

FIGURE 8. VOR ERROR DISTRIBUTION FOR GENERAL AVIATION QUALITY SENSORS

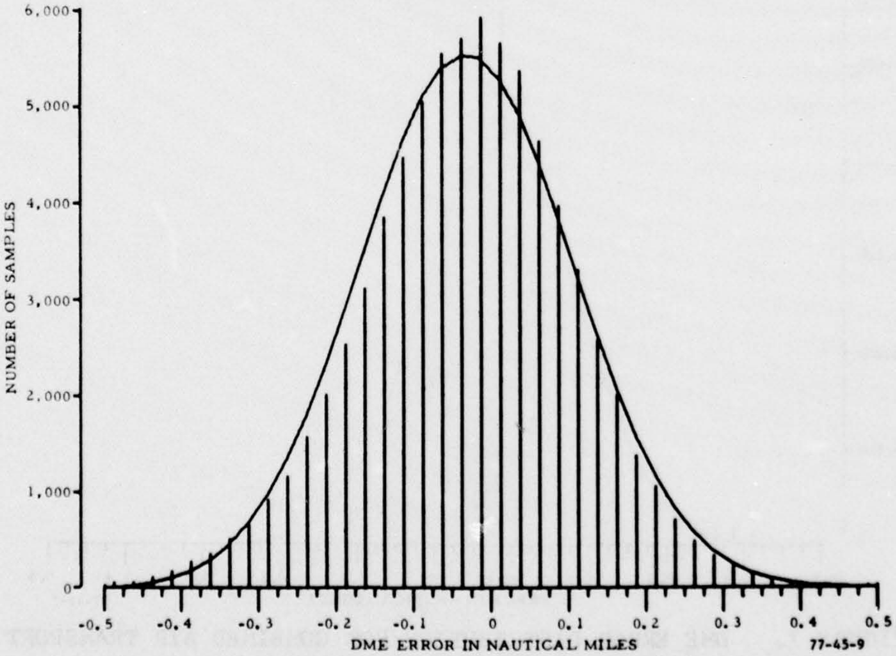

FIGURE 9. DME ERROR DISTRIBUTION FOR GENERAL AVIATION QUALITY SENSORS

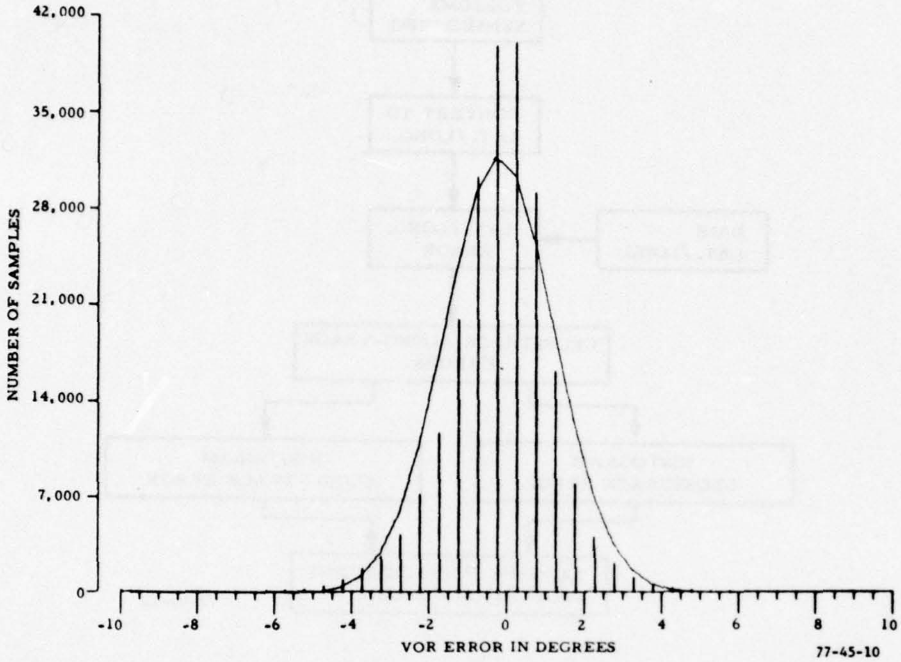

**FIGURE 10.** VOR ERROR DISTRIBUTION FOR COMBINED AIR TRANSPORT AND GENERAL AVIATION QUALITY SENSORS

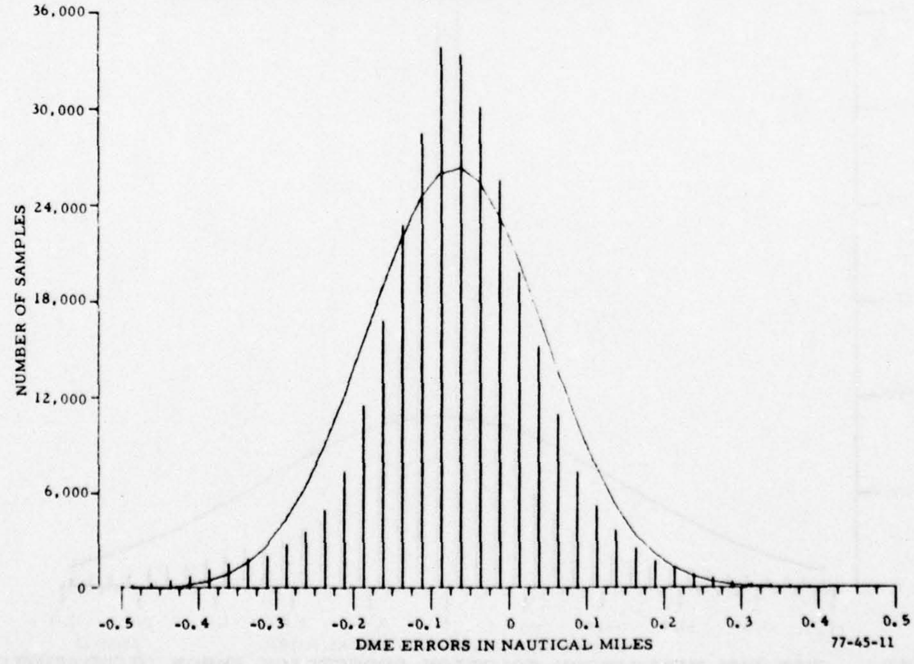

**FIGURE 11.** DME ERROR DISTRIBUTION FOR COMBINED AIR TRANSPORT AND GENERAL AVIATION QUALITY SENSORS

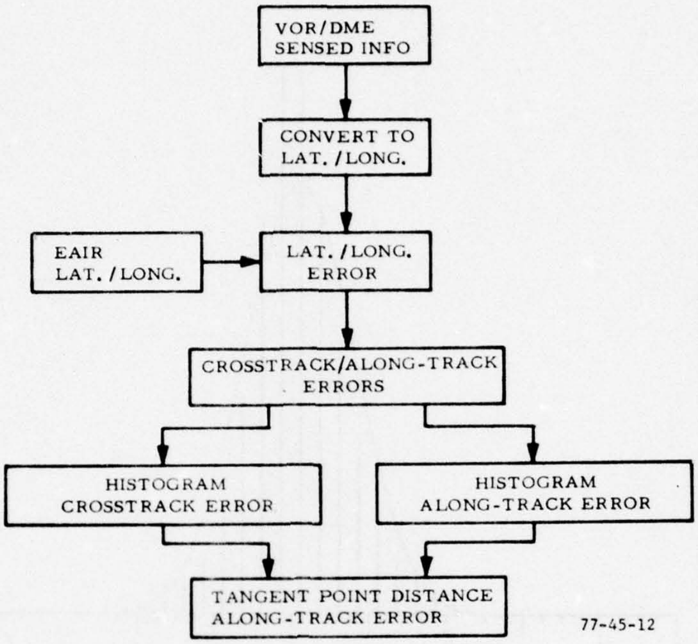

FIGURE 12. NAVIGATION SOLUTIONS FLOW DIAGRAM

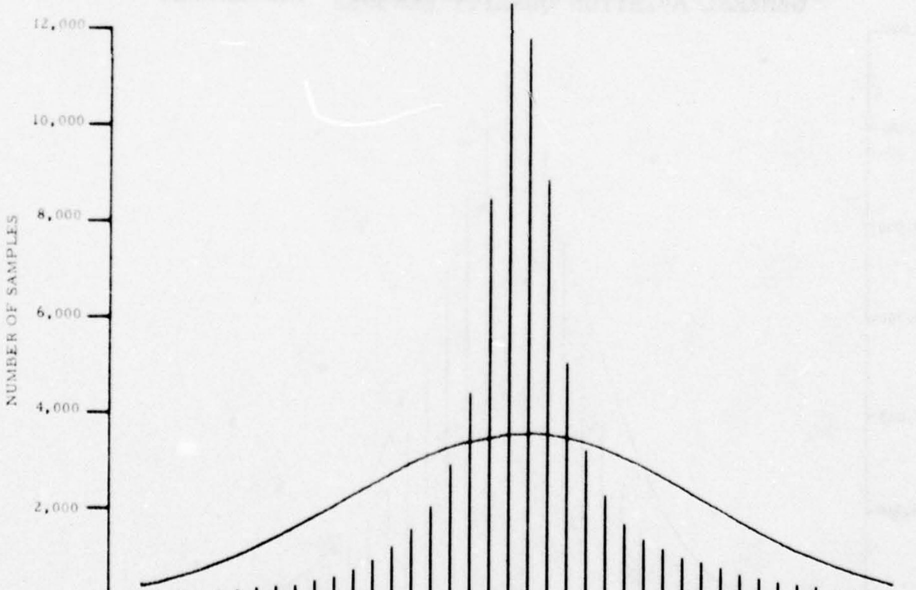

FIGURE 13. VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR DISTRIBUTION--AIR TRANSPORT QUALITY SENSORS--TEST I

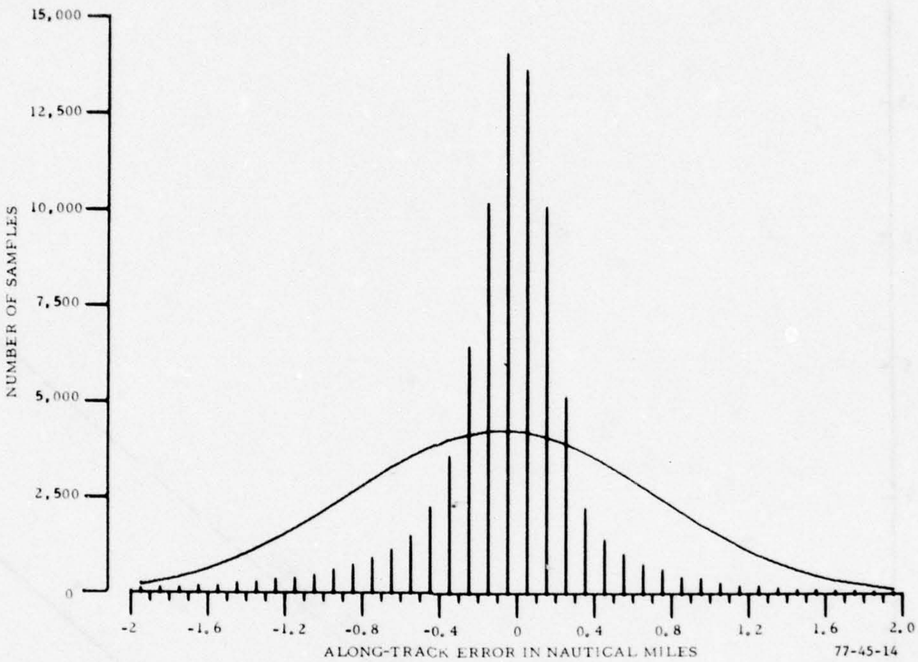

**FIGURE 14.** **VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR DISTRIBUTION--AIR TRANSPORT QUALITY SENSORS--TEST I**

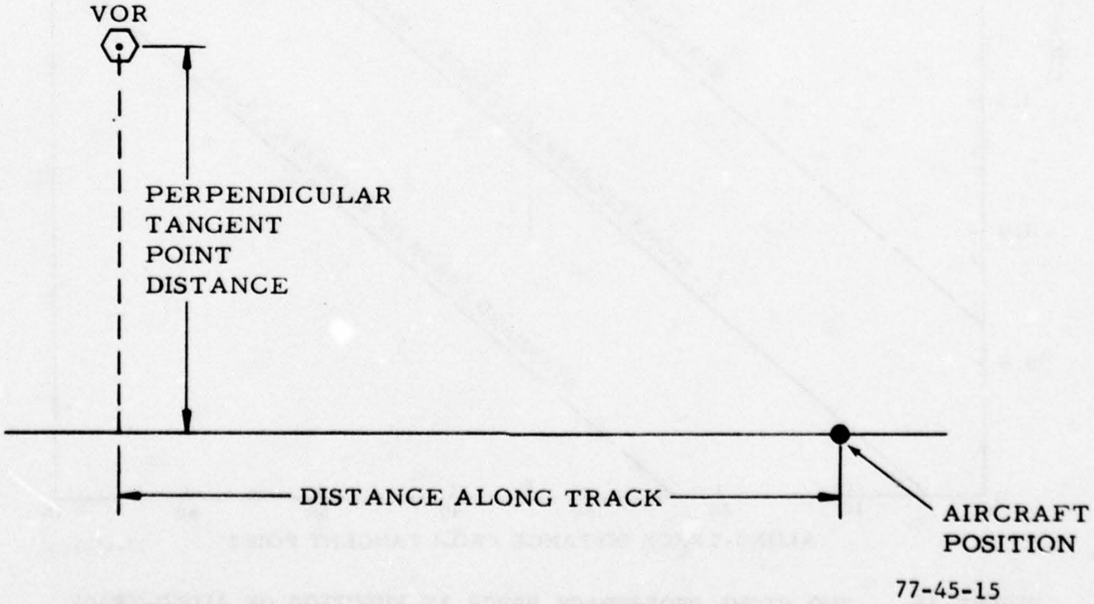

**FIGURE 15.** **ILLUSTRATION OF TANGENT POINT DISTANCE AND ALONG-TRACK DISTANCE**

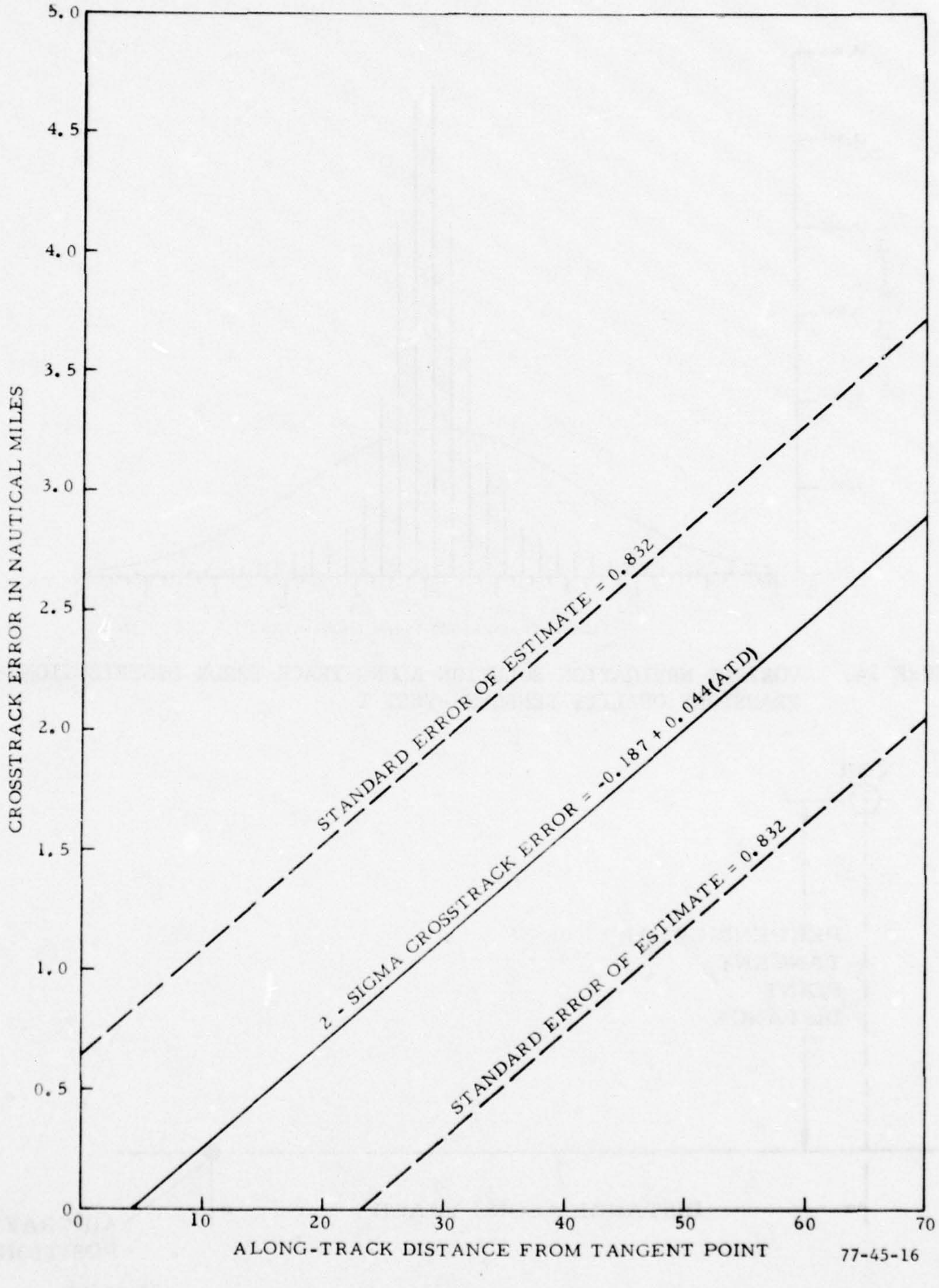

**FIGURE 16.** TWO-SIGMA CROSSTRACK ERROR AS FUNCTION OF ALONG-TRACK DISTANCE--AIR TRANSPORT QUALITY SENSORS--TEST I

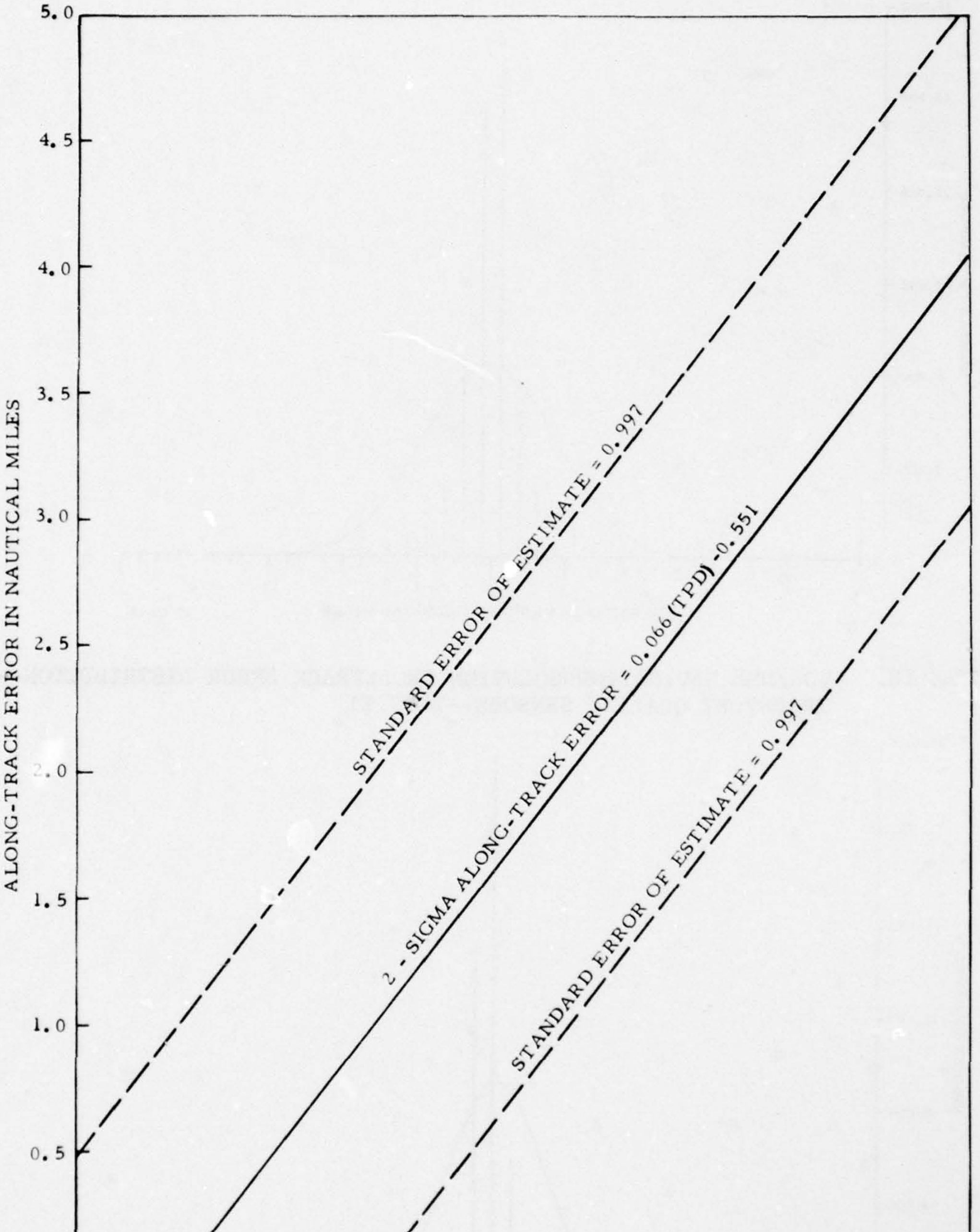

**FIGURE 17.** TWO-SIGMA ALONG-TRACK ERROR AS FUNCTION OF TANGENT POINT DISTANCE--AIR TRANSPORT QUALITY SENSORS--TEST I

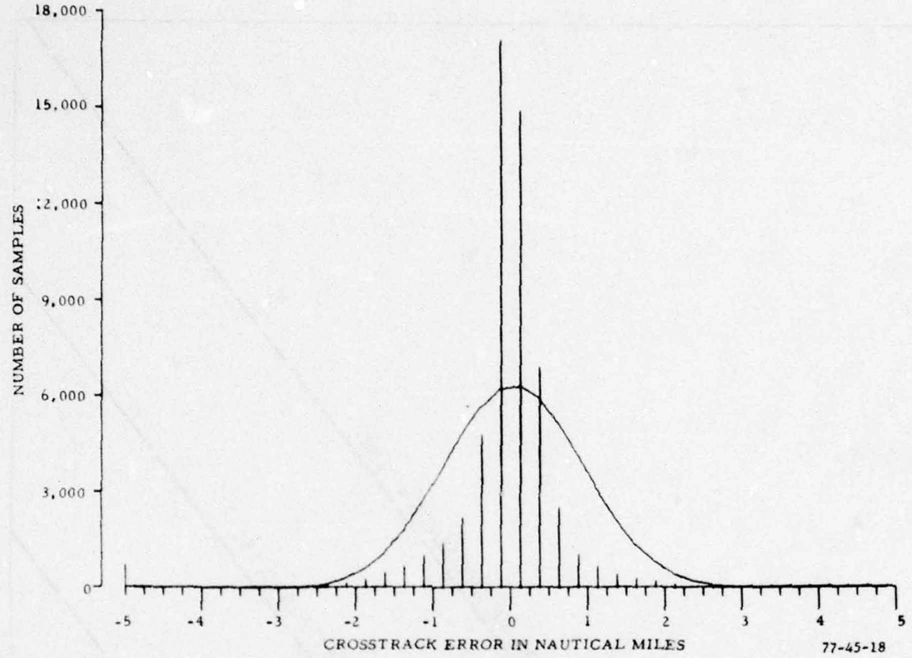

FIGURE 18. VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR DISTRIBUTION--AIR TRANSPORT QUALITY SENSORS--TEST II

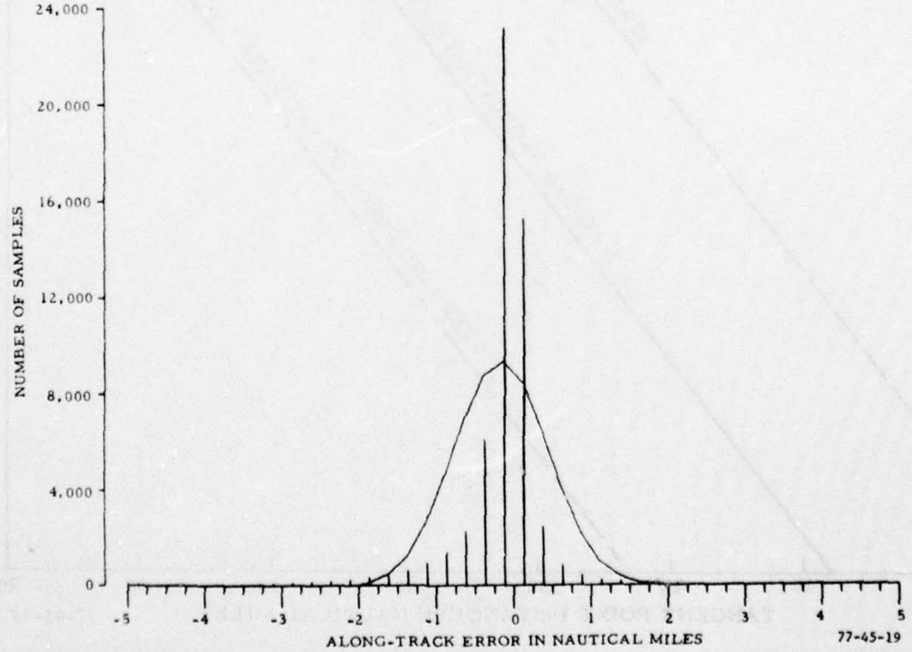

FIGURE 19. VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR DISTRIBUTION--AIR TRANSPORT QUALITY SENSORS--TEST II

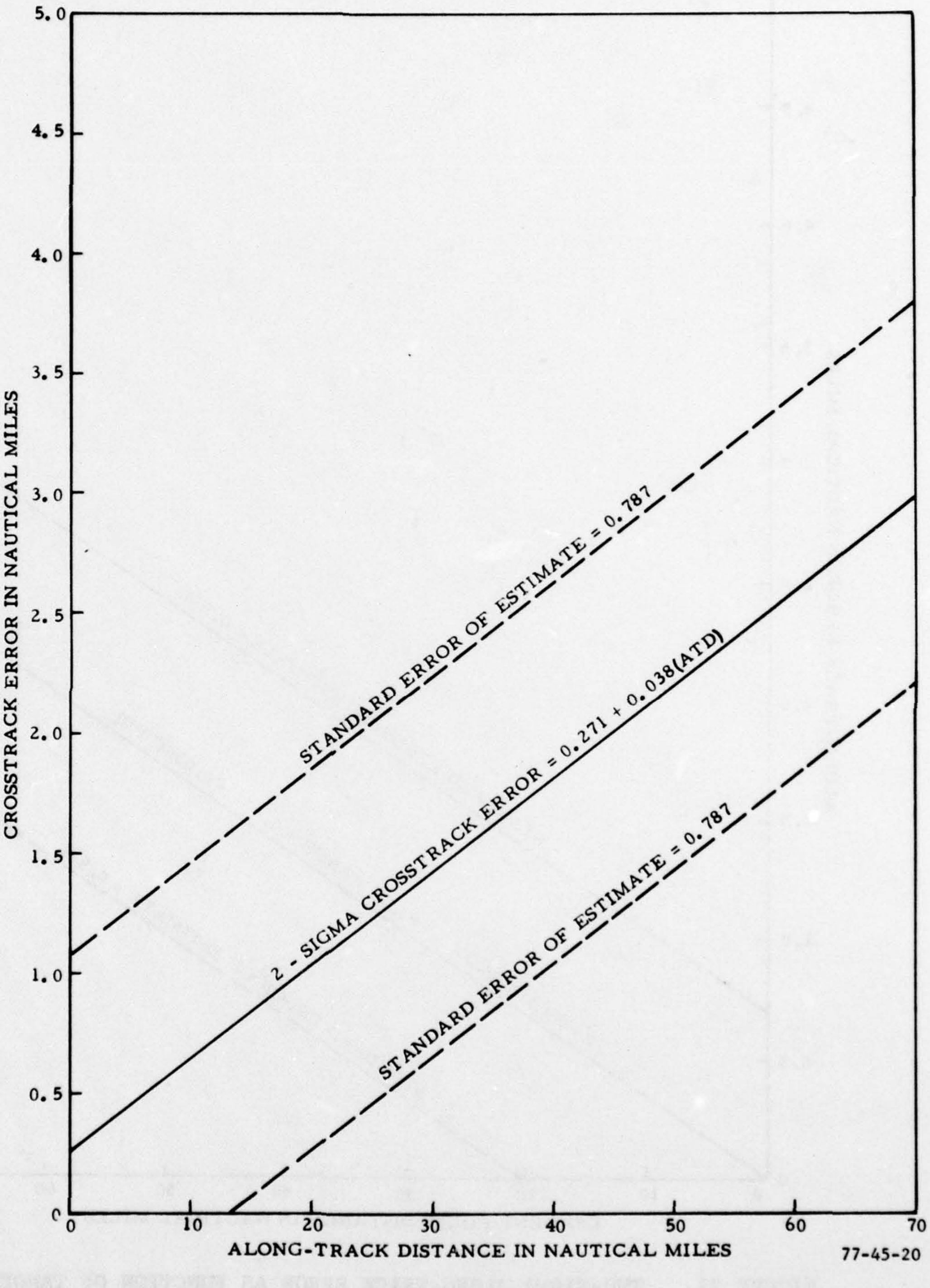

**FIGURE 20.** TWO-SIGMA CROSSTRACK ERROR AS FUNCTION OF ALONG-TRACK DISTANCE--AIR TRANSPORT QUALITY SENSORS--TEST II

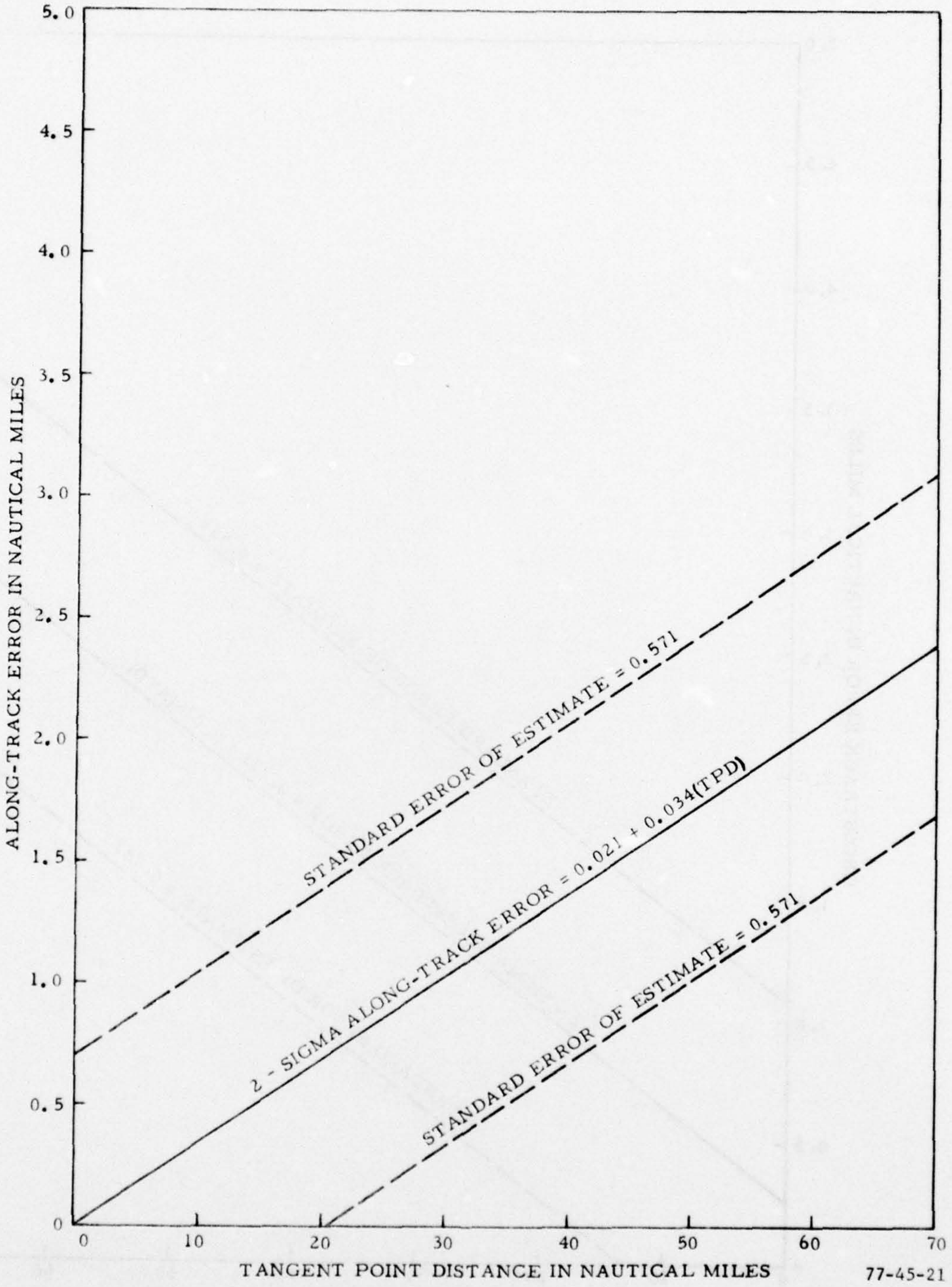

FIGURE 21. TWO-SIGMA ALONG-TRACK ERROR AS FUNCTION OF TANGENT POINT DISTANCE--AIR TRANSPORT QUALITY SENSOR--TEST II

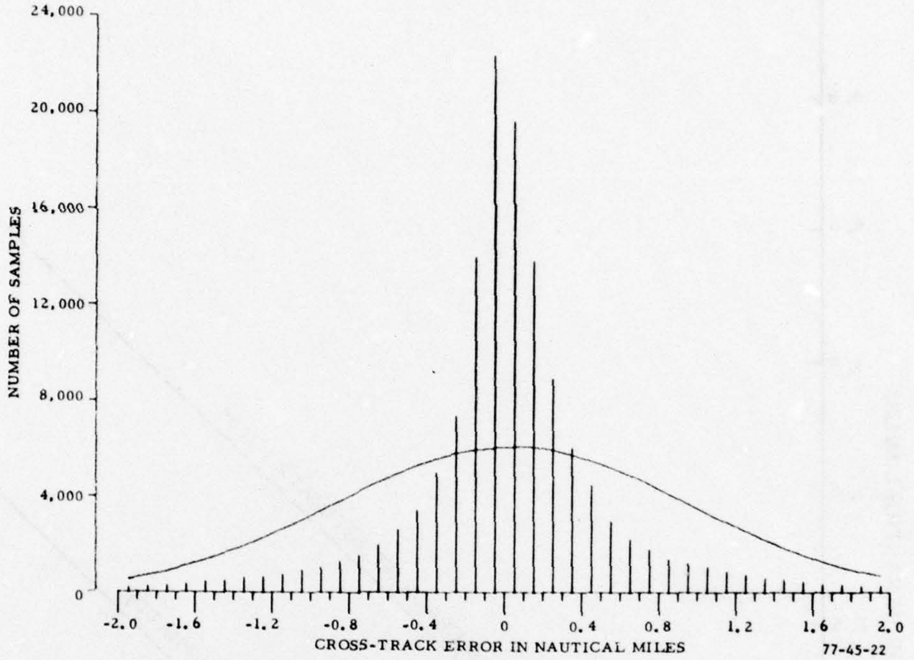

FIGURE 22. VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR DISTRIBUTION COMBINED AIR TRANSPORT QUALITY SENSORS

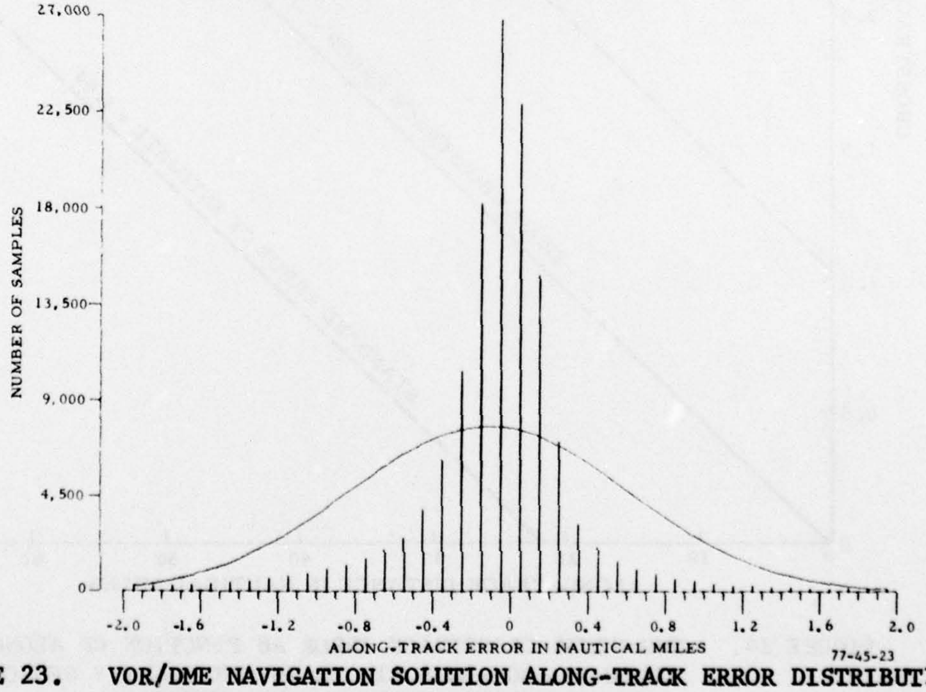

FIGURE 23. VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR DISTRIBUTION COMBINED AIR TRANSPORT QUALITY SENSORS

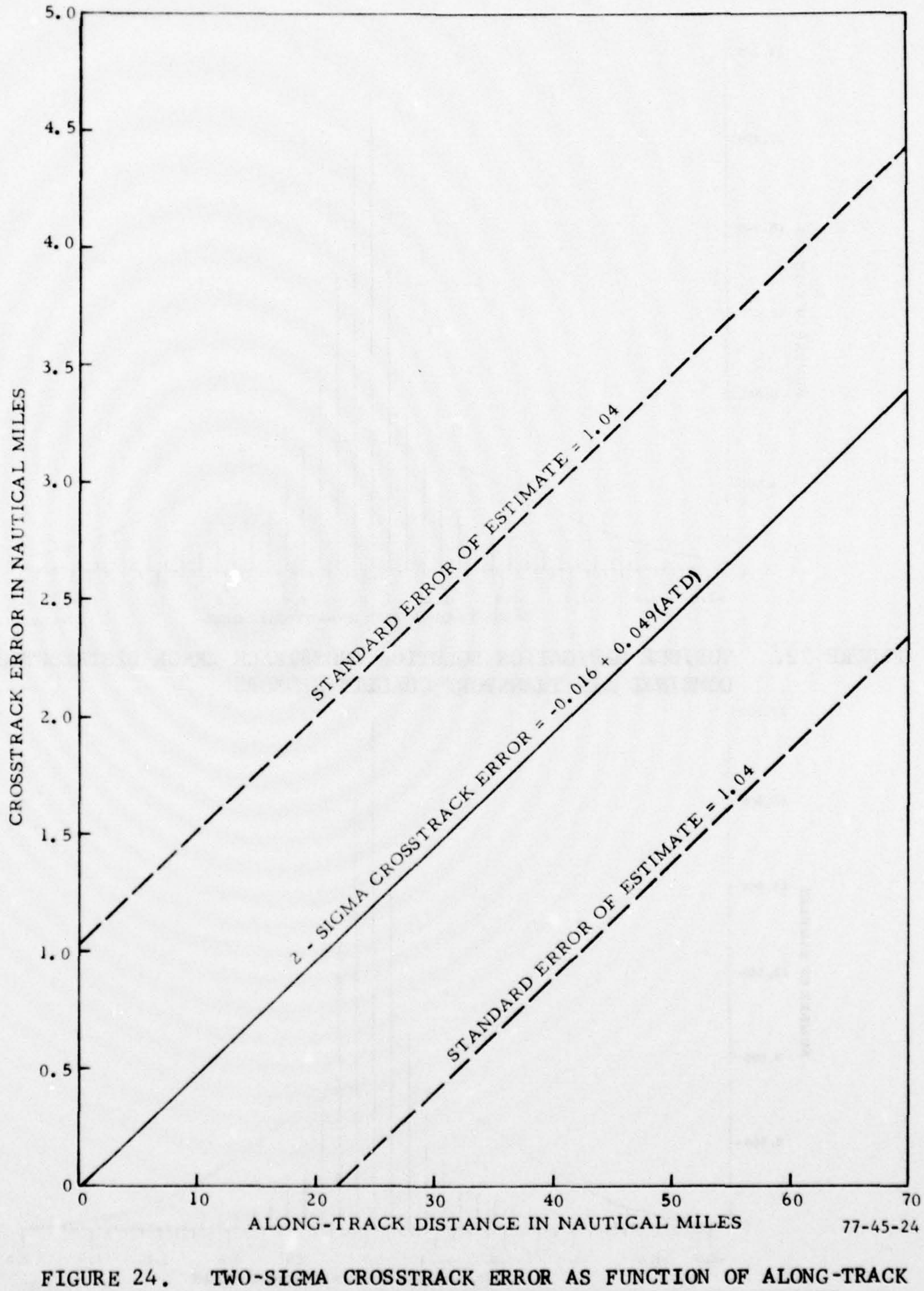

FIGURE 24. TWO-SIGMA CROSSTRACK ERROR AS FUNCTION OF ALONG-TRACK DISTANCE--COMBINED AIR TRANSPORT QUALITY SENSORS

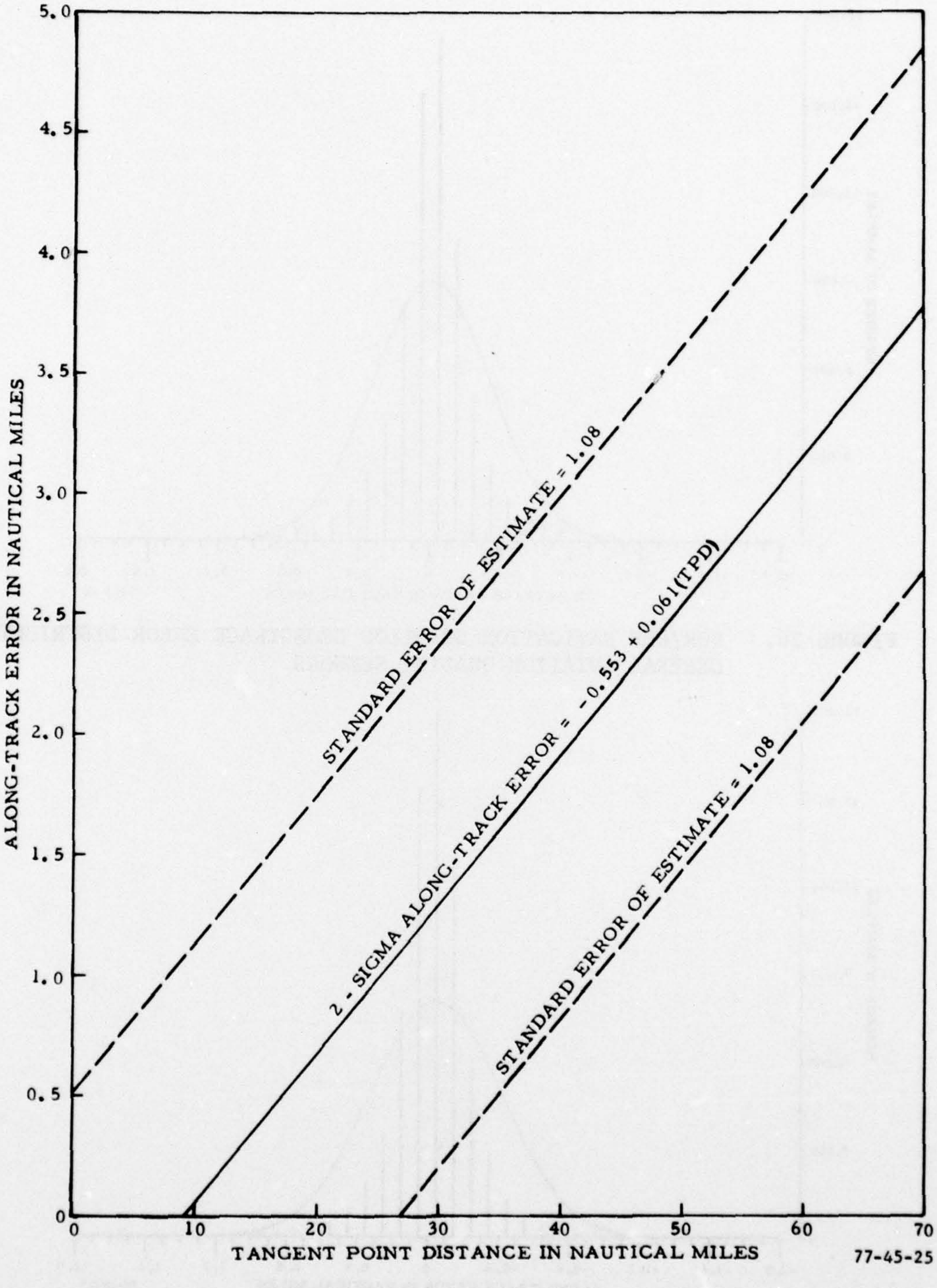

**FIGURE 25.** TWO-SIGMA ALONG-TRACK ERROR AS FUNCTION OF TANGENT POINT DISTANCE--COMBINED AIR TRANSPORT QUALITY SENSORS

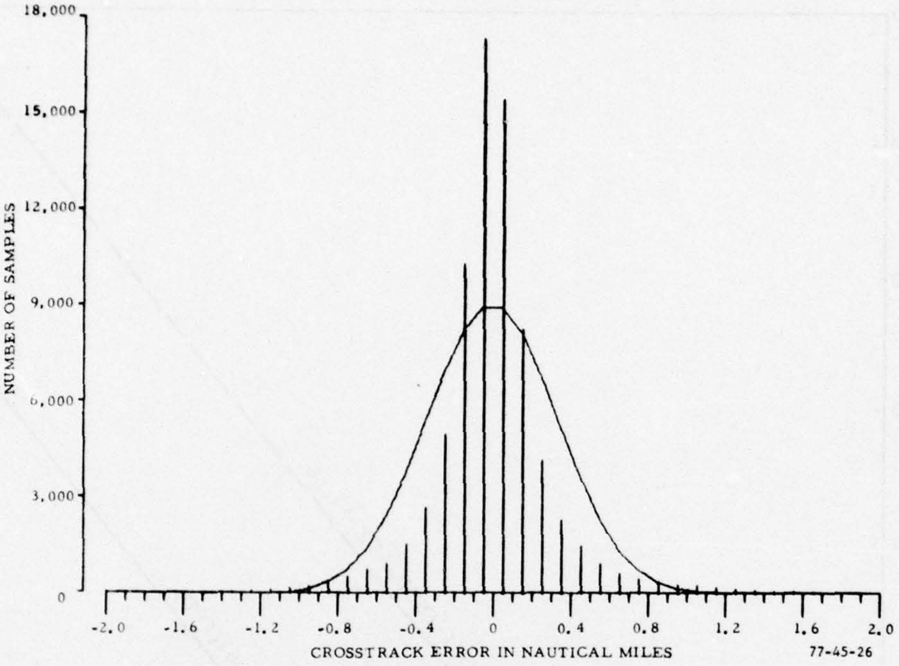

FIGURE 26. VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR DISTRIBUTION GENERAL AVIATION QUALITY SENSORS

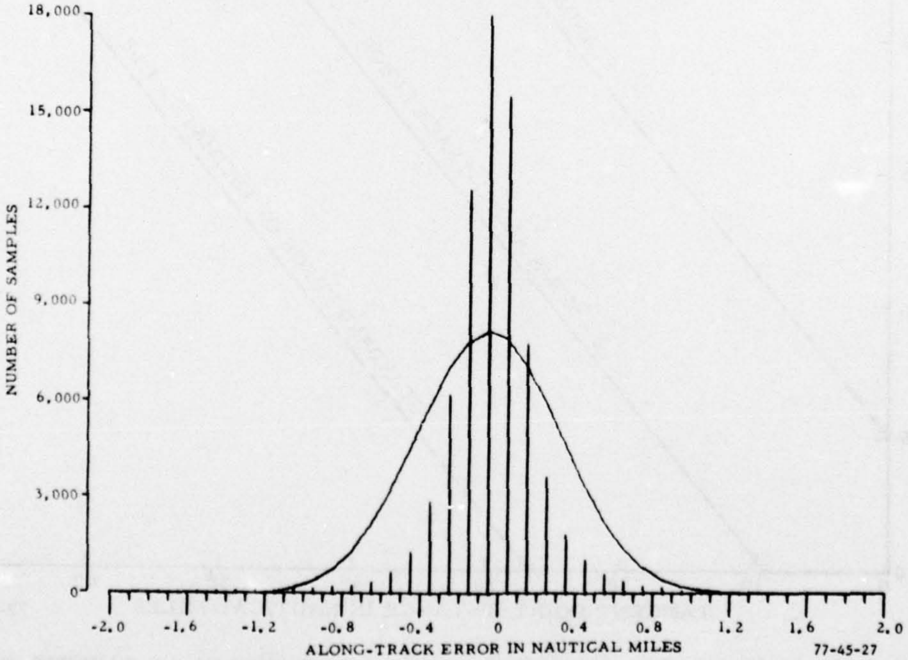

FIGURE 27. VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR DISTRIBUTION GENERAL AVIATION QUALITY SENSORS

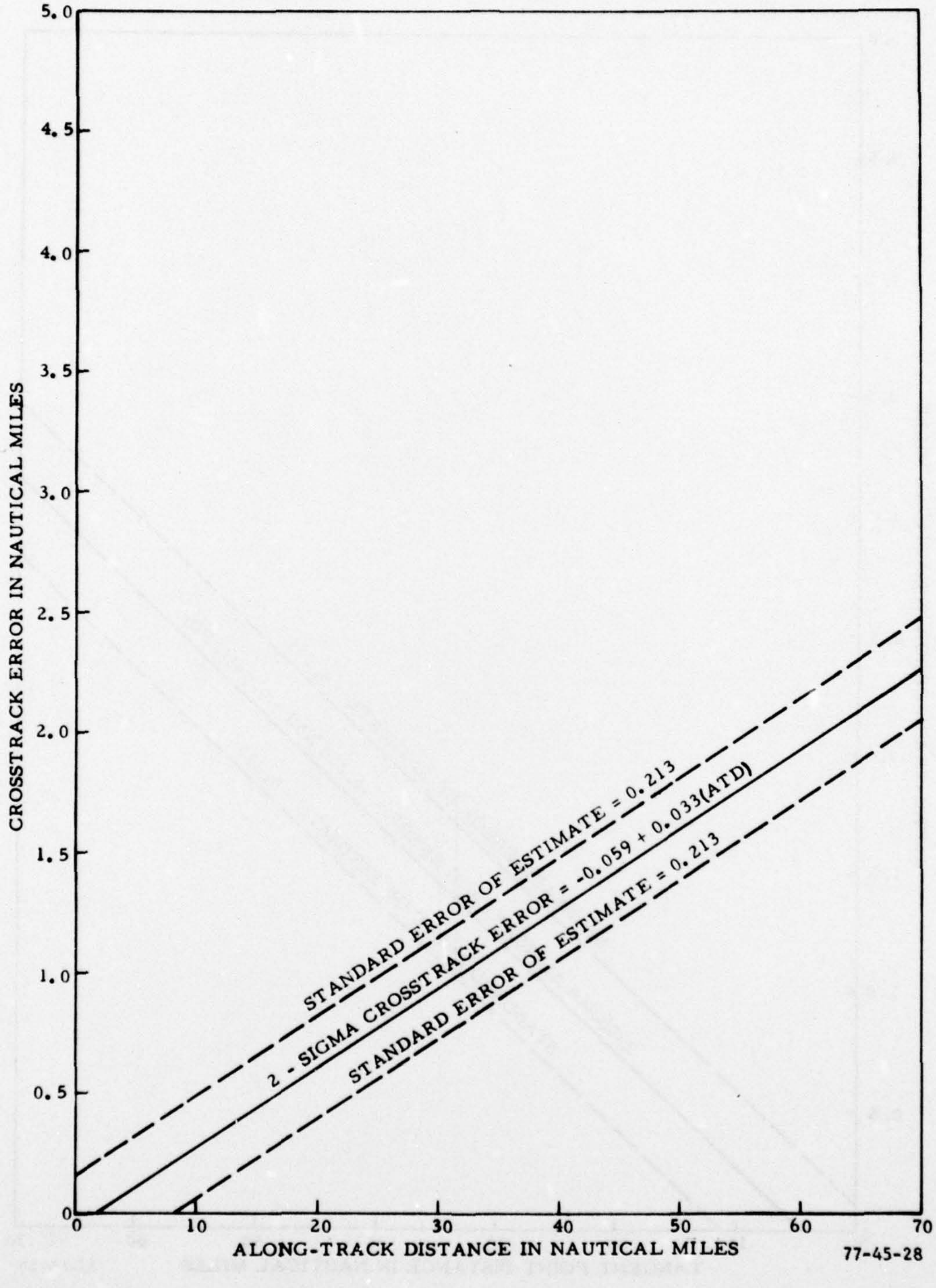

**FIGURE 28.** TWO-SIGMA CROSSTRACK ERROR AS FUNCTION OF ALONG-TRACK DISTANCE--GENERAL AVIATION QUALITY SENSORS

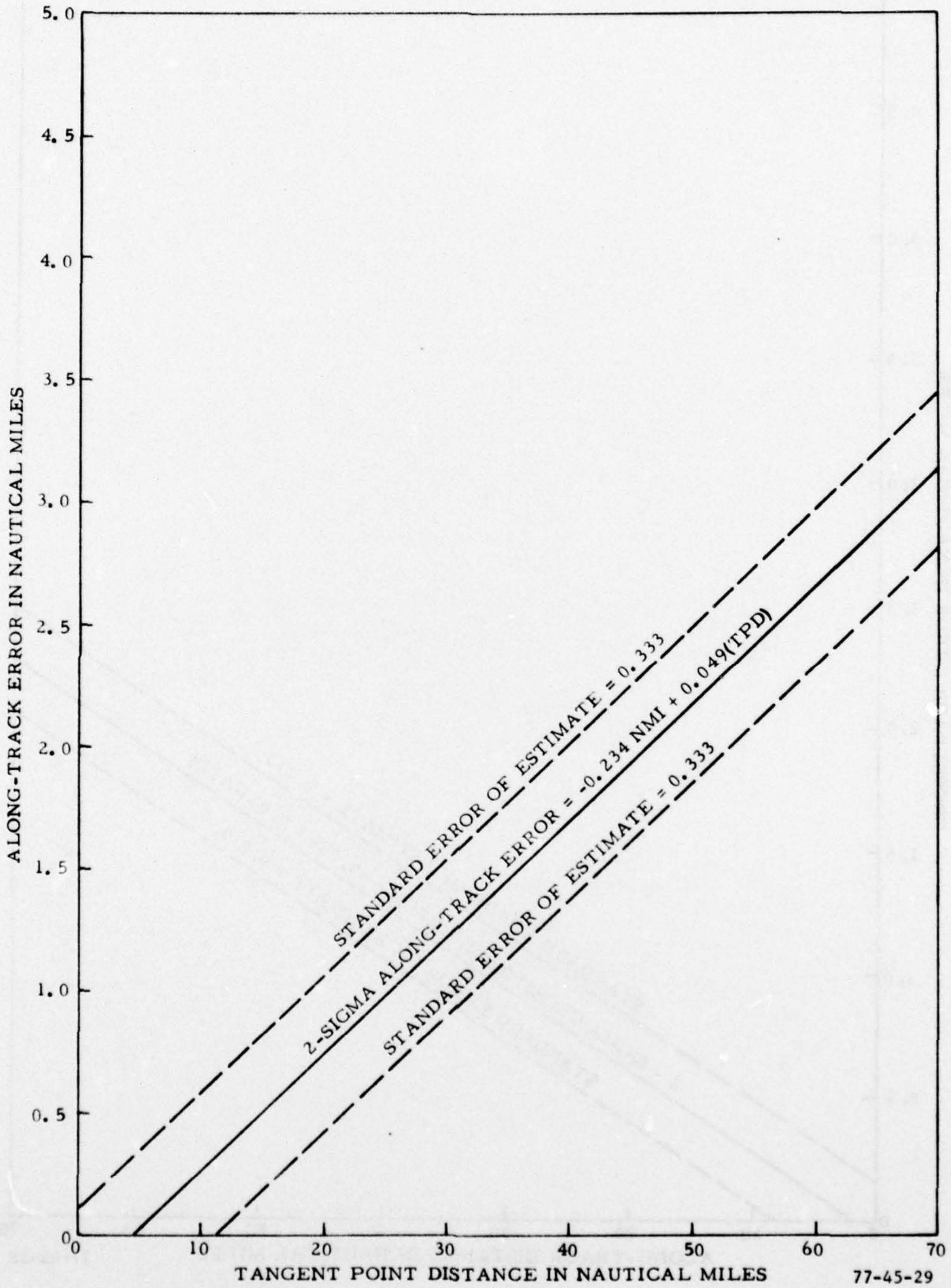

**FIGURE 29.** TWO-SIGMA ALONG-TRACK ERROR AS FUNCTION OF TANGENT POINT DISTANCE--GENERAL AVIATION QUALITY SENSORS

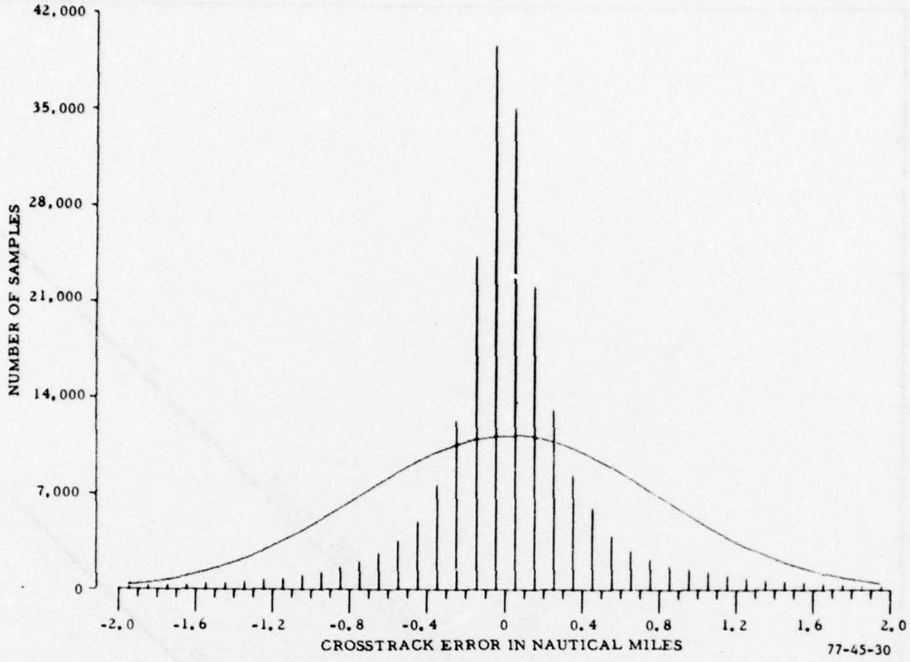

FIGURE 30. VOR/DME NAVIGATION SOLUTION CROSSTRACK ERROR DISTRIBUTION--COMBINED AIR TRANSPORT AND GENERAL AVIATION QUALITY SENSORS

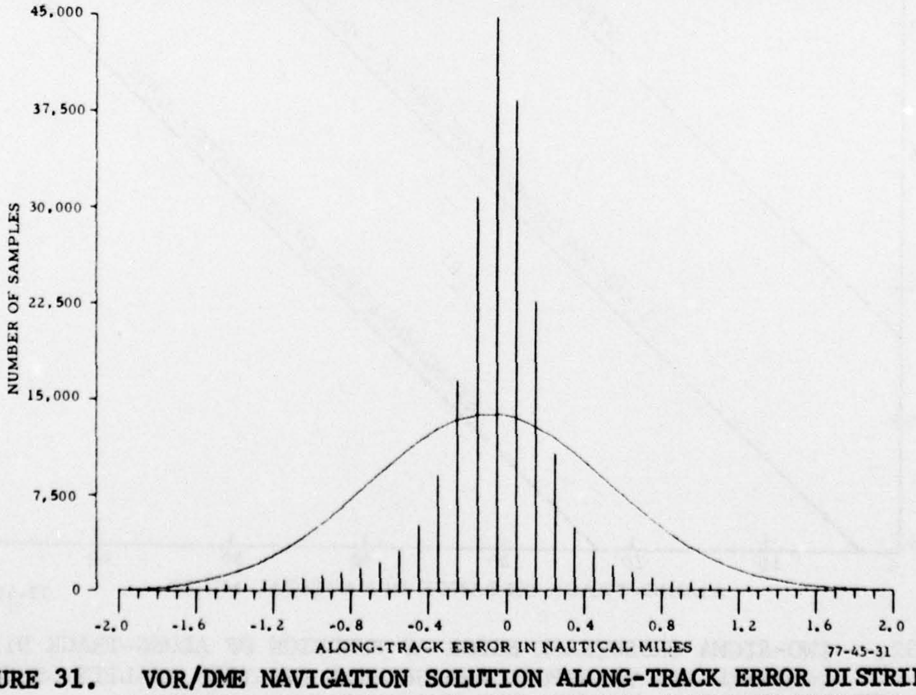

FIGURE 31. VOR/DME NAVIGATION SOLUTION ALONG-TRACK ERROR DISTRIBUTION--COMBINED AIR TRANSPORT AND GENERAL AVIATION QUALITY SENSORS

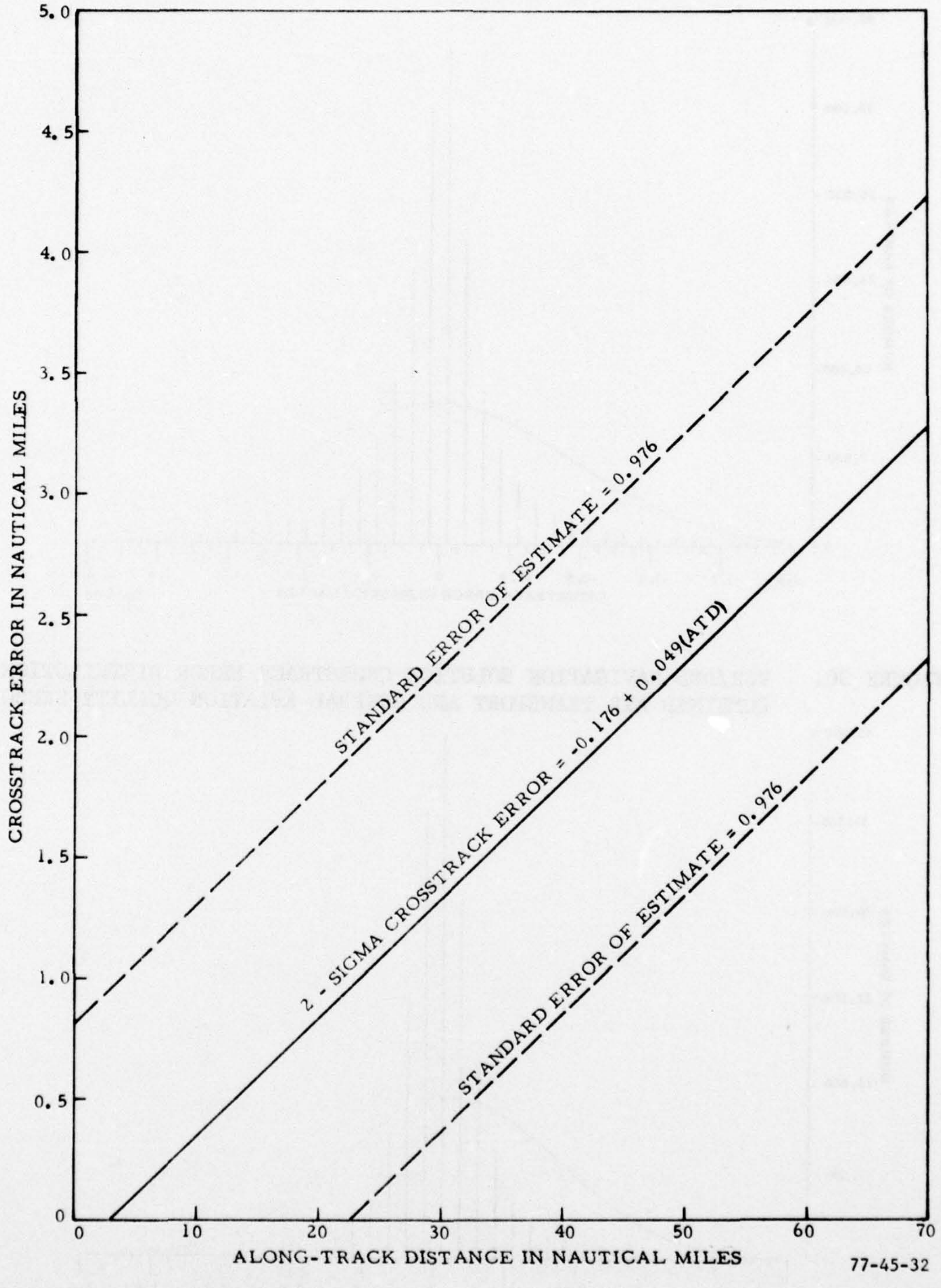

**FIGURE 32.** TWO-SIGMA CROSSTRACK ERROR AS FUNCTION OF ALONG-TRACK DISTANCE--COMBINED AIR TRANSPORT AND GENERAL AVIATION QUALITY SENSORS

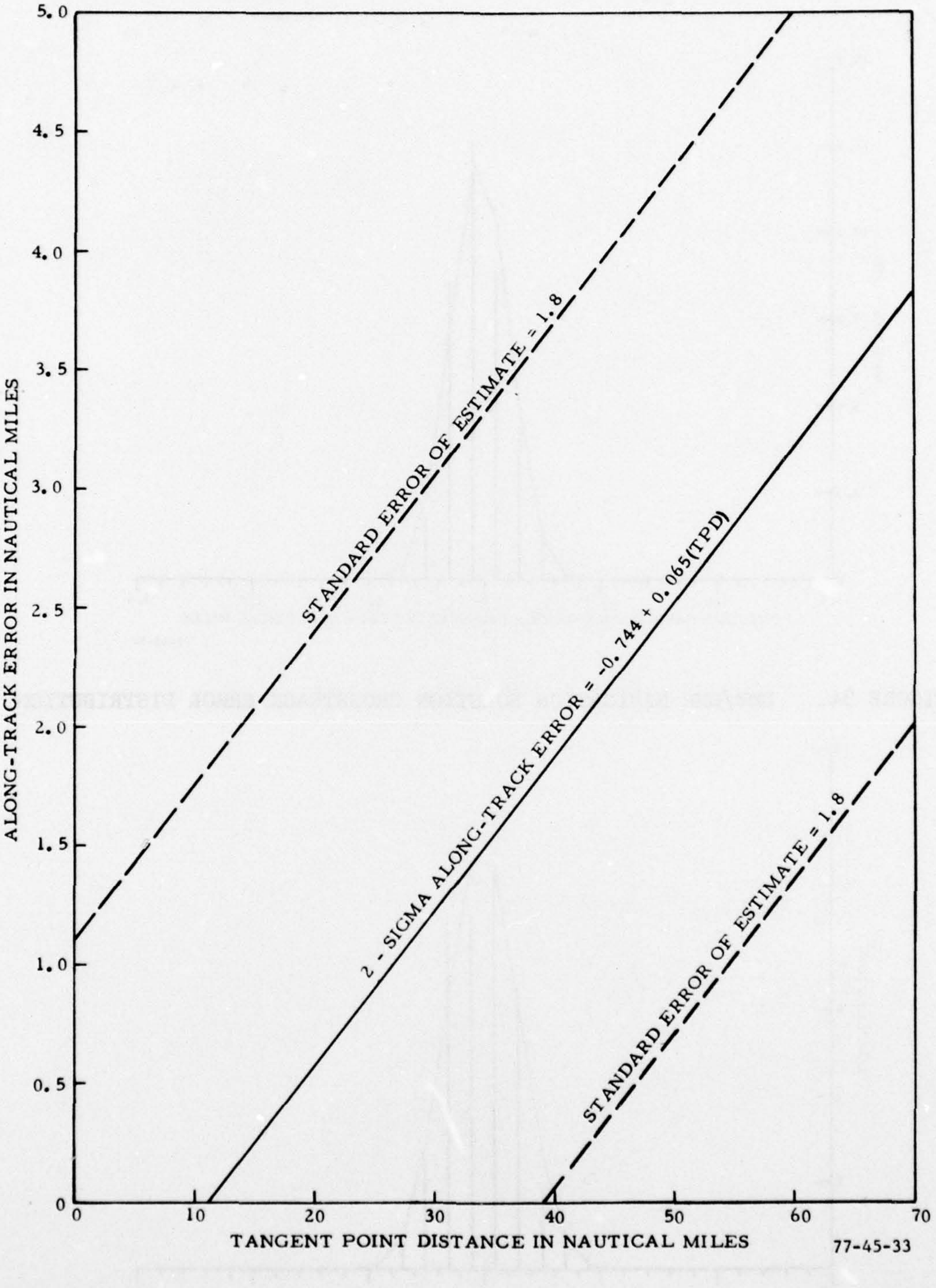

FIGURE 33. TWO-SIGMA ALONG-TRACK ERROR AS FUNCTION OF TANGENT POINT DISTANCE--COMBINED AIR TRANSPORT AND GENERAL AVIATION QUALITY SENSORS

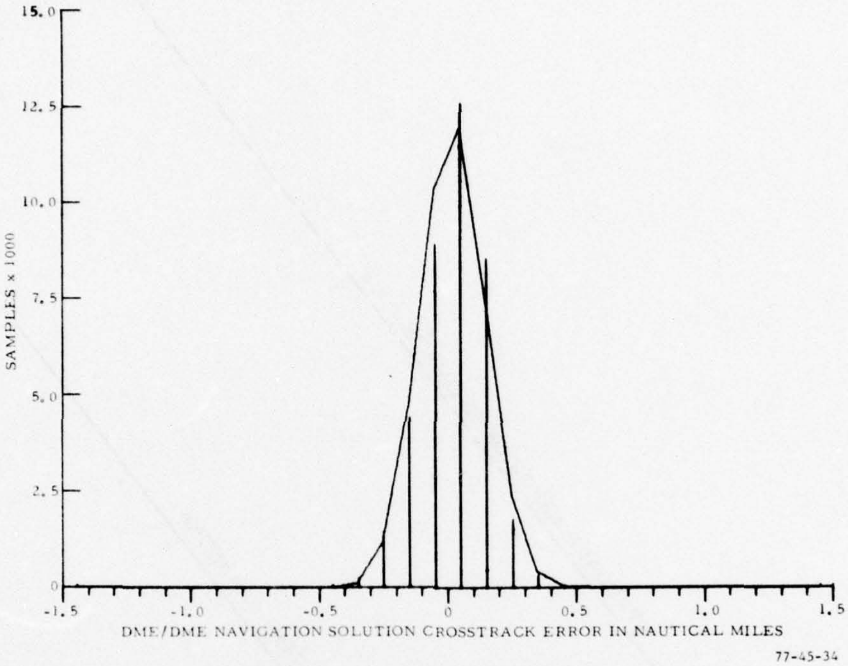

FIGURE 34. DME/DME NAVIGATION SOLUTION CROSSTRACK ERROR DISTRIBUTION

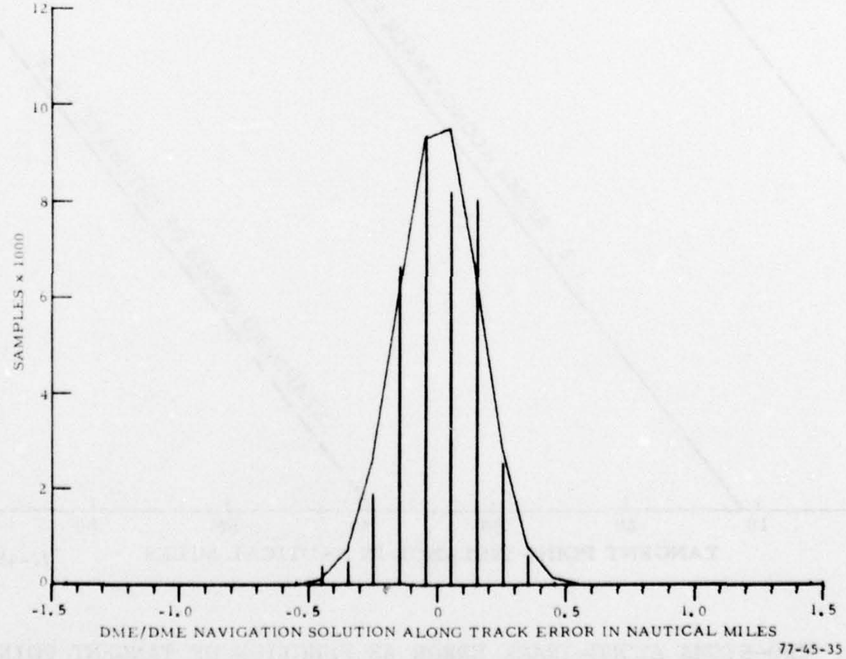

FIGURE 35. DME/DME NAVIGATION SOLUTION ALONG-TRACK ERROR DISTRIBUTION

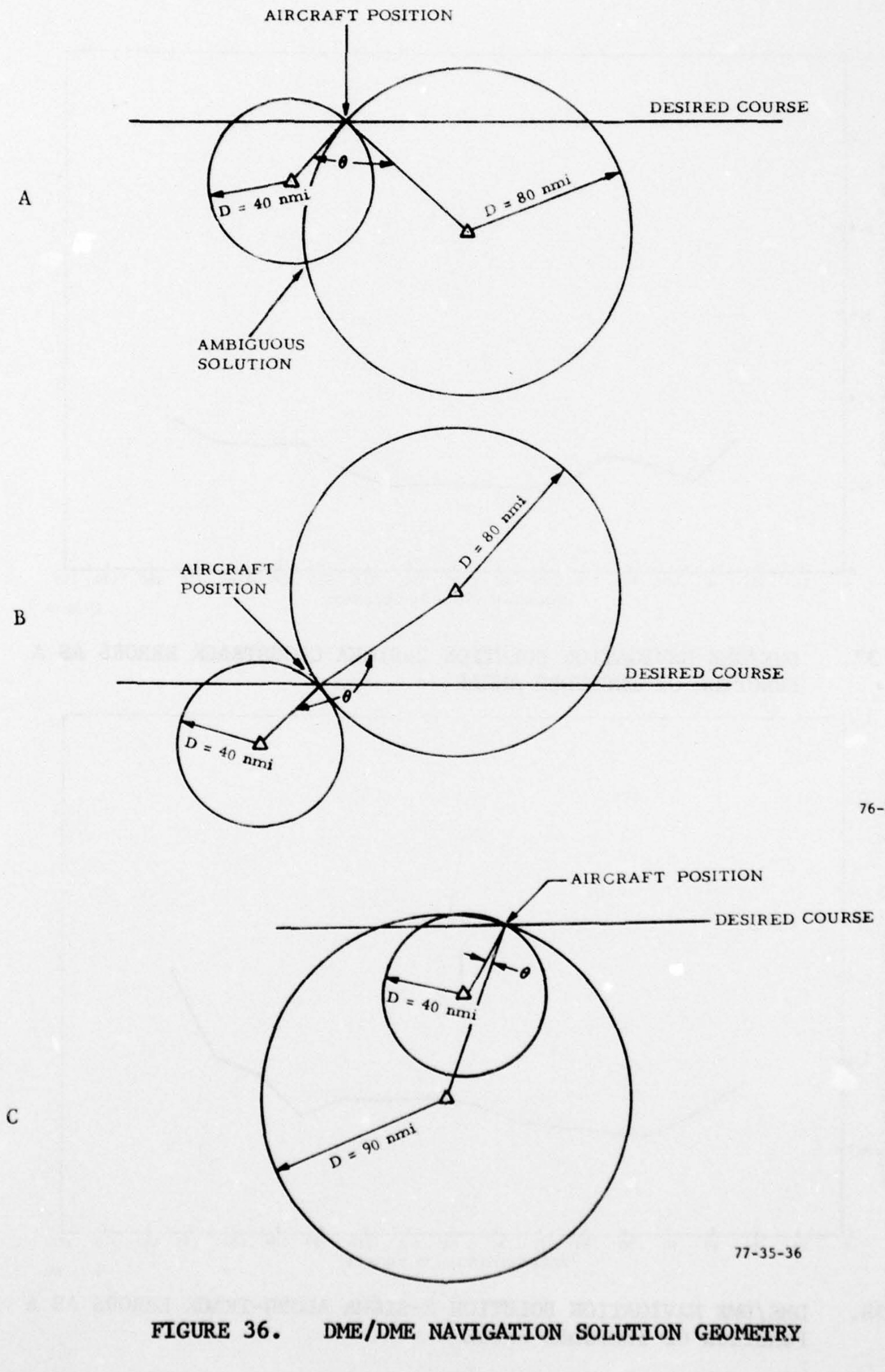

FIGURE 36. DME/DME NAVIGATION SOLUTION GEOMETRY

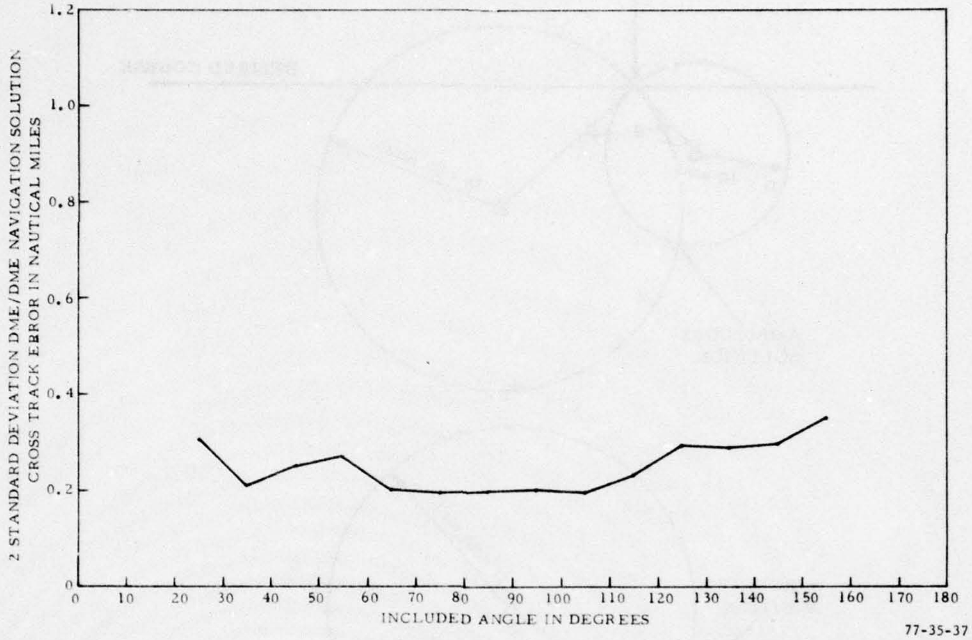

**FIGURE 37.** DME/DME NAVIGATION SOLUTION 2-SIGMA CROSSTRACK ERRORS AS A FUNCTION OF INCLUDED ANGLE

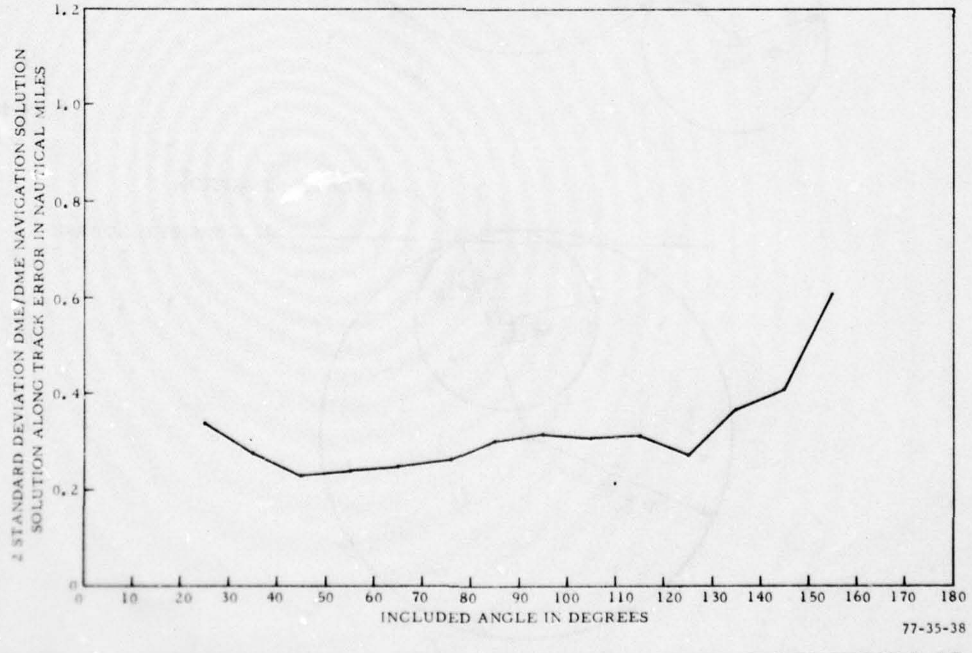

**FIGURE 38.** DME/DME NAVIGATION SOLUTION 2-SIGMA ALONG-TRACK ERRORS AS A FUNCTION OF INCLUDED ANGLE