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FINAL REPORT

Contract Number FA66WA-1550
Project Number 342-002-01N

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ANALYSIS OF USER AIRCRAFT FOR EVALUATING VOR AIRWAY PERFORMANCE

APRIL 1969

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Prepared for
DEPARTMENT OF TRANSPORTATION
Federal Aviation Administration
Systems Research & Development Service

by

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**ANALYSIS OF USER AIRCRAFT
FOR EVALUATING VOR AIRWAY PERFORMANCE**

April 1969

Prepared by

Ted Hooton and Rudy Bonitch

This report has been prepared by Airborne Instruments Laboratory for the Systems Research and Development Service, Federal Aviation Agency, under Contract No. FA66WA-1550. The contents of this report reflect the views of the Contractor, who is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policy of the FAA. This report does not constitute a standard, specification or regulation.

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ABSTRACT

Presently VOR transmitters must be routinely checked by special Flight Inspection Aircraft every 120 to 150 days. This project was conducted to see if the routine checks could be replaced by recording performance data of User aircraft along an airway. With sufficient samples, a statistical analysis might then show VOR radial performance to a degree of accuracy such that Special Flight Inspections would only be required at occasional intervals on those nav aids shown to be out of tolerance. Tests were conducted on the V139/J121 airway based on the 0.059 degree radial of the Sea Isle VOR. Good data on 300 User aircraft was obtained using the JFK airport radar, a Beacon Video Digitizer at the New York Center, and a special recorder. Special calibrations were made of the SIE 0.059 degree radial and compared with the User performance. Detailed analysis of the latter was made with respect to the effects of aircraft operators, aircraft type, and wind. It is concluded that flight checking of nav aids by User aircraft is technically, operationally, and economically feasible.

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I. INTRODUCTION

GENERAL

It has often been suggested that the routine flight checking of navigational aids by flight-inspection aircraft is a rather expensive and time-consuming process. For many years it has been felt that, if the appropriate techniques were available, it might be feasible to statistically sample User aircraft in the airspace while they were actually using the navigation aids. From this sampling, it would be possible to extract data on the accuracy and performance of the navaid in question, and if the performance was up to standard, then no routine flight-inspection would be needed.

Obviously sampling would have to be done on a routine basis, and then if a navaid fell below its appropriate standard, the flight-inspection aircraft would be called in for a more detailed check.

Until a few years ago such a technique was not practical (on a routine basis) within the domestic airspace system. The main reason was that data collection of the kind necessary for accuracy checking was too difficult.

To check a VOR (Very High Frequency Omnidirectional Range) radial defining an airway it would be necessary to record a large number of aircraft flying that airway. Photographic techniques using a radar display are possible, but the problems of data analysis are severe, entailing hours of manual labor. Also one is limited to the accuracy of the radar and resolution of the scope display.

However, in recent years, the use of secondary ground radar - with transponders in the aircraft - and the possibilities of digitizing radar information have changed the outlook. It is now possible through discrete transponder codes to identify a particular aircraft and, with digitized radar data (azimuth and range), automatically process large amounts of such data.

The project which is the subject of this report was an experimental test of such a system.

OBJECTIVES

A prime objective was to record the flight tracks of about 300 normal User aircraft flying an airway defined by a VOR without interference to the flight

plans of those aircraft, and, if possible, without the knowledge of the pilot so as to avoid any bias in the data. The results of this data were to be automatically recorded and then passed into a computer program which would statistically analyze the results. The final objective was to see if User aircraft could define the airway characteristics such that routine flight-inspection could be replaced by such a scheme. This objective was based on the fact that eventually all air traffic control centers would be using digitized radar data and (presumably) some recording facilities.

A secondary objective of the project was to obtain data on the general characteristics of User aircraft flying a VOR airway, for example, maximum deviations, etc.

During the winter of 1958-59 such a study had been carried out by the Armour Research Foundation (reference 1) using manual data reduction. It was desired to update that study.

LOCATION OF TESTS

The decision as to the location of the test site and airway was largely dictated by the fact that AIL was required to use the radar and recording facilities at NAFEC, Atlantic City. This meant that an airway had to be chosen within a 100-mile radius of Atlantic City. AIL Personnel were already quite familiar with the traffic control problems of the New York area. A visit to the New York Air Route Traffic Control Center (NYARTCC) soon confirmed the fact that many aircraft under the Center's control were being vectored by controllers and/or taking "short cuts" between fixes (VOR's).

However, there was one airway which met our specifications with respect to length of straight line flight and absence of vectoring. This was the V139/J121 airway between the Sea Isle (SIE) VOR and MANTA Intersection, the latter being located on the airway at a range of 76 nmi from SIE. The airway is defined by the 0.059 degree radial from SIE, Figure 1. Also shown in the figure are the locations of NAFEC and JFK airport.

This carrier traffic consisted of aircraft that departed from JFK to the southern USA (mostly Miami) and some southbound and northbound traffic to and from the Providence/Boston area. As it turned out, most of the pilots departing from JFK "cut the corner" instead of flying direct to MANTA and then down the airway to SIE. This is shown by arrow "A" in

Reference 1 - "Measurement of Air Navigation Accuracy along certain VOR Airways," Armour Research Foundation, Contract FAA/BRD-28, June 1959.

Figure 1. As a result of this, we asked the traffic controllers to try to encourage the pilots (as discreetly as possible) to join the airway at MANTA. When this occurred it often resulted in a turn-on with an overshoot, shown as arrow "B" in Figure 1.

It should be emphasized at this point that special transponder codes were set up for this project. Most aircraft flying the airways are beacon equipped, but those aircraft selected for this test would need to be identified. Therefore, special codes were allocated, and this simplified the data collection and subsequent analysis.

HISTORICAL SUMMARY OF PROJECT

The original data collection equipment consisted of the Elwood (NAFEC) ARSR surveillance radar feeding the Radar Video Data Processor (RVDP) which, in turn, supplied digitized radar data to a DDP-24 Computer/Recorder, also at NAFEC.

Recordings on nearly 300 User aircraft were taken during July and August 1966. After the recordings had been obtained it was discovered that aircraft beacon replies were being picked up on the radar antenna sidelobes ("ring-around") and thus it was impossible to automatically process the data because on each antenna rotation there were too many spurious targets. Also, data output from the RVDP did not contain any useful target validation checks, so that it was almost impossible to sort out the valid targets.

It was, therefore, decided to explore other possibilities in order to continue the project. After examination of various alternatives, the final solution was to shift the data collection to the NYARTCC using an AIL Beacon Video Digitizer (BVD) and a specially-constructed recorder (BVDR). The BVD was fed from the ARSR located at John F. Kennedy International Airport (JFK).

The construction of the BVDR at AIL was completed in December 1967 and, after a few small modifications (to adapt it to other FAA project requirements) were made, it was debugged and installed at the NYARTCC in April 1968.

Data collection was made during May and June 1968 and good data was obtained. That data provides the basis for this report.

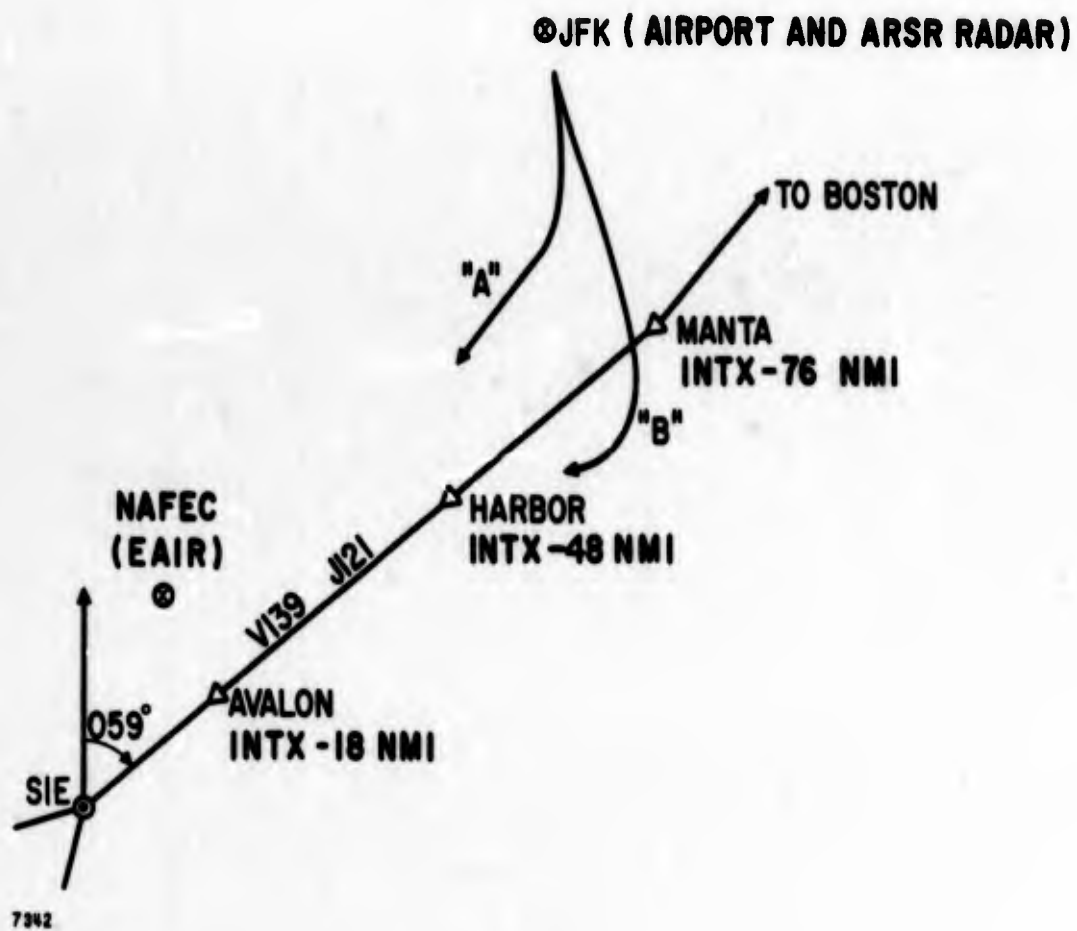


FIGURE 1. TEST AREA SHOWING V139/J121 AIRWAY

CALIBRATION

To determine the actual characteristics of the VOR radial defining Airway V139/J121, special calibration flights were run. During the early phases of the project in July 1966 an FAA Gulfstream aircraft was flown along the 0.058 degree radial in both directions as accurately as possible and tracked by the NAFEC Extended Area Instrumentation Radar (EAIR) and the RVDP. In the final tests, these runs were repeated using the BVDR and EAIR. (By this time other traffic considerations in the area had resulted in the airway being redefined by the 0.059 degree radial.) Two separate flights were made in May and August 1968 to compare the two VOR transmitters. Also, the most recent Flight Inspection data was obtained from the FAA, this being a check in September 1968.

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II. DATA COLLECTION

RECORDING FACILITIES AND PROCEDURES

Data taking during the May to August 1968 phase of the project, for User aircraft, employed the following facilities:

- ARSR Radar, JFK airport
- BVD/BVDR Digitizer and Recorder, NYARTCC
- New York Air Route Traffic Control Center

When recording periods were in progress, the ARSR/BVD sent target report messages containing range, azimuth, code identity, altitude (when reported), to the BVDR for recording. The tape produced was a permanent record of the targets recorded and could be read by either an IBM 7090 or 360 computer.

Through close liaison with an AIL technician at the NYARTCC, the air traffic controllers would request those pilots flying between SIE and MANTA on airway V139/J121 to use one of two special beacon codes. For aircraft below 24,000 feet code 2700 was used; for those above this altitude, 3700 was used. Due to the design characteristics of the BVDR, aircraft having either the 64 or 4096 code capabilities could be recorded with the above scheme.

If an aircraft was vectored off the airway, or left the airway at some intermediate point, controllers were asked to discontinue the code immediately.

The AIL technician was also required to record certain data on each flight assigned the special codes. This data included the following:

- Aircraft callsign
- Aircraft type
- Beacon Identity Code
- Time over MANTA and/or SIE, or off airway
- Altitude
- Routing (northbound or southbound)
- Indicate whether Tacan or VOR was used

He also noted any unusual events such as large track deviations, use of special code beyond the airway, and unusual weather.

The flight strips from all recorded aircraft were later collected and held as a double check on questions that might arise with regard to altitude, routing, identity, etc.

Also, after each recording session, upper wind data was collected from the Weather Bureau for an analysis of its possible affects on the recorded tracks.

CALIBRATION FLIGHTS

For both the original and final phase of the project, supplemental data was recorded using the EAIR at NAFEC. This was done concurrently with the BVDR at the NYARTCC, since the EAIR data was to serve as a reference in determining overall accuracy. The facilities used were:

- ARSR/BVD and BVDR at the NYARTCC
- EAIR Radar, Processor, Plotter and Recorder, NAFEC
- Test Aircraft-Grumman G-159 Gulfstream NAFEC

Prior to a Gulfstream flight, a ramp check of the aircraft VOR receiver was performed. Accuracy data was collected for the radials to be flown outbound and inbound, along the airway. These radials were 0.058 degree and 0.238 degree during 1966, changing to 0.059 degree and 0.239 degree respectively by 1968. (The 1 degree alteration being due to air traffic considerations dictating a radial shift between 1966 and 1968.)

After takeoff from NAFEC, the aircraft proceeded to the SIE VORTAC and performed a procedure turn to fly over and outbound along the radial. The pilot endeavored to fly the aircraft to maintain the radial as accurately as possible, using the autopilot. After passing MANTA intersection the pilot performed a procedure turn to the east of the airway and he returned southbound along the airway to SIE. He then performed a procedure turn to the east and the sequence was repeated.

During all flights along the airway in both directions the aircraft was tracked by the EAIR, and communications with the EAIR were maintained. The EAIR produced both a tape and a track plot of the target X, Y, and H coordinates, plus time on each run.

When the BVDR was used in conjunction with the EAIR, the pilot used beacon code of 3700 outbound and 2700 inbound. When the aircraft was over SIE and over the MANTA intersection, the pilot operated the identity pulse indicator ("squawked I. D. ") of the aircraft's beacon receiver. At the same instant he indicated "mark" to the EAIR site. This procedure entered data marks simultaneously on both the BVDR tape and the EAIR plot, which aided in their correlation during analysis.

DESCRIPTION OF RECORDING EQUIPMENT

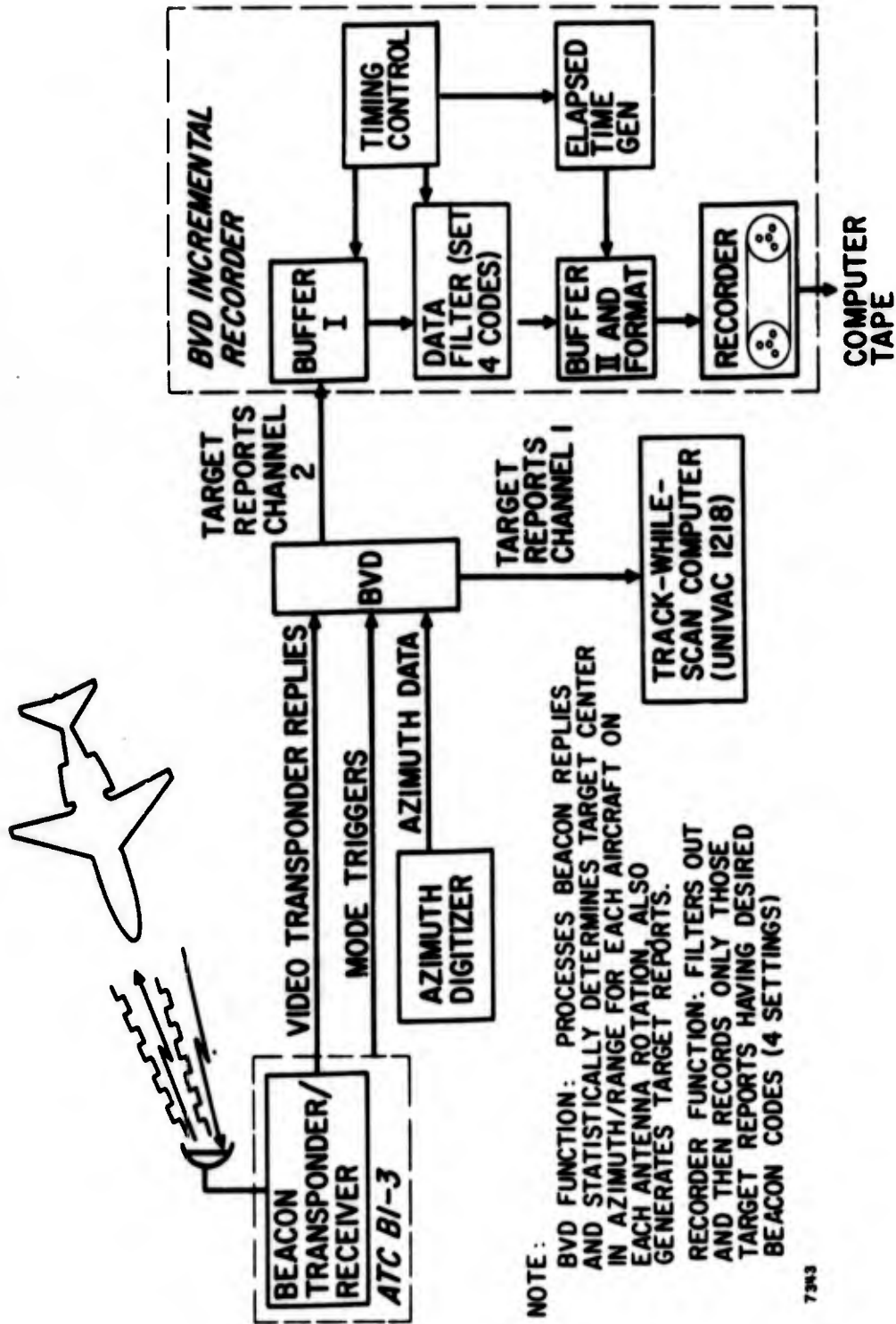
(1) BVD Recorder (BVDR). The basic components necessary for data collection using the BVD Recorder are shown in Figure 2. The ground-based interrogator transmits a coded pulse pair to the airborne transponder, requesting either identity or altitude data. In response, a coded pulse train is transmitted from the aircraft, with the requested information.

These signals, together with digitized azimuth data, are fed to the BVD, which decodes the information present in the reply, and adds a range number, computed by measuring the time delay from transmission of the interrogation to the reception of the reply. As the scanning antenna passes the aircraft, many such interrogate/reply sequences occur. The BVD processes the replies received from each aircraft and statistically determines the target center in azimuth and range for each aircraft on every antenna rotation. After the beam has passed the target, the completed target report message is digitally formatted and sent to the BVD Recorder.

To reduce the amount of tape recording necessary and since only targets assigned specific beacon codes were to be recorded, the BVD Recorder filters all target report messages. Only those targets, which have identities corresponding to those set into the BVD Recorder are then put into proper recording format; elapsed time is added to the resultant message. The complete target message was then entered on an IBM compatible, 7-track tape. The statistical resolution of the BVD in determining aircraft position is 1/32 nmi in range and ± 0.088 degree in azimuth.

(2) EAIR. The EAIR consists of a precision tracking radar, data converter, plotter, and tape recorder. The tracking radar receives either beacon or skin returns from the aircraft, and determines slant range, azimuth angle, and elevation angle from them.

This information is then fed to the analog converter, which accepts the spherical polar coordinate data on the target and produces a three dimensional cartesian coordinate (X, Y, and H) target position. An ink tracing of the X-Y, X-H plot of the course flown, plus timing and reference marks, is



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FIGURE 2. TYPICAL BVD RECORDER INSTALLATION

produced by a plotter from the output of the analog converter. Figure 3 shows a block diagram of the EAIR.

Radar data is also fed to the Digital Data Converter which places the target coordinates into a suitable format, adds a time word, and then places the information on a IBM 7090 compatible magnetic tape. Published data on the accuracy of the EAIR refers to 20 yards in range, and 0.011 degree in azimuth and elevation.

For the calibration runs during this project the EAIR beacon fitted in the Gulfstream was used for tracking.

DATA COLLECTION

(1) User Aircraft. This encompassed a total of 21 days during the period of 25 April to 1 August 1968. Data was recorded between the hours of 0900-1200 and 1300-1700 for sessions from three to five consecutive days during the period. Although the BVDR had the tape capacity to record for up to two weeks, sessions were limited to a maximum of five days. At the end of each five day recording session, tape decks were changed and the tape containing the previous weeks data was returned to AIL for processing. This was done to ensure that good data was being recorded and to reduce the possibility of recording too much erroneous data. Data recording was not resumed until it was ascertained that any problems indicated on a previous weeks' tape were corrected.

A total of 520 User and 12 Gulfstream flight were recorded using the BVDR. For the User aircraft, this was 60 percent more aircraft than was originally planned (330), but it was found that not all aircraft tracks were suitable for analysis. Vectoring of aircraft off the airway due to overall high traffic level, inadvertent reassignment of identity codes due to division of control of the airway by four different control sectors, and communication problems were responsible for the lower yield. Table I shows the breakdown of the flights recorded using the BVDR. Under the column - "Raw Targets" are listed the number of targets logged by the AIL technician as having been given the 2700 or 3700 code assignments by the air traffic controllers. During final analysis, many of these tracks were found to be unsuitable for reasons that will be discussed later, so the "Usable Targets" represents the approximate number suitable for final analysis.

(2) Gulfstream Calibration. Data collected using the EAIR covered two widely separated periods, one during July 1966 when the RVDP was in use, the other during May and August 1968 when the BVDR was in use. The May and August runs were made to see if any detectable differences existed

TABLE I
USER AIRCRAFT RECORDED

<u>Date</u>	<u>Raw Targets</u>	<u>Usable Targets*</u>
25 April	7	6
1 May	20	13
2 May	18	7
3 May	23	21
6 May	43	37
7 May	33	17
9 May	39	24
10 May	24	18
13 May	47	32
14 May	44	16
15 May	44	1
29 May	19	15
31 May	25	16
3 June	23	0
4 June	37	32
10 June	13	10
11 June	42	39
12 June	<u>17</u>	<u>14</u>
Total	520	318

* Initial estimate, subsequently modified. See Section III.

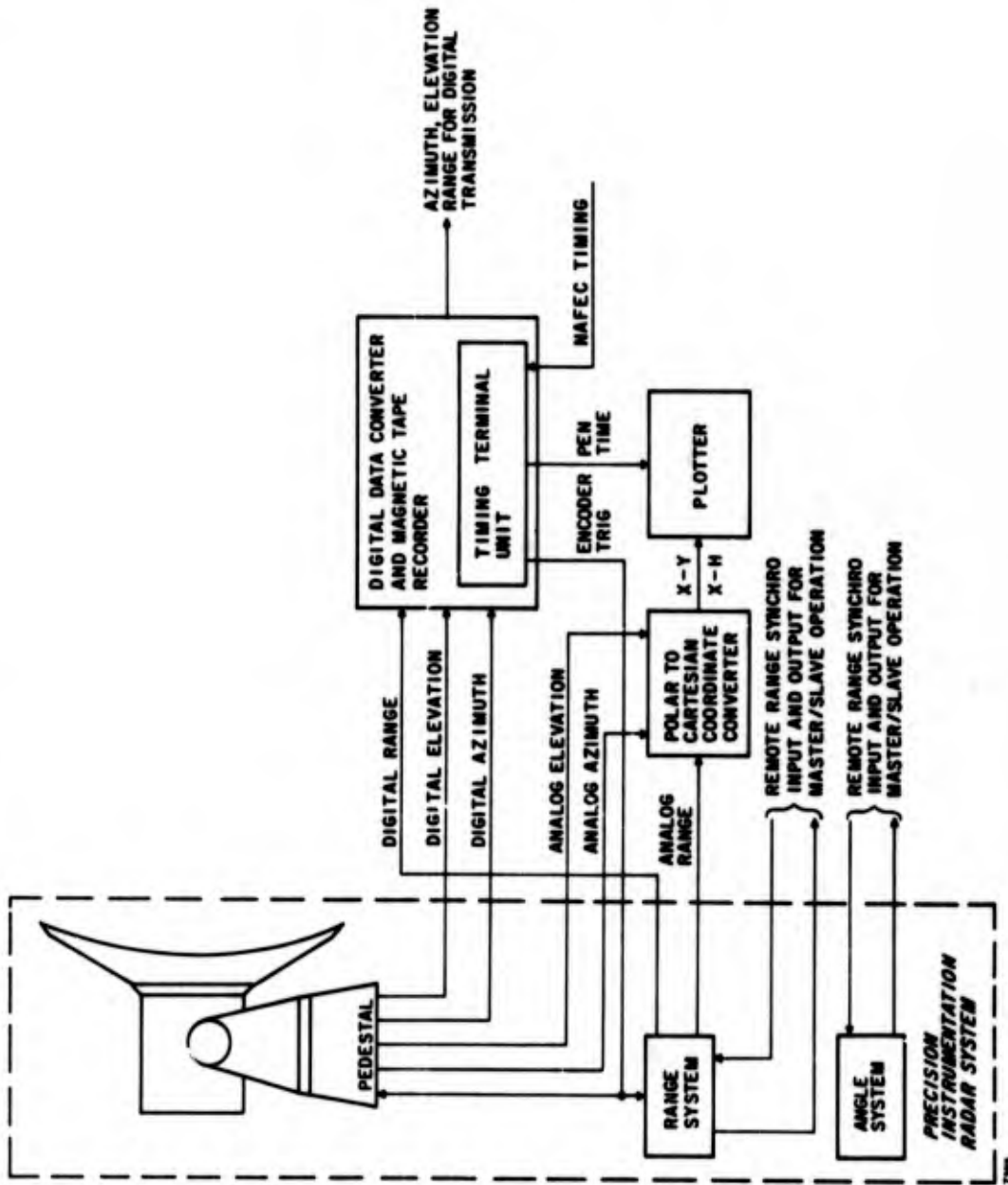


FIGURE 3. EAIR DATA FLOW DIAGRAM

between the two VOR transmitters at SIE. A total of 48 VOR and 6-tacan runs were made during 1966 and 1968. Table II shows the breakdown of each flight.

TABLE II
GULFSTREAM CALIBRATION

<u>Date</u>	<u>No. of Runs*</u>	<u>Altitude</u>	<u>Usable Data</u>
12 July 66	2	26,000	0
14 July 66	4	26,000	3
15 July 66	10	26,000	10
18 July 66	10	10,000	10
19 July 66	10	10,000	10
20 July 66	6 (tacan)	10,000	6
28 May 68	6 (VOR 1)	20,000	5
1 August 68	6 (VOR 2)	20,000	6

* One run constitutes a single outbound or inbound flight along the radial.

III. DATA PROCESSING

GENERAL

It must be remembered that the original objective of this project was to determine whether User aircraft could provide constant flight inspection services in an automatic manner. However, before this conclusion could be made, considerable analysis was required. For example, it was required to know whether aircraft operators made a difference (that is, airlines versus military versus general aviation) or whether altitude had an effect on the accuracy.

Also, looking ahead, one could foresee the day when automatic flight inspection by User aircraft might be quite routine, and air traffic controllers during certain time periods would ask pilots for the special transponder code as a matter of course when they saw an aircraft on the airway.

We had none of the advantages of this routine-type operation and, due to the necessity of identifying individual flights (which would not be required in a final system), we had to insert a manual check and some processing between the recording of data and its final analysis. Therefore, in reading this section, it should be realized that some of the techniques described here were peculiar to this project and would not necessarily be included in any final "production" system.

TECHNIQUE

In summary, the data processing consisted of a series of steps:

- Dumping the contents of each tape recording to obtain a printout listing.
- Examination of the printout and a deletion of all invalid data. Insertion of classification based on some manual plotting of aircraft tracks. Also correlation with the Center log and flight strips.

- Production of a new computer tape containing only the selected data together with classification and relevant flight information inserted. This new processed tape also had each target (slant) range converted to ground range.
- The processed tape was produced on the IBM 360-II at AIL and, after subsequent conversion from 9 to 7 track format, was the tape used for final data analysis on the IBM 7090 at NAFEC.

RAW DATA TAPE

Before each recording tape was listed, an identification card was inserted in the computer to identify the tape and to give a starting time (recorded by the AIL technician at the Center). The starting time was necessary because the BVD recorder only recorded elapsed time and so the conversion to real time (Greenwich) had to be made to allow flight identification to be added later. An example of the raw data listing is shown in Figure 4. The column headings and explanations are as follows:

- Track number. A number sequentially assigned to each target hit during one individual recording session
- Slant range
- Azimuth
- Altitude (if reported)
- Time (with respect to the starting time for the file)
- Aircraft beacon identity code
- Test target ("YES" when ON, "NO" when OFF)
- Overload (0 when OFF, 1 when ON)
- Sector mark (0 when OFF, 1 when ON)
- Confidence check (0 when OFF, 1 when ON)
- Special ID (Blank when OFF, 1 when ON)
- Altitude validation (indicates "NONE" for 0, "GARB" for validation 1, "SR" for single reply or 2, and "CRIT" for Criteria checked or 3)
- Identity validation--same code as altitude validation
- Altitude increments. (In 100-foot increments shows "NO," in 500-foot increments shows "YES.")

TRACK NO	RANGE	AZIMUTH	ALTITUDE	TIME	IBENT	A/C CALLSIGN	A/C TYPE	DIR	M	P	MISC	TY	DL	SM	CC	SP	ID	ALT	VAL	ID	VAL	500	
424	77.3	207.1	28500	14 59 58	3700																		
426	78.1	207.9	28700	15 0 8	3700																		
428	79.0	208.3	28800	15 0 17	3700																		
432	79.9	208.7	29000	15 0 27	3700																		
435	80.8	209.2	29100	15 0 34	3700																		
438	81.6	210.1	29300	15 0 44	3700																		
441	82.5	210.6	29500	15 0 55	3700																		
444	83.4	211.0	29600	15 1 5	3700																		
449	84.3	211.4	29700	15 1 14	3700																		
452	85.2	211.9	29800	15 1 24	3700																		
455	86.1	212.3	30000	15 1 34	3700																		
459	87.1	213.1	30100	15 1 43	3700																		
462	89.0	213.5	30200	15 1 53	3700																		
465	89.0	213.9	30300	15 2 3	3700																		
469	90.1	213.9	30500	15 2 12	3700																		
472	91.2	214.6	30500	15 2 22	3700																		
475	92.3	215.1	30500	15 2 32	3700																		
479	93.5	215.3	30700	15 2 41	3700																		
482	94.7	215.7	30700	15 2 51	3700																		
486	95.9	216.0	30800	15 3 0	3700																		
488	97.1	216.1	30900	15 3 10	3700																		
491	98.3	216.4	31000	15 3 19	3700																		
494	99.6	216.8	31100	15 3 29	3700																		
497	100.8	216.8	31100	15 3 38	3700																		
501	101.9	217.2	31100	15 3 48	3700																		
504	103.2	217.4	31000	15 3 58	3700																		

700

FIGURE 4. EXAMPLE OF RAW DATA TAPE LISTING

It should be noted that even in the initial listing phase, some sorting was done by the computer. For example, a test target is generated by the BVD every 10 seconds. While useful, we did not want to see every test, so the computer eliminated all except for the very first one and at selected intervals (30 minutes). Also, it was found that during recording sessions, controllers sometimes did not always take the particular aircraft off the special code immediately on passing SIE or MANTA. Therefore, any azimuth and/or ranges outside these two points were automatically eliminated. The effects of this can be seen in Figure 4 where there are gaps in the Track Number sequences.

SORTING OF INVALID DATA

Invalid data was manually eliminated on the basis of BVD validity checks for each target report, which appeared in the printed output. The most common cause of invalid data was "ring around" due to transponder interrogation by sidelobes of the radar. Indications of "ring around" were:

- Two target reports at the same time, with the same identity and range but with different azimuths
- A "0" indication in the azimuth confidence check bit of the target report of the invalid target

Aircraft transponder malfunctions were indicated by checking target reports for the following:

- A "0" indication in the azimuth confidence check bit
- Either a "NONE," "GARB," or "SR" (single reply) in the identity validation bit

The only other targets eliminated were the remaining test targets which were indicated by an identity code of 6666 and a "YES" in the test target bit. No BVD overloads or sector mark messages were experienced during data collection.

This process eliminated all invalid data and was most successful. There were no cases of ambiguity and it is considered that in any future recordings using the BVD, the invalid targets could easily be automatically removed during computer processing.

CLASSIFICATION OF TRACKS

As described in Section II, a total of 520 User aircraft were logged during the period of recording. After discarding invalid targets a variety of other aircraft tracks remained. After the rough manual track plots were made, it was then decided to classify the individual tracks (Table III).

TABLE III
CLASSIFICATION OF INDIVIDUAL TRACKS

<u>Class</u>	<u>Flight Characteristics</u>
1	Traveled the entire airway within a distance 7-1/2 miles above or below the radial.
2	Traveled less than the entire airway within a distance 7-1/2 miles above or below the radial.
3	Traveled the entire airway outside a distance 7-1/2 miles above or below the radial.
4	Traveled less than the entire airway outside a distance 7-1/2 miles above or below the radial.
5	Traveled a path crossing the airway but with no other apparent reference to the airway.
6	Traveled a path with no reference to the airway.
7	Traveled only a short distance usually less than 10 percent of the total airway distance.
8	Logged at the NYARTCC as being assigned code 2700 or 3700 but not found on the recording tape. This was because of invalid targets, controller workload (forgot to assign code), technician workload (he had to coordinate between controllers in four sectors), and a few that could not positively be identified on the tape versus the log or flight strips.

Class 1 to 4 targets were selected for use in the subsequent analysis program and the remaining classes were discarded. A check of the flight strips of all aircraft was done to correlate the results. Table IV shows the results of the classification.

TABLE IV
RESULTS OF TRACK CLASSIFICATION

<u>Aircraft Class</u>	<u>Total Aircraft</u>
1	236
2	33
3	26
4	3
5	9
6	19
7	164
8	30
Total	520

As shown in Table IV, some 298 aircraft remained for analysis. During subsequent analysis and data conversion, three more runs were dropped from the sample so that the final analysis was made on 295 aircraft tracks.

It should be emphasized at this point that no attempt was made to bias the data in any way. All aircraft in Classes 1 through 4 were chosen because it appeared as though they were being flown with the airway as the main reference. Some aircraft in Class 3 were 10 miles from the airway but no attempt was made to exclude them. In fact, in the subsequent analysis, Classes 1 through 4 were not examined individually in any way. Those aircraft placed in Classes 5 and 6 were those which quite obviously had been put on the special code in error, or those whose pilots were not attempting to fly the airway (and since we were not attempting to elicit their cooperation, it is not surprising that there should be a few samples).

Finally, Class 7 tracks could have easily been incorporated in the data but their short track lengths would have diluted the sample size, and would have made it rather complicated when trying to come to final conclusions on sample sizes, etc.

PROCESSED TAPE

Working from the manual processing of the raw data listings, only those individual flights required for analysis were picked out by identifying a series of track numbers. These numbers were transferred to data cards, and together with a flight identifier card, were supplied as input to the reduced data generator program, the second program. The flight identifier card listed the aircraft callsign, type of aircraft, direction of flight ("northbound" or "southbound" along the airway), navigation aid used (VOR or tacan), and classification. It also listed upper wind data, starting time, number of miles traveled, and whether or not the altitude was to be interpolated. For those aircraft not reporting altitude and climbing out of JFK (the majority), it was necessary to interpolate between altitude over MANTA and that over SIE, and for those aircraft, an additional card was included which listed the first and last track number for which the interpolation was to be executed, and the aircraft's altitude at those points. Then if that option was selected, the program then carried out a simple straight line interpolation between those points.

These identity cards, together with the raw data tape, form the input to the program. The output consists of a new listing and a reduced data reel. The listing reproduces the card input for each flight together with the number of callsigns and physical records present on the reduced data reel at that time. It also supplies a printout of slant range, azimuth, altitude, time, identification code, and ground range which is computed in the program.

The ground range is arrived at through the solution of a simple right triangle where the slant range (from the raw data), and the altitude form the hypotenuse and one leg respectively. The curvature of the earth was considered as insignificant, over the distances involved in this test (maximum about 110 nmi).

The organization of the reduced data reel is based on sets of tracks, each set identified by the aircraft's callsign. The first record on the reel is a reel identifier record. The first record of each callsign section is basically a reproduction of the flight identifier card plus a field identifying the sequential number of that particular callsign on the reel. The second record of each callsign section lists the track numbers associated with that callsign.

Following this is a section of three records for each track which reproduces the packed data of the raw data tape, and includes the unpacked information which was printed. The inclusion of the raw data makes subsequent reference to the raw data tape unnecessary.

The reduced data reel can be updated by including in the card input for this program as the first card, the number of callsigns presently on the reduced data reel, and the number of records these callsigns represent. This information is available from the last run this program made on the reduced data reel.

IV. DATA ANALYSIS AND RESULTS

TECHNIQUE

To compare all the results of the various recordings (Gulfstream calibration EAIR and BVDR, Flight Inspection, and User aircraft) it is necessary to adopt a common reference and coordinate system. Since it is much easier to understand, interpret, and draw conclusions from pictorial data than pages of numbers it was decided to produce track plots from the data with the backup of other statistical data.

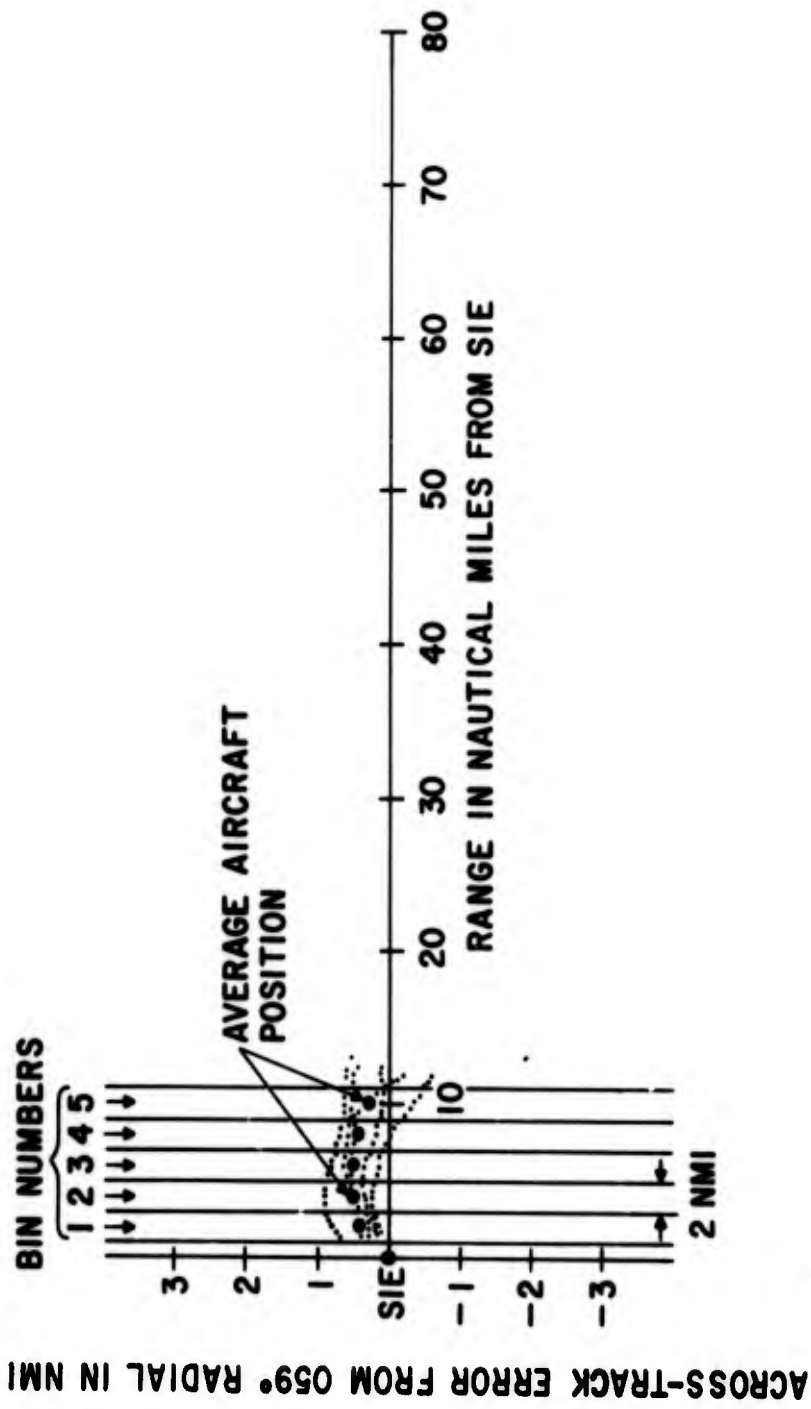
Therefore the coordinate system chosen was one based on the SIE VOR. Each aircraft position (whether derived from the ARSR/BVD or the EAIR) was translated to SIE in terms of range and azimuth. This was done in the analysis program, the input being the processed data tape described in Section III. In the case of both the Gulfstream calibration and the User aircraft, each analysis requires a number of aircraft tracks. Therefore some averaging was carried out in the following manner.

The airway was divided up into a series of "bins." Each bin represented 2 miles of range along the airway (in a few cases 5 miles was used). All the aircraft data points within each bin were then averaged to determine the average aircraft position.

The bin size of 2 miles was chosen to allow some averaging rather than trying to analyze every single aircraft return which would have increased the complexity of the problem and yet it provided a common reference system for all data points. Also, since the average speed of most aircraft was about 300 to 360 knots, this, coupled with an antenna rotation rate of 6 rpm resulted in obtaining two or three target reports per 2-mile bin.

Figure 5 shows the technique used. Bin 1 encompasses all data points from 1 to 3 nmi. Within this bin all data points are averaged. In the example, five aircraft tracks are shown and the average position in Bin 1 is 2 nmi range, and an across-track error of +0.5 nmi. In the final analysis, each average position in each bin is joined up to give the average track.

At the same time, the computer lists the maximum deviations in each bin. Thus, for Bin 1 the maximum deviations either side of the mean are +0.9 and +0.1, while in Bin 5 they are +0.6 and -0.4 respectively. In addition, the computer calculates the standard deviation of the across-track error.



7346

FIGURE 5. DATA PRESENTATION AND AVERAGING TECHNIQUE

The across-track error is defined as the distance in nautical miles measured between the Ideal Radial and the actual aircraft position in each bin. The Ideal Radial is defined as the great circle line described by that VOR azimuth used for showing the airway on flight planning charts and airway maps. In these particular tests it was the 0.058 or 0.059 degree radial from the SIE VOR.

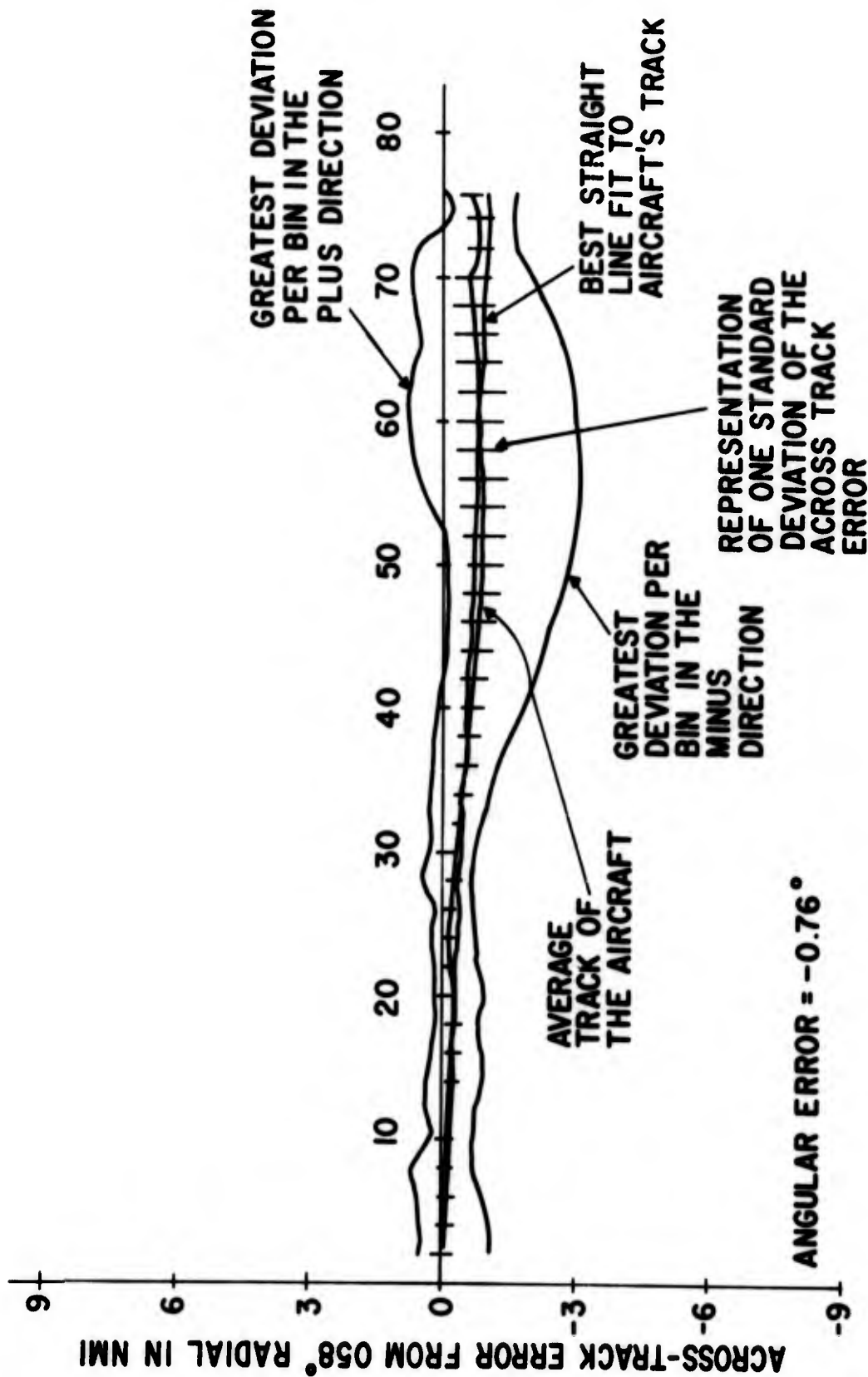
The across-track error is measured perpendicular to the Ideal Radial and is either plus or minus, depending upon which side the actual aircraft position lies.

Finally, when all the average aircraft positions are obtained and the average track can be determined, the computer program then calculates the best straight line fit of the track. In determining the best fit, the assumption is made that the straight line must pass through the zero datum--or in this case--the SIE VOR. Having determined the fit, the angular error, plus or minus, between the straight line fit and the Ideal Radial is calculated. This value is then the angular error between "Apparent Radial," as defined by the straight line fit of the aircraft track(s), and the Ideal Radial. More detail on the mathematical techniques are given in Appendix C.

CALIBRATION RESULTS

(1) 1966 Gulfstream Runs. Two separate sets of data were obtained, the first set at an altitude of 26,000 feet, the second at an altitude of 10,000 feet. The intent was to see if the radial characteristics were any different between the two altitudes. Also, at the time, it was intended that these runs should be a calibration of the BVDP data against the EAIR, but, as described previously, this proved impossible. Figures 6 and 7 therefore show just the EAIR record of these two sets of data as analyzed by the computer program. There are a number of different parameters plotted on the figures. Figure 6 has been annotated to explain the visual presentation. Essentially the figures show the average track and the maximum deviations either side as an "envelope." This envelope is due to a combination of errors:

- Tracking errors (EAIR)
- Pilot error (not exactly flying the radial centerline)
- Aircraft VOR receiver/instrument errors
- Calibration errors when setting up the VOR receiver prior to each flight.



7347

FIGURE 6. EAIR CALIBRATION RUNS-GULFSTREAM AT 26,000 FEET

1966

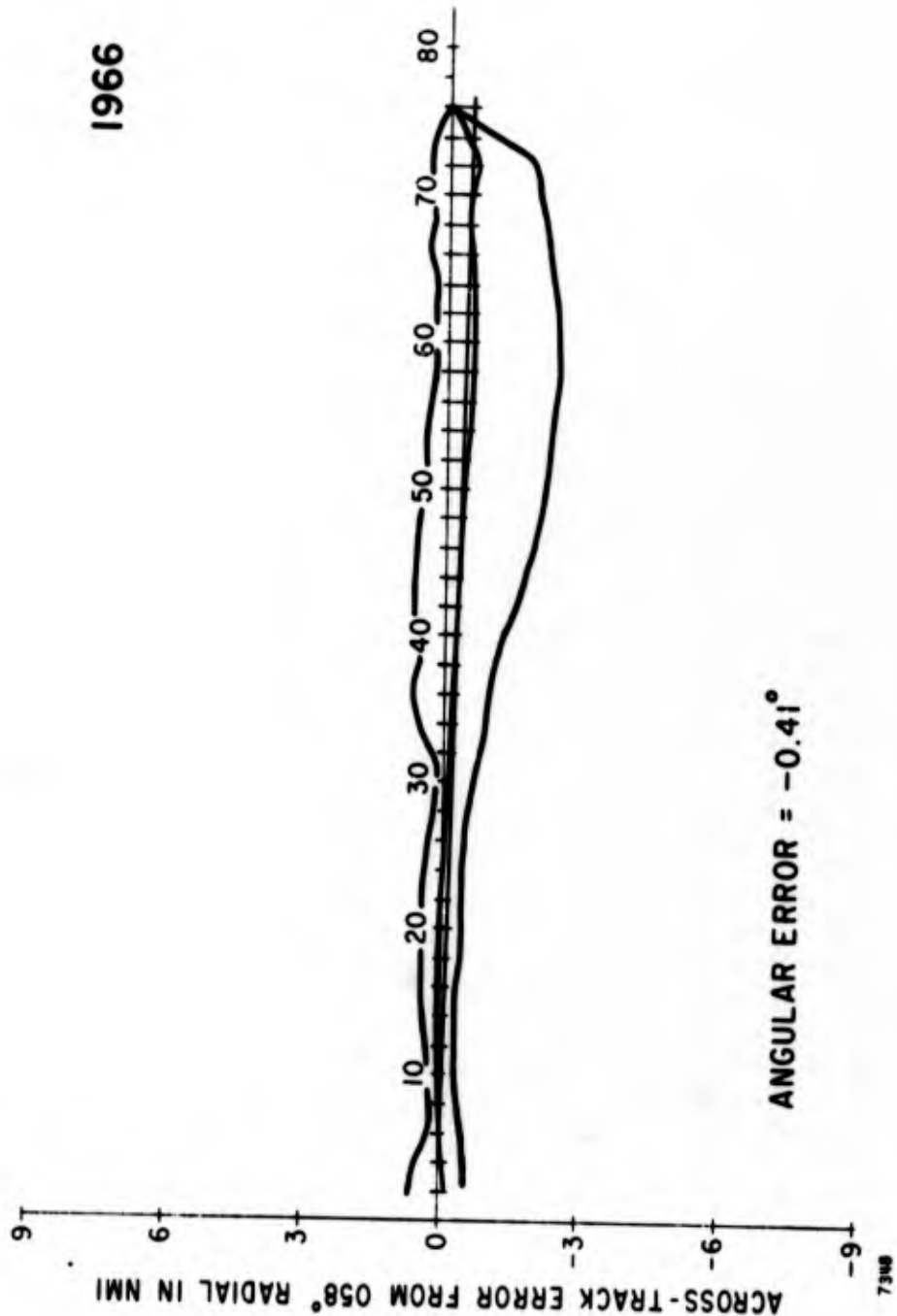


FIGURE 7. EAIR CALIBRATION RUNS-GULFSTREAM AT 10,000 FEET

It is not intended to enter into an examination of the contribution of each error, but rather to draw the conclusion that this is the best that can be achieved under closely controlled conditions (that is, complete pilot cooperation) and use the data for comparison purposes.

Figure 7 shows the results of the Gulfstream calibration at an altitude of 10,000 feet. In comparison with the 26,000-foot calibration, there is an apparent shift in the radial, but it is very small, from -0.76 to -0.41 degree, a difference of 0.35 degree. It was felt that this was not significant enough to draw any firm conclusions. It should be noted that the envelope of maximum and standard deviations is reduced in the 10,000-foot case, but this was probably a function of pilot experience as the test progressed.

(a) EAIR Results. Two separate sets of data were obtained, the first on one ground transmitter in May, the second set being on the second transmitter at SIE in August. These two sets of data are shown in Figures 8 and 9.

All these runs were made at an altitude of 20,000 feet and, in comparison with the 1966 data, it is apparent that the radial has shifted to the north of the airway itself. In comparing Figures 8 and 9 we find that the angular error difference between the two transmitters is only 0.42 degree. It is considered that this is well within the calibration tolerance of the VOR receiver in the aircraft and we therefore concluded that, for practical purposes, we could combine both sets of data.

This is shown in Figure 10 and represents the calibration standard to check the BVD data, which was obtained concurrently with that the EAIR.

It should be noted that we also checked northbound runs along the airway against southbound runs and found no real difference between the two. The results of this check have not been shown here.

Note that the 1968 results show a reduced maximum deviation envelope over those taken in 1966. It is considered that this is due entirely to the difference in sample size--a total of 33 runs in 1966, against 11 in 1968.

(b) ARSR/BVD/BVDR Results. Figure 11 shows two track plots, the EAIR combined data for 1968, and the BVD results superimposed as a dashed line. The two sets show a remarkable similarity, the angular difference between the two being only 0.18 degree and most of this is due to a slight difference beyond the 30 nmi range where the pilot would have more difficulty in flying the radial centerline, and where the aircraft is closer in range to the JFK ARSR and farther away from the NAFEC EAIR.

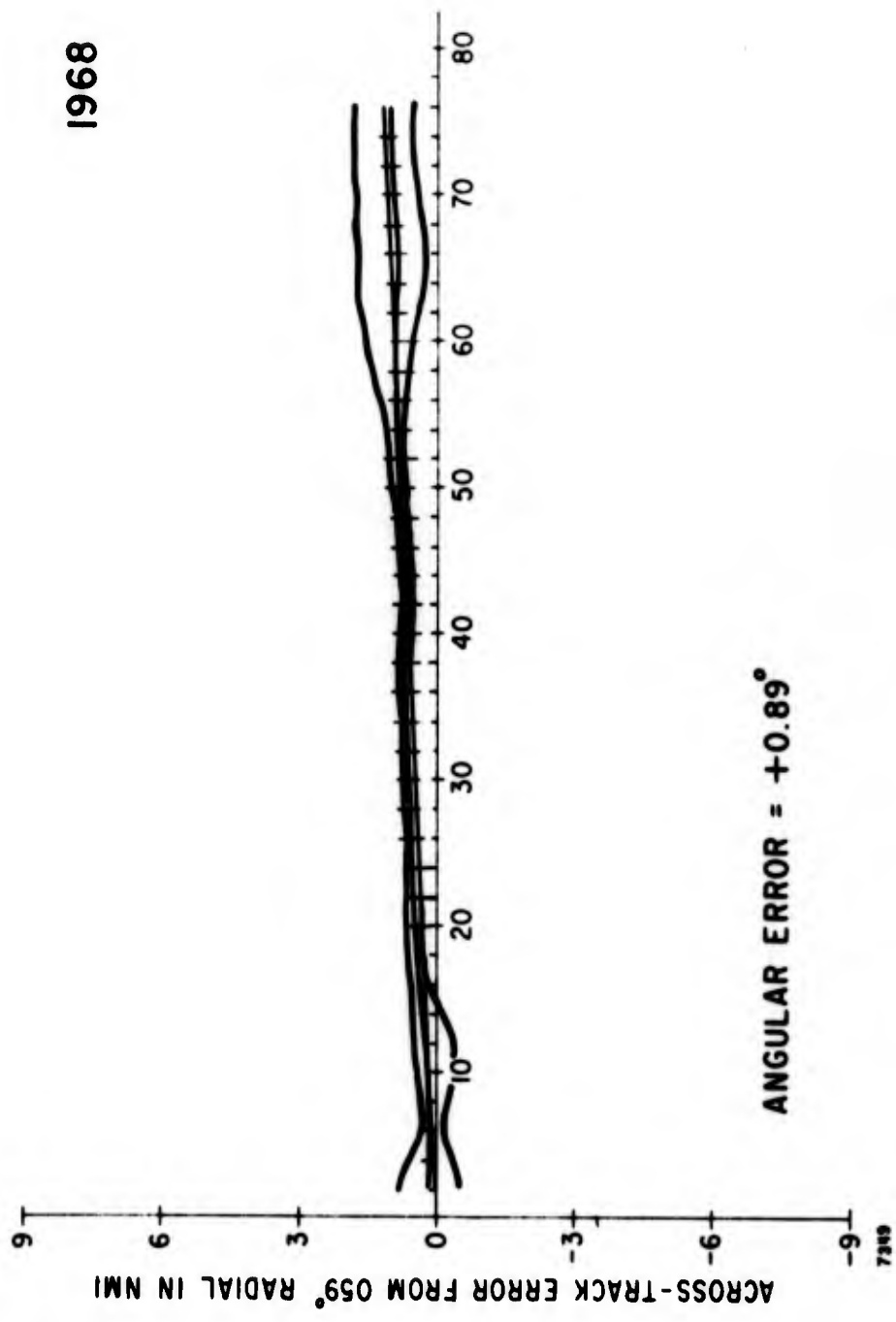


FIGURE 8. EAIR CALIBRATION RUNS-MAY 1968, VOR NO. 1

1968

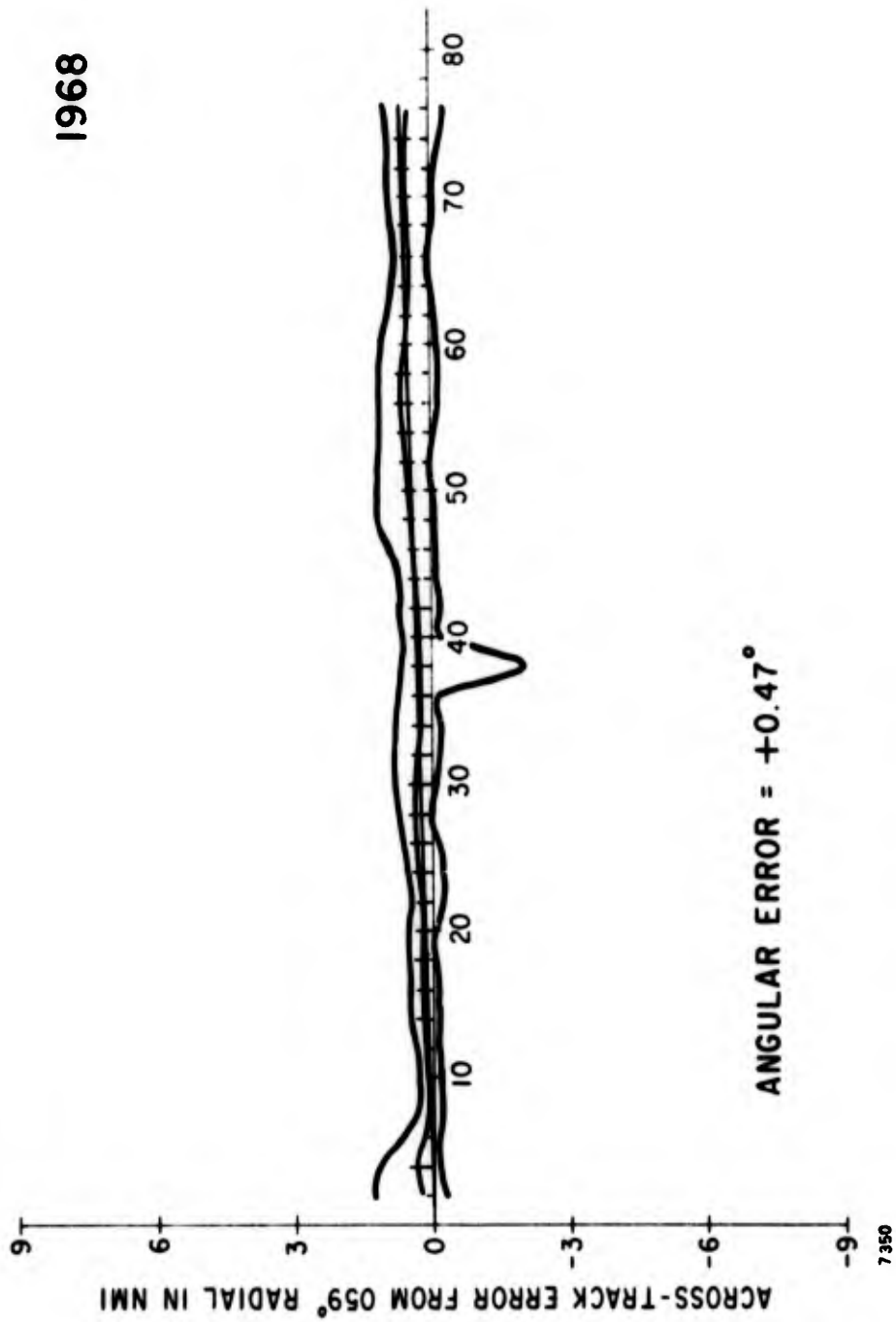


FIGURE 9. EAIR CALIBRATION RUNS-AUGUST 1968, VOR NO. 2

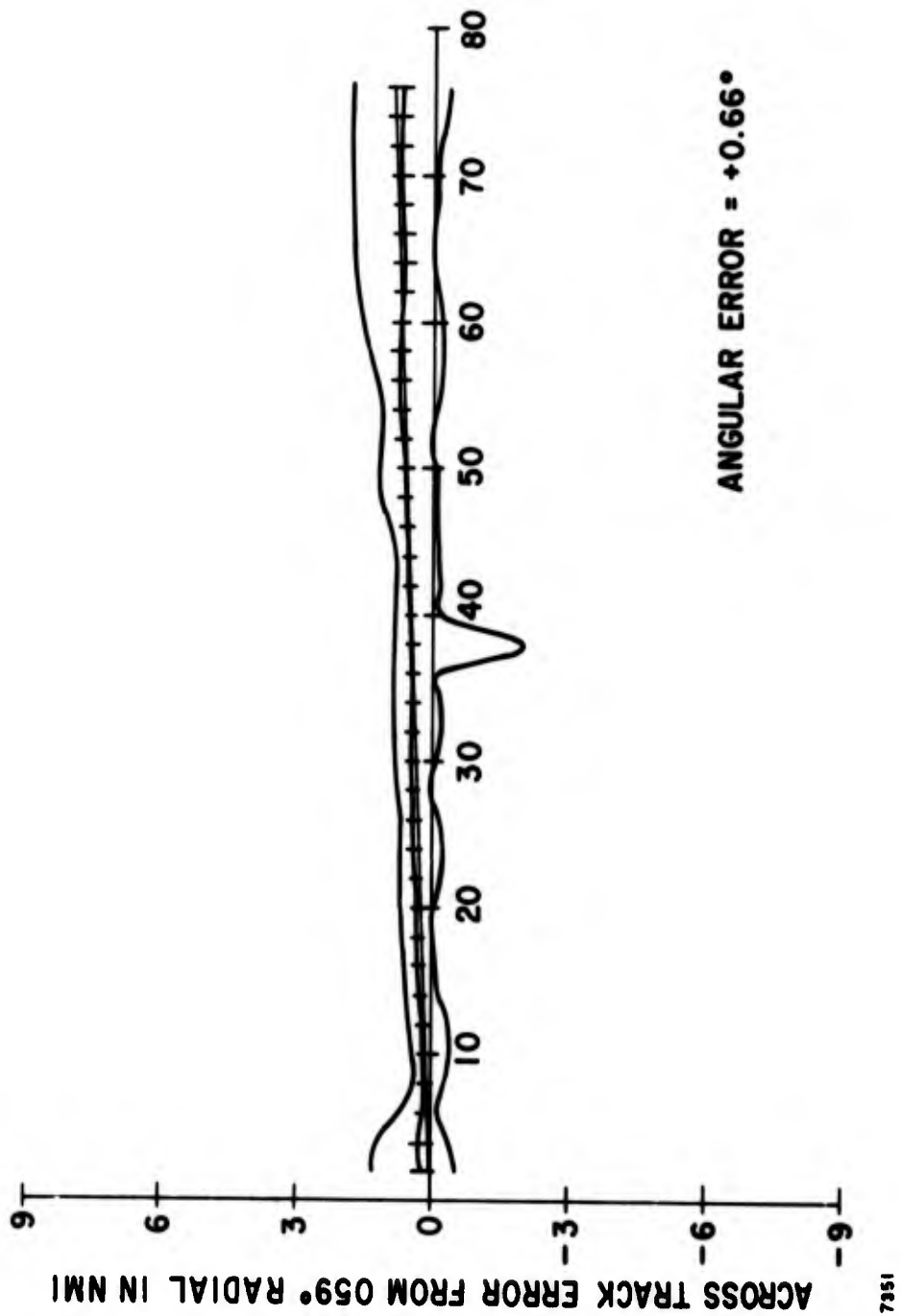
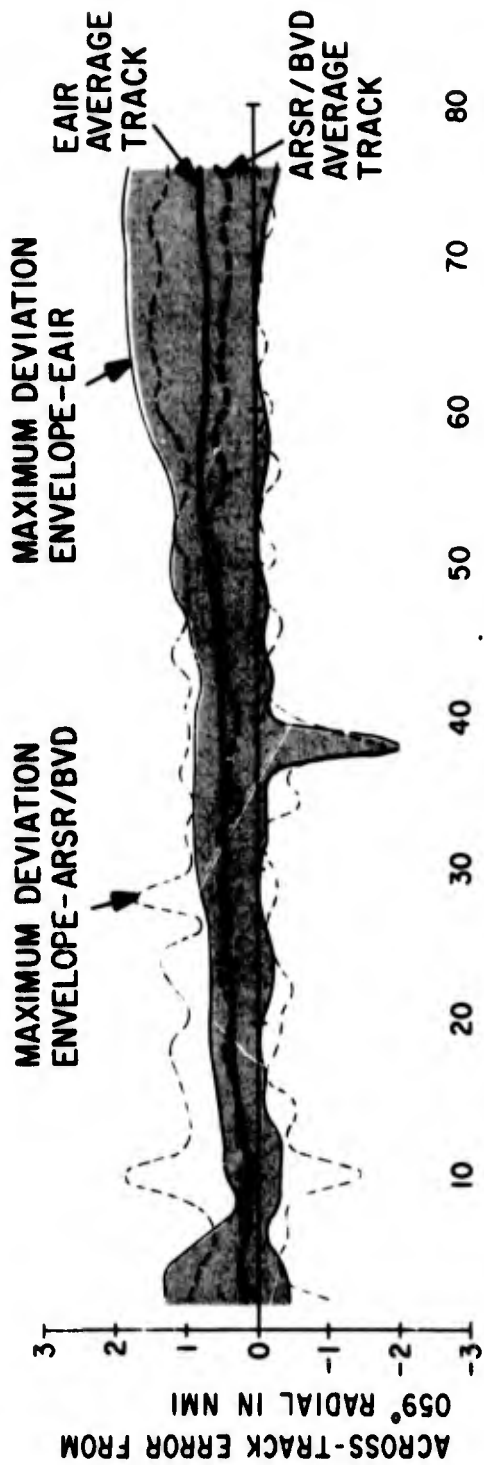


FIGURE 10. FAIR CALIBRATION RUNS-1968 CALIBRATION



— EAIR ANGULAR ERROR = +0.66°

-- ARSR/BVD ANGULAR ERROR = +0.48°

FIGURE 11. ARSR/BVD CALIBRATION VS EAIR CALIBRATION

7352

Note that the Maximum Deviation envelope for the EAIR data shows an increase with range from the EAIR as does the BVD data, but since both the radars are at opposite ends of the airway, the maximum error of the EAIR occurs when the BVD errors are at their minimum, and vice versa.

We have not attempted to analyze the errors in any detail but as a subjective judgment one can say that, in general, the EAIR data appears to be more consistent than the ARSR/BVD. This is accentuated by the fact that the EAIR has a very fast data rate of one hit every 0.1 second, while the ARSR is one every 10 seconds. However, in terms of overall accuracy, the comparison of the average tracks tend to show that the ARSR/BVD combination is just as accurate as the EAIR at ranges up to 75 nmi from the radar site. For example, a comparison of the standard deviation of the across-track error at ranges between 28 and 32 nmi from SIE shows that, for the 1968 data, the standard deviation is between 0.45 and 0.46 nmi for the EAIR data, for the ARSR/BVD it is between 0.33 and 0.49. (At the 30 nmi range from SIE the aircraft is 25 nmi from the EAIR, but 75 nmi from the JFK ARSR.)

However, when the aircraft is at MANTA, the comparative across-track values are 0.72 nmi for the EAIR (range 55 nmi) and 0.43 for the ARSR/BVD (range 45 nmi). The angle of cut between MANTA, NAFEC, and JFK is such that the across-track accuracy measured from the ARSR/BVD data is obtaining its accuracy in range, whereas the EAIR is limited at that point to azimuth data.

In looking at the data presented in Figure 11, it is apparent that when the aircraft reaches a range of 80 miles, or greater, from the ARSR/BVD, the BVD occasionally has more difficulty in obtaining the exact center of the radar return. The result is that "peaks" show up in the maximum deviation envelope. Three of these peaks, or "jitter" as it might be called, are apparent, one at 29 miles, and two, one either side, at 10 miles.

Finally, it will be noted that both the BVD and EAIR data show a "peak" in the maximum deviation envelope at about 38 nmi from SIE. This is due to extreme turbulence encountered during one particular run when the aircraft lost altitude and deviated from the radial. The peak is accentuated by reason of the distorted distance versus across-track error scales, but there is no doubt that the aircraft deviated from the radial by the amount shown since both the EAIR and BVD results are almost identical.

This project was not devoted to a study of the accuracy of the ARSR/BVD system versus the EAIR, so it is unnecessary to go into further analysis. However, the conclusion must be drawn that the ARSR/BVD combination is

an accurate technique, especially when a reasonable number of tracks are obtained for averaging purposes. In fact, it is probably a more accurate system than was thought previously, and that the finding of target centers by the BVD greatly improves the accuracy of the basic ARSR secondary radar.

(c) Flight Inspection Results. The Flight Inspection results are shown in Figure 12. These were the only data that could be obtained from 1968 and no data was taken inside 48 nmi range from SIE. The results can be compared with the May 1968 EAIR data for comparison (since this would be the same VOR transmitter--they alternate each month). Figure 12 shows the comparison, and, if one accepts the across-track accuracy of the EAIR to within a standard deviation of 0.6 nmi in this region, the conclusion must be that while the flight inspection confirms the general trend of the apparent radial (lying to the north of the ideal), the EAIR gives a better idea of the operational characteristics of the airway. This is really not surprising since the EAIR data is an average of at least 10 runs, while flight inspection is one test run.

Again, it is not within the scope of this report to engage in a discussion of relative accuracies, but to ensure that a good calibration was obtained on the radial by means of the ARSR/BVD/BVDR combination.

(2) Conclusions. The combination of the JFK ARSR/BVD/BVDR has the required accuracy for defining the 0.059-degree radial of the SIE VOR. We may generalize and state that the across-track accuracy can be determined to within 1/2 nmi (one standard deviation). Also the average angular error of the 0.059-degree radial appeared to be about 1/2 degree in May-August 1968, so that if an aircraft wished to fly along the Ideal Radial it would be necessary to fly the 0.059.5-degree radial from the SIE VOR.

USER AIRCRAFT DATA

The total of User aircraft tracks analyzed was 295. These were made up as follows: 88 percent airline-operated aircraft, 10-percent military, and 2-percent general aviation.

Averaging all the User aircraft tracks, we find that the resultant track lies quite close to the center of the airway. Figure 13 shows the results compared with the Gulfstream calibration. The best straight-line fit of the User aircraft track shows an angular error of -0.27 degree from the Ideal Radial. Compared with the calibration of the 0.059-degree radial, this is an angular error of 0.75 degree, with the maximum across-track deviation of 1.4 nmi at about 52 nmi from SIE.

ACROSS-TRACK ERROR FROM 059° RADIAL IN NMI

7863

FLIGHT INSPECTION AT 20,000 FT, 4TH SEPTEMBER 1968

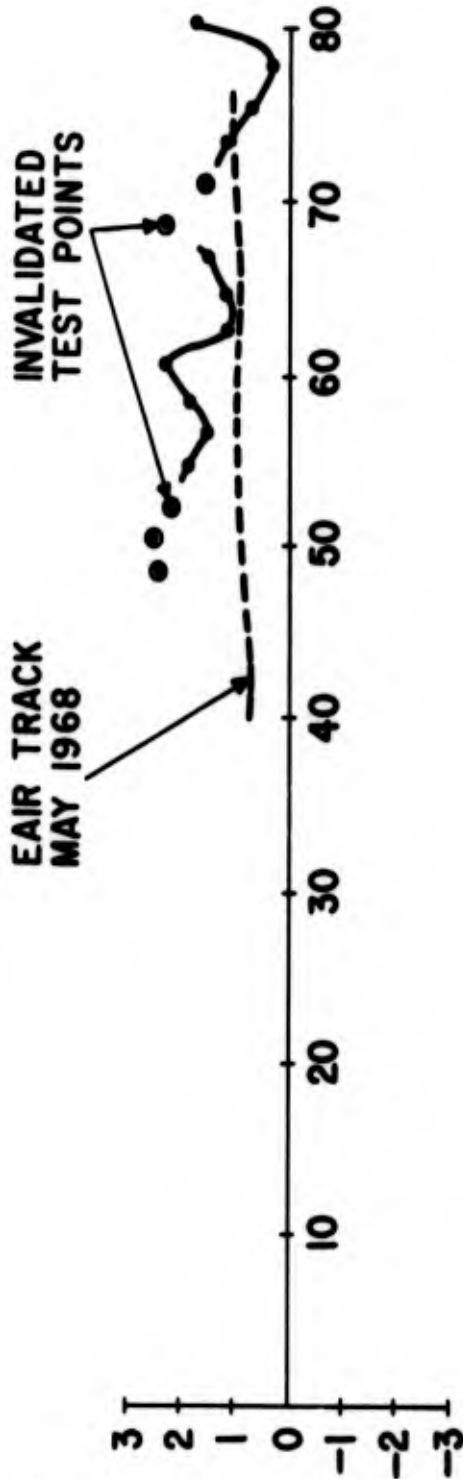


FIGURE 12. FLIGHT INSPECTION DATA - 0.059 DEGREE RADIAL

For the User aircraft the standard deviation of the across-track error (in nautical miles from the center of the average flight track) varied from 1.5 nmi at 10 nmi (from SIE), to 3.6 nmi at MANTA intersection. These values are shown on Figure 13 compared with the values for the Gulfstream calibration.

Before coming to any definite conclusions from this data we should examine various other aspects.

(1) Sample Size and Distribution. Figure 14 shows the average flight track of selected sample sizes--the first 50 aircraft, then the first 100, and the first 150 aircraft.

This figure shows a definite trend, in that as the data sample was increased, the average track came closer to the ideal airway centerline and, in fact, finally averaged out slightly to the south of the airway. A comparison with the average track of all 295 of the User aircraft shows that the track with 150 data samples very closely approximates the former.

Further analysis of the original data showed that of the first 50 aircraft, 50 percent exceeded the airway width. By definition the airway is ± 4 nmi either side of the centerline widening to ± 4.5 degrees at ranges greater than 50.8 nmi. This is shown in Figure 14.

It was significant that nearly all the aircraft exceeding the airway width were to the north of the airway and were in fact taking the "short cut" from JFK to SIE. However, when these first 50 runs were excluded from the data we found that 60 aircraft, that is, 25 percent of the aircraft, exceeded the airway width, and slightly more than half of these were excursions to the south.

Figure 15 is a histogram of the distribution of all the available User aircraft at the 20 nmi range point from SIE. This range was chosen since most aircraft had completed their "corner-cutting" by this range and those that had attempted to fly the airway had eliminated most of the crosswind effects at this point. Therefore, it is felt that this histogram depicts what one might expect to see on a longer cross-country airway when aircraft had settled down to genuine enroute navigation using a VOR.

Figure 16 is a plot of the 60 aircraft tracks out of the final 245 users that exceeded the airway width. A further analysis showed that, on the average, when an aircraft went outside the airway it tended to remain outside for 30 nmi along the airway. We must be careful in drawing conclusions from this data. The following deductions may be made:

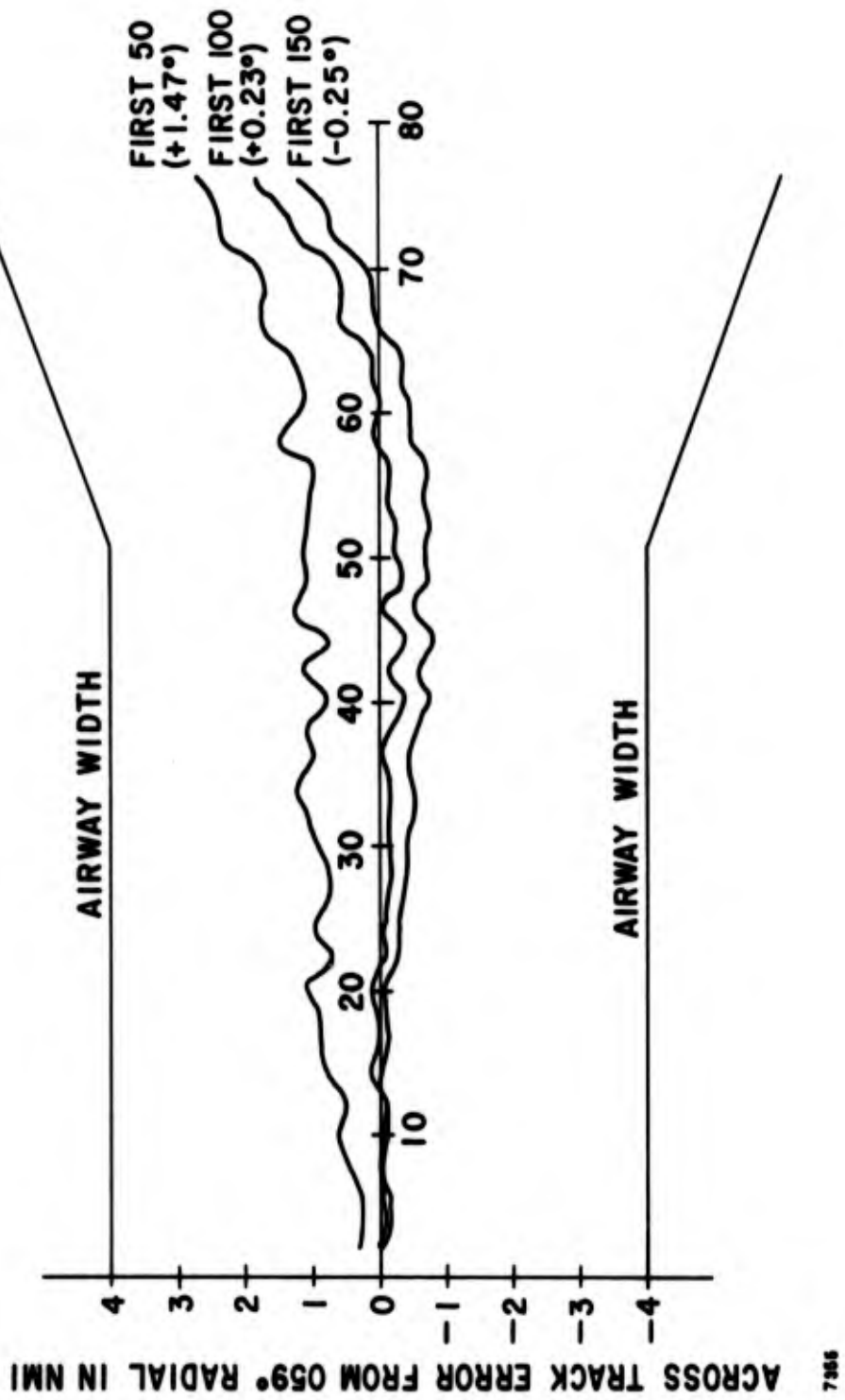
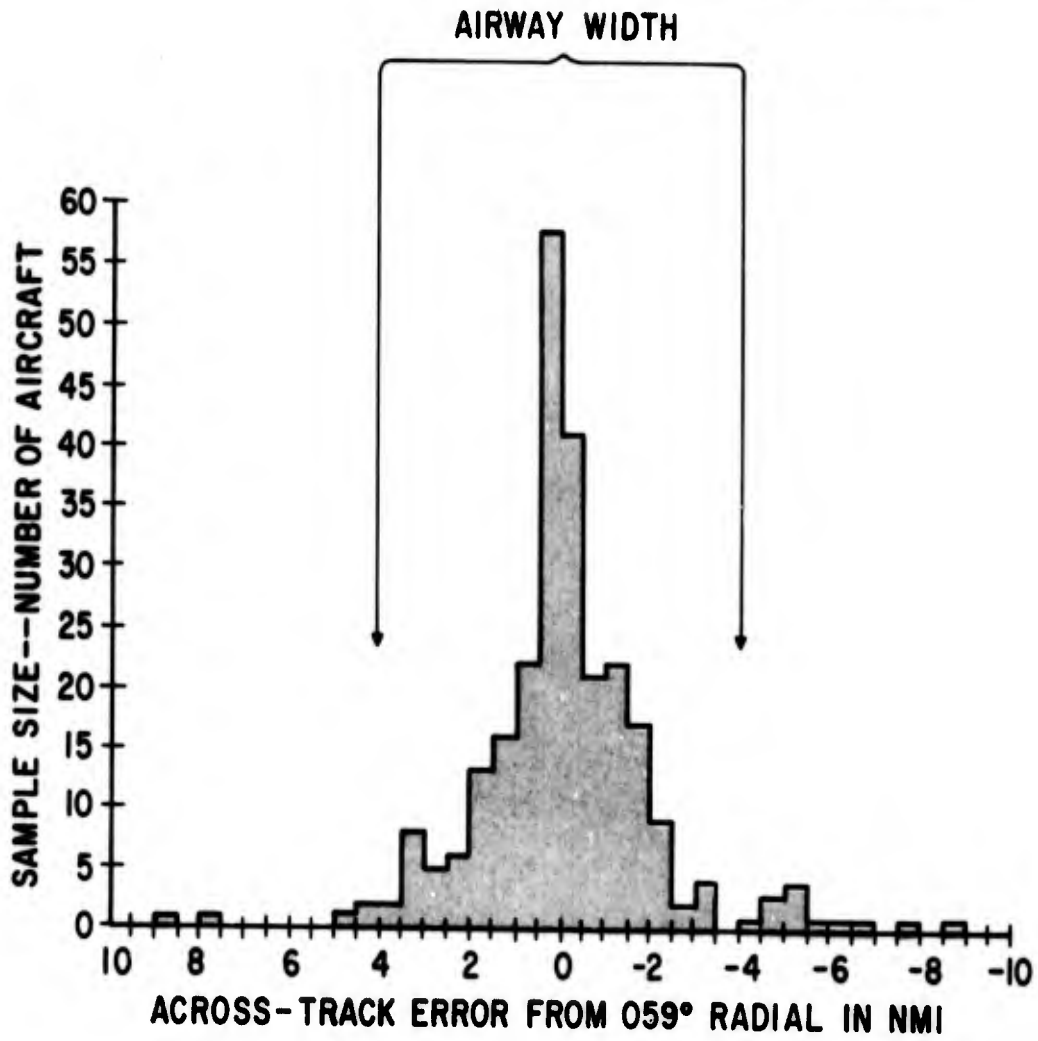


FIGURE 14. EFFECT OF SAMPLE SIZE ON TRACK DATA

TOTAL SAMPLE SIZE
AT THIS DATA POINT
IS 264 AIRCRAFT



7366

FIGURE 15. DISTRIBUTION OF ALL USER AIRCRAFT AT
20 NMI RANGE FROM SIE

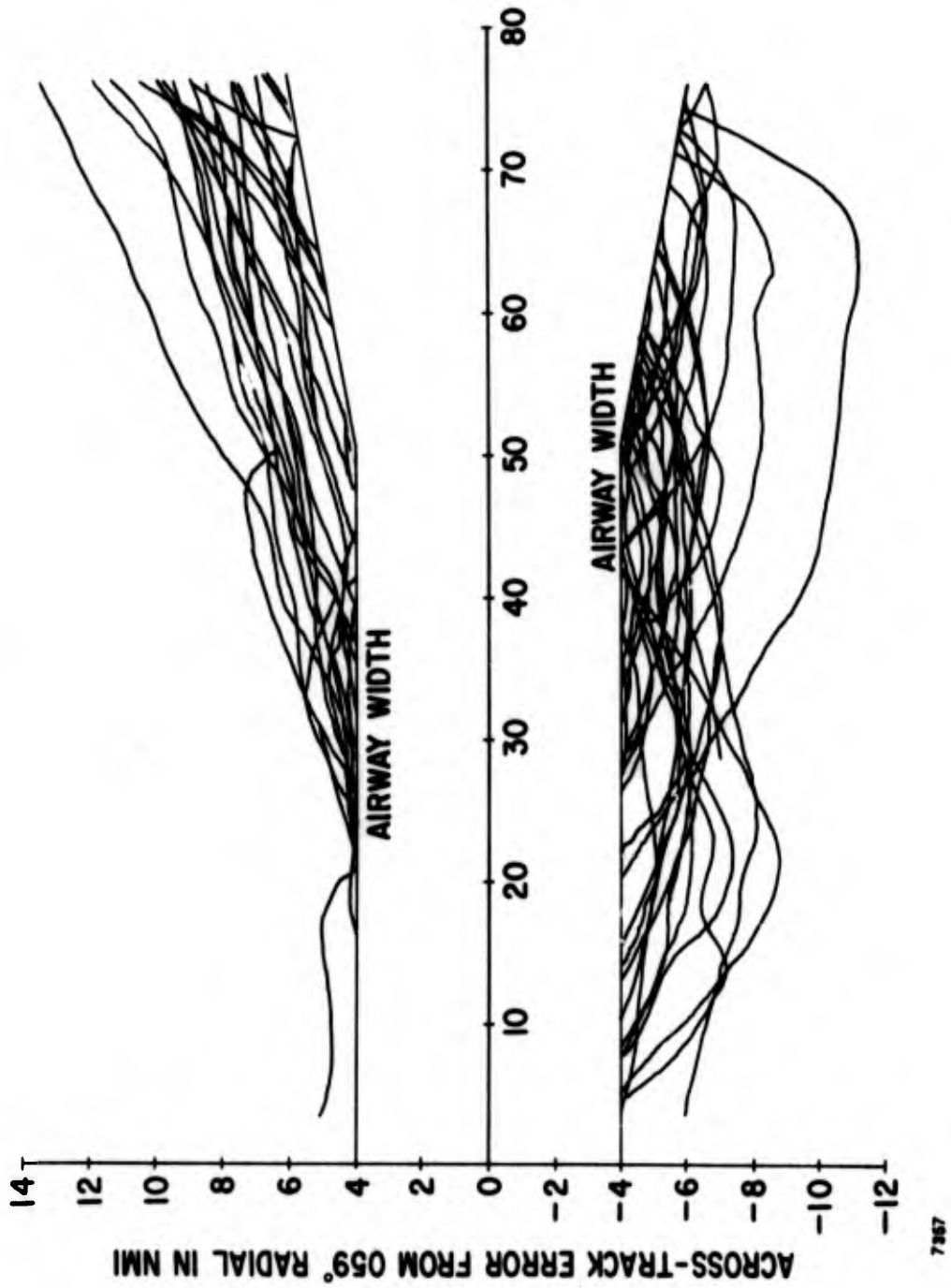


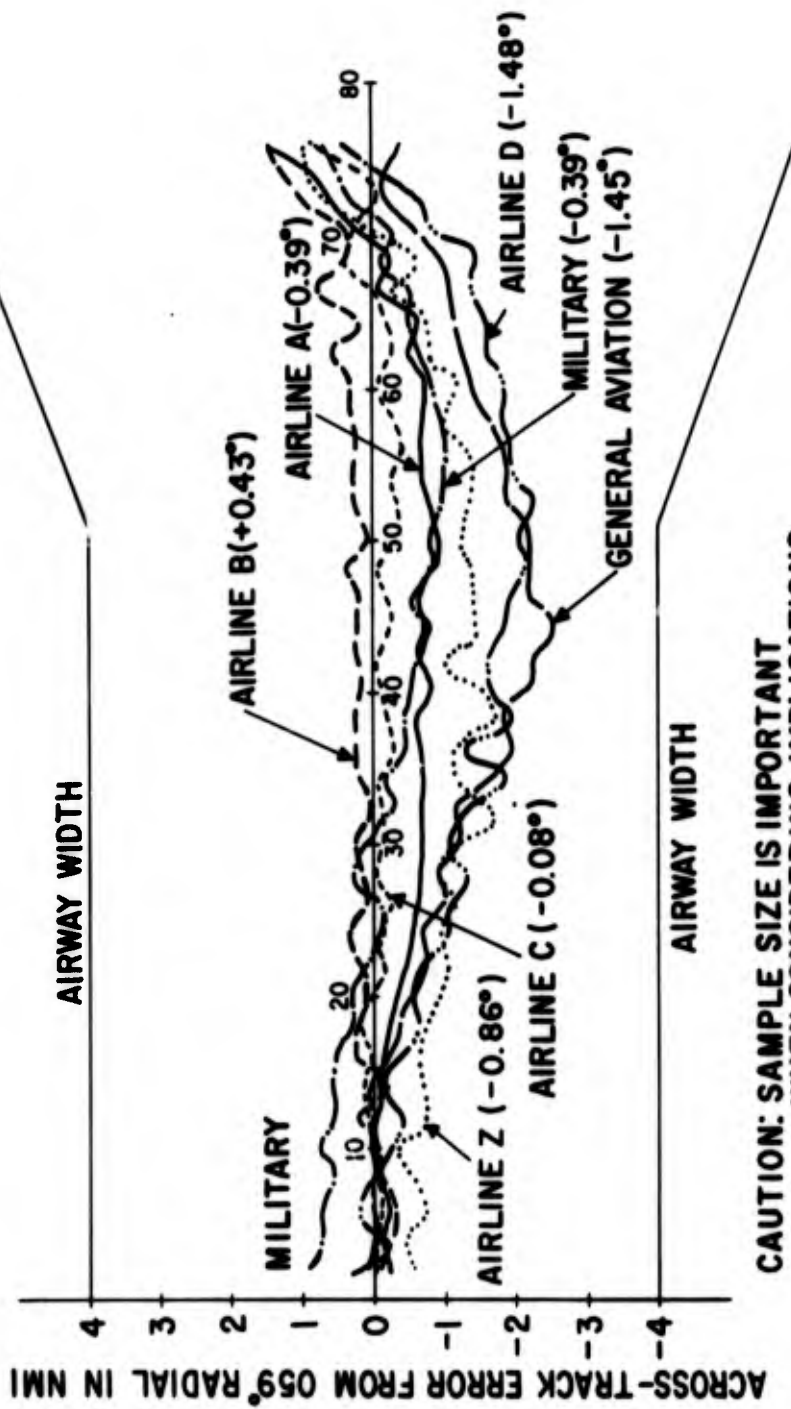
FIGURE 16. INDIVIDUAL TRACKS OF AIRCRAFT EXCEEDING AIRWAY

- It took about 2 days for the controllers at the center to get used to the test. During this time the "short-cuts" to SIE were reduced, but still occurred, and biased the data from the first 40 or 50 aircraft.
- After this, the controllers settled down to the requirements of the test and the result was that many aircraft now joined the airway in the region of the MANTA but, in the turn-on, overshot the centerline, and some exceeded the airway width by some 1-1/2 nmi on the average (Figure 15).
- It should be noted that the controllers were extremely busy while the test was going on and they just could not always remember to take test aircraft off the special codes if they saw any "short-cuts," or when they had to vector aircraft around each other for separation purposes.
- Also, it should be noted that there are no other airways in the vicinity of V139/J121 until an aircraft reaches SIE. Therefore, there is no great incentive to hold the airway centerline--either on the part of the pilot or the controller. It would therefore be inadvisable to apply the results of this test in drawing conclusions as to the flying characteristics on any other airway, except where such other airways had the same conditions regarding turn-on and the proximity of other airways.

(2) Analysis of Aircraft Operators. This was only performed on Class 1 and 3 tracks, that is, those aircraft that flew the entire length of the airway. Analysis of the operators showed four domestic airlines flying this airway that could be individually sampled, and a composite group of domestic and international airlines. The results are shown at Figure 17. Airlines "A" through "D" are the domestic airlines, and the composite group--Airlines "Z." Military aircraft made a sixth group and a few general aviation, the seventh group.

As noted, it is important to consider sample size when judging reliability of the data. Subjectively, with experience of flight test data of a similar kind, it is suggested that less than 20 samples constitute a less-reliable level of confidence. Therefore, it is felt that the tracks of Airlines "A," "B," "C," and "Z," and the military aircraft are the most reliable.

(3) Effect of Wind. While not shown specifically on any one of these figures, the effects of the upper winds were analyzed. The "average wind" throughout these tests was from between the South-West and West-North-West at 30 to 35 knots at 20,000 to 30,000 foot altitudes.



CAUTION: SAMPLE SIZE IS IMPORTANT
WHEN CONSIDERING IMPLICATIONS
OF OBSERVED DATA

SAMPLE SIZE:
 AIRLINE A 98 TRACKS MILITARY 26
 B 52 GEN. AVIATION 9
 C 26
 D 19
 Z 28

7388

FIGURE 17. ANALYSIS BY AIRCRAFT OPERATOR

There is no doubt that it caused the overshooting of the airway centerline to be accentuated, and this would be particularly true of the General Aviation aircraft which were slower than the airline aircraft. Being slower, they are therefore affected more by a crosswind, and this may well account for some of the greater deviations shown by these aircraft.

For jet aircraft climbing out of JFK airport their average speed was about 300 knots. An analysis of the wind conditions showed that the aircraft drift angle, due to wind, would normally be between 2-1/2 and 5-1/2 degrees. Since it takes a short while for a pilot (or autopilot) to accommodate the drift angle, it is quite reasonable to expect that average deviations between 1 and 2 miles would result. The data tends to confirm this.

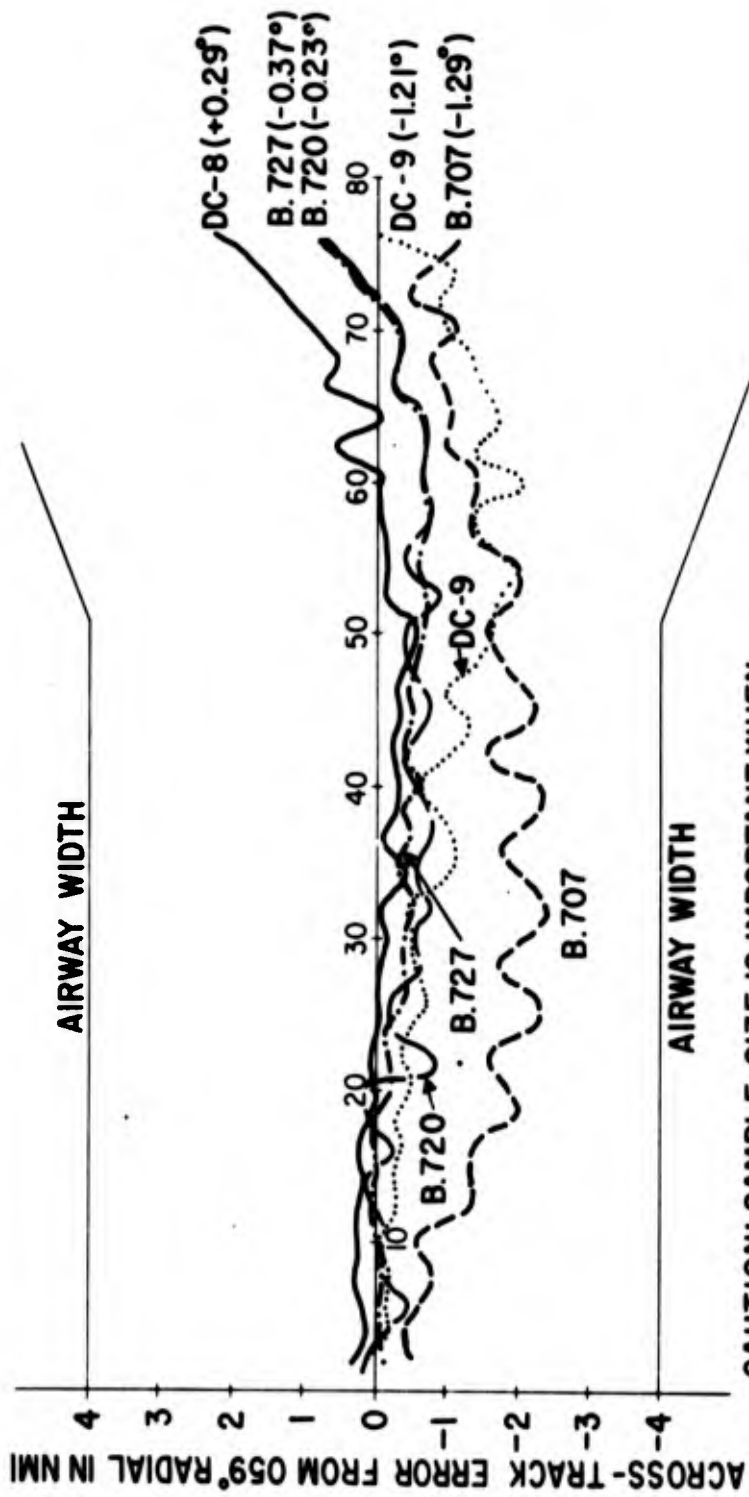
However, it should be noted that with the exception of 13 aircraft (5 percent) in the last 245 data samples, all the aircraft stayed within +10 degrees of the 0.059-degree radial, this value being full-scale deflection on the aircraft's instrument.

(4) Analysis by Aircraft Type. This is shown in Figure 18. Because the majority of the aircraft were airline types, it was found that only five airline types would yield enough samples for analysis:

Boeing 727 - 108 samples
720 - 20 samples
707 - 16 samples
Douglas DC-8 - 62 samples
DC-9 - 12 samples

As in the case of aircraft operators, it is important to consider sample size when drawing any conclusions, and for the same reason, the 727, 720, and DC-8 are considered to be more reliable data. Therefore, it is difficult to say if there is any significance to particular aircraft types. It is possible that the position of the beacon transponder antenna on a particular type of aircraft could cause poor radar reply returns, but since we eliminated all invalid returns during processing, this would not be a factor here. If we eliminate the 707 and DC-9 because of insufficient data, we must conclude that there is no significant difference in aircraft type.

In passing, it should be reemphasized that the effect of crosswinds would be more noticeable on slower aircraft, but in this case there is no appreciable speed difference between the five chosen aircraft.



CAUTION: SAMPLE SIZE IS IMPORTANT WHEN CONSIDERING IMPLICATIONS OF OBSERVED DATA.

SAMPLE SIZE:

BOEING 72 108 TRACKS

720 20

707 16

DOUGLAS DC8 62

DC9 12

7388

FIGURE 18. ANALYSIS BY AIRCRAFT TYPE

(5) Effect of Altitude. It was difficult to analyze this factor in the User aircraft because nearly all the aircraft were climbing out from JFK airport. The average altitude at MANTA was about 15,000 feet increasing to about 30,000 feet at SIE. Some 20 aircraft were in level flight at altitudes between 5000 and 10,000 feet but these were nearly all military, and their tracks were almost identical to the military sample shown in Figure 17.

It is also felt that any such analysis would be complicated by the effect of different winds at the various altitude levels. Therefore, because of this, and the fact that our analysis of the Gulfstream calibration showed very little difference in altitude, we must conclude that there is no great significance in the effect of altitude on airway flying performance.

IMPLICATIONS OF DATA

It must be remembered that the User aircraft were noncooperative targets-- that is, their pilots were unaware of the tests. It must also be remembered that the air traffic controllers were very busy with trying to control traffic in their usual way. Their cooperation was superb in nearly every case.

However, this airway is in close proximity to the New York terminal area and it is a fact that airways, while providing an essential procedural base for control purposes, are of little meaning in the area. "Short cuts" are very common (as we have shown) and vectoring is commonplace.

It is felt that employing User aircraft for airway checking is quite feasible, but not in busy terminal areas. In enroute sectors, such as in the Kansas City-Denver-Minneapolis area, the system would probably be most fruitful and provide better accuracies than those developed in this test.

Also in any future system used on a "production basis," the operators would necessarily have to know that special recordings were being made. Since operator identification would be unnecessary and, in fact, not possible without additional facilities, it is felt that User cooperation could be assumed.

Therefore, an examination of the data obtained on this project would seem to indicate that the basic technique is sound, and that an average data sample of about 100 cooperative aircraft would be needed to flight-check any enroute airway within an accuracy of about 1/2 degree.

As was shown with the Gulfstream calibration, the pilot of a cooperating aircraft will compensate for crosswind effects, and since this was a factor in the User aircraft data, it would increase the accuracy if its effects were

eliminated. There is no doubt that with cooperative User aircraft, there will still be a spread on the data, but 100 samples should be ample for averaging purposes.

Two further points should be stressed. The target validity test features of the BVD used in this project were excellent. Any future "production" system using any other type of radar digitizer would need such automatic validity checking as a prime requirement--with a very high degree of reliability.

Lastly, it must be reemphasized that many of the conclusions pertaining to VOR radial characteristics and aircraft performance relate only to this particular airway, and the VOR at Sea Isle.

Other VOR's in other locations might show differences between transmitters, and other types of airways might show far less excursions of aircraft outside the airway boundaries. In the latter case, it is felt that the V139/J121 airway used here was a worst case.

It is for this reason that we feel that the system is capable of use for enroute airways, and would give an in-service checking ability with semicooperative User aircraft of about $1/2$ degree. This is a subjective opinion based on the fact that 295 noncooperative User aircraft gave an average track that was offset by $3/4$ degree from the apparent radial (that is, the Gulfstream reference). With semicooperative User aircraft one could expect a slightly better result, even with a lower sample size, so that it is felt that $1/2$ degree could be expected.

V. CONCLUSIONS

1. The combination of ARSR and BVD equipment is a very accurate device for determining aircraft position (Figure 11).

2. The reliability of the BVD equipment was excellent, particularly with respect to the validation of target hits. This feature was of great value and its characteristics must be incorporated in any future digitizer if it is to supply good quality target data.

3. The characteristics of the 0.059-degree radial of the Sea Isle VOR are as follows:

- No significant difference in characteristics between altitudes of 10,000 and 26,000 feet.
- No significant difference between the two ground transmitters.
- As of September 1968 the radial is displaced approximately 1/2-degree north of the published airway centerline.
- In operational use there are no serious detectable bends in the radial.

4. Averaging the results from all 295 User aircraft recorded on the airway it was found that the average track, or apparent radial, was within 0.75 degree of the Ideal Radial.

5. There were three bias factors in the data:

- At the beginning of the tests, many aircraft were taking "short cuts" between JFK airport and SIE. These aircraft comprised over 50 percent of the first 50 aircraft.
- As the tests progressed and more aircraft joined the airway at the MANTA Intersection, some overshooting of the radial occurred.
- The overshooting was accentuated by crosswinds during most of the test.

6. Eliminating the 50 aircraft of the early portion of the test, it was found that 75 percent of the aircraft stayed within the boundaries of the airway. When aircraft exceeded the boundaries they tended to remain outside for about 30 nmi along the airway, the average across-track deviation being about 1-1/2 nmi outside the airway.

7. Because of the turn-on characteristics and ease of "short cuts," this airway represents a "worst case" and therefore the final results of the User aircraft analysis are quite significant.

8. When evaluating noncooperative User aircraft it was found that sample size is important. Less than 20 aircraft gave unreliable results, but it is not necessary to sample more than 150.

9. There is some difference between aircraft operators in their performance. Because of their slower speed, some general aviation and military aircraft are more affected by crosswinds during their turn-on and deviate slightly further away from the centerline under these conditions. There are also slight differences between operators using the same type aircraft but the reasons are not known.

- Aircraft type does not seem to affect the accuracy, but as noted above, aircraft speed can have an effect.
- Other than the effect of wind, aircraft altitude has no apparent significance.
- The BVD recorder proved to be useful and reliable and, incidental to its project use, would appear to be useful for maintenance purposes.

VI. RECOMMENDATIONS

1. As a preamble to our recommendations, we must assume that if we are to suggest that User aircraft can supply data for the flight checking of nav aids, and that this can be done on a large scale in the future, then it would be necessary to advertise the fact before such a system went into everyday use.

2. We have shown that under certain circumstances, and with certain constraints, a good sampling of User aircraft can give reliable data. There is no doubt that a "production" system would be economical to operate and should therefore prove attractive to both the users and the FAA. This is covered in more detail in Appendix A.

3. There is no reason why the identity of operators in such a system should be known, and therefore it would seem logical to assume that cooperative User aircraft would participate in the future.

4. Under these circumstances, we could expect that the combination of a secondary radar, beacon digitizer, recording facilities, and a simple computer analysis program could acquire and analyze 100 samples (at a time) of cooperative User aircraft. The results could be expected to give an accuracy of approximately 1/2 degree in determining VOR radial angular errors. This assumption must be qualified by stating that any future beacon digitizer used for this purpose, must have accurate and reliable target validity checks, comparable to those of the BVD used in the tests described here. Such a system might work in the following manner.

5. Appropriate flight checking procedures would be worked out between the FAA and the operators. These procedures would include the use of special discrete beacon codes assigned for flight checking purposes. They would also include simple instructions for pilots, as to how the codes were to be used (only when tracking the airway centerline), and phraseology and simple instructions for controllers.

6. A schedule of User flight checks would be made out for each control center, and, during the check periods, pilots would be asked by controllers to participate, using the assigned codes. A recording system would collect data on 100 tracks for each airway, and when that total was achieved, indicate that fact and, automatically through the Center computer, process the

data to give a tabulation of the airway characteristics. If the radial was found to be within specified limits this would be indicated, if it was outside the limits, this would be immediately signaled in a special way. It would then be necessary to run a special flight inspection of the suspect airway. During the flight inspection the aircraft would be recorded by the system and this would provide a double check on the inspection, and a calibration of the User data. If the inspection data confirmed the VOR as being out of tolerance, the necessary adjustments would be made.

7. It is recommended that when User aircraft are supplying the basic data, that the 100 aircraft be recorded over a period not exceeding 1 month and preferably over a 2-week period. The schedules would have to be set up so as to avoid transmitter switchovers that, apparently, occur at the beginning of each month. When a flight inspection aircraft carried out a special check it would seem desirable to require two runs on the suspect radial. However, this is something that would have to be assessed in the light of more experience in service.

8. Finally, we must consider the controller workload and the nature of air traffic control itself. It must be recognized that much of the traffic control in busy terminal areas presently consists of controller vectoring and "short cuts" taken by pilots (with controller agreement). Once beyond the terminal area in the enroute structure, airway flying is usual, but here again, some "short cuts" are made. It is debatable as to where the terminal area ends and the enroute structure begins. The V139/J121 airway used in this project certainly constitutes a borderline case.

9. It may be argued that vectoring and "short cuts" will continue and may increase in the future. However, it also seems likely that some reorganization of the airspace will eventually come about. It may happen because of the use of "area" navigation techniques, pictorial displays, off-course computers, or even a new navaid. But whatever happens, published airways will still exist, may increase in number, and will be used in a more organized manner.

10. Therefore, viewed in the light of this study, we can come to the following conclusion. Whatever the navaid or system of navigation in use (be it VOR, Omega, Decca, etc.), so long as aircraft fly an airway system and there is radar/beacon coverage of the airways that need to be checked, the techniques suggested in this report will constitute a good method of checking such airways within an accuracy of 1/2 degree. If proper pilot and controller procedures are instituted, there will only be a very minimal increase in workload.

11. We may summarize these and other recommendations as follows:

- Under present techniques of air traffic control in the United States, a system of airways checking by User aircraft is feasible and could be implemented in the enroute airways structure as soon as the Common Digitizer is available, provided that the necessary recording and computational facilities are available.
- It could also be introduced into terminal areas if, and when, traffic control in such areas is done on the basis of airway flying. Some terminal areas may always remain on the basis of true airway flying, in which case, paragraph 1 applies.
- Within the 1/2-degree accuracy to be expected on cooperative User aircraft using VOR airways, it should only be necessary to call for flight inspection when the angular error between the published airway centerline (the Ideal Radial) and the apparent radial exceeds 1-1/2 degrees. (The present tolerances are 2-1/2 degrees.)
- That this technique would provide a simple and accurate device for use in conjunction with flight inspection aircraft (especially in terminal areas) and this aspect should be studied. Some flight testing should be done comparing flight inspection results concurrently with ARSR/BVD recordings.
- The recording of emergency transponder codes should be incorporated in any future recording system for playback purposes in accident location and investigation.
- Other than emergency codes, it would prove very useful to have a ground recorder system similar to the mandatory airborne recorders now in existence. This project has shown that such a system is feasible and capable of good accuracy. With an automatic "wipe-off" feature (to avoid voluminous amounts of recording tapes) it would also prove useful in accident or incident investigation, and for maintenance check purposes.
- The proposed system would not only provide checking facilities for VOR's but can also be used to check other types of nav aids that provide discrete airways, or those providing area navigation facilities. In fact, since this project, the system has been actually used for recent tests of the Decca system in the New York area.

- **There is a great need for determining pilot and aircraft performance in the Air Traffic Control System for developing future traffic procedures and for examining ground equipment performance. The use of techniques developed on this project would seem to offer great possibilities.**

VII. ACKNOWLEDGMENTS

The air traffic controllers, watch supervisors, and maintenance personnel, at the New York Air Route Traffic Control Center were most helpful and cooperative during the entire project. They are kept very busy just handling their normal workload, and special tests, such as described in this report, are always an added burden. They deserve a special "thank you."

Other personnel within the Federal Aviation Administration who were extremely helpful were:

Sam Elliot, FAA Project Manager

George Quinn, NAFEC Coordinator, and in the computer processing at NAFEC, the following people were most helpful:

George Krafft, Vince Mazza, Jim Howell, Don Nelson, and Bob Mixner.

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APPENDIX A
COST/BENEFIT ANALYSIS OF AN
AUTOMATIC FLIGHT CHECKING FACILITY

There are presently some 20 Air Route Traffic Control Centers in the country. There are a total of 1229 VOR's, VORTAC's, and tacan's which require flight checking as follows:

	<u>Number</u>	<u>Average Flight Hours Per Facility</u>	<u>Total Flight Hours</u>
FAA VOR	320	8	2560
MIL VOR	106	22	2332
FAA VORTAC	565	12	6780
MIL TACAN	238	14	2332
	<u>1229</u>		<u>14,004</u>

A very conservative figure for the cost per flying hour for flight inspection is \$215.00. Without calculating the additional costs of manpower and data processing involved in flight checks, and assuming that during an initial period only half of the facilities would be amenable to User checking this would result in a reduction of flight inspection flying costs of \$1,613,000 annually. This is \$80,650 per Center, on the basis of 20 Centers.

Using a techniques described in this report it is estimated that the following costs per Center would result:

Initial Costs (nonrepetitive)

1 Recorder	= \$30,000
Programming	= \$15,000
	<u>\$45,000</u>

Note: For 20 Centers this is \$900,000.

Annual Costs

1 Computer Technician	= \$15,000
Computer running	= <u>\$15,000</u>
	\$30,000

If we assume that the annual cost estimate is under estimated by 50 percent, this would result in a revised figure of \$45,000 per Center compared with the flight inspectio. costs of \$80,650 per Center (assuming only half the present inspection load can be taken over by the automatic facilities).

This argument does not imply that eventually all flight inspection would cease, because special checks would still be required. However, it is suggested that much of the routine-type flying could be eventually eliminated. This would free the flight inspectors and other staff of the routine, and permit them to concentrate on specific problem areas not amenable to the automatic checking. It is suggested that this is entirely in keeping with the philosophy that computers take over automatic data-processing, leaving the human free to exercise his reasoning and decision-making role.

APPENDIX B

OTHER USES OF BVD RECORDER

During the period that the recorder was being used in the New York Center, it was found that it provided useful checking facilities.

1. BVD Offset. During the early comparison of the BVD versus EAIR data from the Gulfstream calibration it was observed that the track plots derived from the ARSR/BVD/BVDR combination showed that the aircraft was apparently not passing over the top of the SIE VOR, whereas the EAIR showed the aircraft over the fix. It appeared as though there was a constant across-track error of about $3/4$ nmi to the north on the BVD data. This was then investigated by means of the special identify pulse used on each Gulfstream run--as the pilot passed over the top of SIE he "squawked I.D." From the raw data tape we extracted the average azimuth and range at this point. It confirmed that the aircraft was apparently north of the VOR and that the azimuth error was $1/2$ degree, with no range error. Checking with the maintenance staff at the Center we subsequently found that they had, in fact, added $1/2$ -degree offset to the North pulse data entering the BVD from the radar. We were informed that this was done early in the installation of the BVD (before our tests began) because they had been told that there was an "error" of $1/2$ to $3/4$ degree in the BVD output.

We were not able to trace the source of this supposed "error" but we may theorize and presume that somewhere on one or more of the center displays a fix, or an airway displayed on the video map, did not appear to agree with where the User aircraft were flying. Therefore the remedy was applied.

We must emphasize that we never found the exact reason for the introduction of the offset, and that prior to our testing, there may have been a justifiable reason for the correction. However, our subsequent calibration of the airway and the position of SIE showed that the $1/2$ -degree offset had skewed the data and was, at that time, not correct.

Therefore, in our subsequent analysis of both Gulfstream and User aircraft data, we corrected for the $1/2$ -degree offset to determine the true ground position and track of the aircraft. In this way we obtained a true comparison between the EAIR, BVD Gulfstream, and BVD User aircraft data.

The implications of this analysis are of some significance.

If the BVD offset was introduced as a result of a video map check, it implies that the video mapping is not the best way to check accuracy. Conversely, the offset was only 1/2 degree (and this is rather small) and would perhaps be undetected in a Flight Inspection. The tolerance allowed on fix positions during an inspection of a surveillance radar is 3 percent of the fix-to-station (radar) distance. Since the SIE VOR is 105 miles from the JFK ARSR, a tolerance of 3 miles would be acceptable, and our special check showed an error of 3/4 mile.

Nevertheless it is significant that the BVD data was accurate enough to show the 1/2-degree offset.

Therefore, it is suggested that the techniques used in this project would further enhance the Flight Inspection of surveillance radar in the future, as well as providing backup facilities for the inspection of VOR radials.

2. BVDR as a Maintenance/Equipment Check Monitor. Even though the BVD has self-checking facilities within the equipment (as would any other digitizer, in some form or other), malfunctions of a short duration, or of a transitory nature, may go undetected. Such malfunctions may occur in the digitizer itself, or in units which supply it with data. In many cases, the malfunctions are not easily found by a technician using an oscilloscope, or controllers watching a scope display.

However, the listing of the data tape produced on this project presents invaluable data for long-term performance checking and historical data on maintenance reliability.

For example, during our data taking in May 1968, the raw data tape listing showed instances of equipment malfunction in that certain test target azimuths were incorrect. This was subsequently traced to a noisy North pulse data being transmitted to the BVD. Since it is only occurred for very short periods of time, 10 to 30 seconds, it went undetected until the recording tape was processed.

Together with the detection of the 1/2-degree offset error we concluded that the recorder was a useful device on its own merits.

It was also possible to pick out individual aircraft that were giving poor transponder returns (for a variety of reasons), and this could lead to remedial action in the future--if suitable procedures were organized to deal with the reporting aspects.

APPENDIX C
MATHEMATICAL DERIVATIONS

The position of the aircraft relative to SIE was calculated by the following mathematical scheme.

Point B is the origin of the Ideal Radial at SIE and point A is the position from which the range and azimuth data were taken, that is, JFK or the EAIR site. Let

- θ_{ab} = Azimuth of SIE from point A
- θ_{ba} = Azimuth of point A from SIE
- D_{ab} = Distance between SIE and point A
- ρ = Radius of the earth
- θ_m = Azimuth of the Ideal Radial from SIE
- Var_b = Magnetic variation at SIE
- Var_a = Magnetic variation at point A
- Alt = Altitude of the aircraft
- AZ = Azimuth reading of the aircraft from point A
- $SRNG$ = Slant Range of the aircraft from point A
- θ = Angular position of the aircraft from the Ideal Radial with respect to SIE
- R = Distance of aircraft from SIE
- $\theta_{sc} = D_{ab}/\rho$ = Angular distance from SIE to point A with respect to the center of the earth
- $\theta_t = \theta_m - Var_b$ = True azimuth of the Ideal Radial from Sea Isle

$$\text{Define } havf(X) = 1/2 [1 - \cos(X)]$$

$$ahavf(X) = \text{Arccos}(1 - 2x)$$

Now, calculate the following:

$$\text{AZA} = \theta_{ab} - (\text{AZ-Vara})$$

$$\text{CA} = \text{Arccos} \frac{(\rho + \text{ALT})^2 + \rho^2 - \text{SRNG}^2}{2\rho(\rho + \text{ALT})}$$

$$\text{HAVA} = \text{havf}(\text{CA} - \theta_{sc}) + \sin(\text{CA}) * \text{SIN}(\theta_{sc}) * \text{havf}(\text{AZA})$$

$$\delta = \text{Arctan} \tan(\text{CA}) \cdot \cos(\text{AZA})$$

$$\beta = \text{Arctan} \frac{\sin(\delta) \cdot \tan(\text{AZA})}{\sin(\theta_{sc} - \delta)}$$

Now, the variables θ and R can be calculated

$$R = \rho \cdot \text{ahavf}(\text{HAVA})$$

$$\theta = B + \theta_{BA} - \theta_T$$

The perpendicular distance of the aircraft from the Ideal Radial (across-track error) is given by the relation:

$$\text{ATE} = R \cdot \text{SIN}(\theta)$$

The track range along the Ideal Radial is given by:

$$\text{TR} = R \cdot \text{COS}(\theta)$$

The bin number corresponding to the position of the aircraft was calculated by the relation:

$$\text{BIN } \emptyset = \text{INTEGER} \frac{(\text{TR} + 1)}{2}$$

For example, if the aircraft is 10.3 miles along the Ideal Radial from SIE his position would correspond to $\text{INTEGER } 11.3/2 = 5$, or the fifth bin (Figure 5).

All the across-track errors and track ranges were summed up for each bin and their averages and standard deviations printed out after the runs were processed. The formula for the standard deviation used was of the form:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (a_i - a, \text{avg})}{N - 1}}$$

The straight line fit, or the LMS (least-mean-square) path was the best straight line fitting the data and passing through the origin at point B. It was calculated as follows. Let

SUMATE = Sum of all the across-track-errors

SUMTR = Sum of all the track ranges

then, the equation of the line is given by

$$Y = MX$$

where

$$M = \text{Arctan} \left[\frac{\text{SUMATE} \cdot \text{SUMTR}}{\text{SUMTR}^2} \right]$$

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1. Page 9, delete statistical from the description of BVD resolution.
2. Overall measurement accuracy was not a requirement; the manufacturer claims 1 sigma accuracies of $.075^\circ$ with ARSR radar and 0.16° with ASR. The source is independent testing, conducted by the manufacturer. Claimed range accuracy is 400 feet.
3. These accuracies are obtained from tracking one aircraft. The B.V.D. statistically determines the target center in azimuth and range on every antenna rotation.