FAA-79-12

REPORT NO. FAA-RD-79-115

TESTS OF AN ATCRBS BASED TRILATERATION SENSOR AT LOGAN INTERNATIONAL AIRPORT

P.E. Manning

U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
Transportation Systems Center
Cambridge MA 02142

NOVEMBER 1979

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research and Development Service
Washington DC 20591

PREFACE

The Transportation Systems Center (TSC) under the sponsorship of the Systems Research and Development Service (SRDS) of the FAA has been pursuing the development of a beacon based trilateration system for the purposes of locating transponder equipped vehicles on the surface of an airport and extracting beacon codes. This project is part of an airport surface traffic control program being conducted by the Airport Systems Branch at TSC.

This report describes accuracy and coverage tests of the beacon trilateration sensor that were conducted at Logan International Airport during late summer 1978. The sensor was previously tested for feasibility at the National Aviation Facilities Experimental Center (NAFEC), and while the tests were successful it was recommended that futher tests be performed at an airport with more typical numbers of aircraft operations and multipath objects. Logan International Airport was selected because of its severe multipath environment, its large number of aircraft operations and its proximity to TSC.

Results of tests of the sensor at Logan indicate that closely spaced aircraft (transponder antennas separated by less than 150 feet) on the surface can be easily resolved, located to accuracies well within expected operational requirements, can provide excellent coverage and can reliably extract beacon codes. However, since the sensor used in these tests lacked real time data processing and a display and also lacked computer-controlled interrogations, system level questions are not addressed in this report. Therefore, it is recommended that the sensor be upgraded for purposes of assessing system level parameters that would impact operational system specifications.

During the preparation and conduct of the Logan tests many people at TSC, the New England Region of the FAA, the Massachusetts Port Authority, Kentron International, Inc. and Bendix Communications Division contributed to its success. In particular, the author wishes to thank TSC test team members, M.J. Moroney, R.W. Wilmarth and I. Golini; J. Vinatieri of Kentron for data processing support; W. Miner, FAA Logan Tower; J. Davis, D. Finch and R. Fuller of the Massachusetts Port Authority for assistance in installation, surveying, supplying electrical power and for numerous instances of assistance during testing; and P.J. Woodall of Bendix for his technical assistance.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF TABLES

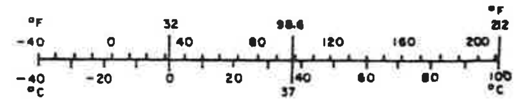
METRIC CONVERSION FACTORS

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

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



1. INTRODUCTION

This report describes tests of a beacon (ATCRBS) based trilateration data acquisition subsystem (DAS) for Airport Surface Traffic Control (ASTC) that were performed at Logan International Airport (BOS). This task is part of the ASTC program being conducted for the Federal Aviation Administration (FAA) by the Transportation Systems Center (TSC). This DAS was previously tested for feasibility and performance at NAFEC, and the results indicated that the concept was not only feasible but could perform well within performance levels required for ASTC operations. However, since NAFEC lacks the large amount of aircraft traffic and multipath objects seen at most busy operational airports, it was recommended that the trilateration sensor be tested at Logan International Airport which has severe multipath, a large number of aircraft operations and is conveniently close to TSC.

1.1 BACKGROUND

Beacon trilateration is a technique being investigated for locating and identifying aircraft (and other transponder equipped vehicles) on the surface of an airport. The technique being investigated does not require any modifications to transponders. A more complete description of this technique is given in the Appendix and in the final report of the tests performed at NAFEC: A. L. Brockway, et al., Design, Fabrication, and Testing of a Brassboard Model ATCRBS Based Surface Trilateration Data Acquisition Subsystem, Report No. FAA-RD-78-63, June 1978. Briefly, however, the problem to be overcome with the use of ATCRBS on the surface of an airport is to be able to elicit replies from one aircraft at a time even though aircraft can be in close proximity to each other. Normal ATCRBS operation cannot separate aircraft when they are within about a mile and a half of each other on a radial or within about seven degrees of each other in azimuth when at the same range. Aircraft that close will cause overlapped (garbled) replies.

The beacon trilateration sensor makes use of an interrogator transmitter antenna pattern that differs considerably from the standard beacon interrogator antenna pattern. The P2 pattern (See Appendix) in the beacon trilateration sensor is generated by a phased array antenna. This pattern is broad (approximately 60 degrees) and has a narrow, deep, steerable null. The width of the null is dependent on the number of antenna elements and peak power used. The P1 and P3 pattern is essentially similar to the P2 pattern, but without a null and with less power. Over the sixty degree width, transponders are suppressed (P2 being greater than P1) except for transponders that are located in the region of the null. When P3 is then radiated, transponders in the null will reply, but transponders outside the null will not reply, having been suppressed. The beacon trilateration sensor has two stations with phased array antennas with steerable nulls, and a third station that serves a receive only function. The intersection of the two nulls from the phased-array antennas defines an area or cell where a transponder can reply. Scanning of these nulls moves this cell to different locations over the airport surface. When a transponder replies, each of three stations receives the reply and the time-of-arrival (TOA) at each site is measured. The reply is also decoded at each site to extract the beacon code. The differences in times-of-arrival (Δ TOA) for all pairs of the three stations are used to perform a trilateration calculation to determine the location of the signal source. Inasmuch as the Δ TOA's are used in the position calculations, transponder turn around time and jitter have no effect on the position determination. The pointing angles of the nulls also do not enter into the position determination, although in an operational beacon trilateration system, pointing angle information can be extremely useful in discriminating valid from invalid data points, controlling receiver range gates and for programming transmitter power levels to obtain relatively constant cell sizes over the surface of the airport.

1.2 NAFEC TESTS

Feasibility testing of the beacon trilateration sensor, built by Bendix Communications Division, began at NAFEC with the installation of three sites (Master, Slave and Receive) on August 7, 1975. Sensor operation commenced on August 14, 1975. Testing of the sensor encompassed seven key technical issues:

- o Accuracy
- o Surface coverage
- o Resolution
- o Update Rate
- o Multipath
- o Vehicle effects
- o RF Interference.

Details of these tests can be found in the NAFEC test Report, but the conclusions from that report are summarized as follows:

- o Trilateration accuracy was measured to be 38.1 feet, 3σ, well within the objective of 100 feet, 3σ.
- o Resolution was measured at a reply probability >97% for vehicles separated by 150 feet.

- Sensor coverage was measured to 1.13nm for aircraft with an antenna height of 3 feet above the ground.
- Update rate was confirmed over the available NAFEC test area up to 1.13nm maximum range and up to a rate of 10 per second.
- Sensor performance was not adversely affected by multipath in the NAFEC test environment. The sensor has a multipath rejection capability, however, NAFEC is also relatively clear of multipath and is not typical of most operational airports.
- There were no serious signal blocking and fading problems caused by vehicle effects for aircraft types available at NAFEC.
- The sensor was tested beyond projected operational PRF's without mutual interference with local ATCRBS systems either at NAFEC or at surrounding sites. These tests show that synchronization of the ASTC sensor with the local ASR may not be necessary for operational deployment.
- NAFEC tests of the sensor did not reveal any technical limitations or inherent shortcomings.

It was recommended that since NAFEC lacked sufficient multipath objects and did not have a suitable number of aircraft operations that further testing be conducted at an operational airport such as Logan International.

1.3 LOGAN TEST OBJECTIVES

The major objective of Logan tests was to determine if severe multipath conditions and high aircraft traffic densities would support or alter the results of feasibility tests that were conducted at NAFEC. In particular, tests at Logan concentrated on determining to what extent multipath would effect positional accuracy measurements and coverage.

2. LOGAN INTERNATIONAL AIRPORT FIELD TESTS

Upon completion of trilateration tests at NAFEC the equipment was left in storage for about two years until approval was obtained to proceed with tests at Logan Airport. Prior to Logan installation refurbishment, repairs and calibration to the equipment were accomplished.

2.1 INSTALLATION

The installation of the test sites at Logan represented a coordinated effort of the New England Region of the FAA, Logan tower personnel, the Massachusetts Port Authority (Massport) and TSC. The FAA and Massport were especially helpful in site selections and providing electrical power and the Massport Engineering Department provided surveys not only for the sites but also for various locations on the airport surface to be used for accuracy tests. It was originally planned that the slave site would be located on FAA land located across the bay from the approach end of runways 22L and 22R. However, it was found that line of sight between the slave and Master sites would be blocked by land masses in Winthrop, disabling the data link between the stations. Inasmuch as it was not the intent that the entire airport surface be covered for this test phase, the slave station was then located between runways 22L and 22R (Figure 1) near the approach end. The three sites chosen did, however, provide coverage (within the triangle formed by the three stations) of almost 70% of the airport surface. During accuracy and moving target tests it was shown that accurate coverage was obtained even outside of the triangle and effectively considerably more than 70% of the surface was covered by the siting arrangement that was chosen.

2.2 EQUIPMENT TESTING

After completion of installation of the beacon trilateration stations in the spring of 1978, equipment shakedown tests revealed a series of hardware failures. A considerable period of time was spent in troubleshooting, repairing and modification. Most of the time lost was due to transmitter repairs and in repairing phase shifters in the antennas and replacing the phase shifter drivers. In addition, monitoring circuits for the phase shifter drivers were installed. Sensor accuracy tests commenced in August, 1978.

2.3 ACCURACY TESTS

Beacon trilateration sensor accuracy tests consisted of interrogating a test transponder placed at a known location, obtaining several thousand replies, processing the data and calculating the position for every reply using the trilateration position algorithm. Plots of the error in position for each reply were then produced as histograms on a computer line printer.

In preparation for these tests, Massport provided surveys with position accuracies of approximately one-half-foot for selected locations on the airport surface. Figure 1 is a map of Logan Airport identifying the locations of the test sites (Master, Slave, Receive) and the surveyed test points. Test data were compared to the surveyed locations to determine the accuracy of the sensor. Paint markings were used on hard surfaces and survey stakes were used on grassy areas to identify permanently the surveyed locations.

To calibrate the sensor a transponder was placed at a surveyed location (antenna directly over the survey marker) close to the center of the triad and replies were recorded. The FAA provided a dedicated beacon code, 4501, for use in all trilateration tests at Logan. A computer algorithm was then used to calculate all site fixed delays (hardware delays, data link propagation path delays, etc.) that would minimize position errors. These fixed delays were then used with all other surveyed locations when tests were conducted for accuracy or moving targets. Using more than one location for calculating fixed delays and taking an average value would provide more accurate figures. All data collected at Logan were based on using only one survey point for calibration.

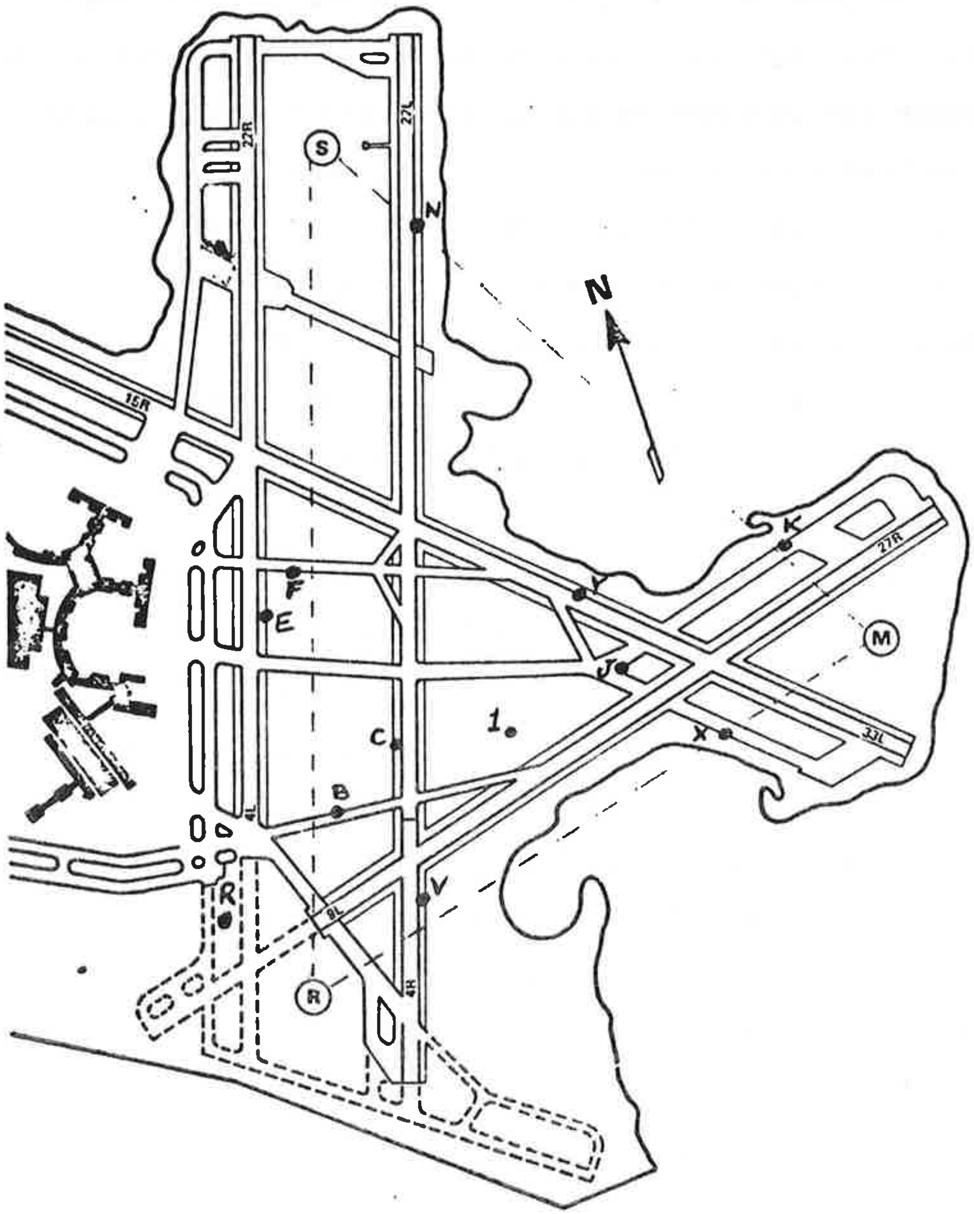


FIGURE 1. LOGAN AIRPORT TEST POINTS

In order to reduce computer processing time and to acquire a large amount of data in a short time, the interrogator antenna nulls were "fixed" on the test transponder, during accuracy tests. This eliminated recording replies from other transponders and enabled obtaining replies from the test transponder at a rate of about 450 per second contінously rather than in short bursts every 5 to 10 seconds. With recordings of about 10 seconds, 4500 replies were obtained.

During tests, a log was maintained to record information such as power settings, unusual weather conditions, tape start and stop times, aircraft activity in the vicinity of the test transponder, vehicles that appeared to block line of sight from one of the stations, and TOA's displayed on the Test Control Unit. Figure 2 is a sample log sheet used during tests.

Several output formats for test data were used in computer processing, but the most useful were a histogram output of x and y position errors, and a "readable dump" that provided for each reply the time-of-arrival and beacon identity at each site. The readable dump and log notations provided information on blocked signals and multipath and were especially useful in trouble shooting when equipment malfunctions occurred.

ASTC DATA TAPE LOG

TAPE NO._____ FILE NO._____ DATE_________DATA/INFO CODE_____

TEST START TIME:_____ HRS_____ MIN_____ SEC_____

TEST STOP TIME:_____ HRS_____ MIN_____ SEC_____

SCAN LIMITS: MASTER____________________

SLAVE____________________

STEERING INCREMENT______ INT'S/SSR FRAME______ INT'S/CELL______

INTERROGATOR TRIGGER: INTERNAL_____ SSR SYNC.______

MASTER		SLAVE	TOA:
______	P1 to P3 Spacing	_____	Master_______________
______	Off	_____	Slave_______________
______	Continuous	_____	Receive______________
______	SLS only	_____	
______	Pattern (dB)	_____	
______	P2 Atten (dB)	_____	
______	High Voltage (KV)	_____	
______	Antenna Elements	_____	
______	Receiver Sensitivity	_____	
CALIBRATION TRANSPONDER CODE		_____	

TEST VEHICLE________________ LOCATION_________________

OTHER:

TEST DESCRIPTION/COMMENTS:

FIGURE 2. DATA LOG

Generally, when multipath was present it would display itself on the readable dump by indicating the wrong identity at a station, momentarily for a moving reflective object such as an aircraft, and consistently if the reflective object was fixed such as a building or parked vehicle. The TOA readings however, were consistent and unchanging; the leading edge of the first pulse was not being corrupted by the multipath. Also, at each station a test team member observed the video output of the receiver and made a notation and recorded the time when anything unusual occurred such as loss of reply signals of display of a multipath signal. Communications via walkie-talkie were used among test team members.

Samples of the histograms for errors in x-position and y-position and the radial error magnitude, $(x^2+y^2)^{1/2}$, are given in Figures 3 to 14. Each histogram shows 250 samples or replies. Although several thousand replies were obtained for each test point, the processing routine produced histograms in blocks of 250 samples. For any test point, comparisons of the many histograms produced even under different environmental conditions, did not reveal any significant differences. The histograms given in Figures 3 to 14 are typical samples of the many histograms examined for each test point.

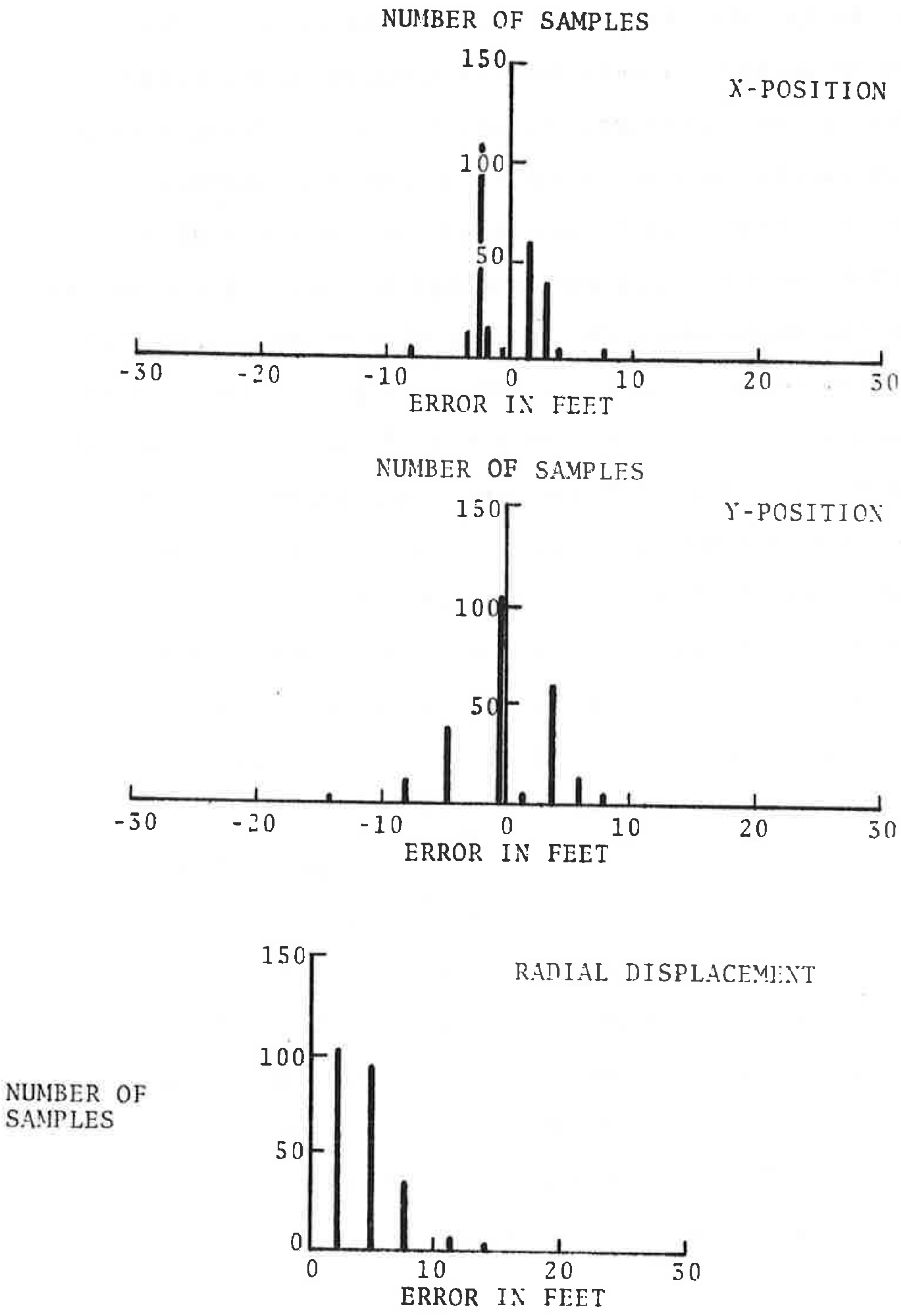


FIGURE 3. ERROR HISTOGRAM - TEST POINT J

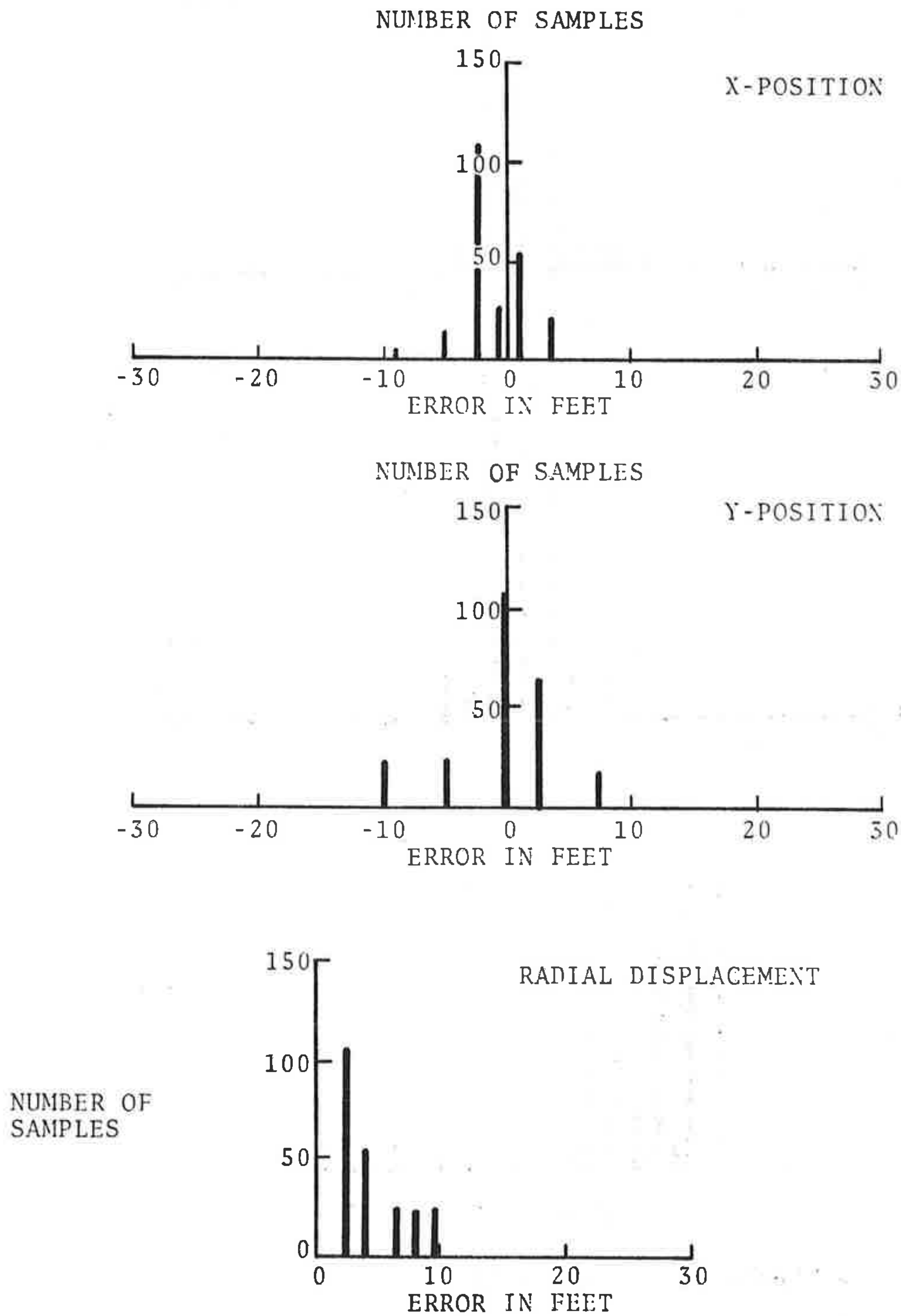


FIGURE 4. ERROR HISTOGRAM - TEST POINT V

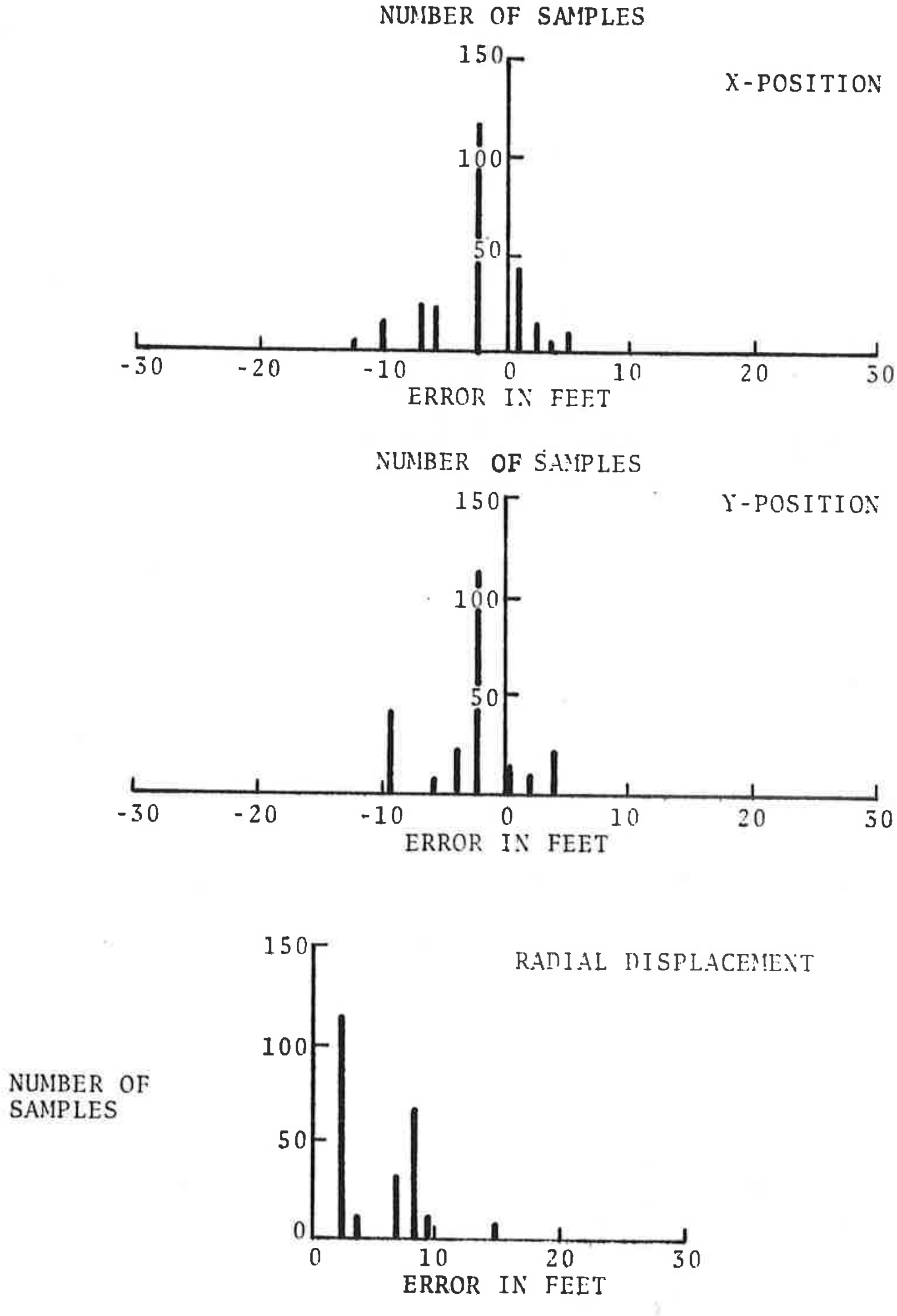


FIGURE 5. ERROR HISTOGRAM - TEST POINT C

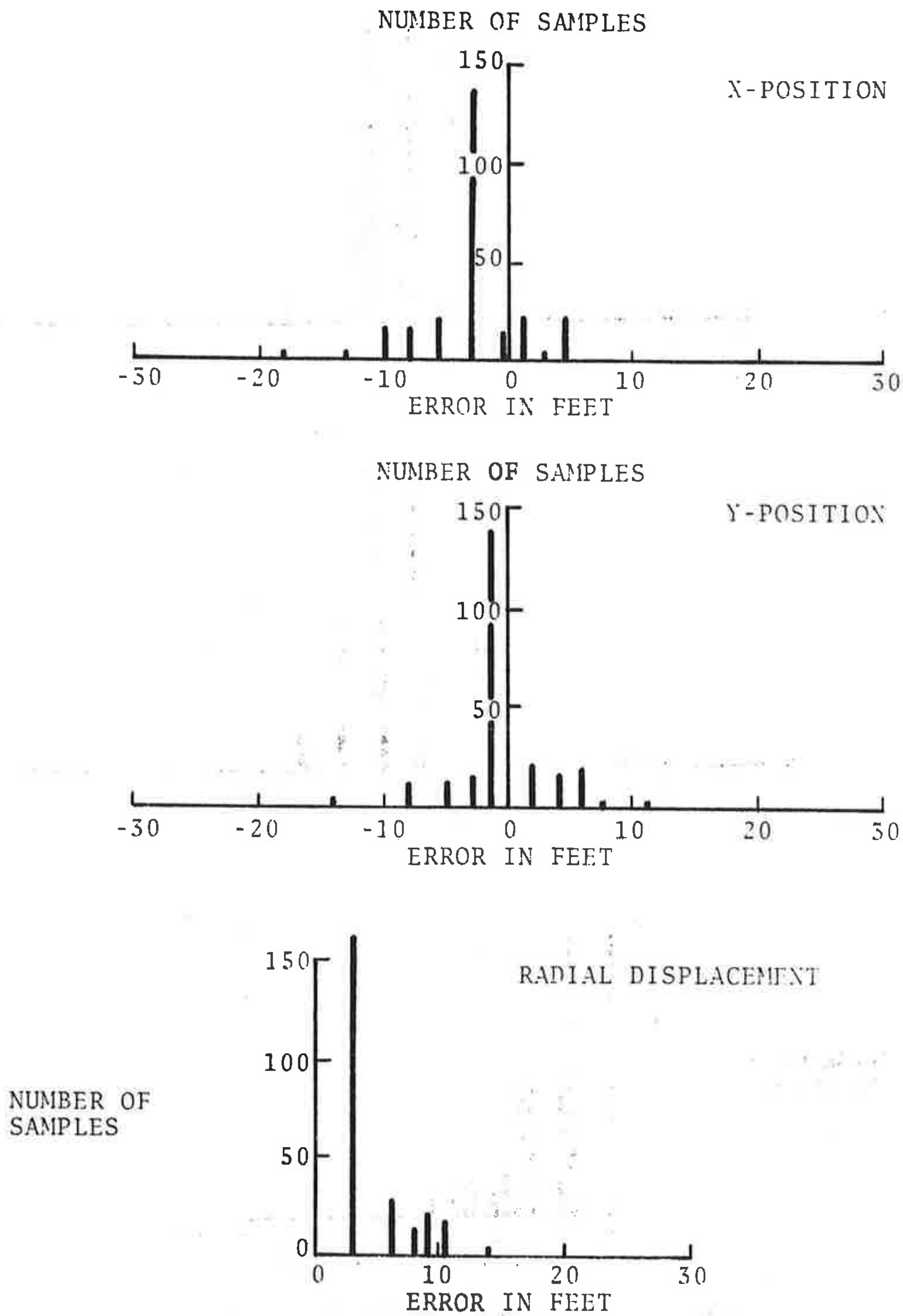


FIGURE 6. ERROR HISTOGRAM - TEST POINT B

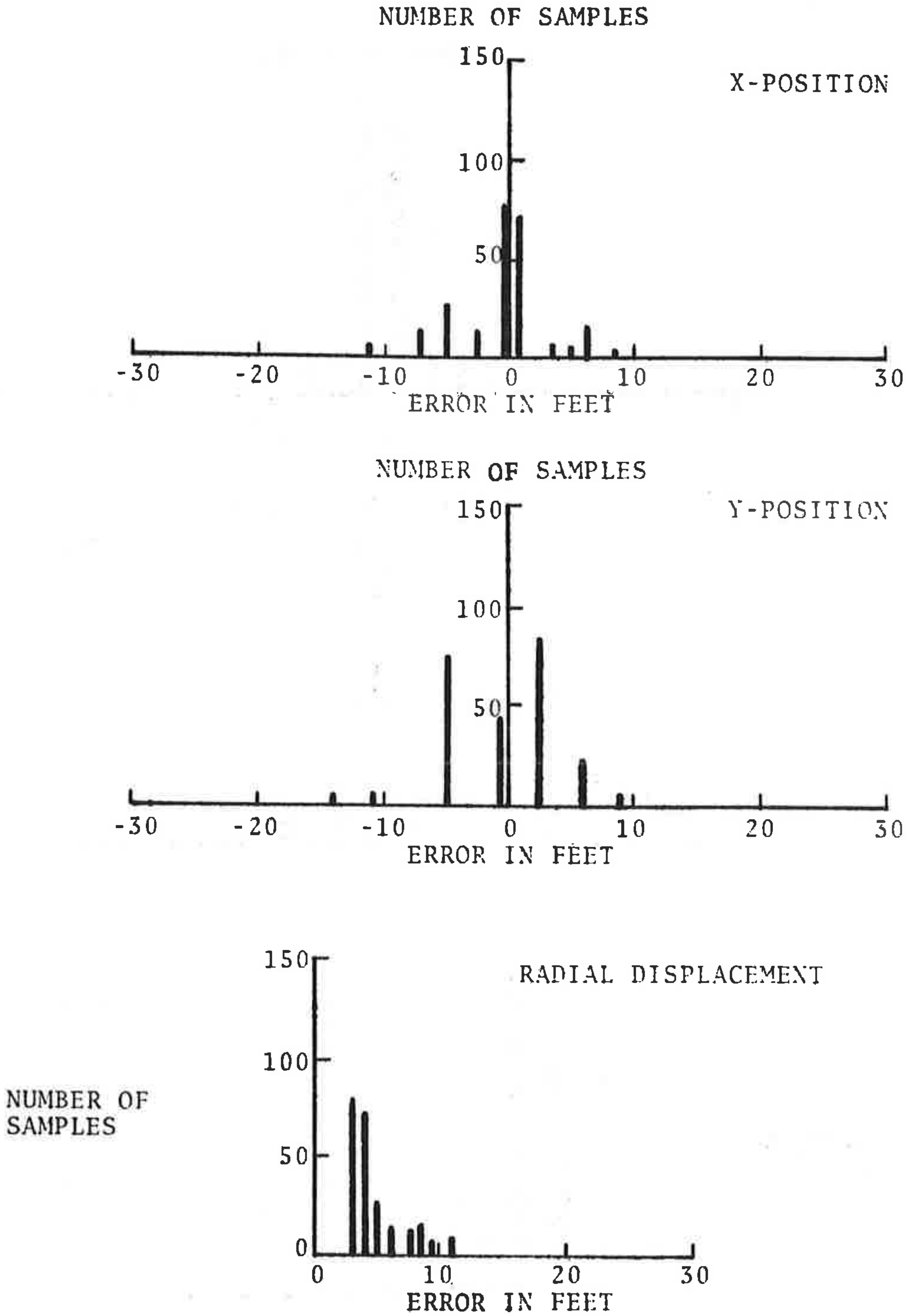


FIGURE 7. ERROR HISTOGRAM - TEST POINT 1

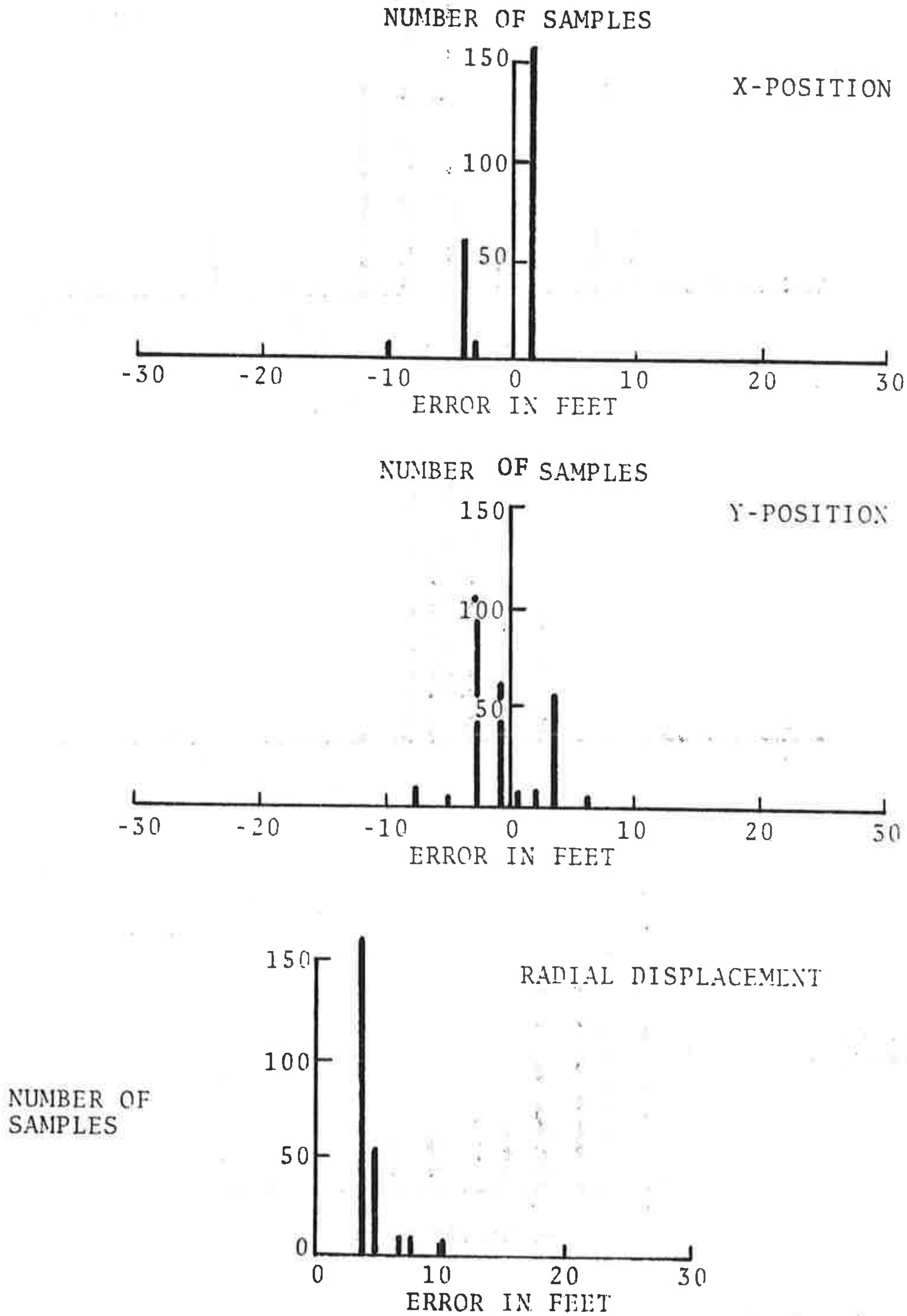


FIGURE 8. ERROR HISTOGRAM - TEST POINT Y

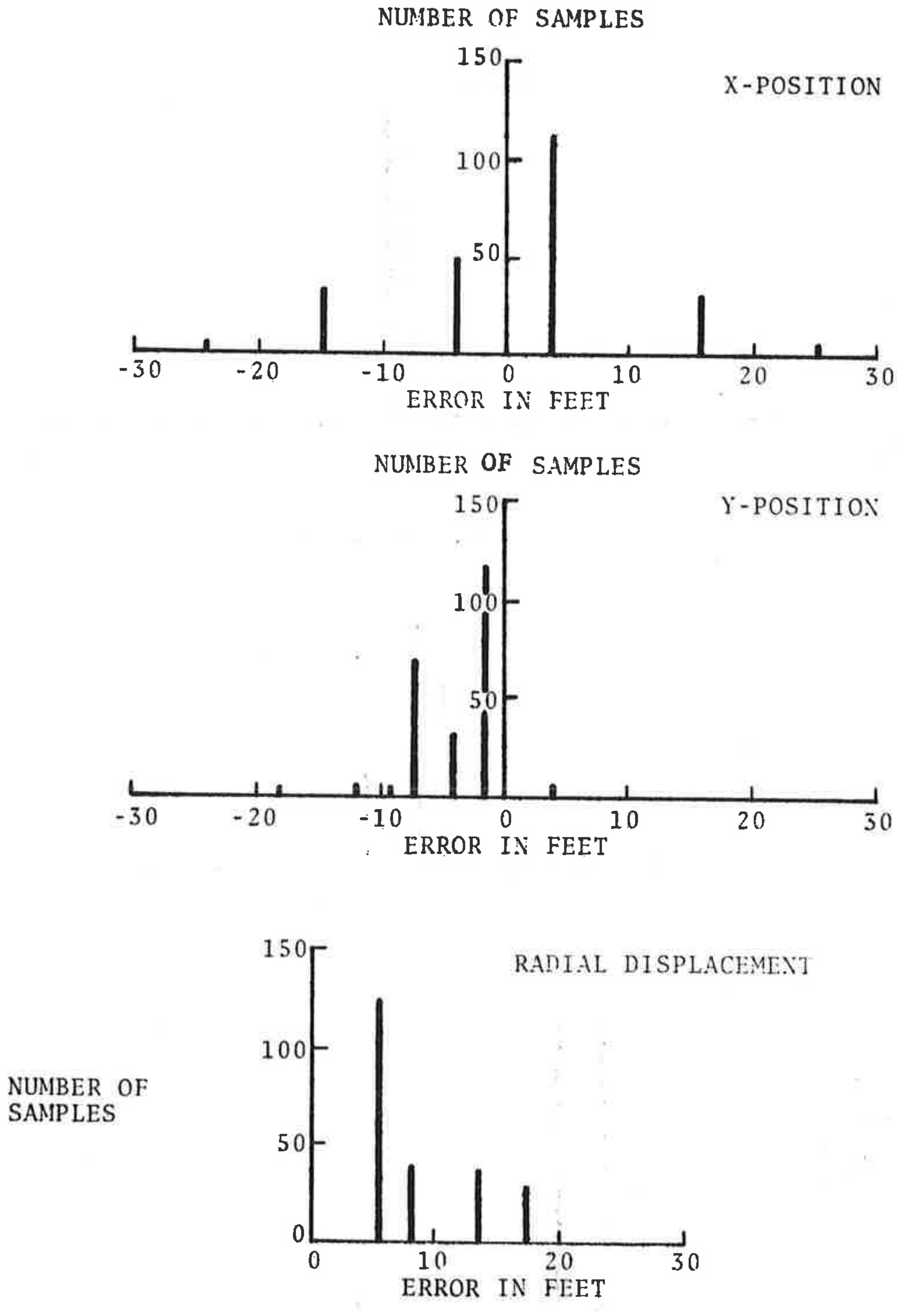
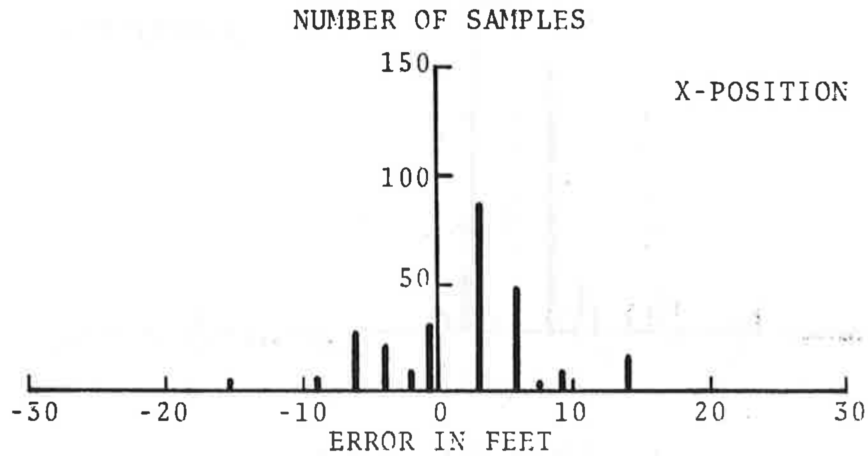
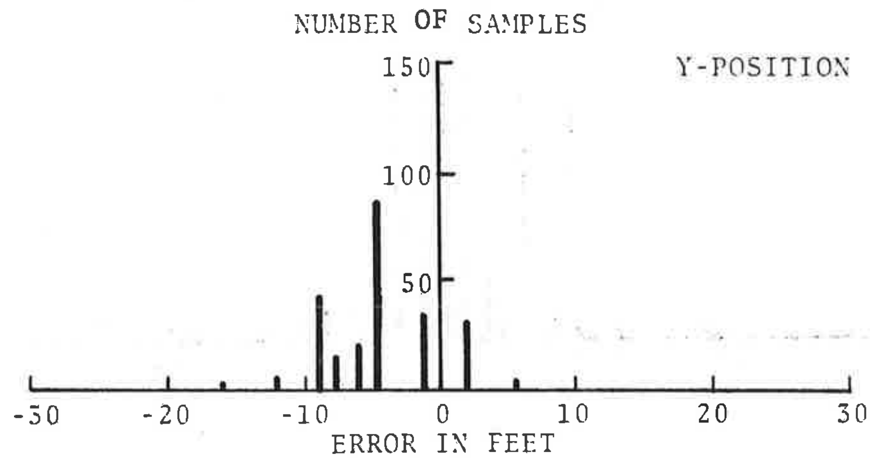


FIGURE 9. ERROR HISTOGRAM - TEST POINT R





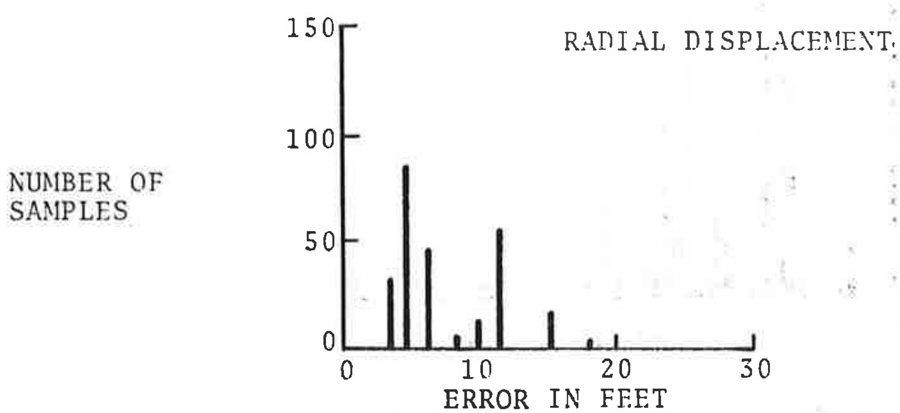


FIGURE 10. ERROR HISTOGRAM - TEST POINT F

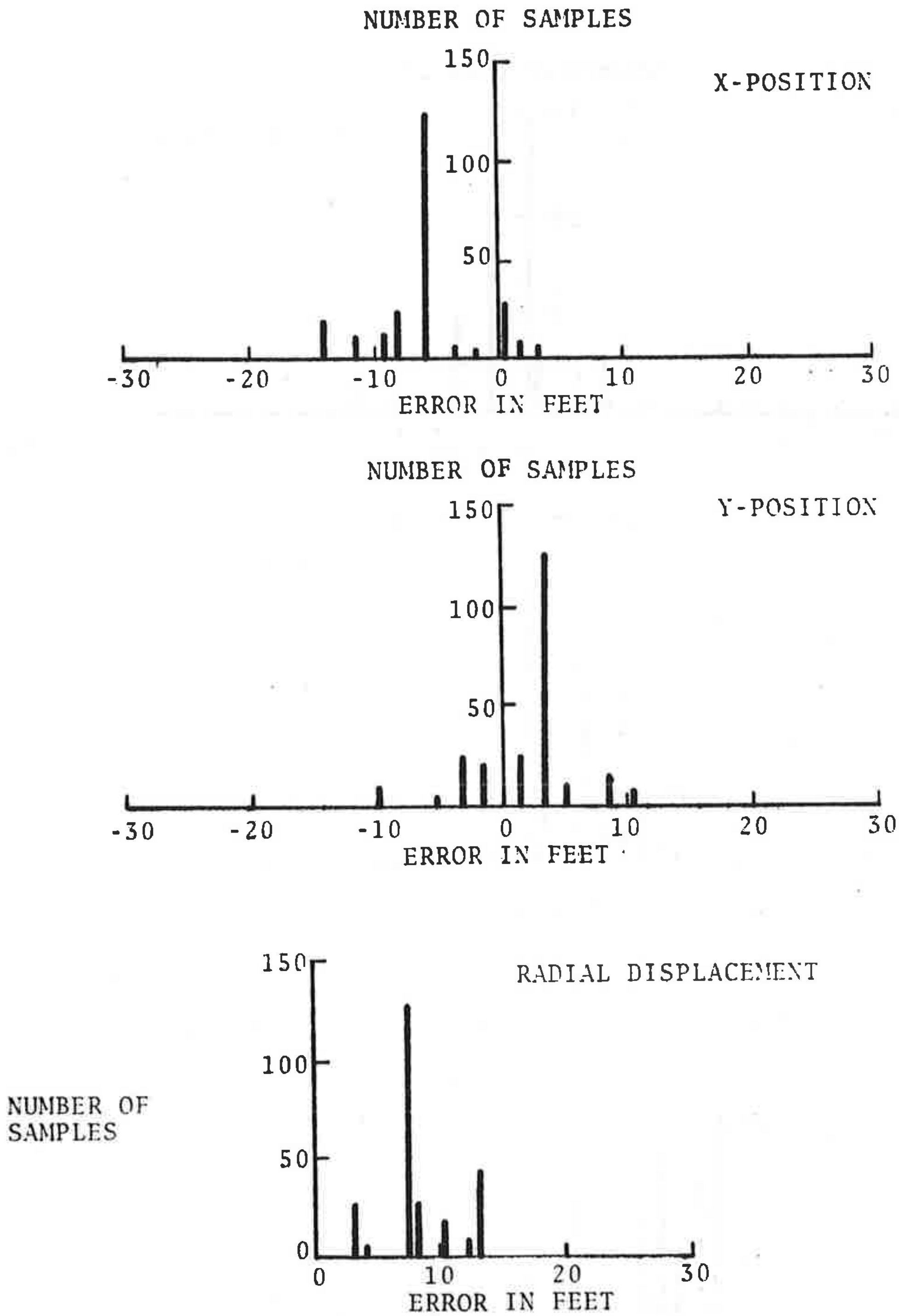


FIGURE 11. ERROR HISTOGRAM - TEST POINT K

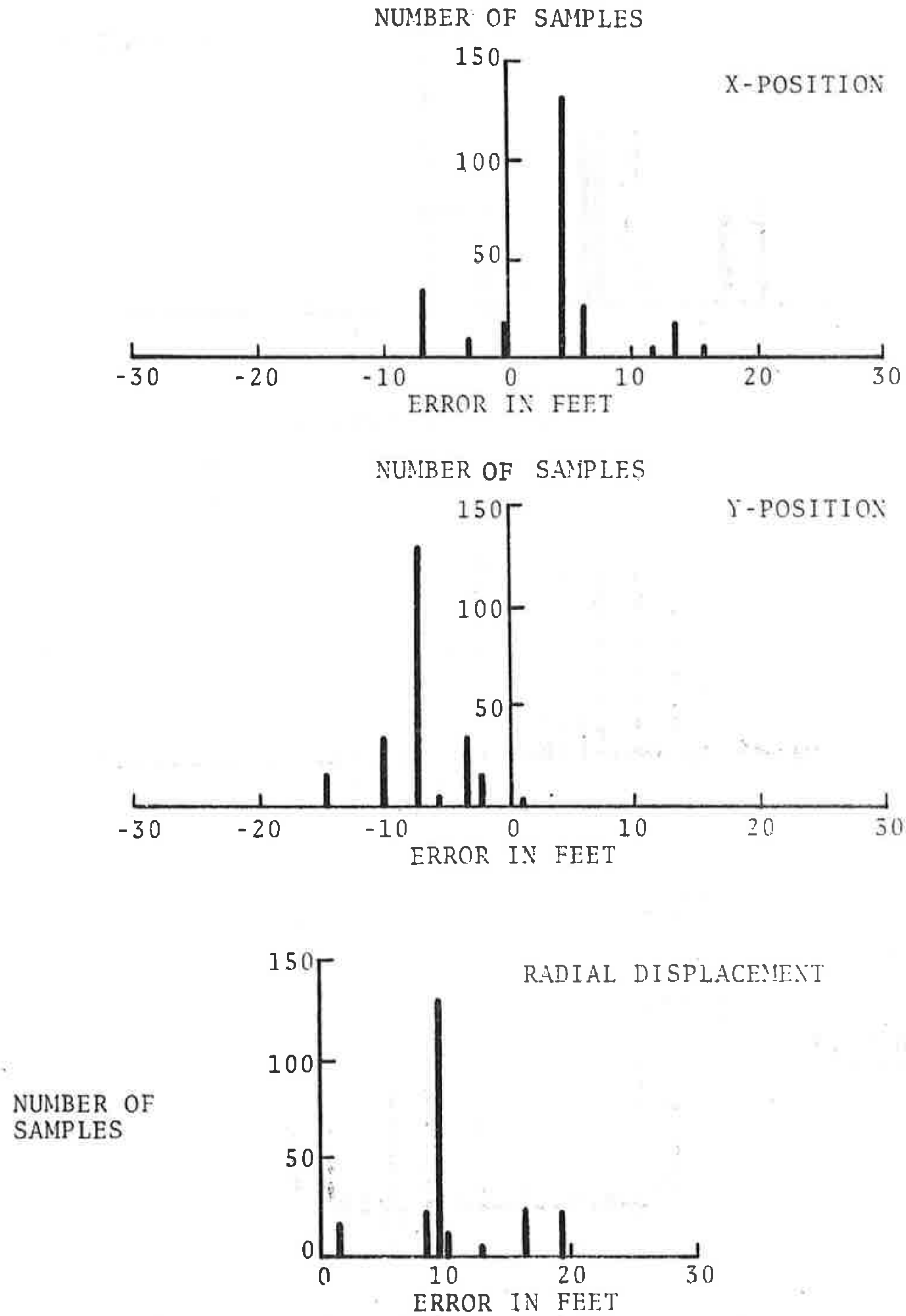


FIGURE 12. ERROR HISTOGRAM - TEST POINT E

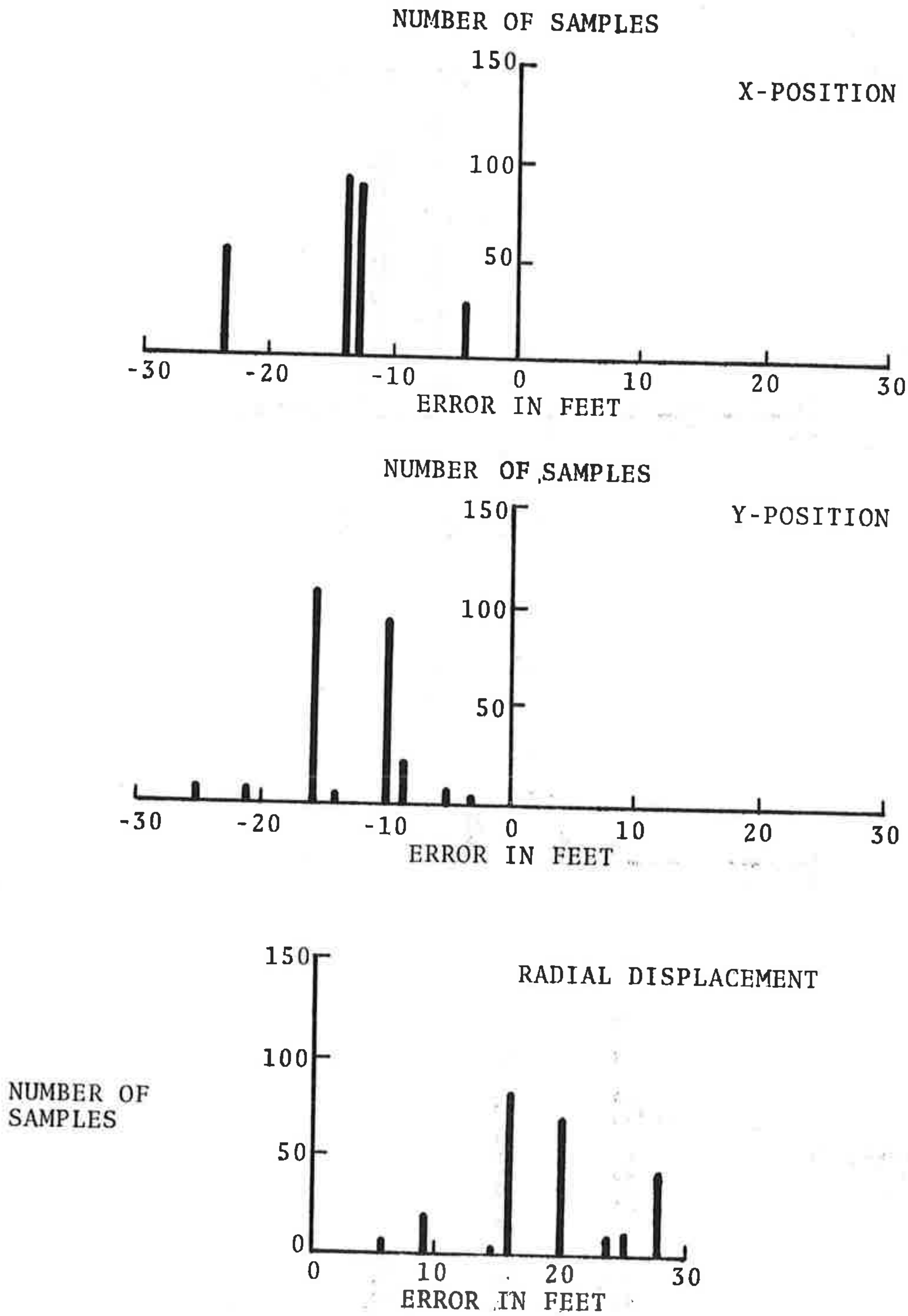


FIGURE 13. ERROR HISTOGRAM - TEST POINT N

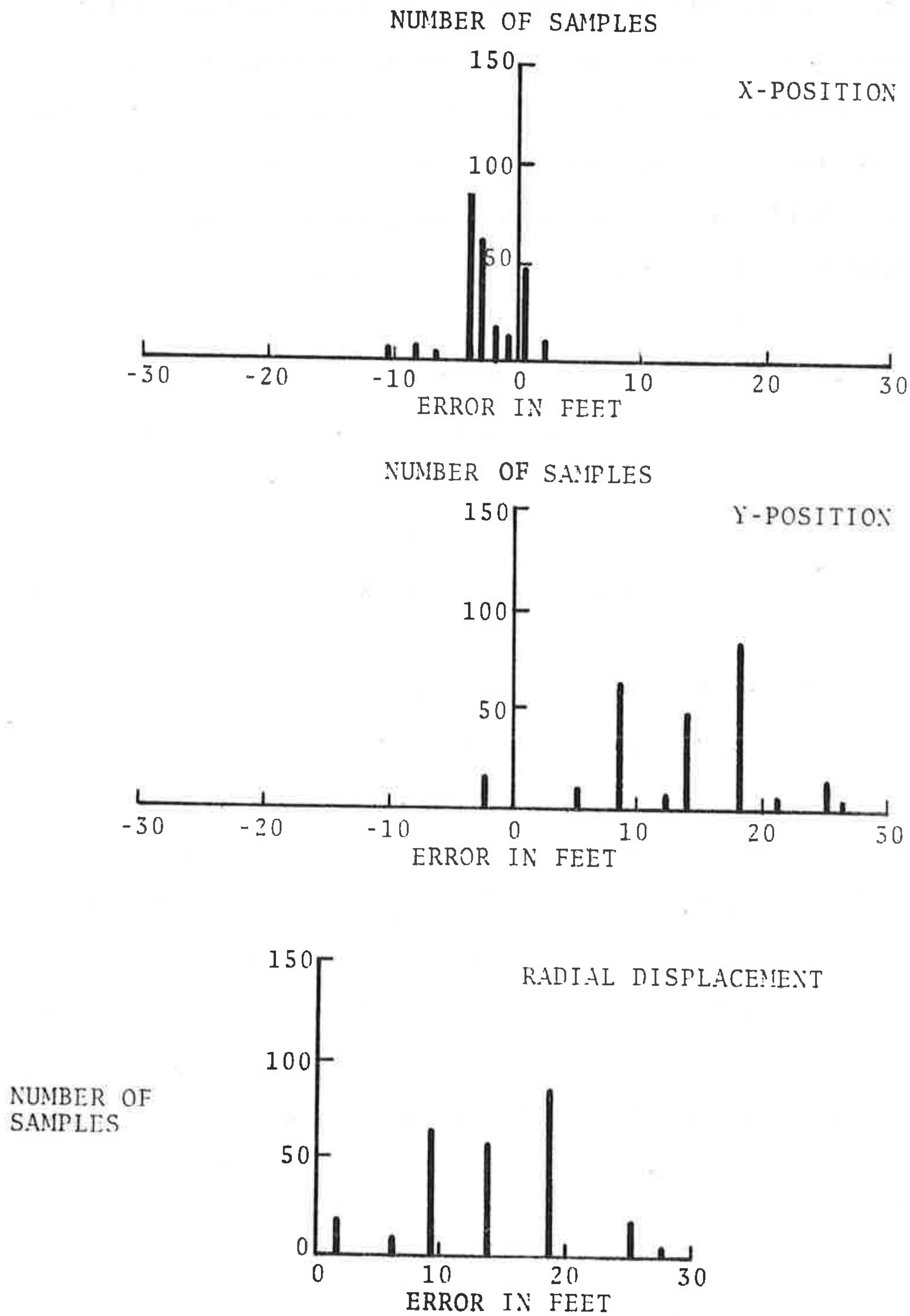


FIGURE 14. ERROR HISTOGRAM - TEST POINT X

Table 1 summarizes information obtained from data shown in the histograms. Average error, standard deviation, total data spread for all samples, and the mode (the error value with the highest probability of occurrence) for the radial errors for each test point are tabulated. Examination of the table and the histograms for error values of data taken: a) inside the triangle, b) along the baselines and c) outside the triangle reveals the following:

- Inside the triangle, as one would predict, the average error was the smallest, about 5 feet. The distribution of the samples of error was Gaussian with the mode representing the smallest error value for the samples. The total spread in the data (all of the data samples) also was quite small, about 12 feet being the worst case.
- Outside the triangle the average error was about 10 feet, which is double that measured inside the triangle. It is clear that in those areas, geometric dilution of precision was a factor as predicted. The total spread in the data also increased to about 17 feet. The histograms indicate a degeneration of the Gaussian shape observed for the radial error distribution inside the triangle. Interestingly, the mode also was less prominent and was not consistently representative of the smallest error measured at the test point.

TABLE 1. SUMMARY OF ACCURACY DATA

TEST POINT	AVG. RADIAL ERROR IN FEET	STANDARD DEVIATION IN FEET	TOTAL DATA SPREAD IN FEET	MODE IN FEET
J*	4.73	3.37	11.6	2.1
V*	5.06	3.81	6.5	2.2
C*	5.41	3.62	12.1	2.1
B*	5.30	4.05	11.2	2.6
1*	5.25	2.71	8.2	3.0
Y*	4.39	2.01	6.5	3.2
R	10.46	5.47	12.5	5.3
F	7.71	4.10	14.5	4.4
K	8.00	3.28	9.8	6.7
E	10.16	4.31	17.3	8.7
N	19.50	5.38	22.1	15.9
X	14.33	6.01	25.5	17.8

*INSIDE TRIANGLE (OTHER POINTS OUTSIDE OR ON BASELINE)

- The highest average errors were measured along the baselines of the triangle (test points N and X). These errors approached 20 feet. The total data spread was the widest measured for all the test points, about 25 feet, and the mode was less predominant and far removed from representing the data samples with the lowest errors.

The accuracy tests have shown that the trilateration sensor can locate a transponder antenna on the surface of Logan Airport with positioning accuracies in excess of that thought to be required in an operational ASTC system. Furthermore, this conclusion is based on raw data results with no filtering or smoothing applied. In an operational system filtering and smoothing algorithms would be employed and use of the interrogator null pointing angle would be employed for discarding wild data points. Positional error values recorded in Logan tests were smaller than were seen during NAFEC tests. This was due primarily to hardware improvements and modifications performed on the sensor during shakedown tests. Other hardware improvements can reduce errors even further. For example, improvements in the peak amplitude estimator circuit design have been identified that should be accomplished if further work with beacon trilateration is undertaken. While the accuracy attained with the sensor would be acceptable in an ASTC system, any improvement in accuracy would greatly simplify smoothing and filtering requirements.

2.4 MOVING TARGET TESTS

Moving target tests were conducted using a transponder equipped van with a roof mounted antenna. In order to have some freedom and flexibility in driving this vehicle down runways and taxiways, the moving target tests were conducted during the early morning hours from midnight to six. Present sensor limitations such as no real-time display, no computer control of transmitter output power, no computer control of null steering, range gating, etc. made it necessary, at least for initial tests, a) to drive the vehicle down the center lines of runways and taxiways, b) that null scanning be rapid (1 second update rate), and c) that the tests be conducted during inactive periods at the airport to minimize computer processing time for the large amounts of data that would be obtained.

Data were recorded while the transponder equipped vehicle was driven down the center-lines of all the major runways and taxiways. Over 6,000 replies were recorded for each mile travelled. The primary interest in the data was the lateral error with respect to the center-lines, and the coverage. The data for each runway and taxiway were plotted separately on an x-y recorder peripheral to the computer and also on a line printer.

Each plot on the x-y recorder revealed a series of closely spaced dots, each dot representing a position determination for a single reply. No smoothing or filtering of the data was done in the processing. The coordinates of the end points were aligned with an aerial photograph of Logan Airport with the same scale. The plots were observed to overlay the center-lines and in fact obscured the center-line markings. At the ends of some of the runways and taxiways, outside of the triangle, it was observed that some lateral dispersion and scattering took place. Some wild points were seen, but were few in number, and they occurred as single isolated points rather than as a series of several points. These wild points are strongly suspected to be a result of Distance Measuring Equipment (DME) interference. This interference was observed on the receiver video to arrive in front of the first reply pulse interfering with the leading edge TOA measurement. This occurred infrequently, in a non-synchronous, random fashion. Any wild points that occur outside of the nulls or cell could easily be filtered by making use of the pointing angle information that is available.

Some of the plots revealed holes in the coverage. Examination of the readable dumps showed that the beacon code was incorrect at one of the stations and coincided with the holes in the coverage. This appeared to be due to the multipath garbling the reply. The computer plotting routine was programmed to accept data that had the correct beacon code (4501) at all three stations. The program was revised to accept as data the correct beacon code at any two, or three, stations. Re-plotting revealed that the holes in the coverage were filled-in and the positional information was correct. Again, the data has shown that while multipath may garble the reply it does not necessarily corrupt the TOA measurement.

Figure 15 shows two line printer plots of the raw data for a moving target along the center line of runway 27. One plot shows holes in the coverage when three correct ID's are required as the criteria for a valid reply. The other plot shows the result of accepting a minimum of two correct ID's. In an operational beacon trilateration ASTC system it is reasonable to assume that at least after target acquisition it is not necessary that all stations have correct ID's at all times to track a vehicle.

Figure 16 is an aerial photograph of Logan Airport showing the locations of the sites. Figure 17 is the same aerial photograph of Logan Airport with moving target raw data overlaying the center-lines. The quality of the data is evidenced by how closely the data coincides with the center-lines. Runway width is 150 feet. It can be seen in this figure that both coverage and positional accuracy of the raw data were well within what is expected to be required operationally.

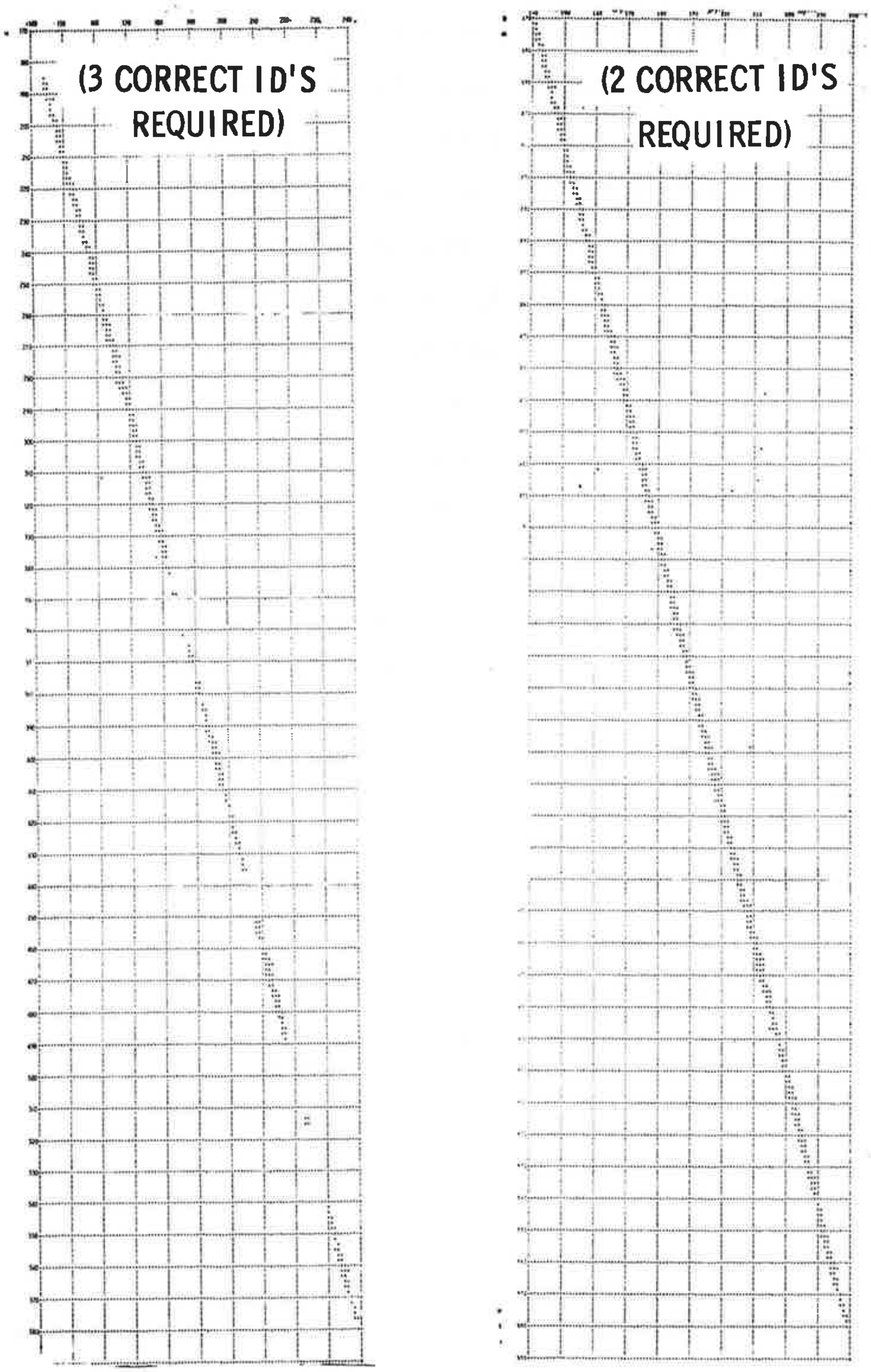


FIGURE 15. MOVING TARGET TEST RUNWAY 27

FIGURE 16. LOGAN AIRPORT

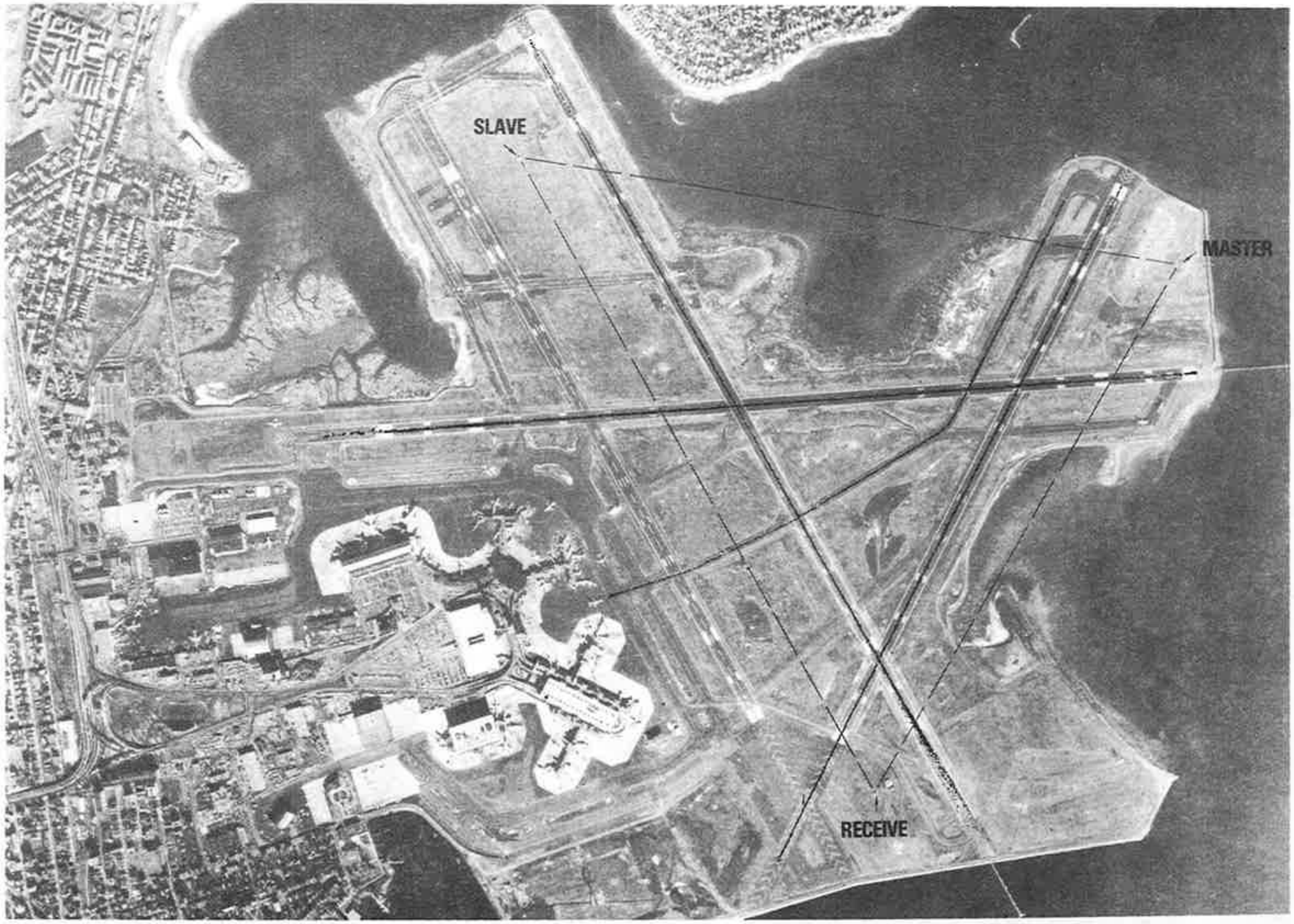


FIGURE 17. LOGAN AIRPORT WITH MOVING TARGET DATA OVERLAYED

In addition to the moving target tests described in the previous paragraphs it should be noted that a great deal of information was obtained on moving aircraft at Logan Airport by observations during the many hours spent in operating the sensor. No hard copy data of these observations is available, but there were hundreds of instances when an aircraft was visually observed landing, departing or moving along the terminal or taxiway areas. The progress of these aircraft was monitored on the Test Control Unit (TCU) display for ID's and TOA's and replies also were observed on an oscilloscope. This experience gave the test team a high degree of confidence in the coverage that this sensor could provide. In places where multipath could be observed, even when severe enough to garble the identity, it was seen on the oscilloscope that the leading edge of the first reply pulse (where the TOA measurement is made) was always steady and in the clear. Good coverage was not only observed on the airport surface, but out to more than six miles for an approaching or departing aircraft.

2.5 INTERFERENCE

The beacon trilateration sensor has the capability of synchronizing with the airport local ATCRBS so that the sensor will interrogate/suppress during the ATCRBS dead time. At Logan an antenna at the trilateration sensor master station received signals from the local ATCRBS omni antenna on the ASR-7 tower. In hundreds of hours of operation of the sensor, with and without synchronization with the local ATCRBS, no interference was seen in the ARTS-III. In fact, neither the terminal nor the en route (the radar at Fort Heath has line-of-sight to Logan) operations had any indication in their systems that revealed whether the trilateration sensor was on or off the air.

External interference with the trilateration sensor was observed during tests at Logan. The Vortac/DME station is sited in close proximity to the Master station. Non-synchronous pulses were observed at different times in the receiver output, and in a random fashion would arrive slightly ahead of a transponder reply causing an erroneous TOA measurement. While it did not seriously impact the Logan tests, it was clear that in any further testing, especially system level tests, that filtering of this interference may be required in the future.

3. CONCLUSIONS AND RECOMMENDATIONS

Tests of the beacon trilateration sensor at Logan International Airport not only confirmed the feasibility tests that were conducted at NAFEC, but indicated, after some hardware modifications were made, that:

- o Positional accuracies of less than 10 feet were obtained inside the area of the triad.
- o Outside the area of the triangle errors of less than 20 feet were obtained.
- o Multipath, while causing garbling of the beacon identity, did not effect the positional accuracy.
- o Excellent coverage could be achieved if the correct identity at any two or more stations is used as a criterion rather than requiring that all stations have the correct or same identity at all times.
- o While a minimum distance for resolution was not determined, it was however, confirmed that two aircraft whose beacon antennas are separated by less than 150 feet can be resolved.
- o The sensor can function without mutual interference with the operational ATCRBS.

The trilateration sensor, the front end of a trilateration ASTC system, has been demonstrated to be feasible. It is recommended that this sensor be upgraded in order that system level tests can be performed. Real time data processing, dynamic hardware control and a real time display showing a map of the airport and the location and identity of each aircraft are required. This system can then be utilized to investigate system level problem areas that are beyond the capabilities of the sensor such as update rates, round reliability, acquisition/track/lost target algorithms, filtering/smoothing algorithms, automated hardware functions, software, interfacing and display requirements and ASTC operation in terminal/gate areas.

Inasmuch as the trilateration sensor can only detect transponder equipped vehicles, it may be desirable or perhaps necessary to consider equipping ground vehicles with transponders. The development of such a transponder should be considered. While aircraft transponders can be used in ground vehicles, they are overdesigned for this purpose and thus unnecessarily costly. Ground vehicles do not require all the modes, functions, codes or the transmitter power output required of a standard ATCRBS transponder. A ground vehicle transponder can be low in cost, portable and perhaps have a single, unique mode or two modes for emergency vehicles.

Finally, interfacing the trilateration system with the ARTS/III/TIPS would provide the necessary conversion from beacon code to aircraft code and also provide information on aircraft type.

APPENDIX

DESCRIPTION OF TRILATERATION SENSOR

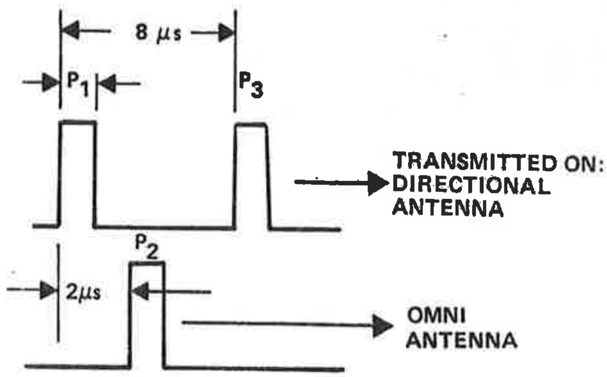
A.1 INTRODUCTION

The following is a description of the beacon trilateration sensor operation. The photographs and drawings were taken from the NAFEC final report: A. L. Brockway, et al., Design, Fabrication, and Testing of a Brassboard Model ATCRBS Based Surface Trilateration Data Acquisition Subsystem, Report No. FAA-RD-78-63, June 1978. A more detailed description of the hardware may be obtained from that document.

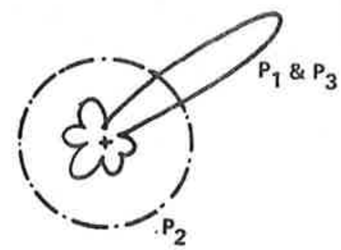
Beacon Trilateration Technique

The process of trilaterating, or locating the position of an RF transmitter by measuring the time of arrival (TOA) of the signal at three separate receiver sites, is a well known technique with numerous applications. In beacon trilateration TOA differences are used in the position determination. After measuring the TOA at each of three stations the differences in TOA between pairs of sites are calculated. Each pair of TOA measurements describes a hyperbolic line which passes between two stations. The intersection of a pair of lines defines the location of the RF transmitter. The position determination is a simple calculation and does not represent any new technology. The uniqueness of the beacon trilateration sensor is in the method used to elicit replies, separately, from closely spaced aircraft on the surface of an airport. The sensor is capable of obtaining ungarbled replies from closely spaced aircraft without requiring modifications to the transponders and without interfering with the operational ATCRBS.

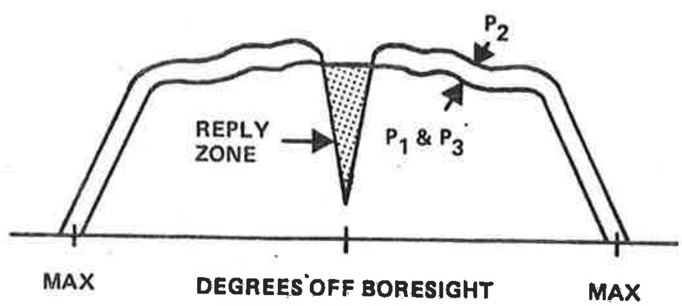
Figure A-1 describes the ATCRBS Mode A interrogation characteristic and shows the difference in the ATCRBS and the trilateration sensor antenna patterns. As shown, the trilateration interrogation beam is broad, with P2 being greater than P1 and P3 everywhere except in the null of the P2 pattern. Aircraft transponders located outside of the null will be suppressed. Before the transponder can come out of suppression P3 is emitted and only transponders located in the null will reply. Figure A-2 shows the suppressed region generated by transmitting the P1-P2 pattern from the suppressor (slave) station. Figure A-3 shows the same suppressed region, but in addition another suppressed region generated by the interrogation (Master) Station. The Master Station then transmits the P3 pulse and the only transponder that can reply is the one that is located in the cell defined by the intersection of the two nulls.



MODE A. ATCRBS Interrogation Characteristics



ATCRBS
Antenna Patterns



Trilateration Antenna Pattern

FIGURE A-1. ATCRBS AND TRILATERATION ANTENNA PATTERNS

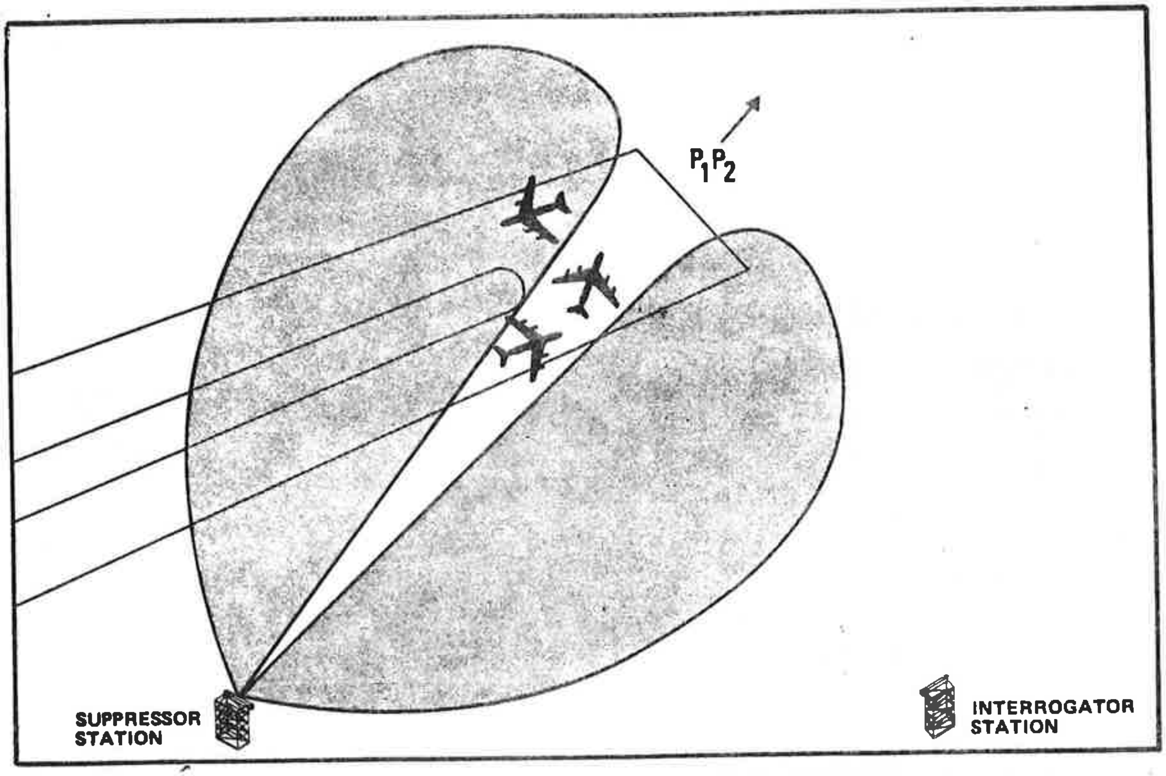


FIGURE A-2. SUPPRESSOR STATION TRANSMISSION SHOWING SUPPRESSED REGION

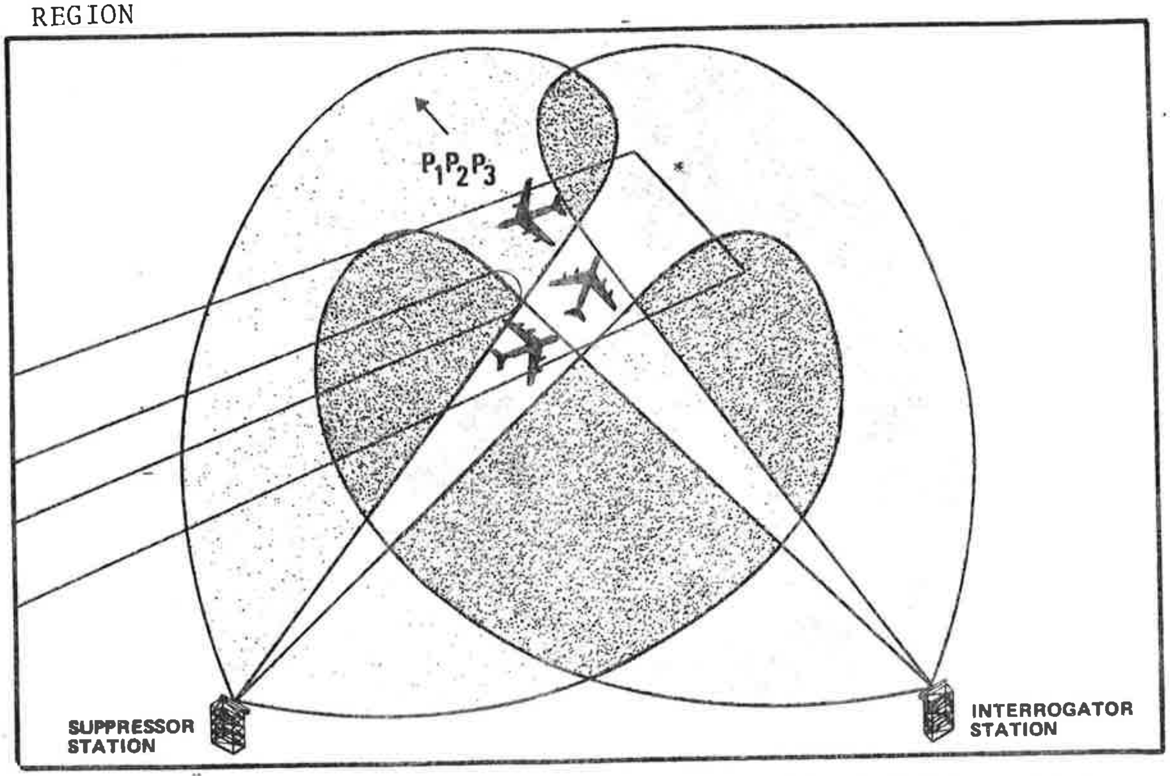


FIGURE A-3. INTERROGATOR STATION TRANSMISSION SHOWING ADDITIONAL SUPPRESSED REGIONS

A.2. SENSOR OPERATION

The trilateration sensor is a three-station network interconnected by a microwave data link. All three stations have receivers and two of them also have interrogators. Replies received at the Receive Station and the Slave Station are data linked to the Master Station where the time of arrival is referenced to a single clock, eliminating synchronization errors. Calibration of the Sensor determines the fixed delays for each site, including data link delays. Sensor timing, control and data collection are accomplished at the Master Station. Suppression signal emission and null steering from the Slave Station are controlled from the Master Station via a data link.

Figure A-4 is a simplified block diagram of the trilateration sensor. Except for the test control unit (TCU) and recorder the Slave and Master Stations have the same, essentially interchangeable equipment complement. Real time tracking is not done in the sensor. The TCU sequences the scanning of the Slave and Master antennas in a raster pattern. After the Master Station antenna pattern null is incremented (in selectable steps of 1/4 to 1 degree) over the entire azimuth from -32° to + 32°, the Slave Station is incremented once and

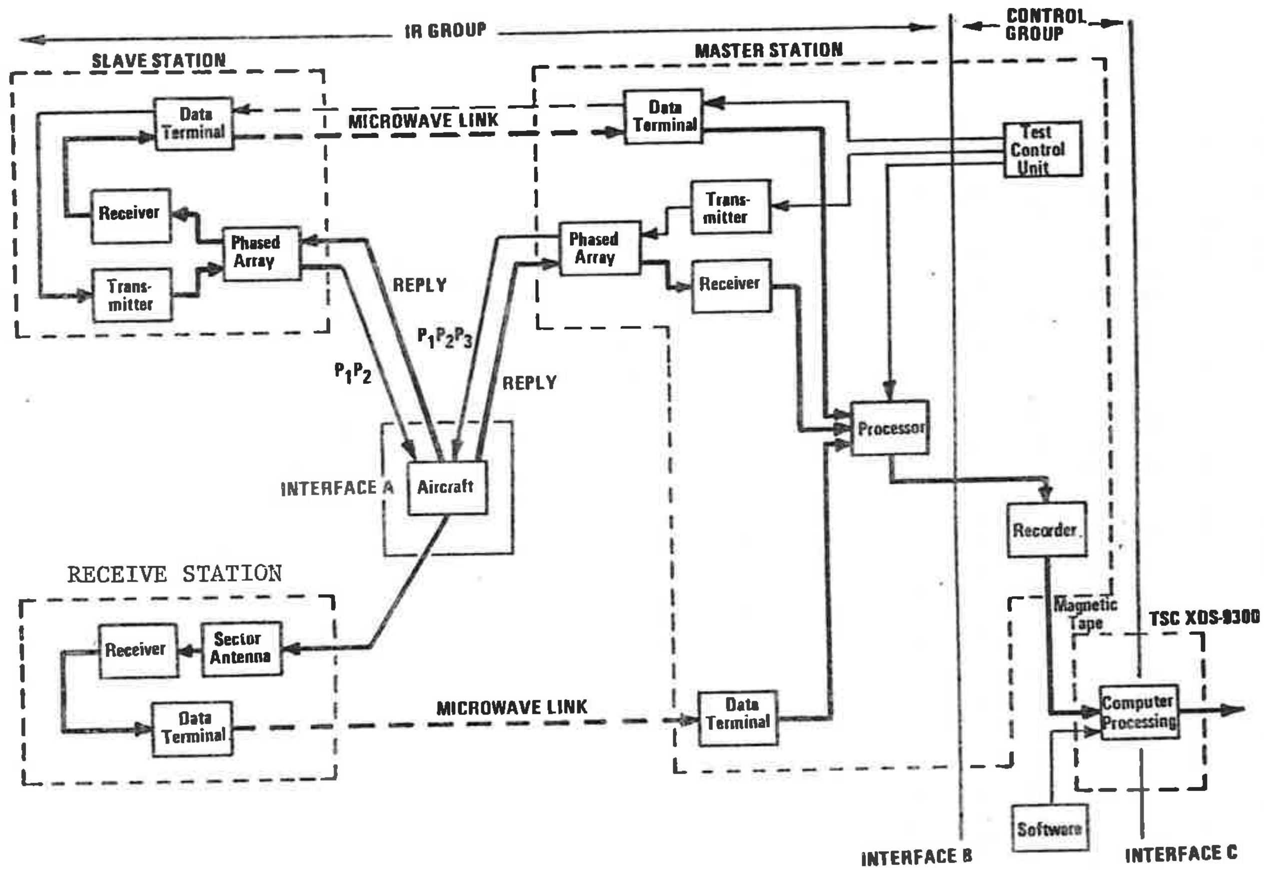


FIGURE A-4. TRILATERATION SIMPLIFIED BLOCK DIAGRAM the process is repeated. Figure A-5 depicts the scan geometry. Selection of scan limits, the number of interrogations per cell, steering increments, and the number of interrogations per local ATCRBS dead time are switch controlled at the TCU. The null widths are determined by P1 and P2 power output (attenuator controls) and the number of antenna elements used in the phased array antennas (6 or 16 selectable). A data monitor readout on the TCU displays TOA and ID for each site and the time of day. At the start of a test a Test Run switch on the TCU is enabled. Immediately test data codes and certain switch setting information go on the magnetic tape in two test heading words, after which the test sequence is initiated. During the test antenna steering angles, time of day, time of arrival and ID for all three stations are recorded on the magnetic tape. Processing of the tape is performed at TSC on the XDS-9300 computer.

A.3. SENSOR EQUIPMENT AND INSTALLATION

Three trailers approximately 8 by 16 feet house the electronics equipment for each station. The antennas for each station, when dismantled, can be stored in the trailers for shipment to another location.

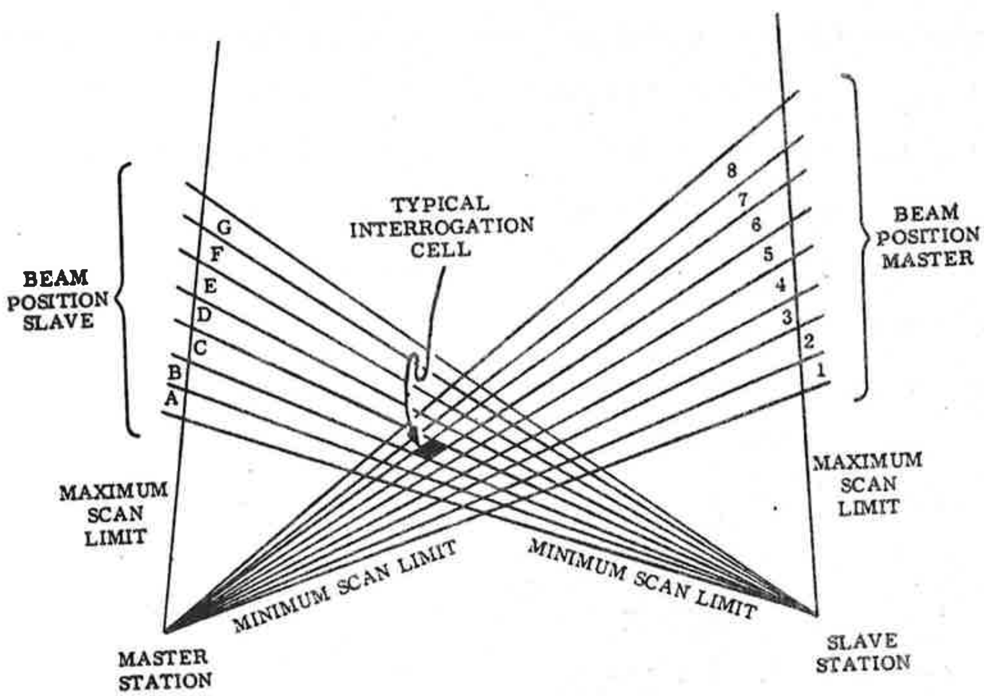


FIGURE A-5. SYSTEM SCAN GEOMETRY

The Master Station contains most of the electronics equipment and has two six-foot racks. A layout of the Master Station is given in Figure A-6. Air conditioning and heat are provided as well as a work bench and space for storage and tools. A 7.5 KW electric generator is also supplied. Although this generator is capable of full time operation, at Logan external power was supplied and the generator was only used during power outages when tests were being performed. The Slave and Receive trailers are similar to the Master except that they contain less equipment (one small rack), have smaller generators, and the Receive Station trailer does not have air conditioning. Photographs of the Master, Slave and Receive equipment racks are shown in Figures A-7, A-8, and A-9.

Prior to installation, site selection is made and is based primarily on obtaining as much airport surface coverage as is possible with only three stations. A goal is to obtain the largest practicable equilateral triangle with the stations located at the vertices. Installation entails erecting antenna towers, installing guy wires, antennas and cabling to the trailers and obtaining external electrical power. Surveys are then made to locate the position of the receive element for all three antennas, boresight markers, and for various loca-

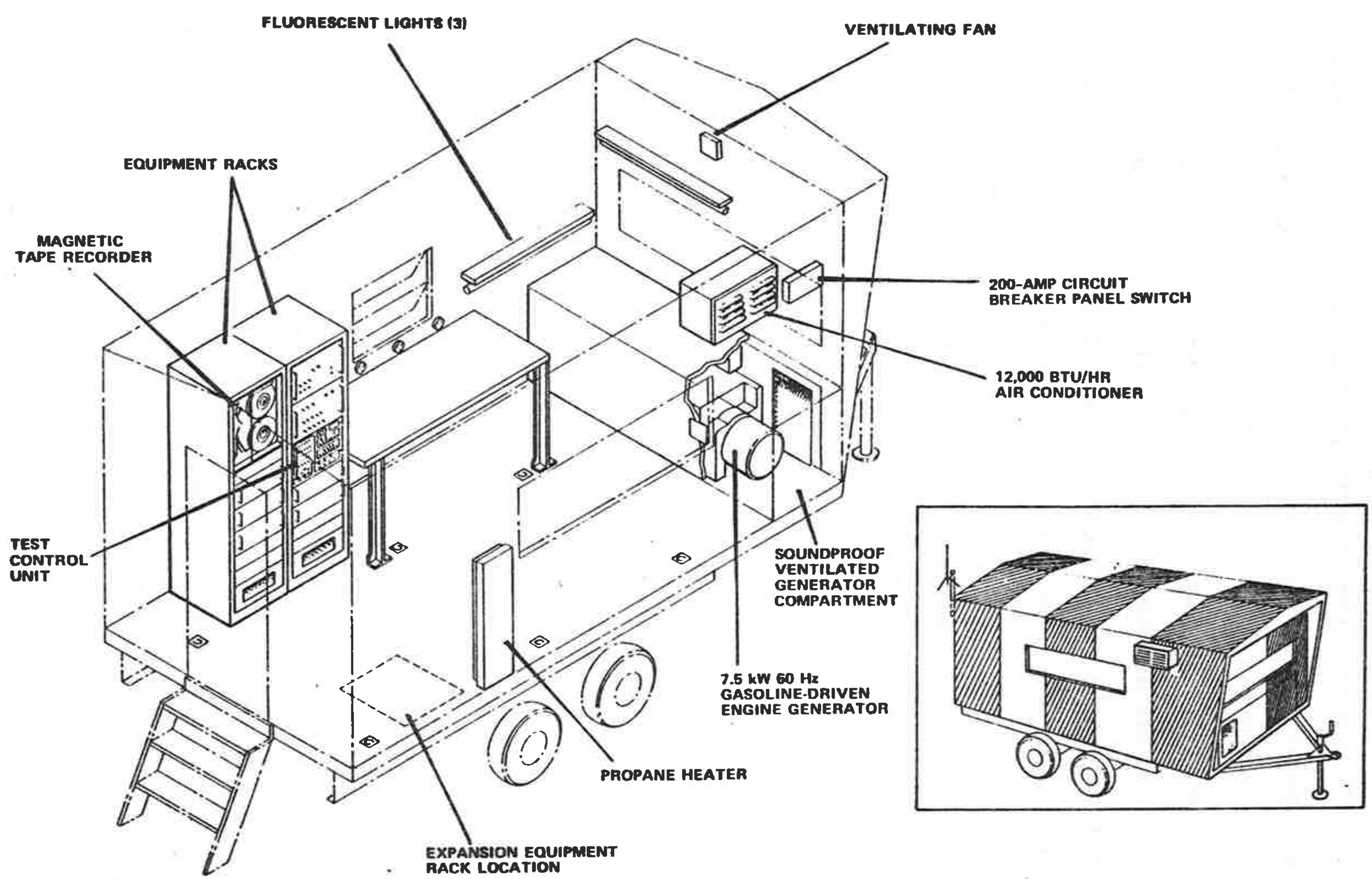


FIGURE A-6. MASTER STATION TRAILER DETAILS

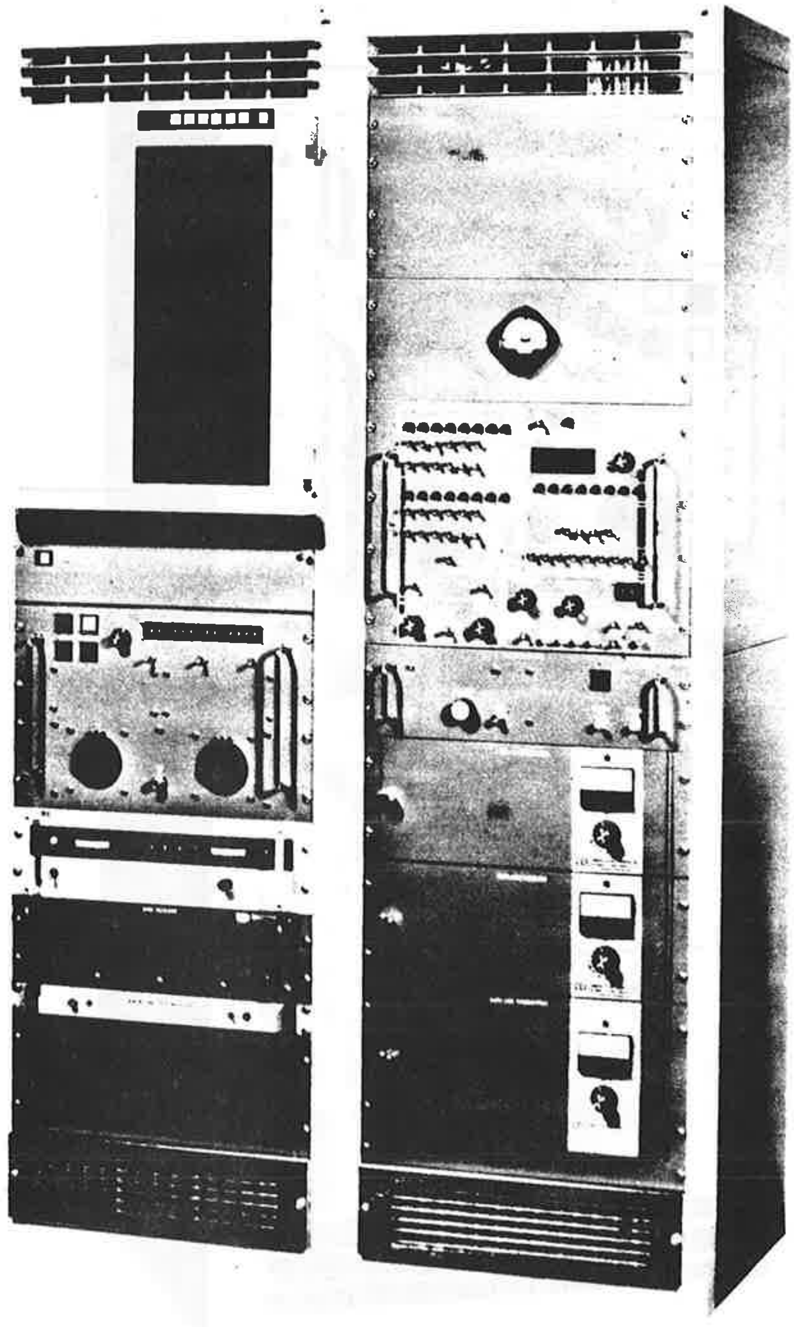


FIGURE A-7. MASTER STATION ELECTRONICS EQUIPMENT

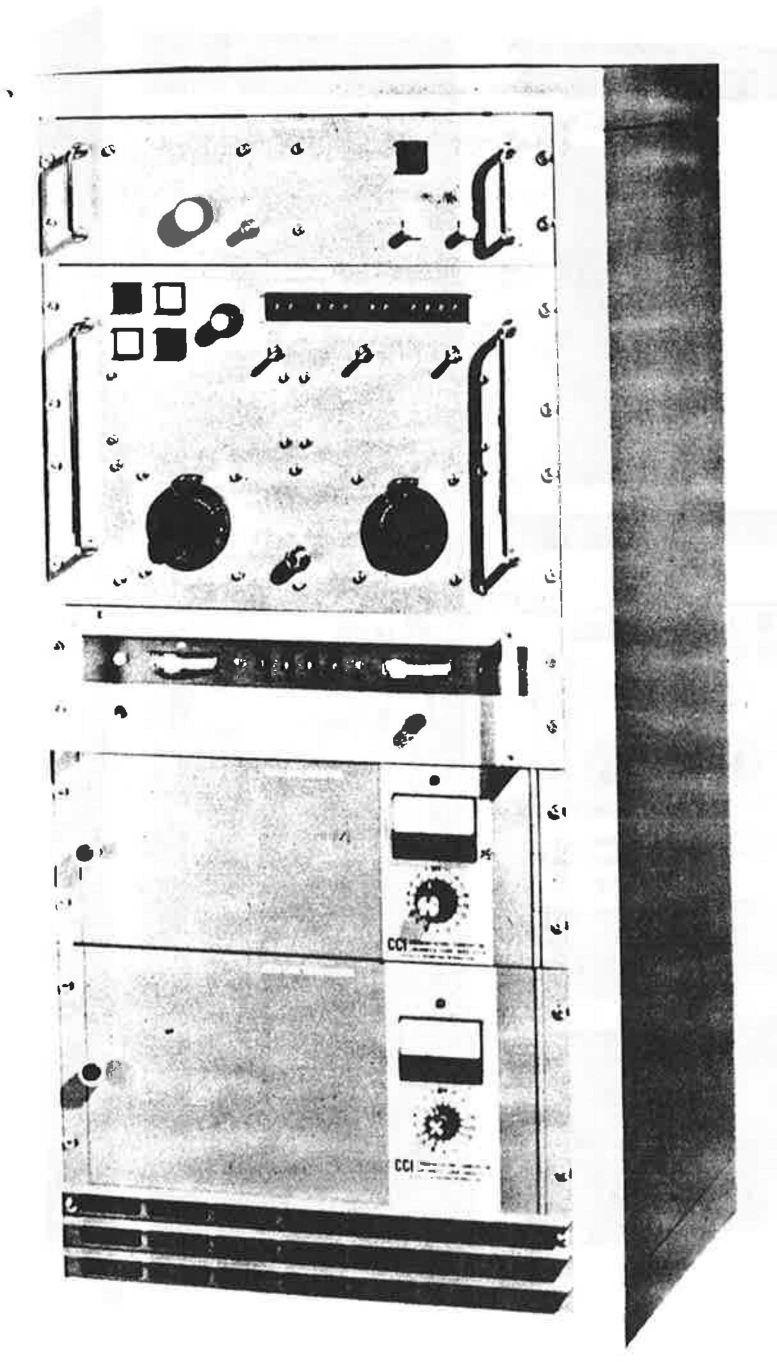


FIGURE A-8. SLAVE STATION ELECTRONICS EQUIPMENT

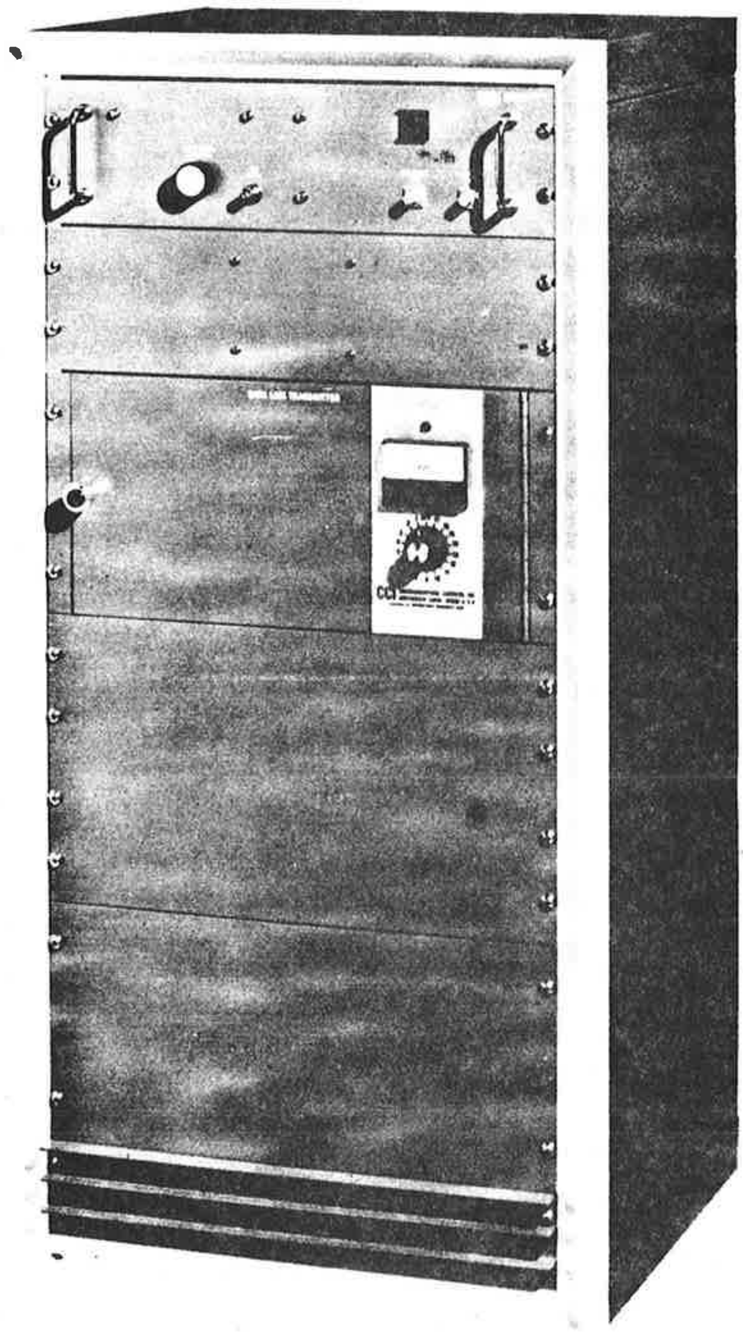


FIGURE A-9. RECEIVE STATION ELECTRONICS EQUIPMENT tions on the surface for calibration and accuracy tests.

A.4 PHASED ARRAY ANTENNAS

A key element in the technique used by beacon trilateration to selectively interrogate closely spaced aircraft on the surface of an airport is the antenna radiation pattern generated by the phased array antennas.

These antennas, located at the Master and Slave Stations generate two patterns: a broadbeam sector pattern for transmitting the P1 and P3 pulses and for receiving replies, and a similar pattern with a narrow, deep steerable null in the azimuth plane for transmitting the P2 pulse. The first pattern is achieved by using a single element of the phased array antenna. The second pattern, with the steerable null, is produced by a linear phased array of 16 active antenna elements. These patterns, measured during factory range tests, are shown in Figure A-10. A block diagram of the phased array antenna is given in Figure A-11, and a photograph of the antenna taken during range tests is shown in Figure A-12. The enclosure at the rear of the antenna, with cover removed, contains the null steering electronics.

The Receive Station only serves to receive transponder replies and does not require a phased array antenna as used at the Master and Slave Stations. This antenna is

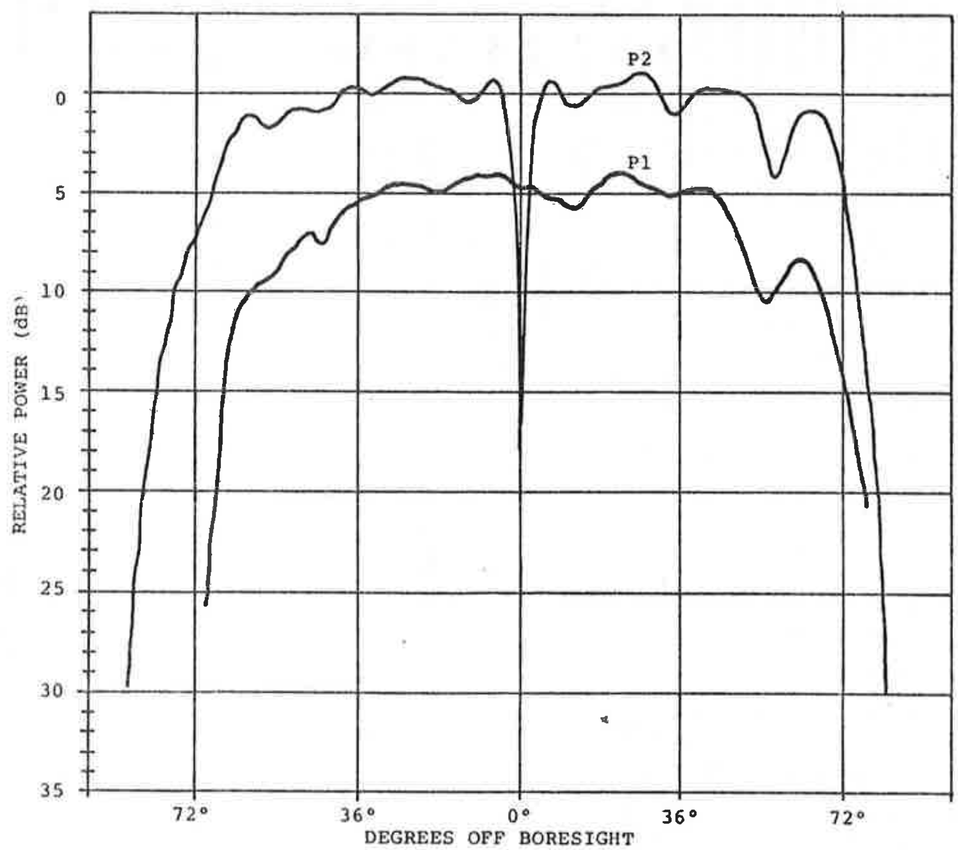


FIGURE A-10. MEASURED BRASSBOARD DAS ANTENNA PATTERNS
Null at Approximately 54° Generated by Antenna Range, Not an Antenna Characteristic

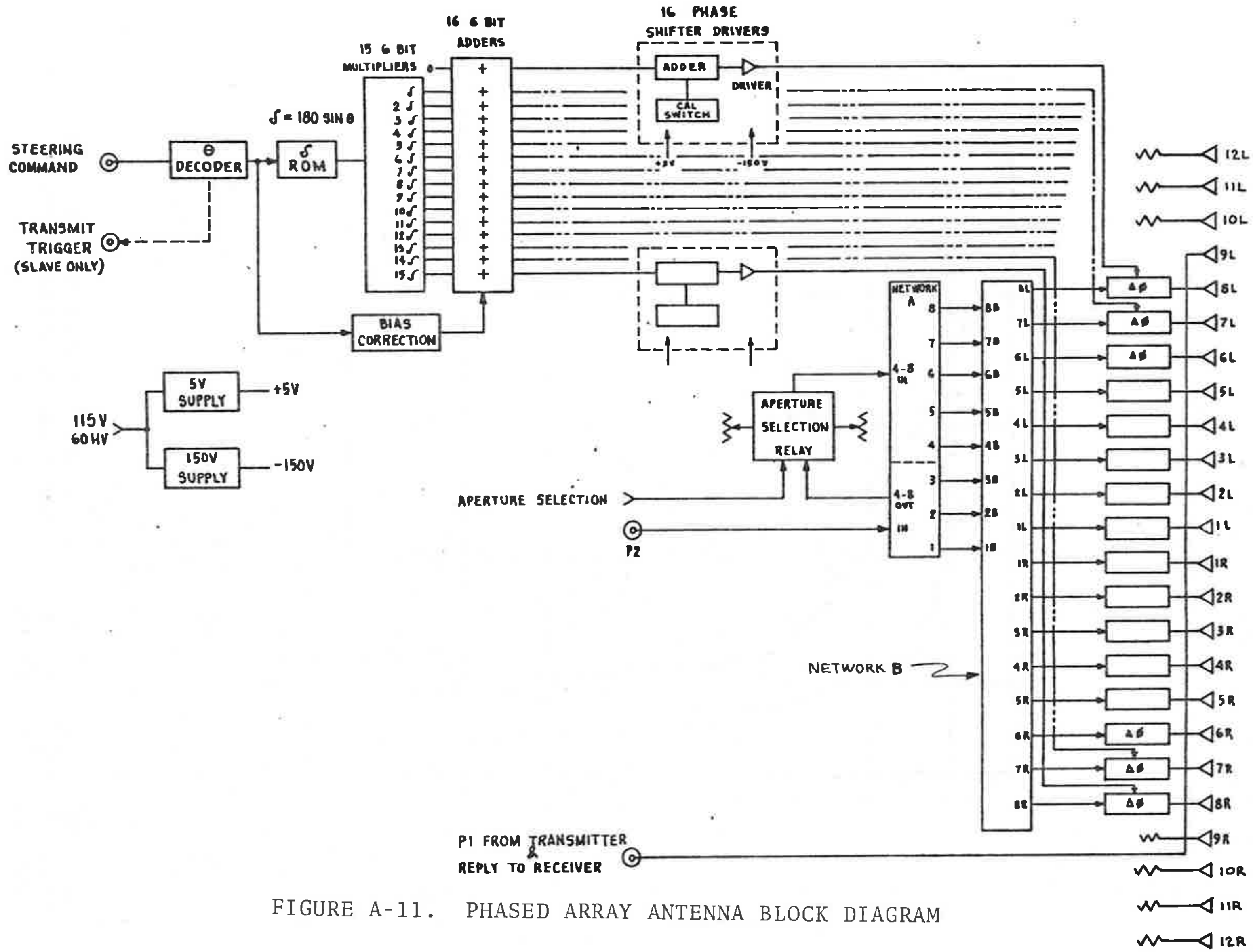


FIGURE A-11. PHASED ARRAY ANTENNA BLOCK DIAGRAM simple in construction, using three stacked dipoles above a ground plane. The stacked dipoles have a tapered illumination that closely matches the vertical pattern of the Master and Slave antennas. The receive antenna, being small and light in weight, uses a triangular, telescopic tower as opposed to the more substantial rectangular tower required for supporting the large and heavy (12 feet long and about 450 lbs.) phased array antennas.

FIGURE A-12. PHASED ARRAY ANTENNA DURING RANGE TESTING

U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
TRANSPORTATION SYSTEMS CENTER
KENDALL SQUARE, CAMBRIDGE, MA 02142

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF TRANSPORTATION
513

U S MAIL