FTL REPORT R81-2

USE OF LORAN-C
FOR GENERAL AVIATION AIRCRAFT NAVIGATION

KRISHNAN NATARAJAN

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ABSTRACT

This report describes an extensive evaluation of Loran-C for use by general aviation. Flight, ground, and antenna tests were done. Flight tests measured the accuracy and the ability to make approaches. Receiver reliability and susceptibility to atmospheric noise were also studied. Ground tests looked into grid stability and grid warpage. Antenna tests were done to evaluate three antenna configurations -- ADF, vertical whip, and trailing wire antennas.

The measured accuracy met FAA AC 90-45A requirements for all phases of flight. Loran-C was found to be satisfactory for approaches within AC 90-45A specifications. Reliability was 99.7%, the receiver was insensitive to atmospheric noise. The time difference grid was stable in the long run. Antenna tests showed the ADF and vertical whip antennas to be suitable for airborne use.

It is concluded that Loran-C is suitable for navigation as an alternative to VHF RNAV. This navigation system is suitable for use in general aviation aircraft.

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Table of Contents

List of Figures

List of Tables

GLOSSARY

ADF	Automatic Direction Finding
ATC	Air Traffic Control
AVM	Automatic Vehicle Monitoring
DABS	Discrete Address Beacon System
DOT/TSC	Department of Transportation / Transportation Systems Center
FAA	Federal Aviation Administration
FAF	Final Approach Fix
GRI	Group Repitition Interval
GPS	Global Positioning System
IFR	Instrument Flight Rules
ILS	Instrument Landing System
MAP	Missed Approach Point
NDB	Non-Directional Radio Beacon
RNAV	Area Navigation
SNR	Signal to Noise Ratio
TACAN	Tactical Air Navigation
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR/DME	VHF Omnidirectional Range / Distance Measuring Equipment
VORTAC	VHF Omnidirectional Range Tactical Air Navigation

1.0 SUMMARY

1.1 Overview of Test Program

The basic purpose of the test program was to find the suitability of using Loran-C for navigation in general aviation aircraft. To fulfill this purpose three types of tests were carried out. These were air, ground, and antenna tests.

A Loran-C receiver was test flown to evaluate several factors such as accuracy, reliability, failure rate, and susceptibility to atmospheric noise such as P-static. The test program comprised 32.5 hours of test flight time. This test flying was done in 5 different aircraft under various conditions.

As a part of the test program 24 approaches to 7 runways were flown to evaluate the capability of Loran-C to make non-precision approaches. Here, 5 different airports were used in the approach testing.

In addition to the flight tests ground tests and airport surveys were carried out from April 1980 to October 1980. A total of 12 survey points at 4 airports were used for the survey tests. Data was also collected at a fixed laboratory site over the same period. One of the major aims of the ground test program was to evaluate the magnitude and long term stability of grid corrections.

Antenna tests were done with 3 types of E-field antennas. These were ADF (Automatic Direction Finding), vertical whip, and trailing wire antennas. All 3 antenna types were evaluated in flight, the vertical whip and ADF antennas were tested on the ground.

1.2 Test Objectives

One of the major test objectives was to see if Loran-C could meet the accuracy criteria in the FAA (Federal Aviation Administration) advisory circular AC 90-45A. Here, the accuracy criteria for enroute, terminal, and approach flight phases are given for area navigation systems.

Qualitative and quantitative observations on the performance of Loran-C in aircraft were desired. Of interest were to evaluate Loran-C on cross country flights, and to use Loran-C to make non-precision approaches under simulated IFR (Instrument Flight Rules) conditions. A part of these tests was to investigate the reliability and failure rate of Loran-C equipment, and to study its susceptibility to atmospheric effects such as P-static.

Another area of interest was to quantify the long term stability of the Loran-C time difference grid. This result was important to evaluate the possible use of grid corrections for improved accuracy.

The last test objective was to find antenna configurations which gave good performance. This study was restricted to E-field antennas.

1.3 Experimental Procedure

The various tests carried out were divided into 3 major parts - flight, ground, and antenna tests. A total of 32.5 hours of flight test time was accumulated. Ground and antenna tests were done from April 1980 to October 1980.

Accuracy tests were the first part of the flight test program. These consisted of 4 hours of flight time. For these tests the aircraft was being tracked by the DABS (Discrete Address Beacon System) tracking radar at Lincoln Laboratory. The main area of interest here was the along and cross track errors of the Loran-C system.

Approach testing consisted of 6.5 hours of flight time designed to evaluate the capability of Loran-C to make non - precision approaches. This testing was done in simulated IFR conditions with both corrected and uncorrected coordinates. The approach accuracy was estimated by visual sighting over the runway MAP (Missed Approach Point).

During the flight testing a detailed log was maintained to monitor operation of the Loran-C receiver. Note was made of factors such as loss of lock, transmitter loss, and low SNR (Signal to Noise Ratio).

Ground testing was divided into two parts. First, Loran-C time differences were measured in the laboratory regularly from April to October. Second, 7 survey points at 3 airports were surveyed on two separate occasions. The aim of these tests was to evaluate the stability of the Loran-C time difference grid.

Antenna testing consisted of evaluating 3 antenna configurations in flight. These were the ADF, vertical whip, and trailing wire antennas. The ADF and vertical whip antennas were evaluated on the ground. Performance of the antennas was quantified in terms of SNR and relative signal strength.

1.4 Results

The accuracy requirements in AC 90-45A were met by Loran-C. Loran-C cross track and along track accuracies were much less than required for enroute and terminal areas, and were adequate to meet approach accuracy specifications.

With prior measurement of the exact Loran-C coordinates the accuracy of subsequent Loran-C approaches was similar to ILS localizer approaches. Without prior measurements the approach accuracy was still sufficient to meet AC 90-45A requirements.

Reliability of the test receiver was very high. With a good antenna the receiver functioned correctly 99.7% of the demanded time. No problem with P-static was recorded when good antennas were being used.

The Loran-C time difference grid was found to be very stable in the long run. From April to October the typical variation of time differences was 0.3 microsecond peak-to-peak. Antenna tests showed that the ADF and trailing wire antennas provided very good signal levels and SNR's. The vertical whip antenna provided poorer performance on the ground and in the air, while the ADF antenna had very good performance on the ground.

1.5 Conclusions

It was concluded that Loran-C could be used for general aviation aircraft navigation. Loran-C was capable of providing reliable and accurate navigation information within AC 90-45A guidelines.

The Loran-C time difference grid was stable in the long run. This made it feasable to use a one time correction to increase the accuracy. Test results indicated that a correction for each airport was desireable. The grid stability also lead to Loran-C having a highly repeatable position fixing capabilty.

Of the antennas tested, none were found to be critical to proper operation of the receiver. Tests showed the ADF and vertical whip antennas to be practical. Both antenna types warranted further study,

Finally, flight tests demonstrated the need to carefully design the Loran-C / pilot interface.

2.0 INTRODUCTION

2.1 Background

2.1.1 Theory of Operation

A detailed description of the Loran-C system is given in reference 1. Loran-C is a pulsed, low frequency, long range radionavigation system operating at 100 kilohertz. It is a hyperbolic system which uses 3 or more transmitters in each chain. These are divided into a master and two or more secondaries. All transmitters are synchronized with individual cesium clocks.

All transmitters transmit groups of 8 or 9 pulses. These pulses are shaped to keep 99% of the transmitted energy in a 20 kilohertz bandwidth. First, the master transmits, followed by the secondaries. A coding delay ensures that for every point signals from two transmitters do not arrive at the same time. The entire sequence of transmissions is repeated after a group repetition interval , typically .04 to .1 second.

The Loran-C receiver measures the time differences between the master and secondary signals. Since two time differences are usually used this generates two hyperbolic lines of position, the intersection being the position fix.

2.1.2 Operational Testing

This section discusses literature describing tests done to evaluate Loran-C operation in field conditions. There are 3 different test categories - airborne, marine, and terrestrial testing.

2.1.2.1 <u>Airborne Testing</u>

Two major flight test programs already completed are the Coast Guard program and the joint Department of Transportation/ State of Vermont flight test program. Two studies were done for the Coast Guard, the Vermont program consisted of one major study.

The first study done for the Coast Guard is described in reference 2. This study investigated several things. First, the accuracy of Loran-C and its compatability with the present VOR/DME (VHF Omnidirectional Range / Distance Measurement) enroute navigation environment.was studied. Then, this study looked into the suitability of Loran-C for area navigation in the abscence of VOR/DME coverage. A part of this was to study the suitability of Loran-C area navigation under present and future FAA standards. Finally, the use of Loran-C for offshore Coast Guard search and rescue missions was evaluated.

The first result of this study was that Loran-C accuracy was sufficient to meet FAA AC 90-45A accuracy specifications for all phases of flight. Loran-C was found to be compatible with RNAV routes and procedures, as well as the current VOR/DME environment. The system performed well in overwater conditions in the abscence of VOR/DME coverage. Finally, Loran-C met the navigation requirements for Coast Guard search and rescue missions.

This study was followed up with another study described in reference 3. In the previous study a prototype Loran-C navigator was used, here a production navigator was used.

The second study covered the same areas as the first in greater depth. There was more extensive flight testing in the Northeast Corridor. This testing included pilot workload and ATC (Air Traffic Control) interface studies. There was more accuracy testing to study AC 90-45A compliance. Offshore testing investigated Loran-C behaviour in overwater missions. Signal anomaly and search and rescue mission tests were also done.

The results here were consistent with those of the previous study. Loran-C was found to be suitable for navigation in the Northeast Corridor. It was compatible with ATC requirements and demanded an acceptable workload from a 2 pilot crew. Also, Loran-C was found to be suitable for point - in - space approaches.

Accuracy tests showed that Loran-C met all AC 90-45A requirements except the along track requirement for approach flight. Offshore testing showed no signal anomaly along the coastline. Loran-C was found to be suitable for navigation on long (100 to 200 n.m.) overwater missions. It was found useful as an approach aid to oil rigs, as well as for search and rescue missions.

The third major flight test study was done in Vermont for the Vermont Agency of Transportation (Ref. 4). These tests were done to evaluate the use of Loran-C for enroute, terminal, and approach navigation in the State of Vermont. A lack of conventional VOR/DME coverage, due to mountainous terrain, as well as the relative scarcity of IFR qualified airports provided the motivation for this study.

The main result of this study was that Loran-C could be used for enroute, terminal, and approach navigation. Accuracy requirements for these phases of flight, stated in AC 90-45A, were all met. The reliability of the receiver was found to be 99.5%, there were no problems with terrain or atmospheric effects. It was concluded that Loran-C would greatly benefit the general aviation community in Vermont. Some of the benefits were to provide non - precision approaches to non IFR qualified airfields, improving existing approach profiles, and reducing ATC personnel workload.

2.1.2.2 Marine Testing

Loran-C was tested in marine applications in two major studies. A Coast Guard study looked into Loran-C for navigation in the St. Marys' river. The Coast Guard also studied retransmitted Loran-C for Vehicle Traffic Service operations in San Francisco Bay.

The St. Marys' river study is described in reference 5. Here, the major aim was to see whether Loran-C could give accurate navigation information. Navigation requirements were stringent because the river was traversed by ships 1000 ft. long and 105 ft. broad, with the channel being only 300 ft. narrow at several points.

A Loran-C minichain was installed to give good signal coverage in that region. Tests were done to find the Loran-C accuracy, as well as the value of guidance information derived from it. Typical accuracies were 37 ft. cross track (2σ) and 59 ft. along track (2σ). Loran-C provided useful guidance information. The time difference grid was repeatable, the stability of the grid is yet to be verified.

Vehicle Traffic Service tests were done in San Francisco (Ref. 6). Ships in the San Francisco Bay were equipped with Loran-C receivers. Time difference data was sent to a base station via radio links. This data was used to generate a San Francisco Bay map with displayed ship locations. Ships were tracked by radar to find Loran-C accuracy.

At the time of writing this report the feasability of Loran-C as a Vehicle Traffic Service tool was still under study. Raw data was being analysed to determine the Loran-C accuracy.

2.1.2.3 Terrestrial Applications

There were two areas of interest for terrestrial applications of Loran-C. Both were sponsored by the DOT/TSC (Department of Transportation / Transportation Systems Center). These studies were both involved with AVM (Automatic Vehicle Monitoring).

The first study is shown in reference 7. AVM was studied for use by transit support vehicles in the Los Angeles area. Loran-C was being studied for the location subsystem requirement. Signal survey tests done in the Los Angeles area showed the difficulty of getting useable signals. This problem was more prevalent in downtown high rise areas. Studies showed that a hybrid system would be needed to meet the location subsystem requirements. A Loran-C / signpost hybrid was being evaluated.

Reference 8 describes the second study being done in the State of New York. The aim here was to study applications of Loran-C in vehicles. First of all, the use of Loran-C time difference coordinates for indexing traffic records and highway inventories was evaluated. Next, the use of time difference coordinates for emergency vehicle dispatch was looked into. A test program was drawn up to study the feasability of Loran-C for these applications. The ultimate objective of this ongoing study was to build suitable Loran-C based systems and evaluate them.

2.1.3 FAA Certification Requirements for Loran-C

The FAA has been charged with making a decision, by 1983-85, about the replacement of the current VORTAC (VHF Omnidirectional Range Tactical Air Navigation) enroute navigation system. Some of the contenders for replacement of this system are VOR/DME, VORTAC, TACAN, LORAN-C, and NAVSTAR/GPS (Ref. 9). Studies are being done to determine the future roles of each of these systems. Loran-C has to be seriously considered for this purpose. Some of the certification issues are considered below.

2.1.3.1 Advantages of Loran-C for Navigation in CONUS

There are several advantages Loran-C has if it is used for aircraft navigation in CONUS (Continental United States). These are discussed below in relation to other systems being considered by the FAA.

Loran-C is non-saturable and can accomodate an unlimited number of users. This contrasts with the VOR/DME and VORTAC systems, which are user saturable.

The system is proven with over 30 years of developmental experience. Several independent studies, including this one, show Loran-C to be accurate enough to meet AC 90-45A specifications (Ref. 10). These accuracy tests have already been discussed in section 2.1.2.1.

Loran-C is cost competitive with other systems. A FAA study (Ref. 9) shows Loran-C to be cost competitive with other systems under study. This system was shown to have one of the lowest estimated costs of all systems under study. Reference 11 is another report which indicates that Loran-C has the lowest ownership and operation cost of all equal performance systems.

That report (Ref. 11) also shows how the entire CONUS could be covered by 16 1.6 megawatt transmitters. These would be organized into 4 chains. Each chain would be a complete or partial 7 station hexagon with nominal 1100 km. baselines. Coverage would be provided for the coastal region and the Great Lakes. VORTAC coverage of the CONUS requires a far greater number of transmitters.

Another possible advantage of Loran-C is for ATC purposes. One proposal (Ref. 11) suggests the possibility of Loran-C receivers in aircraft retransmitting position data to ATC centers. The ATC system would use this information for collision avoidance and route generation. This is made possible since Loran-C has a fixed grid referenced to the earth.

2.1.3.2 FAA Concerns about Loran-C

A spokesman for the FAA has expressed various concerns about the certification of Loran-C as an area navigation system. These concerns are discussed in relation to the author's experience and the available literature.

The FAA will be required to define a minimum Loran-C receiver for airborne use. The specification must take into account single pilot IFR conditions. A suggested set of minimum requirements are given here. The minimum receiver should have automatic signal lockup and tracking loops, automatic noise rejection, and error warning lights. Manual station pair selection and manual chain selection are acceptable for the minimum receiver. In addition there should be a coordinate convertor, a minimum of 3 waypoints, and waypoint input blunder checks.

The FAA is concerned about having to provide a NOTAMS service for Loran-C. It should be noted that there is no such service for Omega, which is a similar radionavigation system.

There is concern that Loran-C will not be able to perform accurately near the transmitters. One reason for this is the large grid curvature near them. Flight test results described in section 5.1.6 of this report show no such difficulty although tests were done very close to the Loran-C transmitter at Nantucket, Mass. If this problem becomes apparent with more detailed testing then there are several ways to correct it. The first is to place transmitters in remote areas, and indicate areas to be avoided around them. Another alternative is to deselect a particular transmitter when using a Loran-C receiver near it.

Another difficulty is what to do about transmitters going off the air because of failures or maintenance. From the user viewpoint there are several ways around this problem. First, current airborne receivers can choose between two Loran-C triads. These receivers can also operate in a master independent mode. In the event of a failure these features can be used to overcome transmitter loss. State of the art Loran-C receivers have the capability of automatic station pair selection based on signal strength and geometry. Loss of a station is automatically handled by selection of an alternate triad.

Another issue is what would happen if a transmitter should go off the air while on final approach. From the pilot's standpoint this would be treated just like an ILS receiver failure. One possibility is to specify primary and secondary triads on the approach plate. A transmitter failure would require selection of an alternate triad. If both triads are unusable because of transmitter failure then an alternate airport would be selected.

There has been very little work done on the effects P-static and power line carriers have on Loran-C. Flight test work done in the State of Vermont (Ref. 4) did not find power line carriers to have any noticeable effect on Loran-C performance. Reference 12 is a study done with ground based Loran-C. It was found that asynchronous carriers on power lines affected receiver performance upto a distance of 300 metres. Synchronous carriers were found to affect receiver performance up to 1000 metres from the power line. These tests did not include any airborne tests, however. Aircraft would not fly closer than 1000 metres to power lines for reasons such as possible collision, and minimum altitude requirements. The power line carrier problem was not noticed in this test program. P-static was not observed to be a problem in the Vermont flight test program as well as in this program.

Another issue is the use of marker beacons as a check when flying Loran-C approaches. A spokesman for the FAA has expressed concern that a receiver cycle slip error could go undetected. As described in section 5.1.5 cycle slippage is infrequent and quickly detected and corrected by the receiver. Use of marker beacons as a check should be regarded in the same light as their use for checks on an ILS approach. The available literature indicates that cycle slip is very rare and such a marker beacon check is not essential.

When making long distance flights it will be necessary to switch between chains. Such a chain switchover procedure should be handled like VORTAC selection. Different chains would have an overlap zone, which would be marked on enroute charts. Pilots woud be instructed to select a new chain while crossing these zones.

The last concern is what should be done about a Loran-C receiver failure in an aircraft. This would be no different in principle from a VOR, DME receiver failure or a ILS receiver failure. A set of rules will have to be developed by the FAA for this situation, which would be similar to rules concerning what to do if some of the other navigation aids should fail.

2.1.4 Related Usage Issues

There are several issues related to usage of Loran-C for navigation. These are divided into propagation effects, pilot interface, and grid corrections. The test program described in this report addressed some of these issues.

2.1.4.1 Propagation Effects

Loran-C can be affected by various propagation effects. Some of these are P-static, diurnal and temporal variations, and grid warpage. The effects of these factors on Loran-C performance is very much of interest.

P-static is caused by the accumulation of charge on the aircraft skin. Charged clouds and rain droplets are two sources of this charge. The discharge of this accumulated charge to the atmosphere generates electrical noise, which may interfere with Loran-C signals. P-static flight experience was discussed in section 2.1.3.2.

Diurnal and temporal variations refer to short (1 day) and long (1 year) term variations in the time difference grid. Ground based data collection done by the TSC in Vermont shows typical yearly variations of 0.3 microsecond peak - to - peak. Also, Coast Guard studies in the St. Marys' river minichain show similar results. Here, annual peak - to - peak variations of 0.4 microsecond have been typical.

Grid warpage refers to a repeatable shift in the time difference grid from a calculated smooth earth value. Some of the causes of this shift are varying terrain, natural obstacles, and varying dielectric constant of the earth surface. Simulation results (Ref. 13) show that hills taller than 250 metres can cause appreciable grid warp at great distances. Grid warpage is discussed in detail in section 5.1.3.

2.1.4.2 Pilot Interface

The Loran-C / pilot interface is very important. Qualitative flight test results described in section 5.1.4 show that pilot workload is greatly increased with a poorly designed interface. Also, a poor interface can lead to pilot error through misinterpretation of displayed data.

Current airborne Loran-C receivers have complicated keypad interfaces and control units. This leads to very high pilot workload which is unacceptable under single pilot IFR conditions. The time required to perform Loran-C functions such as station pair selection, interference filter tuning, and course offset selection could be reduced by making these functions automatic or simplifying the inputs needed to perform them.

Waypoint entry is error prone and time consuming if waypoints are specified in numerical terms such as latitude and longitude. It would be desireable to be able to input waypoints by name. Also, the capability of calling up waypoints for entire approaches is desireable.

Finally, some means of checking waypoint input blunders, incorrect chain selection, and incorrect station pair selection is needed. The use of fault tolerant, error checking software is appropriate to achieve this goal.

2.1.4.3 Grid Corrections

There are several modes in which Loran-C can be used. Each mode has different requirements to implement and leads to different accuracies.

In the uncorrected mode Loran-C uses waypoints which are published in latitude / longitude coordinates. Here, the accuracy is reduced because of errors due to grid warp, surveying errors, position roundoff errors, and coordinate conversion errors in the receiver.

Corrections are made by going to a point and taking Loran-C measurements. The best form of corrections are those in time differences, since these are common to all receivers. With this type of correction, the stability of the time difference grid determines the usefulness of the corrections. Advantage is taken of the high repeatability of Loran-C.

Differential corrections are similar to those described above. As before, Loran-C receivers are used to determine corrections, which are transmitted in real time to aircraft. This system of corrections is only necessary if there is significant grid shift.

2.2 Purpose of the Test Program

The main purpose of this test program was to see if Loran-C was suitable for navigation use by general aviation aircraft. To answer this question several issues were addressed.

First, the question of whether Loran-C could meet the accuracy specifications in AC 90-45A was addressed. These requirements cover enroute, terminal, and approach phases of flight.

Second, the test program studied any possible problems with using Loran-C receivers in aircraft. Some of the possible problem areas were P-static, signal reliability, and receiver failures.

Third, propagation and atmospheric effects were examined. In particular, short and long term grid variations, grid calibrations, and grid warpage were investigated.

Finally, some empirical work was done to find antennas suitable for use by airborne Loran-C receivers.

2.3 Organization of this Report

The remainder of this report discusses the detailed technical objectives, test procedures, test results, and conclusions. Primary technical objectives are discussed in detail in section 3. A detailed description of test procedures used is described in section 4. The results of these tests are stated in section 5, with the conclusions drawn from these results given in section 6.

3.0 Detailed Technical Objectives

The aim of the test program was to achieve the following test objectives. Each technical objective was tested and the results analysed to get answers to the technical questions.

1. See if Loran-C meets AC 90-45A accuracy specifications given in table 3.1. Quantities of interest are the along and cross track errors for enroute, terminal, and approach phases.
2. Study the ability of Loran-C to make non-precision approaches. Evaluate the use of calibration to improve approach accuracy. Quantify the improvement in accuracy for corrected versus uncorrected approaches.
3. Evaluate the reliability of a Loran-C receiver and the signal availability. Compare the time of proper receiver operation with the demand time. Monitor signal loss and hardware and software failures in the receiver.
4. Examine atmospheric effects which affect Loran-C performance such as P-static. Study long and short term grid variations. Also study the nature of grid warpage and the use of corrections to reduce its effect on accuracy.
5. Study the suitability of several antenna configurations for airborne use. Rate these antennas according to measured signal level and SNR's.

	Along Track (2σ)	Cross Track (2σ)
Enroute	1.50 Nm.	1.50 Nm.
Terminal	1.10 Nm.	1.10 Nm.
Approach	0.3 Nm.	0.3 Nm.

Table 3.1

AC 90-45A Accuracy Specifications

4.0 TEST PROCEDURES

The tests carried out were divided into 3 main areas - flight, ground, and antenna tests. These are described in more detail below.

The receiver used in the test program was a Digital Marine Electronics Corporation Northstar 6000 Loran-C receiver. This is described in appendix A. It was a marine receiver which was not modified for airborne use. Some of the main features were a latitude / longitude coordinate convertor, single waypoint capability, cross track error indicator, as well as ground speed, track, and time-to-go outputs.

Several aircraft were used for the test flights. These were a Cessna 172, a Mooney 201, and a Cessna 210. All of these were single engined and IFR certificated. In addition a Cessna 172 and a DC-3 were used. Professor W. M. Hollister of M.I.T. was the test pilot for all the aircraft except the DC-3 which was flown by Dr. R. H. McFarland of Ohio University.

4.1 Flight Tests

The flight test matrix is shown in table 4.1. A total of 32.5 test flight hours were logged. These total hours were broken down into 4 main categories - accuracy, approach, cross country, and antenna tests.

All the tests used the northeast Loran-C chain with a GRI of 9960 microseconds. Transmitters making up this chain are listed in table 4.2. Tests done in the vicinity of Boston used the triad made up of the master and the W and X secondaries.

Flight No.	Duration (hours)	Purpose of Flight	Test Aircraft
1	1.5	Initial test flight.	Cessna 210
2	2.0	Accuracy and approach testing.	Cessna 210
3	3.0	Cross country flight to Hampton, Virginia.	Cessna 210
4	1.5	Approach testing.	Cessna 172
5	2.0	Cross country flight to Princeton, New Jersey.	Cessna 210
6	2.0	Cross country flight returning from Princeton.	Cessna 210
7	3.0	Approach testing.	Cessna 172
8	2.0	Antenna testing and airport survey.	Mooney 201
9	3.0	Cross country flight to Athens, Ohio.	Cessna 310
10	3.0	Cross country flight returning from Athens, Ohio.	Cessna 310
11	1.5	Antenna testing.	Cessna 172
12	2.0	Airport survey.	Mooney 201
13	4.0	Accuracy testing.	Douglas DC-3
14	2.0	Transmitter proximity testing.	Mooney 201

Table 4.1

Flight Test Matrix

Station	Latitude and Longitude	Station Function	Coding Delay & Baseline Length (microsec.)	Radiated Peak Power
Seneca, New York.	42-42-50.60 N 76-49-33.86 W	Master	-------	1.0 MW
Caribou, Maine.	46-48-27.20 N 67-55-37.71 W	W Secondary	11000 2797.20	350 KW
Nantucket, Massachusetts.	41-15-11.93 N 69-58-39.09 W	X Secondary	25000 1969.93	300 KW
Carolina Beach, North Carolina.	34-03-46.04 N 77-54-46.76 W	Y Secondary	39000 3221.65	700 KW
Dana, Indiana.	39-51-07.54 N 87-29-12.14 W	Z Secondary	54000 3162.06	400 KW

Table 4.2

Transmitters for the 9960 Loran-C Chain

Lines of position for this triad are shown in figure 4.1.

4.1.1 Accuracy Tests

Accuracy tests were done in a DC-3 owned by Ohio University. The airborne equipment used is shown in figure 4.2. A 10 foot wire antenna was used which went from the top of the fuselage to the tail. This connected to an antenna coupler inside the fuselage. The coupler was connected to the receiver, which was attached to a test rack in the cabin. Power for the receiver came from a 24 volt electrical supply bus on the aircraft.

The ground reference used was the DABS tracking radar at Lincoln Laboratory. This was used in the beacon tracking mode in conjuction with the transponder on board the aircraft. As stated in reference 14 accuracy for the radar was a range error of 20 ft. (1σ), and a azimuth error of 0.035 deg. (1σ). The primary radar information was the range and azimuth of the aircraft. Other information obtained was the time of fix, altitude, ground speed, and ground track angle.

The nominal flight test profile is shown in figure 4.3. Nine waypoints per circuit were used, these are listed in table 4.3. In all, 4 circuits were flown. Each circuit took about one hour to complete. All circuits were flown in a counterclockwise direction.

During the test flight the aircraft was continually being tracked by the DABS radar. A Loran-C position fix was taken over each waypoint when the pilot judged it to be

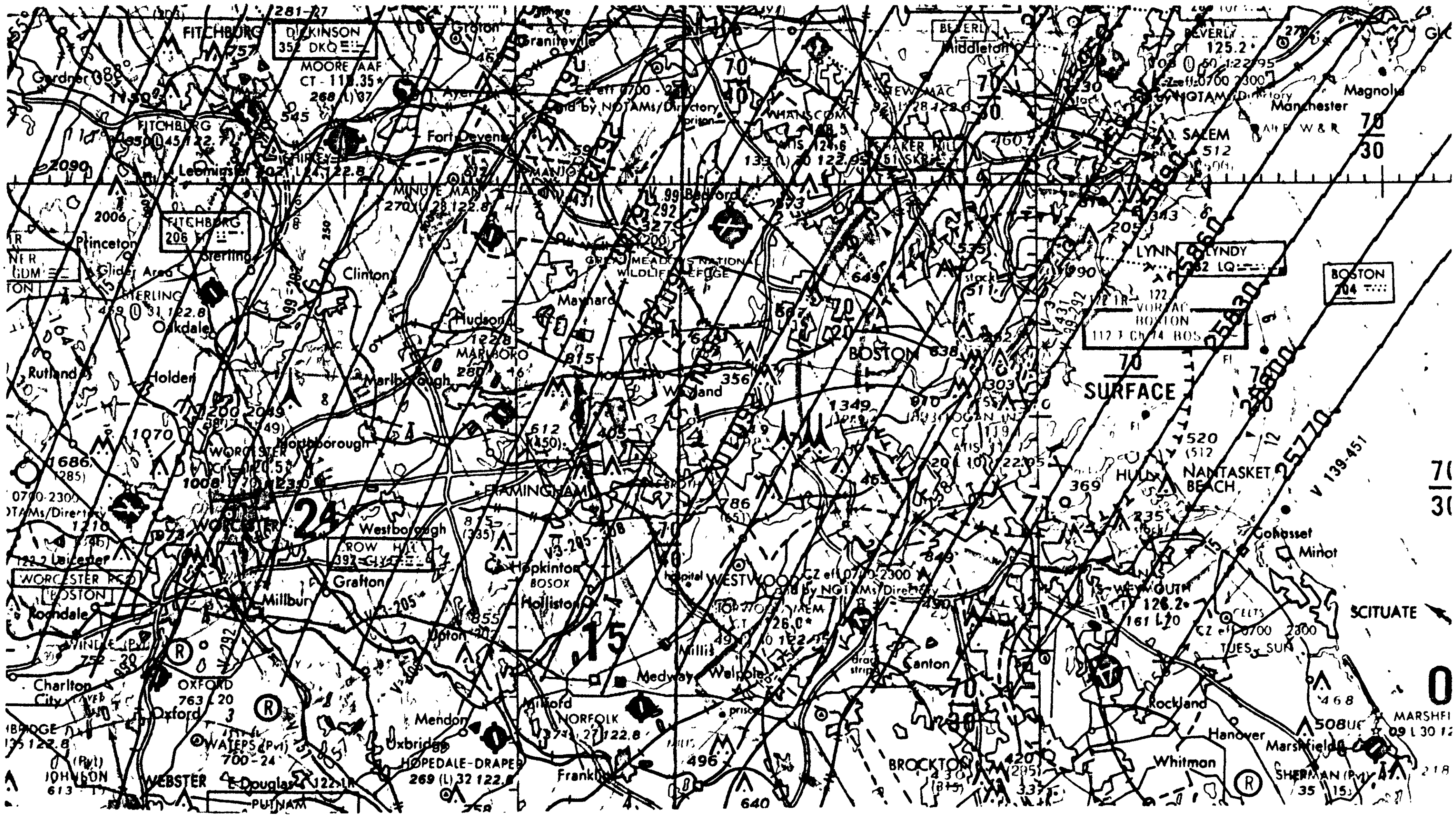


Figure 4.1
Loran-C Lines of Position for the Primary Triad

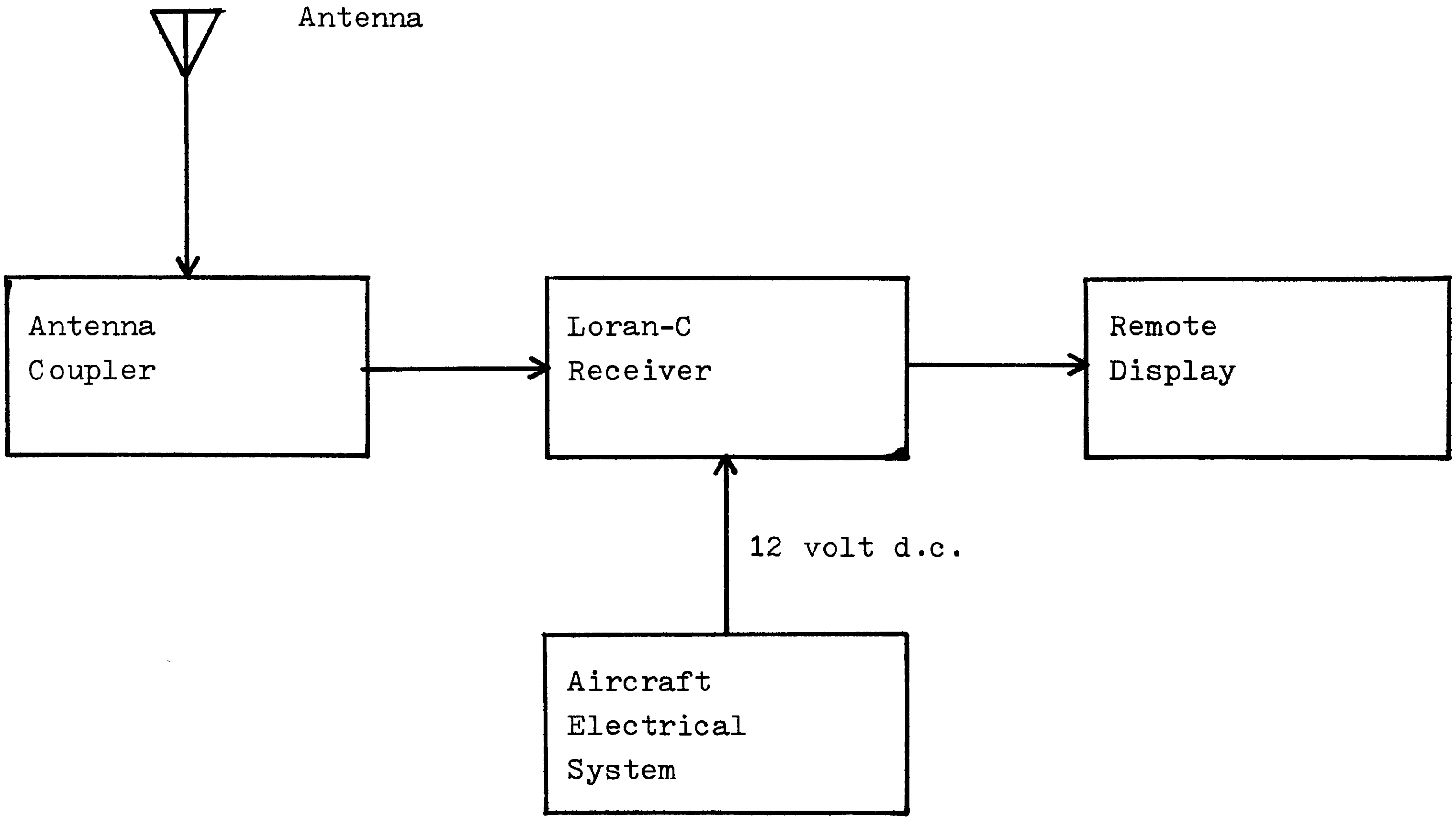


Figure 4.2
Airborne Equipment for Accuracy Tests

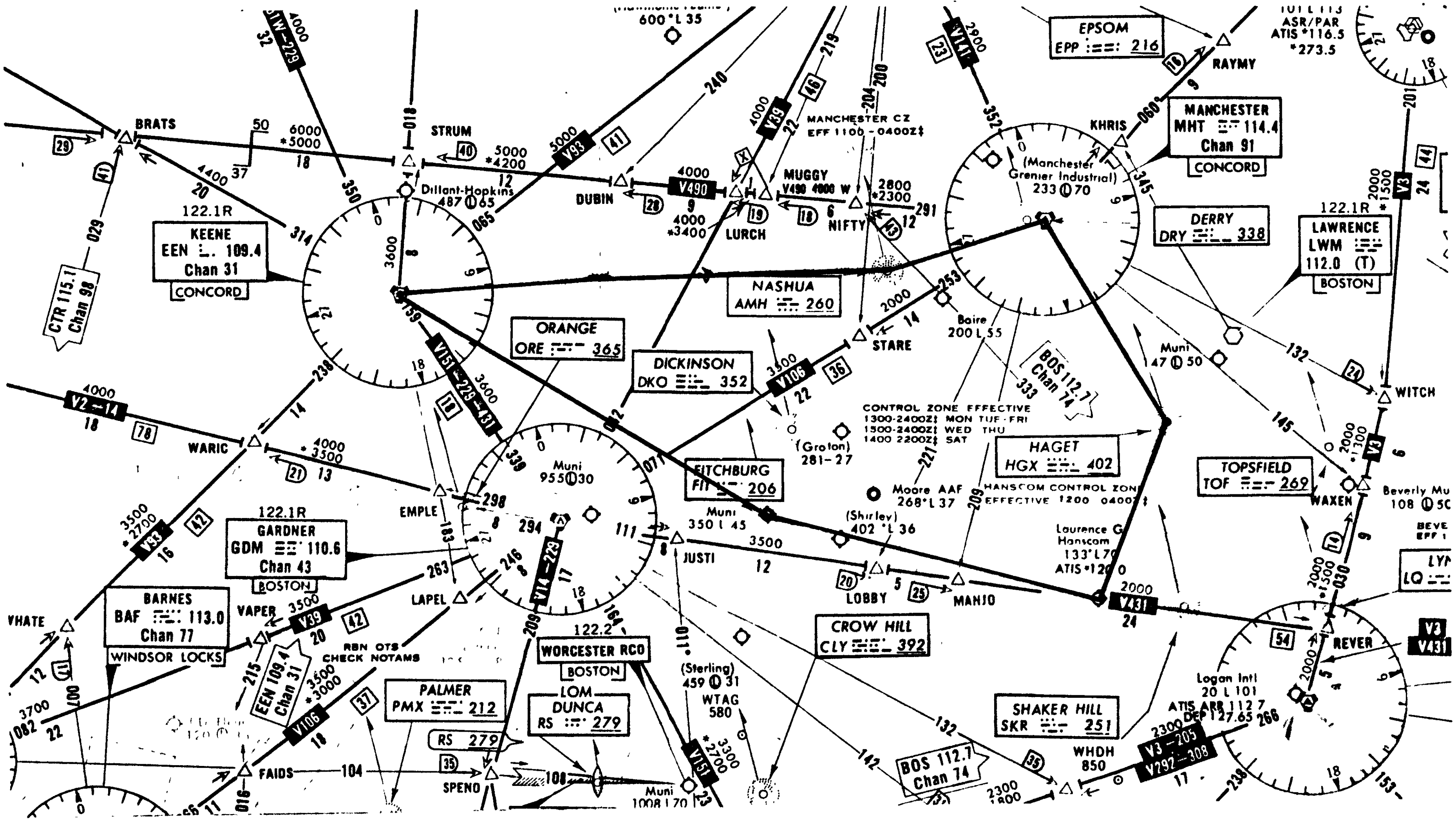


Figure 4.3
Flight Profile for Accuracy Tests

Number	Name	Type	Latitude (deg. N)	Longitude (deg. W)
1	Haget	NDB	42-38-44	71-11-47
2	Manchester	VOR	42-52-06	71-22-12
3	Lowis	NDB	42-49-05	71-35-35
4	Jaffrey	Runway	42-48-00	72-00-00
5	Keene	VOR	42-47-39	72-17-32
6	Fitchburg	NDB	42-33-20	71-45-20
7	Hanscom	Runway	42-28-12	71-17-24

Table 4.3

Waypoints for Accuracy Flight Test

directly under the aircraft. The following information was recorded for each Loran-C position fix :

1. Latitude / Longitude
2. Four time differences and SNR's for all transmitters
3. Time of the Loran-C fix.

The along and cross track equipment errors for the Loran-C receiver were calculated post flight. Here, DABS data as well as Loran-C position data was used. Data reduction procedures are described in detail in appendix B.

4.1.2 Approach Tests

Approach testing was done in the Cessna 172, Cessna 210, and the Mooney 201. The experimental setup was similar to that described in section 4.1.1. A trailing wire antenna was used in the Cessna 172 and Cessna 210, a ADF antenna was used in the Mooney 201. These antennas are described in section 4.3. The triad used was the M-W and M-X triad (master and W and X secondaries) of the northeast Loran-C chain (GRI 9960).

The first part of the approach tests was to find the approach accuracy without using corrections. Three runways were selected, these are listed in table 4.4. Geographic coordinates of the missed approach points (MAP) were taken from the approach plates. Time differences were predicted for these coordinates using a prediction algorithm described in appendix C. Waypoints were entered into the Loran-C receiver in time difference coordinates. This was the reason

Runway Name	No. of Approaches
Boire runway 32	3
Claremont runway 29	1
Manchester runway 06	1

Table 4.4

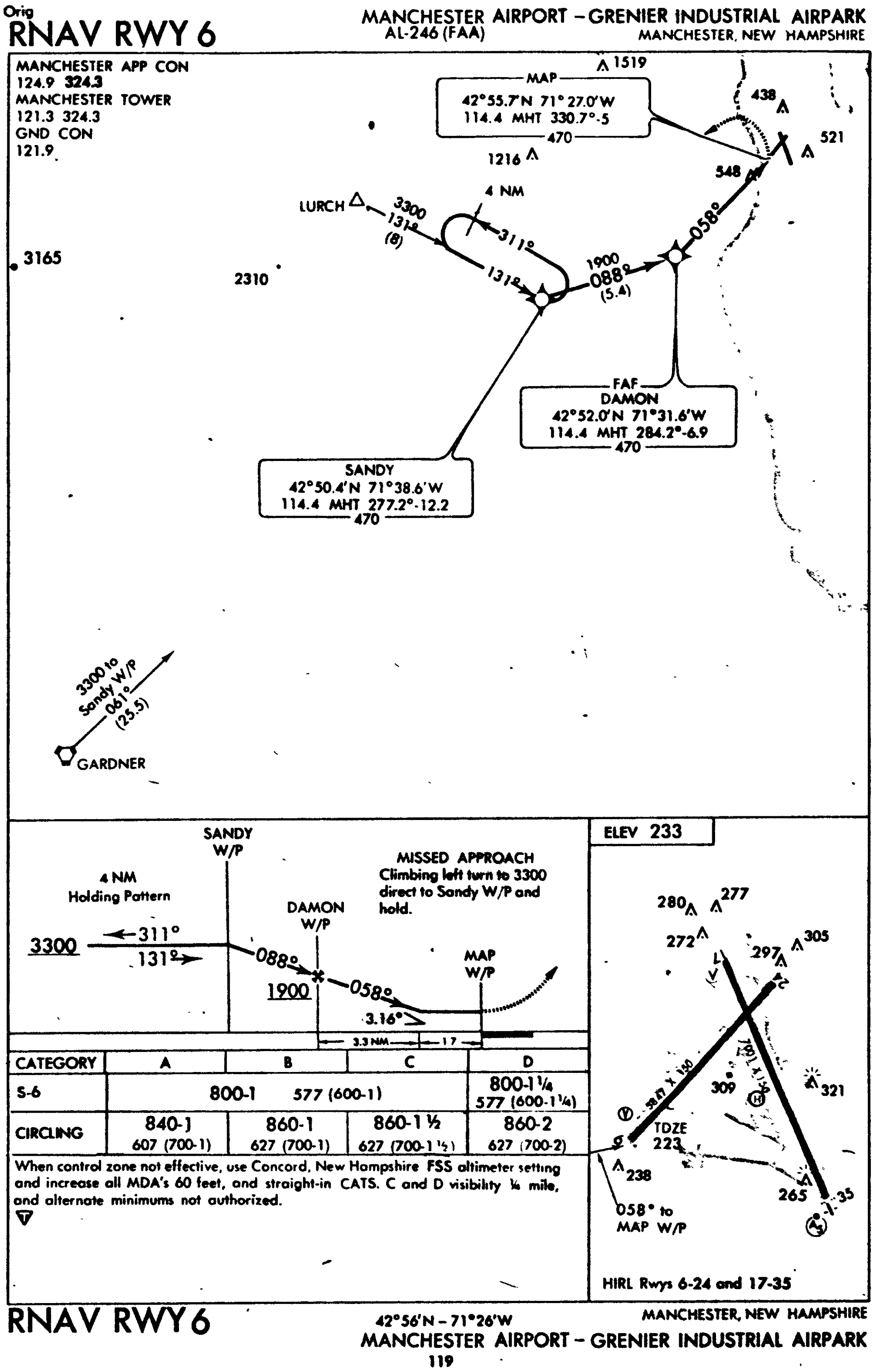
Runways used for First Part of Approach Tests for using the prediction algorithm. Other waypoints were similarly converted to time difference coordinates.

Approaches were made to the three runways using the approach plates shown in figures 4.4, 4.5, 4.6. The Manchester runway 6 and Boire runway 32 approaches were standard RNAV approaches. Figure 4.6 shows the Claremont NDB approach. This was made into a RNAV approach with the end of runway 29 as the MAP and the Claremont NDB as the final approach fix (FAF).

In all, 5 approaches were flown to the 3 runways, as shown in table 4.4. When the Loran-C receiver indicated arrival at the MAP the aircraft was visually located relative to the runway. The difference between actual aircraft position and the MAP was the total system error, which was resolved into along and cross track components.

Approaches were then flown to find approach accuracies when measured coordinates were used. A total of 19 such approaches to 5 runways were made, these are listed in table 4.5. These approaches are shown in figures 4.7, 4.8, 4.9, 4.10, and are referenced in table 4.5. The MAP and FAF for these approaches is listed in table 4.5.

Measurements of the time differences were made by landing at each MAP and holding the aircraft fixed. The aircraft was then flown at low altitude over each FAF and again time differences were measured. Approaches were then flown using these measured coordinates. As before, the aircraft was visually located relative to the runway when



Orig **RNAV RWY 6**

MANCHESTER AIRPORT – GRENIER INDUSTRIAL AIRPARK
AL-246 (FAA)
MANCHESTER, NEW HAMPSHIRE

MANCHESTER APP CON
124.9 324.3
MANCHESTER TOWER
121.3 324.3
GND CON
121.9

MISSED APPROACH
Climbing left turn to 3300 direct to Sandy W/P and hold.

CATEGORY	A	B	C	D
S-6	800-1 577 (600-1)			800-1¼ 577 (600-1¼)
CIRCLING	840-1 607 (700-1)	860-1 627 (700-1)	860-1½ 627 (700-1½)	860-2 627 (700-2)

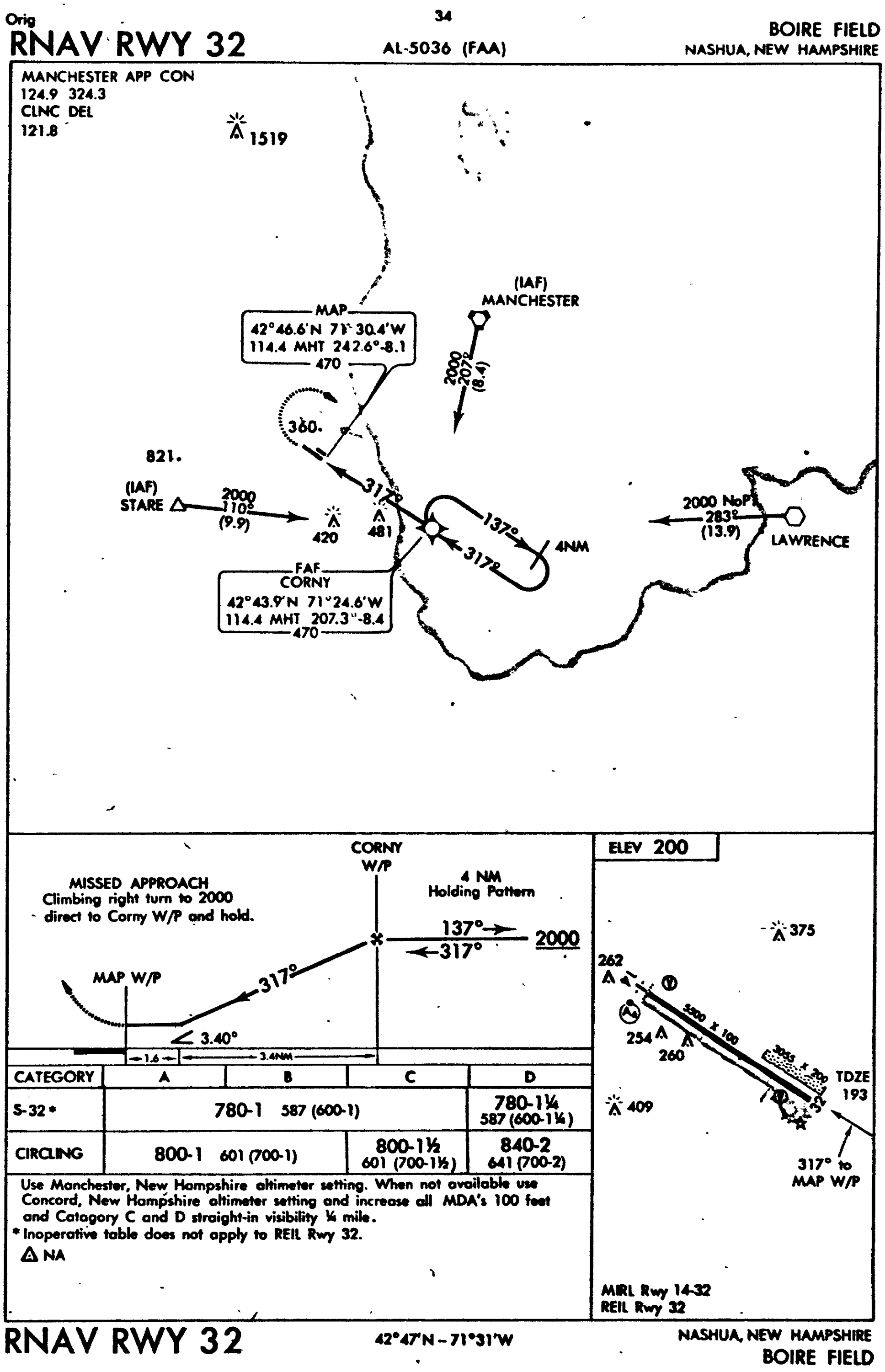
When control zone not effective, use Concord, New Hampshire FSS altimeter setting and increase all MDA's 60 feet, and straight-in CATS. C and D visibility ¼ mile, and alternate minimums not authorized.

ELEV 233

HIRL Rwys 6-24 and 17-35

RNAV RWY 6
42°56'N – 71°26'W
MANCHESTER, NEW HAMPSHIRE
MANCHESTER AIRPORT – GRENIER INDUSTRIAL AIRPARK
119

Figure 4.4
Manchester Runway 06 Approach Plate



CATEGORY	A	B	C	D
S-32*	780-1 587 (600-1)			780-1¼ 587 (600-1¼)
CIRCLING	800-1 601 (700-1)		800-1½ 601 (700-1½)	840-2 641 (700-2)

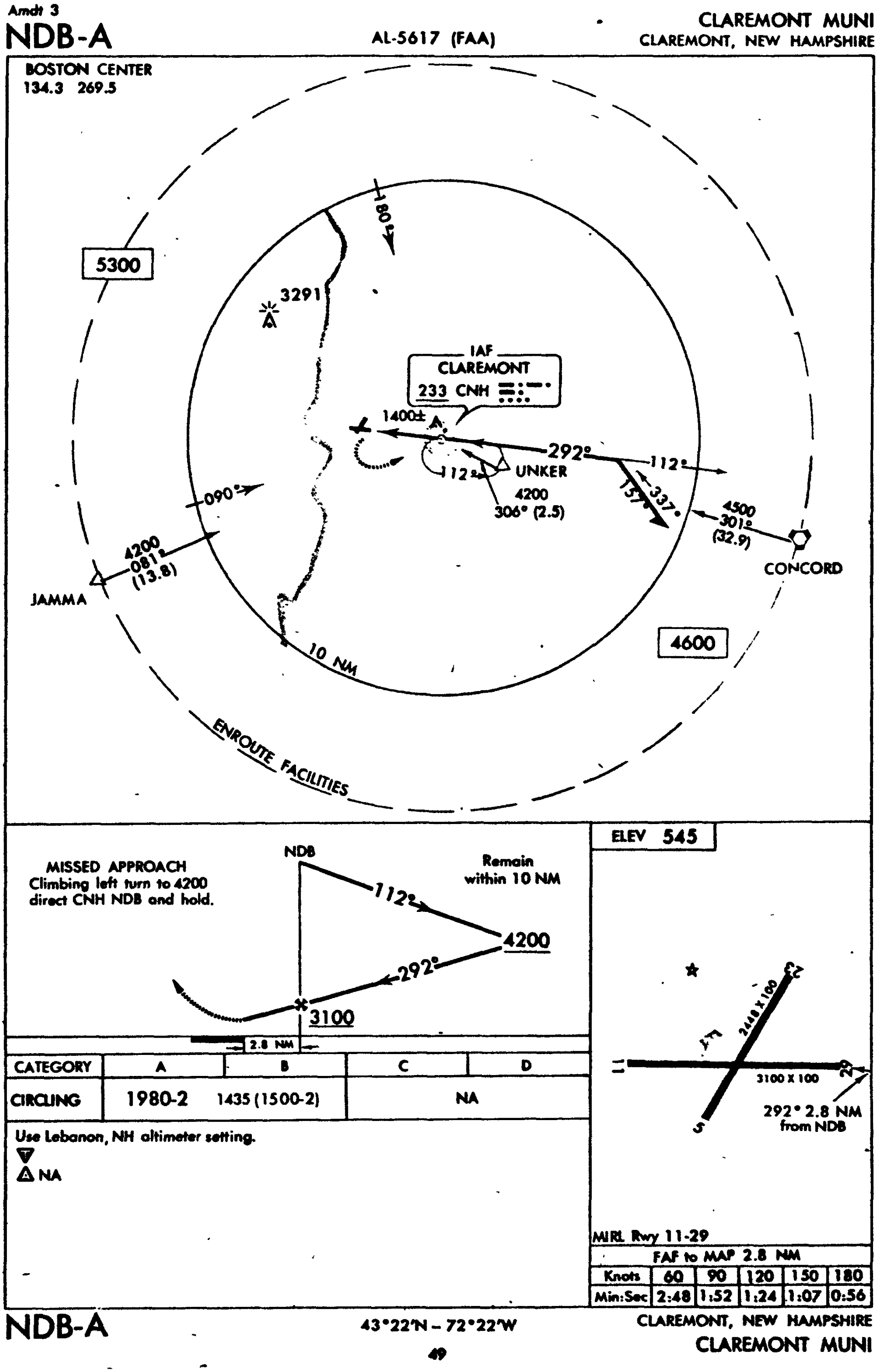
Use Manchester, New Hampshire altimeter setting. When not available use Concord, New Hampshire altimeter setting and increase all MDA's 100 feet and Catagory C and D straight-in visibility ¼ mile.

* Inoperative table does not apply to REIL Rwy 32.

△ NA

Figure 4.5

Boire Runway 32 Approach Plate



CATEGORY	A	B	C	D
CIRCLING	1980-2	1435 (1500-2)	NA	

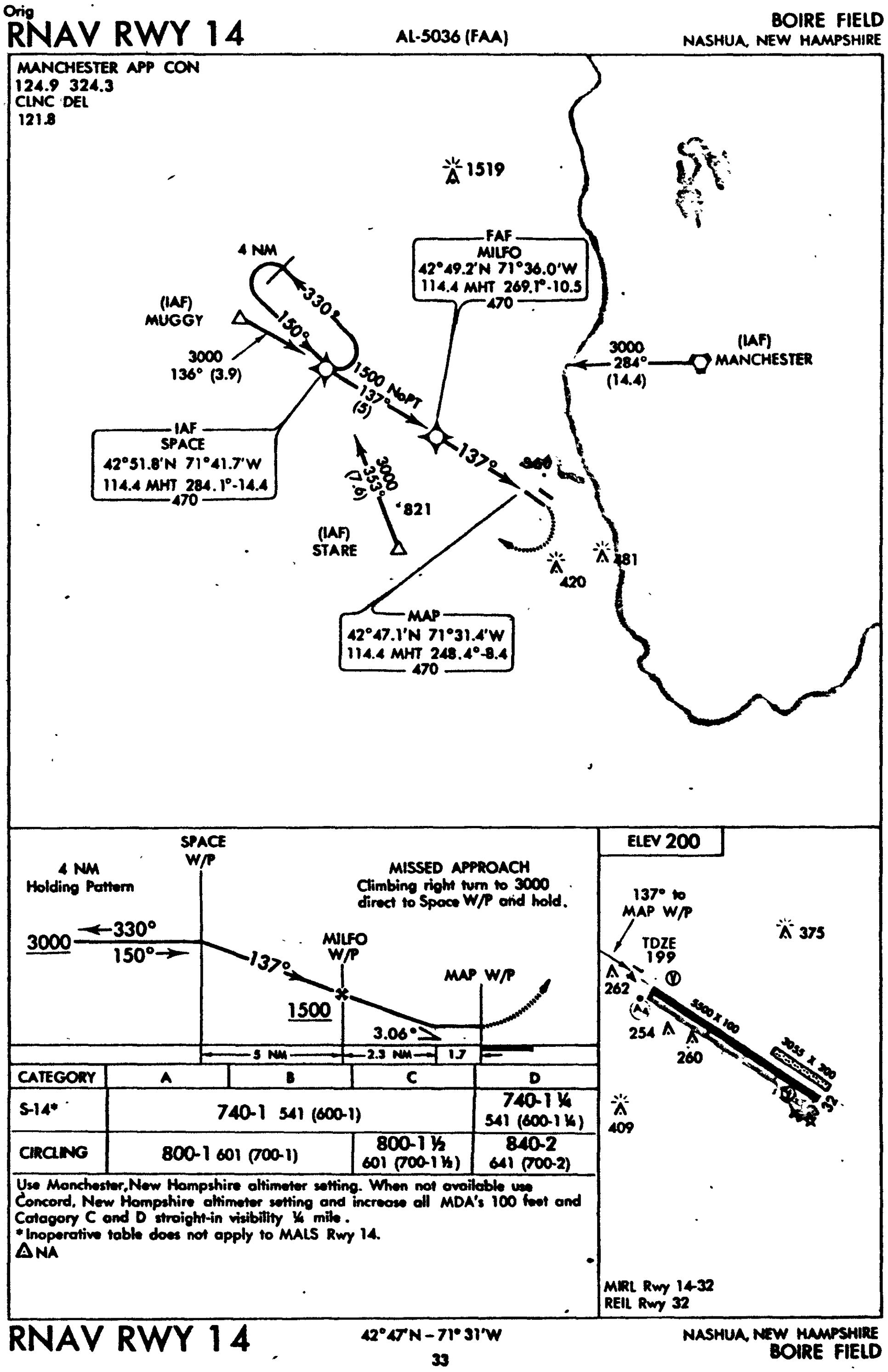
FAF to MAP 2.8 NM

Knots	60	90	120	150	180
Min:Sec	2:48	1:52	1:24	1:07	0:56

Figure 4.6
Claremont Runway 29 Approach Plate

Runway	No. of Approaches	Final Approach Fix
Boire runway 14	2	Milfo waypoint
Boire runway 32	5	Corny waypoint
Lawrence runway 05	8	Haget NDB
Lawrence runway 23	2	Lawrence VOR
Hanscom runway 11	2	Bedds LOM

Table 4.5
Runways used for Second Part of Approach Tests



Orig
RNAV RWY 14
AL-5036 (FAA)
BOIRE FIELD
NASHUA, NEW HAMPSHIRE

MANCHESTER APP CON
124.9 324.3
CLNC DEL
121.8

MISSED APPROACH
Climbing right turn to 3000 direct to Space W/P and hold.

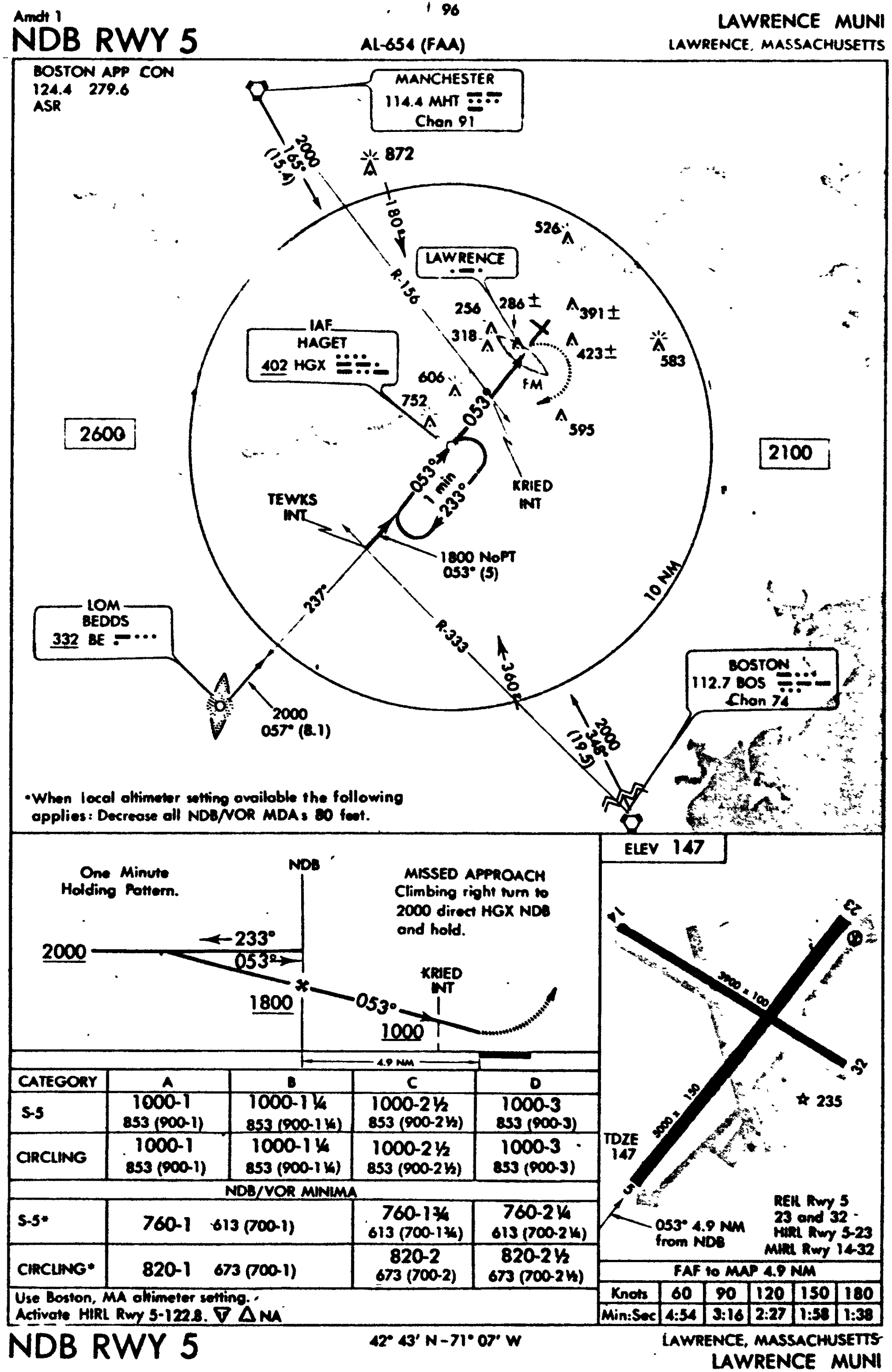
CATEGORY	A	B	C	D
S-14*	740-1 541 (600-1)			740-1 ¼ 541 (600-1 ¼)
CIRCLING	800-1 601 (700-1)		800-1 ½ 601 (700-1 ½)	840-2 641 (700-2)

Use Manchester, New Hampshire altimeter setting. When not available use Concord, New Hampshire altimeter setting and increase all MDA's 100 feet and Catagory C and D straight-in visibility ¼ mile.
* Inoperative table does not apply to MALS Rwy 14.
△NA

MIRL Rwy 14-32
REIL Rwy 32

RNAV RWY 14
42°47'N - 71°31'W
33
NASHUA, NEW HAMPSHIRE
BOIRE FIELD

Figure 4.7
Boire Runway 14 Approach Plate



Amdt 1 · 96

NDB RWY 5

AL-654 (FAA)

LAWRENCE MUNI
LAWRENCE, MASSACHUSETTS

BOSTON APP CON
124.4 279.6
ASR

•When local altimeter setting available the following applies: Decrease all NDB/VOR MDAs 80 feet.

One Minute Holding Pattern.

MISSED APPROACH
Climbing right turn to 2000 direct HGX NDB and hold.

CATEGORY	A	B	C	D
S-5	1000-1 853 (900-1)	1000-1¼ 853 (900-1¼)	1000-2½ 853 (900-2½)	1000-3 853 (900-3)
CIRCLING	1000-1 853 (900-1)	1000-1¼ 853 (900-1¼)	1000-2½ 853 (900-2½)	1000-3 853 (900-3)
NDB/VOR MINIMA				
S-5*	760-1 613 (700-1)		760-1¾ 613 (700-1¾)	760-2¼ 613 (700-2¼)
CIRCLING*	820-1 673 (700-1)		820-2 673 (700-2)	820-2½ 673 (700-2½)

Use Boston, MA altimeter setting.
Activate HIRL Rwy 5-122.8. ▽ △ NA

ELEV 147

TDZE 147

053° 4.9 NM from NDB

REIL Rwy 5 23 and 32
HIRL Rwy 5-23
MIRL Rwy 14-32

FAF to MAP 4.9 NM

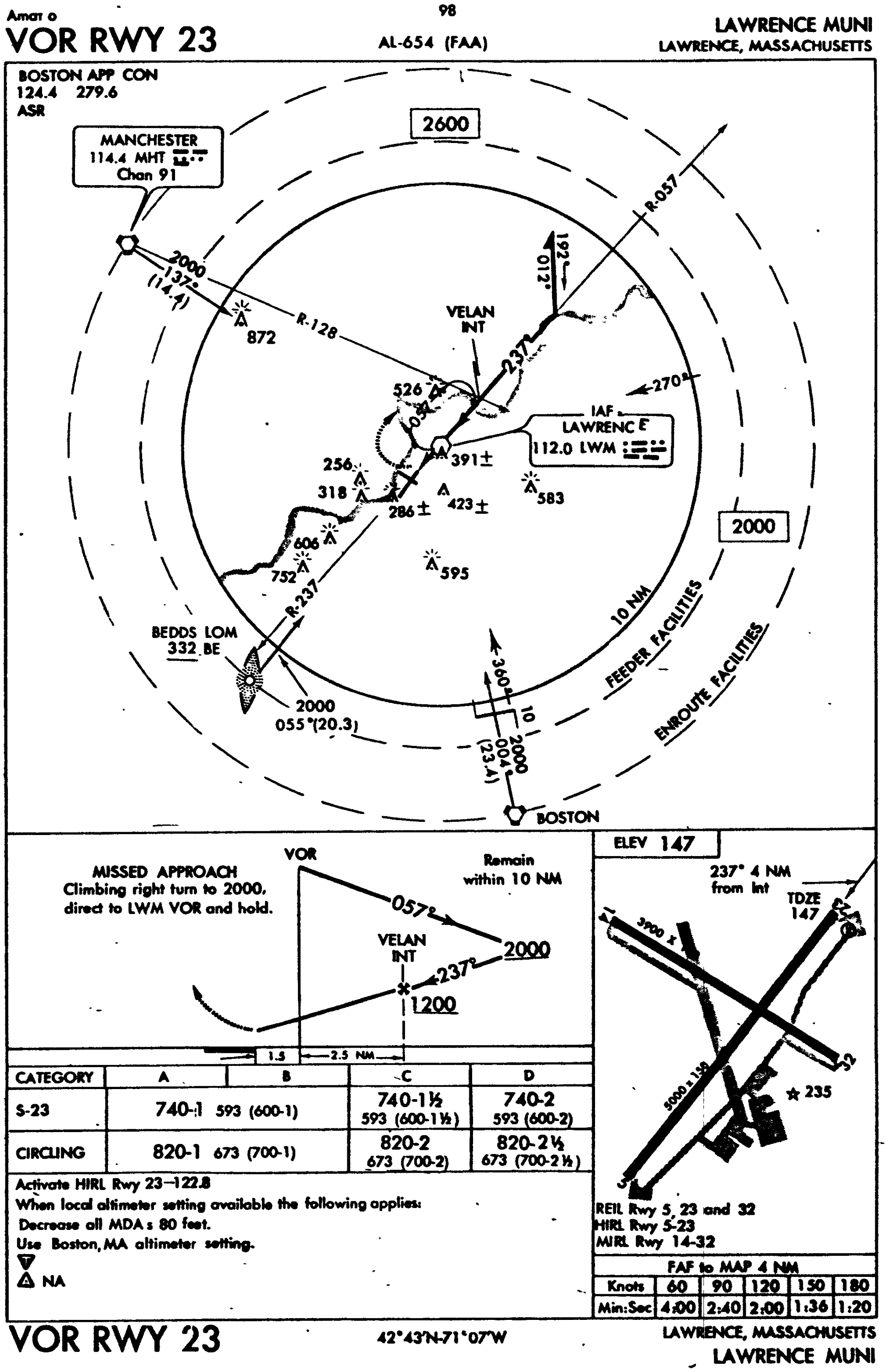
Knots	60	90	120	150	180
Min:Sec	4:54	3:16	2:27	1:58	1:38

NDB RWY 5

42° 43′ N-71° 07′ W

LAWRENCE, MASSACHUSETTS
LAWRENCE MUNI

Figure 4.8
Lawrence Runway 05 Approach Plate



CATEGORY	A	B	C	D
S-23	740-1 593 (600-1)		740-1½ 593 (600-1½)	740-2 593 (600-2)
CIRCLING	820-1 673 (700-1)		820-2 673 (700-2)	820-2½ 673 (700-2½)

Activate HIRL Rwy 23–122.8
When local altimeter setting available the following applies:
Decrease all MDA s 80 feet.
Use Boston, MA altimeter setting.
▼
△ NA

REIL Rwy 5, 23 and 32
HIRL Rwy 5-23
MIRL Rwy 14-32

FAF to MAP 4 NM					
Knots	60	90	120	150	180
Min:Sec	4:00	2:40	2:00	1:36	1:20

VOR RWY 23
42°43'N-71°07'W
LAWRENCE, MASSACHUSETTS
LAWRENCE MUNI

Figure 4.9
Lawrence Runway 23 Approach Plate

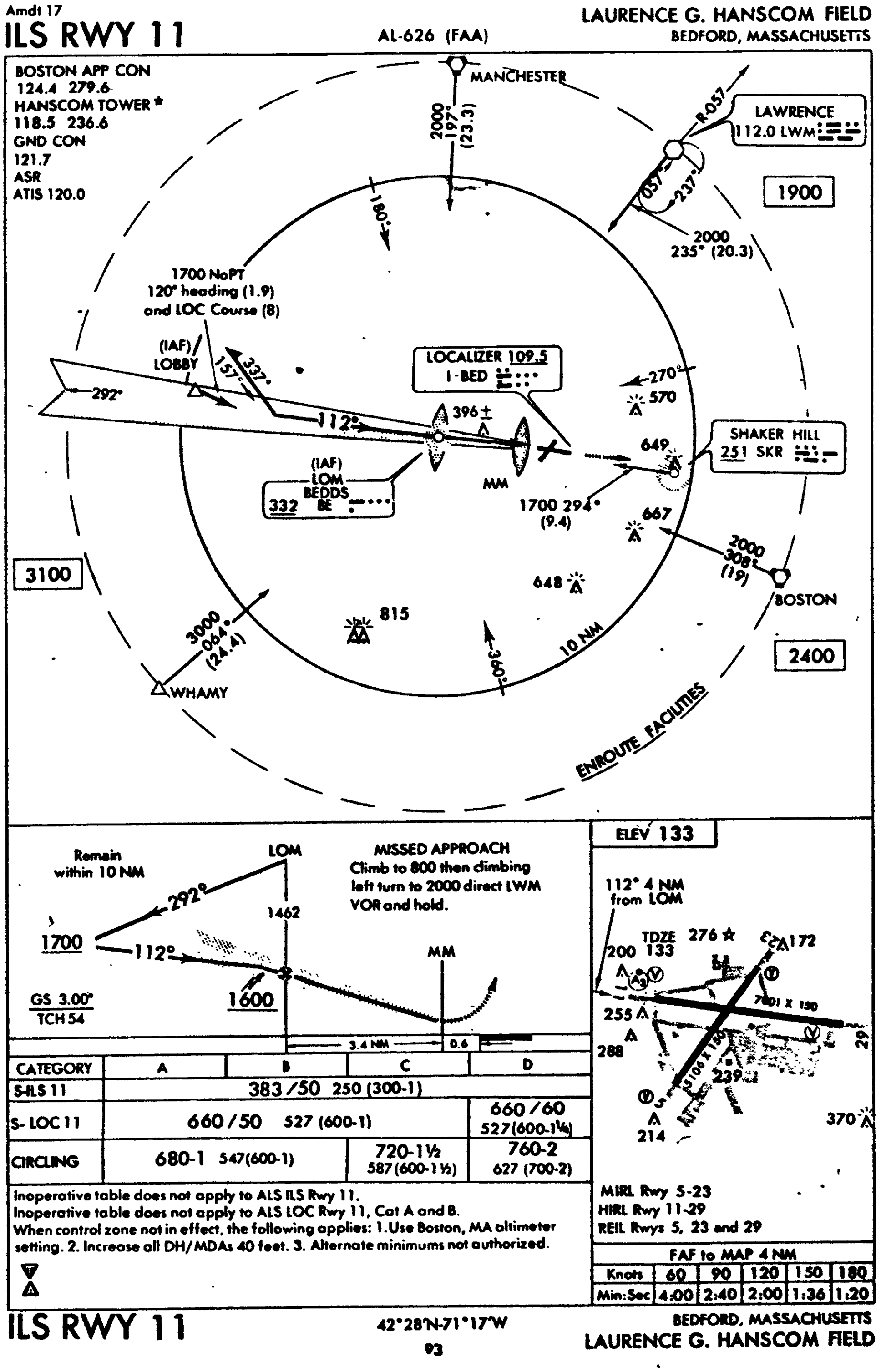


Figure 4.10

Hanscom Runway 11 Approach Plate

the Loran-C receiver indicated arrival at the MAP. This error was the total system error and was resolved into along and cross track components.

4.1.3 Airport Surveys

There were two purposes for carrying out the airport surveys. The first was to study grid stability, the second to evaluate grid warpage. A total of 12 survey points were used for both parts of these tests. These 12 survey points are listed in table 4.6, together with the survey points used in the transmitter proximity tests.

Survey measurements were made by taking the aircraft to each point. The aircraft was then held fixed on the ground at these points to remove velocity induced errors. Time differences at these points were then noted. Seven points were surveyed twice from April to October. The other 5 survey points were surveyed only once.

4.1.4 Cross Country Test Flights

Cross country test flights were carried out to evaluate Loran-C on cross country flights. A total of 3 round trip flights were made from Bedford, Mass. to Hampton, Virginia, Princeton, New Jersey, and Athens, Ohio.

Two test aircraft were used for these tests. The trips to Hampton and Princeton were done in the Cessna 210, the Athens trip was flown in a Cessna 310. Figure 4.2 shows the equipment setup used. For these flights the optional remote

Survey Point	Latitude (deg. N)	Longitude (deg. W)
Lawrence runway 05	42-42-36	71-07-48
Lawrence runway 23	42-43-18	71-07-12
Lawrence runway 14	42-43-12	71-07-54
Lawrence runway 32	42-42-54	71-07-12
Boire runway 14	42-47-06	71-31-24
Boire runway 32	42-46-36	71-30-24
Hanscom runway intersection	42-28-13	71-17-25
Hanscom ramp	42-27-56	71-17-58
Fitchburg runway 02	42-33-00	71-45-42
Fitchburg runway 20	42-33-36	71-45-36
Fitchburg runway 14	42-33-30	71-46-00
Fitchburg runway 32	42-33-00	71-45-12
Nantucket runway 06	41-14-48	70-04-24
Nantucket runway 24	41-15-36	70-03-24
Nantucket runway 15	41-15-30	70-03-42
Nantucket runway 33	41-15-06	70-03-00

Table 4.6

Airport Survey Points

display was used. A trailing wire antenna was used in the Cessna 210, an ADF antenna below the fuselage was used in the Cessna 310.

For each trip a flight plan was organized with several alternative routes. Navigation aids to be used on these routes were listed. The latitude and longitude of these navaids were obtained from the IFR supplement. Time differences were then calculated for these locations using the algorithm of appendix C.

Loran-C was used as the primary navigation device under VFR (Visual Flight Rules) conditions. Cross checks of Loran-C position information were made with other navaids. Detailed logs were kept which recorded any waypoint input blunders, receiver malfunctions, signal loss, or P-static interference. Qualitative records were also kept of the usefulness of Loran-C as a source of navigation information.

4.1.5 <u>Flight Logs</u>

For all the test flights detailed logs were kept to document performance of the Loran-C receiver. Pilot error, receiver malfunction, signal loss, interference signals, and other factors affecting receiver performance were noted. The aircraft used, time and duration of the flight, the weather, and test pilots were other factors which were also noted.

4.1.6 <u>Transmitter Proximity Tests</u>

As discussed in section 2.1.3.2 there is concern about the posssble degradation of Loran-C receiver performance when operating close to a Loran-C transmitter. A series of tests was carried out to investigate this. The Caribou, Maine and Nantucket, Mass. secondaries were used in these tests.

Transmitter proximity testing was done at the Nantucket secondary transmitter. There were two types of tests carried out. The first part was to evaluate Loran-C accuracy during flight. Here, two landmarks were chosen. One was the Loran-C transmitter and the other was the Nantucket consolant transmitter. The consolant transmitter was located approximately 8 n.m. to the west of the Loran-C transmitter.

The aircraft was flown over each landmark 4 times at magnetic headings of 000, 090, 180, and 270. Loran-C receiver coordinates were measured over each landmark. These coordinates were compared to the published coordinates for each landmark.

Ground accuracy tests were carried out at Nantucket airport. Here, the 4 survey points which were used are listed in table 4.6. The aircraft was taxied to these points and the Loran-C receiver coordinates were recorded.

4.2 Ground Tests

The aim of the ground tests was to evaluate the long term grid stability. This was done by measuring time differences at the same point from April to October.

These tests were conducted at a laboratory at M.I.T. The approximate latitude and longitude was 42-21 N, 71-05 W.

A 6 foot vertical whip antenna was connected to an antenna coupler. This coupler was attached to a 3 foot mast anchored to the roof. There was a coaxial cable connecting the coupler to the receiver in the laboratory. Power for the receiver was supplied from a d.c. power supply.

As before, the northeast Loran-C chain (GRI 9960) was used for these tests. Time difference data was collected in the morning. All 4 time differences were averaged over 10 measurements and this average was recorded. SNR's for the received signals were also recorded. Note was made of the weather, including such factors as visibility, precipitation, and temperature.

4.3 Antenna Tests

Three types of antennas were evaluated to find which were suitable for Loran-C use in aircraft. These antennas were the trailing wire, vertical whip, and ADF antennas. The trailing wire and vertical whip antennas were tested in the Cessna 172, The ADF antenna was tested in the Mooney 201.

A 20 foot length of #18 insulated wire was used as the trailing wire antenna. The antenna was kept in tension during flight with a funnel attached to its end. Strain relief was provided at the aircraft door, through which the antenna entered the cabin. This antenna was only used during flight. Once at cruise the antenna was deployed by opening the cabin door and slowly feeding out the antenna. Once deployed the antenna went under the tail, away from the fuselage.

The vertical whip antenna was a 3 foot long stainless steel whip antenna. This was mounted vertically to a threaded base bolted to the aircraft. The base was located at the fuselage, just behind the passenger cabin. A wire connected the base to the coupler. The coupler was connected to the Loran-C receiver with a coaxial cable.

A 10 foot long insulated wire was used as the ADF antenna. One end of the wire was attached to the top of the tail. The other end was attached to the VHF antenna on the top of the cockpit. From here, the wire led into the passenger compartment through the baggage door. Care was taken to insulate the wire from the aircraft skin and to minimize capacitance between the antenna and the fuselage.

Test equipment used here was as shown in figure 4.2. All antennas were connected to the same coupler. The coupler was connected to the Loran-C receiver. Power for the receiver came from the aircraft electrical system.

4.3.1 Ground Tests

First, a ground test of the antennas was done. Ground tests were done at Hanscom field. The vertical whip and ADF antennas were evaluated on the ground. As stated earlier, the trailing wire antenna was only tested in flight.

At first, ground tests were done with the aircraft engine and avionics turned off. The receiver was turned on and allowed to settle into lock. Then, SNR's for each transmitter

(master and 4 secondaries) were recorded. Also, the relative signal strength was noted.

With the aircraft still on the ground the engine and avionics were turned on. The receiver was again allowed to stabilize. Signal strength and SNR's for the transmitters were recorded as before.

4.3.2 Flight Tests

All 3 antenna types were evaluated in flight. Flight tests were conducted in the vicinity of Hanscom field.

The aircraft was first flown to cruising altitude. If needed, the antenna was deployed (trailing wire antenna only). The receiver was turned on and allowed to stabilize. Then, SNR's for all the transmitters and the relative signal strength were measured as on the ground.

5.0 RESULTS

5.1 Flight Test Results

This section discusses the results of the various flight tests. These tests, which are described in section 4, were carried out in accordance with the detailed technical objectives of section 3.0.

5.1.1 Accuracy Test Results

Data analysis procedures used to process the accuracy test data are described in appendix B. Definitions of and sign conventions for the various errors are described there. Accuracy test results are based on 25 data points.

Figure 5.1 shows a scatter plot of the north-south and east-west Loran-C errors. Statistical parameters for these errors are also given. A positive north-south error means the Loran-C fix was north of the actual position, a positive east-west error means that the Loran-C fix was east of the actual location.

Along and cross track error distributions are given in figure 5.2. The cross track flight technical error distribution is given in figure 5.3. A positive along track error means the Loran-C fix was in front of the aircraft, a positive cross track error means the Loran-C fix was to the right of the aircraft. Positive cross track flight technical error means the waypoint was to the right of the aircraft ground track. Appendix B defines these errors in more detail.

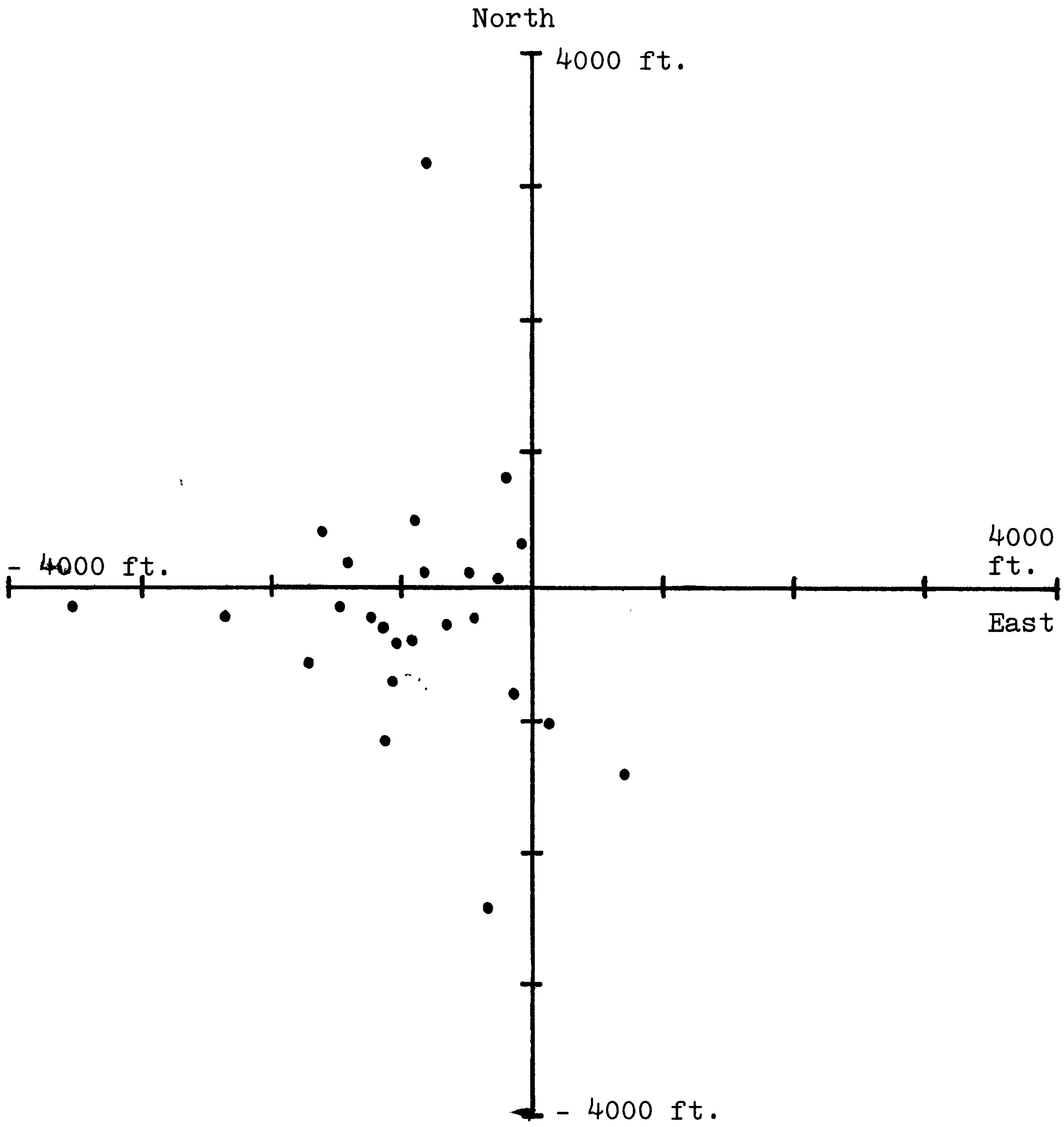


Figure 5.1
Loran-C Error Plot

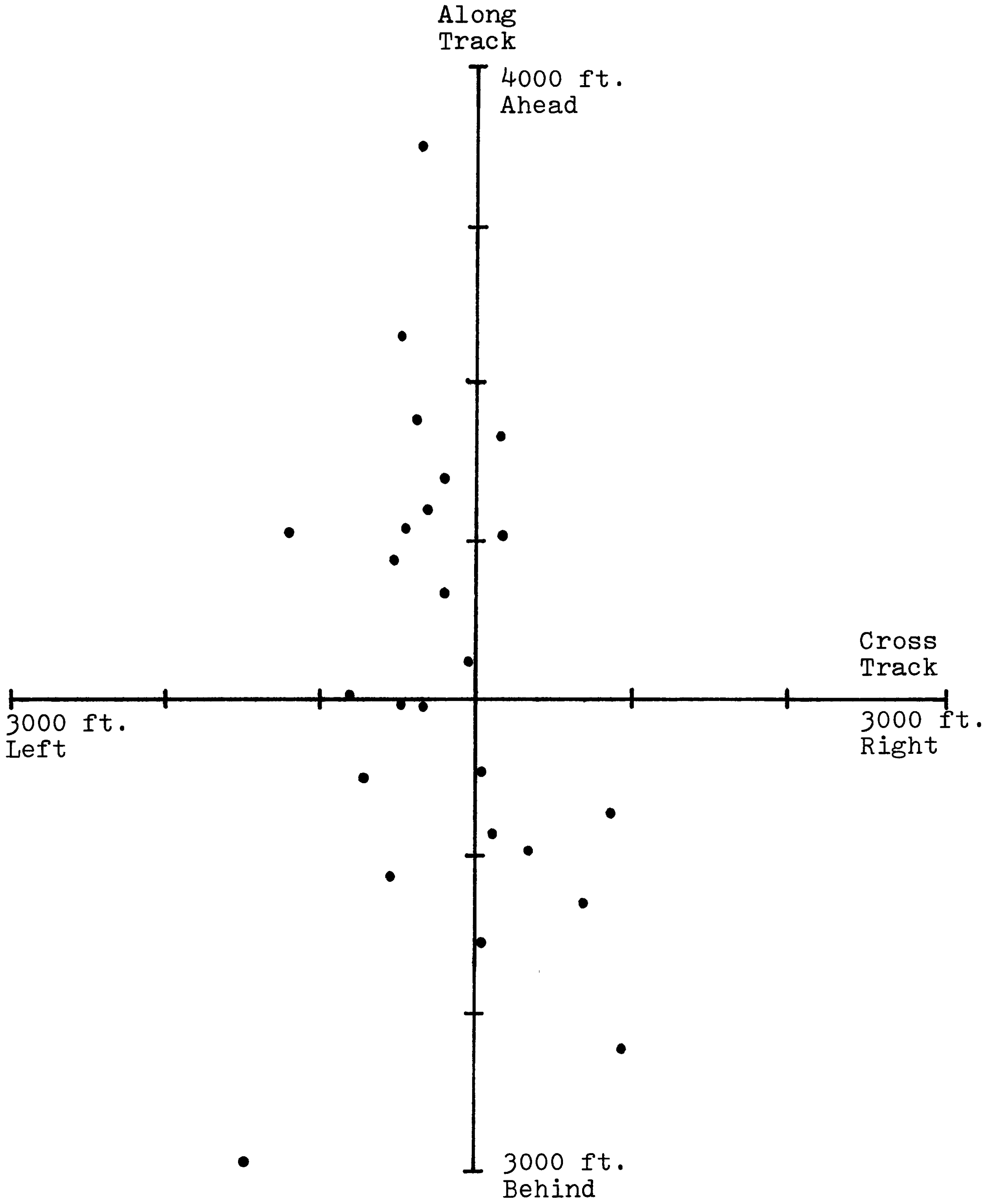


Figure 5.2
Along and Cross Track Error Plot

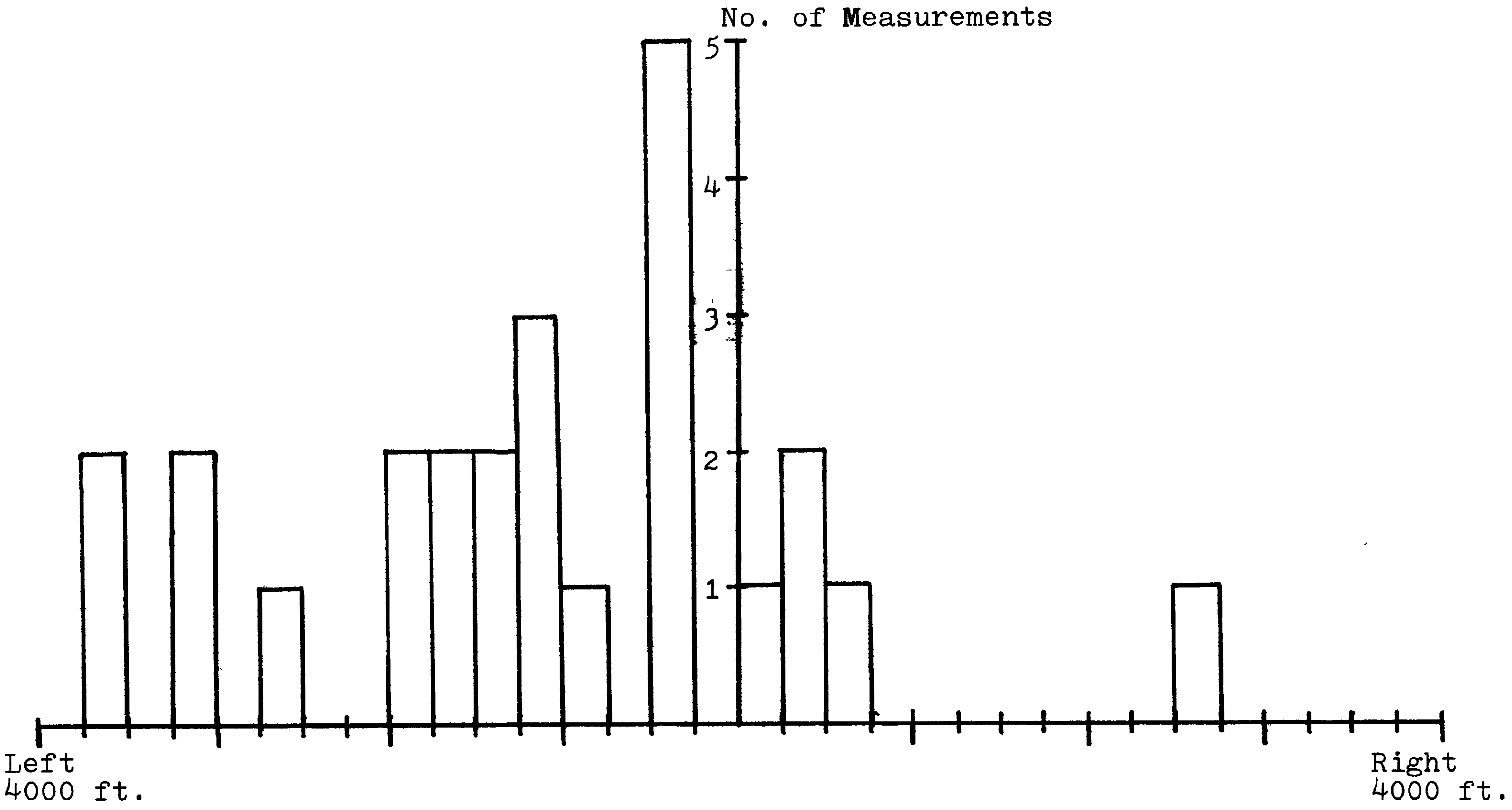


Figure 5.3
Cross Track Flight Technical Error Plot

Table 5.1 lists the statistics for all the errors. These can be compared to the AC 90-45A requirements given in table 3.1. The equipment error in the along track direction was within the requirement for all phases of flight. This was also true for the cross track direction. Loran-C equipment accuracy was independent of the phase of flight (enroute, terminal, or approach) since the same equipment and signals were used for all these phases. It is also seen that the cross track flight technical error was less than that used in AC 90-45A for enroute flight.

All the measured Loran-C errors include the errors of the DABS tracking radar. The stated accuracy of the radar (Ref. 14) is a range error of 20 ft. (1 σ) and a azimuth error of 0.035 deg. (1 σ).

5.1.2 Approach Accuracy Tests

Approach tests were done in two phases as described in section 4.1.2. The first phase was done using uncorrected coordinates. Here, 5 approaches to 3 runways were made. Along and cross track errors are shown in figure 5.4. Sign conventions for these errors are shown there. It should be noted that the cross track error includes any flight technical error.

In the second phase of the approach tests measured coordinates were used. A total of 19 approaches to 5 runways were flown. Along and cross track errors are shown in figure 5.5. The sign convention is the same as before. Here, the

	Loran-C Equipment Error		Cross Track Flight Technical Error
	Along Track	Cross Track	
Mean	-.01 Nm.	.03 Nm.	-.18 Nm.
Standard Deviation	.13 Nm.	.09 Nm.	.24 Nm.
95 % limits (mean ± 2σ)	-.27 Nm. .25 Nm.	-.16 Nm. .22 Nm.	-.66 Nm. .30 Nm.

Table 5.1
Error Statistics for Flight Test Results

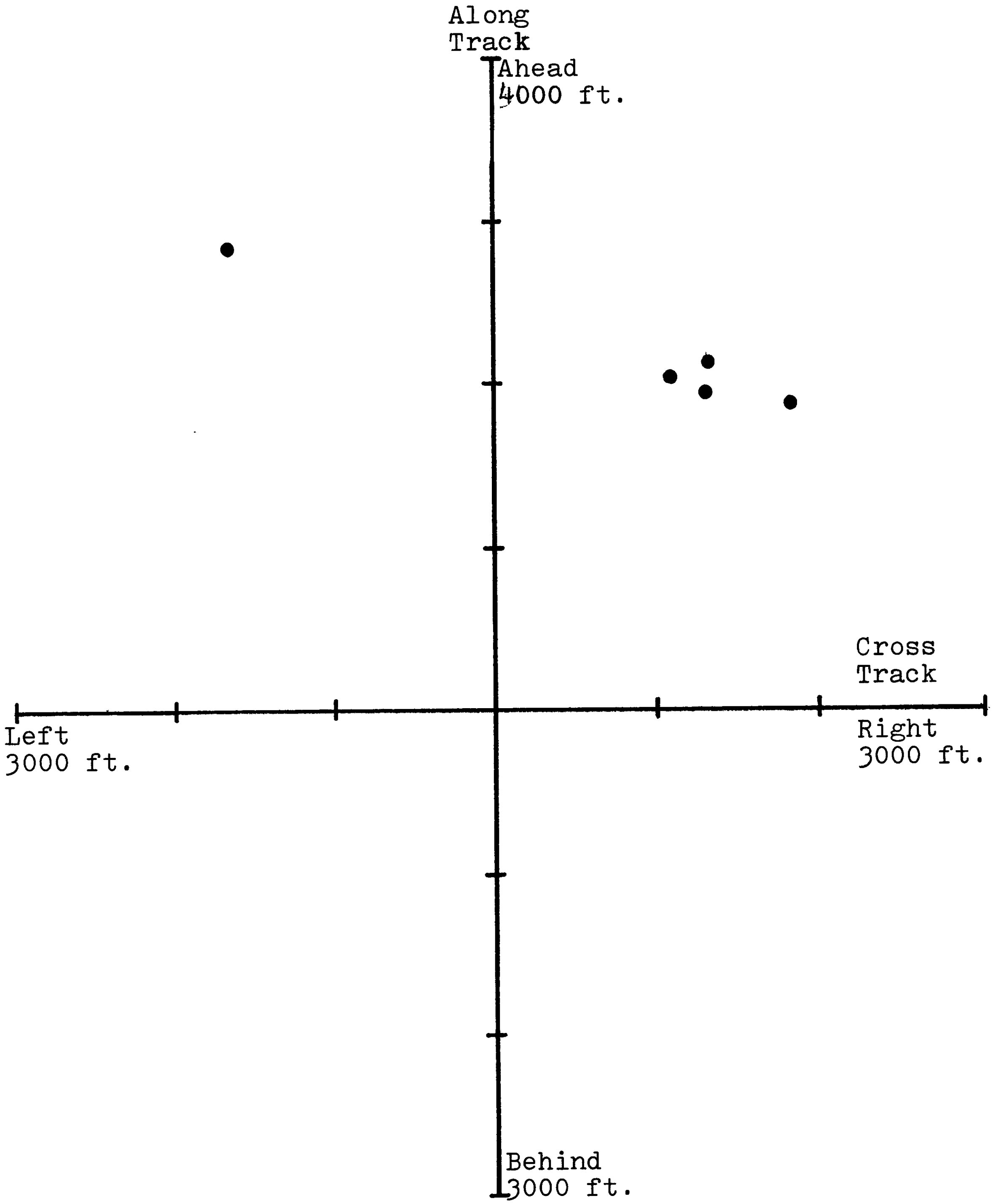


Figure 5.4

Along and Cross Track Errors with Uncorrected Coordinates

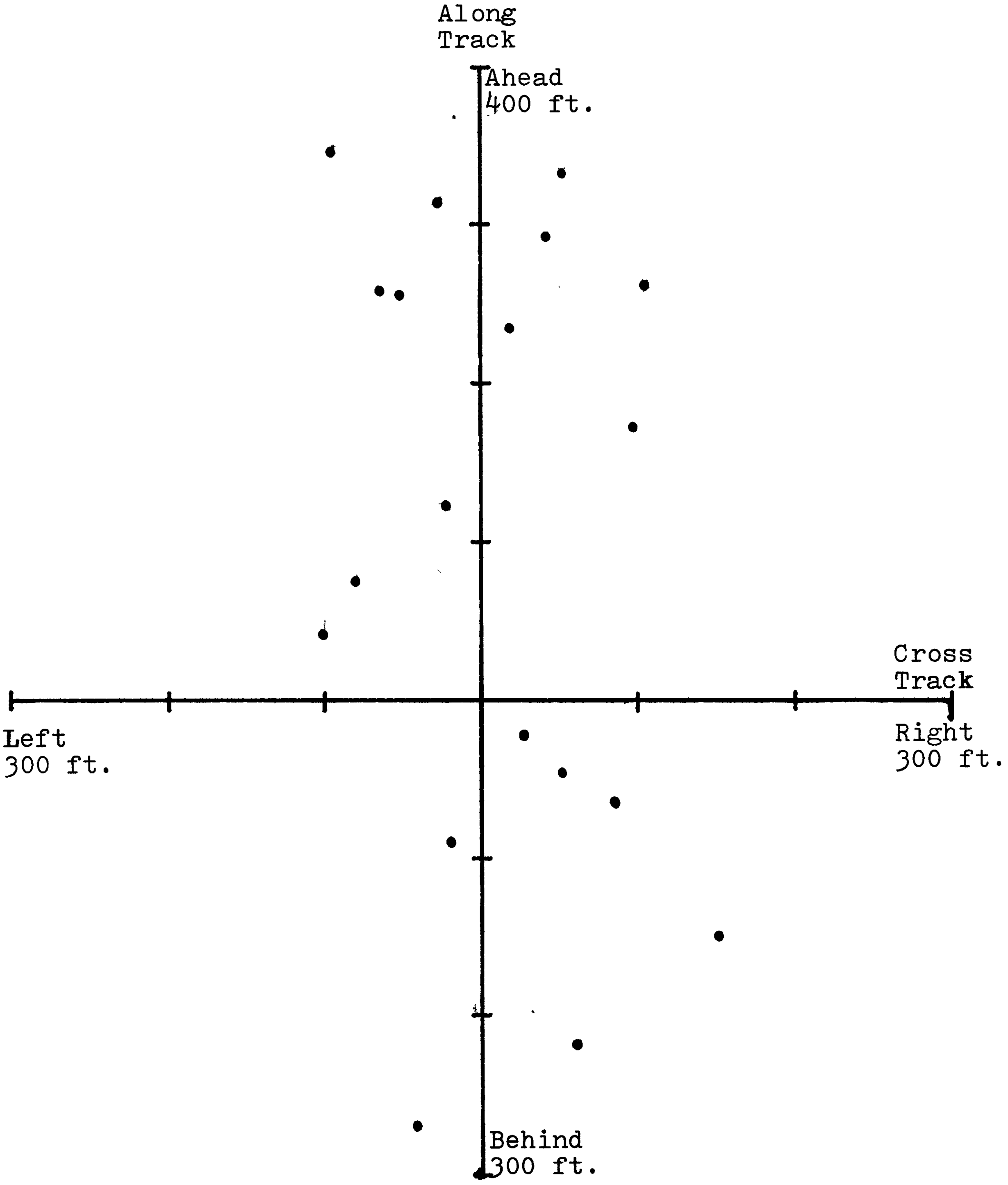


Figure 5.5
Along and Cross Track Errors with Corrected Coordinates

cross track error also includes any flight technical error.

Although only a few data points were used for the uncorrected approaches, it is seen that they generally satisfy AC 90-45A requirements. All the approaches were within the cross track error requirement. All but one approach met the along track requirement. This one approach fell just outside the required along track requirement.

A significant improvement in accuracy was seen when corrected coordinates were used. Here, both the along and cross track errors were well within AC 90-45A requirements. These tests showed that the repeatability of Loran-C was very good. With corrected coordinates, the accuracy of approaches was similar to ILS localizer approaches.

5.1.3 Airport Survey Results

Grid stability was evaluated in the first part of the airport survey. Here, 7 survey points were used. Time differences were measured at each point twice, once in April and once in October. Table 5.2 shows the results of these surveys. The time difference grid was found to be stable over this period. The maximum peak-to-peak time difference variation was 0.3 microsecond. These results are consistent with ground test results shown in section 5.2.

The next part of the survey was to test grid warpage. Here, 12 survey points were used which are listed in table 4.6. Three time differences were measured at each point. The fourth time difference was not used because of poor SNR for

Survey Point	Date	TD 1 (μsec.)	TD 2 (μsec.)	TD 3 (μsec.)
Hanscom runway intersection	4/19/80	14116.1	26028.2	44366.7
	10/01/80	14116.2	26028.0	44366.7
Boire runway 14 MAP	4/19/80	14116.1	26229.4	44499.9
	10/01/80	14116.0	26229.4	44500.0
Boire runway 32 MAP	4/19/80	14111.6	26219.7	44495.2
	10/01/80	14111.7	26219.6	44495.4
Lawrence runway 05 MAP	4/19/80	13978.4	26036.9	44426.9
	10/01/80	13978.3	26036.9	44426.8
Lawrence runway 23 MAP	4/19/80	13970.4	26035.9	44429.0
	10/01/80	13970.4	26035.7	44429.1
Lawrence runway 14 MAP	4/19/80	13975.2	26040.7	44429.5
	10/01/80	13975.1	26040.6	44429.5
Lawrence runway 32 MAP	4/19/80	13972.4	26034.0	44427.0
	10/01/80	13972.3	26033.8	44426.9

Table 5.2
Airport Survey Results

the fourth secondary transmitter. Latitude and longitude coordinates for each survey point were obtained from airport runway maps. Results for this part of the airport survey tests are given in table 5.3.

Next, time differences were calculated for the survey points using the algorithm described in appendix C. Corrections were calculated as the difference between predicted and actual time differences. These corrections are listed in table 5.4. The mean and standard deviation of the corrections for every airport was calculated. These statistics are listed in table 5.5.

Corrections were due to several factors. The first was the secondary phase of the signals from the transmitters. This secondary phase was due to propagation anomalies such as irregular terrain, and varying dielectric constant of the ground. The second factor was the geographic uncertainity of the survey points. There were several parts of this uncertainity. First was the survey inaccuracy and roundoff (to 0.1 arc minute) of the coordinates of the airport reference point. The second source of geographic uncertainity was the error in relating survey points on the airport to the airport reference point.

The mean correction for an airport reflected the secondary phase uncertainity, the reference point survey inaccuracy, and coordinate roundoff. Standard deviation of the correction at an airport reflected map reading error and jitter in the receiver (0.1 microsecond rms.). It is

Survey Point	Latitude (deg. N)	Longitude (deg. W)	Measured (microsec.)			Predicted (microsec.)		
			TD1	TD2	TD3	TD1	TD2	TD3
Lawrence rwy. 05	42-42-36	71-07-48	13978.3	26036.9	44426.8	13979.2	26040.0	44425.9
Lawrence rwy. 23	42-43-18	71-07-12	13970.4	26035.7	44429.1	13971.5	26039.8	44428.4
Lawrence rwy. 14	42-43-12	71-07-54	13975.9	26040.6	44429.5	13976.7	26044.0	44429.3
Lawrence rwy. 32	42-42-54	71-07-12	13972.3	26033.8	44426.9	13973.6	26037.6	44426.3
Boire rwy. 14	42-47-06	71-31-24	14116.1	26229.4	44500.0	14116.2	26231.7	44498.9
Boire rwy. 32	42-46-36	71-30-24	14111.7	26219.6	44495.4	14113.0	26220.9	44493.1
Hanscom rwy. int.	42-28-13	71-17-25	14116.1	26028.2	44366.7	14116.5	26030.7	44365.9
Hanscom ramp	42-27-56	71-17-58	14121.3	26030.6	44366.0	14121.5	26033.3	44365.3
Fitchburg rwy. 02	42-33-00	71-45-42	14285.8	26268.8	44452.6	14285.9	26271.7	44451.9
Fitchburg rwy. 20	42-33-36	71-45-36	14282.3	26270.7	44455.9	14282.3	26273.8	44455.1
Fitchburg rwy. 14	42-33-30	71-46-00	14285.5	26273.6	44456.3	14285.6	26276.5	44455.4
Fitchburg rwy. 32	42-33-00	71-45-12	14282.6	26265.5	44451.7	14282.5	26267.8	44450.8

Table 5.3

Survey Point Test Results

Survey Point	Correction (microsec.)		
	TD1	TD2	TD3
Lawrence rwy. 05 MAP	0.9	3.1	-0.9
Lawrence rwy. 23 MAP	1.1	4.1	-0.7
Lawrence rwy. 14 MAP	0.8	3.4	-0.2
Lawrence rwy. 32 MAP	1.3	4.8	-0.6
Boire rwy. 14 MAP	0.1	2.3	-1.1
Boire rwy. 32 MAP	1.3	1.3	-2.3
Hanscom rwy. intersection	0.4	2.5	-0.8
Hanscom ramp	0.2	2.7	-0.7
Fitchburg rwy. 02 MAP	0.1	2.9	-0.7
Fitchburg rwy. 20 MAP	0.0	3.1	-0.8
Fitchburg rwy. 14 MAP	0.1	2.9	-0.9
Fitchburg rwy. 32 MAP	-0.1	2.3	-0.9

Table 5.4
Grid Corrections at Survey Points

Airport	Mean Correction (microsec.)			Standard Deviation (microsec.)		
	TD 1	TD 2	TD 3	TD 1	TD 2	TD 3
Lawrence	1.0	3.6	-0.6	0.22	0.44	0.29
Boire	0.7	1.8	-1.7	0.85	0.71	0.85
Hanscom	0.3	2.6	-0.75	0.14	0.14	0.07
Fitchburg	0.03	2.8	-0.83	0.10	0.35	0.10

Table 5.5
Statistics of Grid Corrections

seen that the mean correction varies between airports. Since all the airports were within a 19 n.m. by 29 n.m. rectangular region one would expect the secondary phase correction to be the same for all of them. The variance of the mean correction among airports is attributed to the geographic survey and roundoff errors.

The next step was to see if the geographic uncertainities were a bias. If so, the geographic error could be attributed to incorrect surveying and / or roundoff error. Map reading error and time difference jitter in the receiver would cause the geographic uncertainities to be random.

Survey points at Hanscom field were much more accurately surveyed than those at other airports. This implied that the geographic uncertainities were small here. Therefore, the corrections were mainly due to secondary phase anomalies. Mean corrections for each of the time differences were applied to the corrections at the other airports. Residuals were calculated as the phase corrections at Hanscom minus the mean correction at the other airports.

Residual time differences at the 3 other airports were used to make position corrections to the published coordinates of the airport reference point. Appendix D describes the method used to make these geographic corrections. The 3 residuals were used 2 at a time to get 3 corrections.

First, geographic corrections were made without the use of calibration at Hanscom. These corrections are shown in figure 5.6. Then, the geographic corrections were made with the

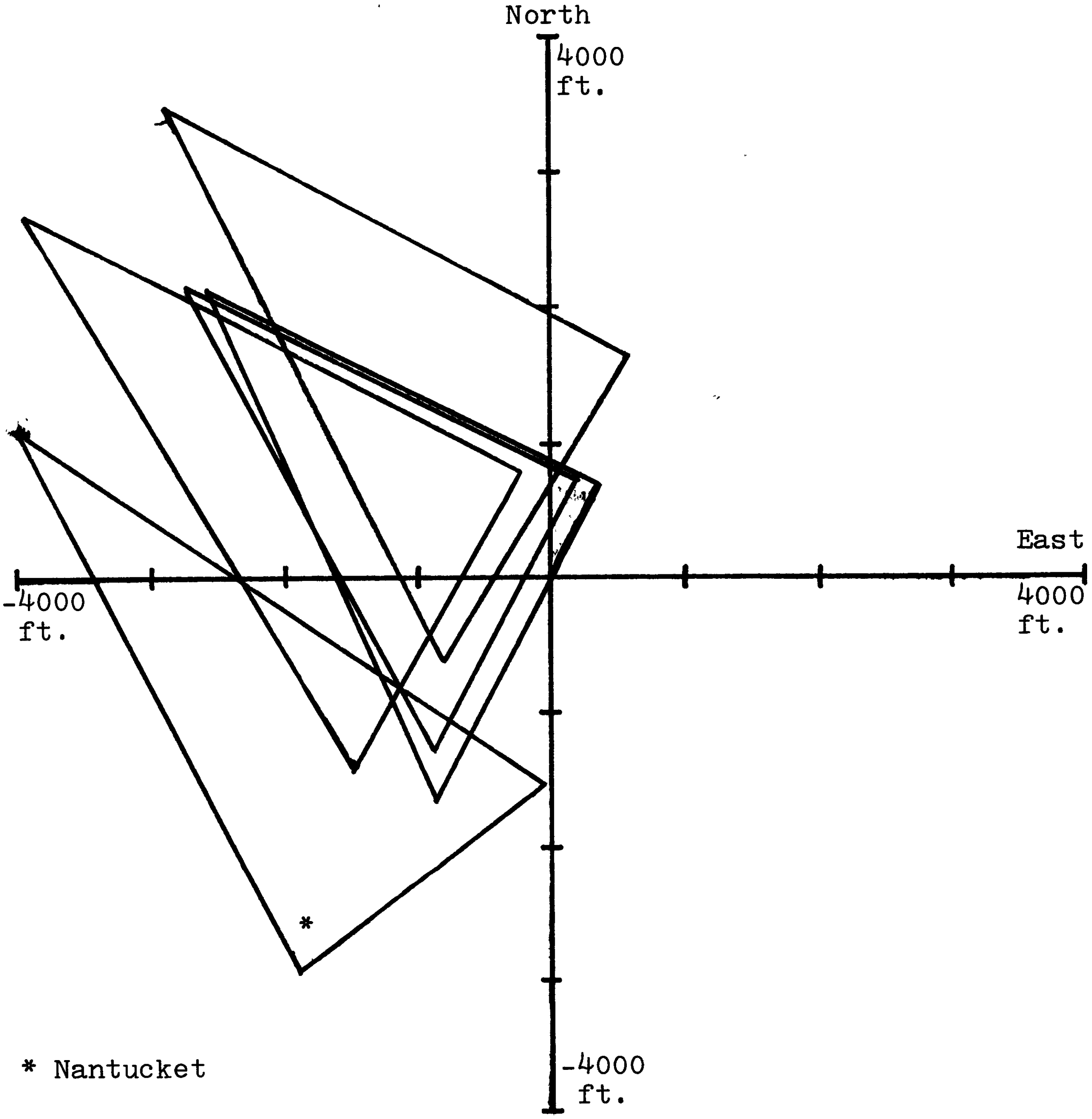


Figure 5.6
Position Corrections without Calibration

calibration. Figure 5.7 shows the corrections with calibration.

Position corrections were used to find out if there were mapping errors. Boire airfield had a mapping bias since all corrections were relatively close to each other but far away from the published airport reference point. Lawrence had a smaller bias, but this was contaminated by more scatter in the position corrections. Fitchburg did not seem to have any significant geographic bias.

The main conclusion to be drawn here was that accurate airport surveys are important to being able to accurately predict time differences. Since the Loran-C grid has been shown to be stable it would be best to do the surveys with Loran-C receivers. Such surveys would not only account for geographic errors but would also correct for propagation errors.

5.1.4 Cross Country Test Flight Observations

The test flight experience obtained on the cross country test flights lead to the following qualitative observations.

Waypoint entry for the Loran-C receiver was in time differences. This was inconvenient since most people cannot think in terms of these coordinates. It would be preferable to have waypoint entry in latitude and longitude. Also, entry of waypoints in terms of numbers required a high workload. An alternate means of waypoint entry, such as by name would be desireable.

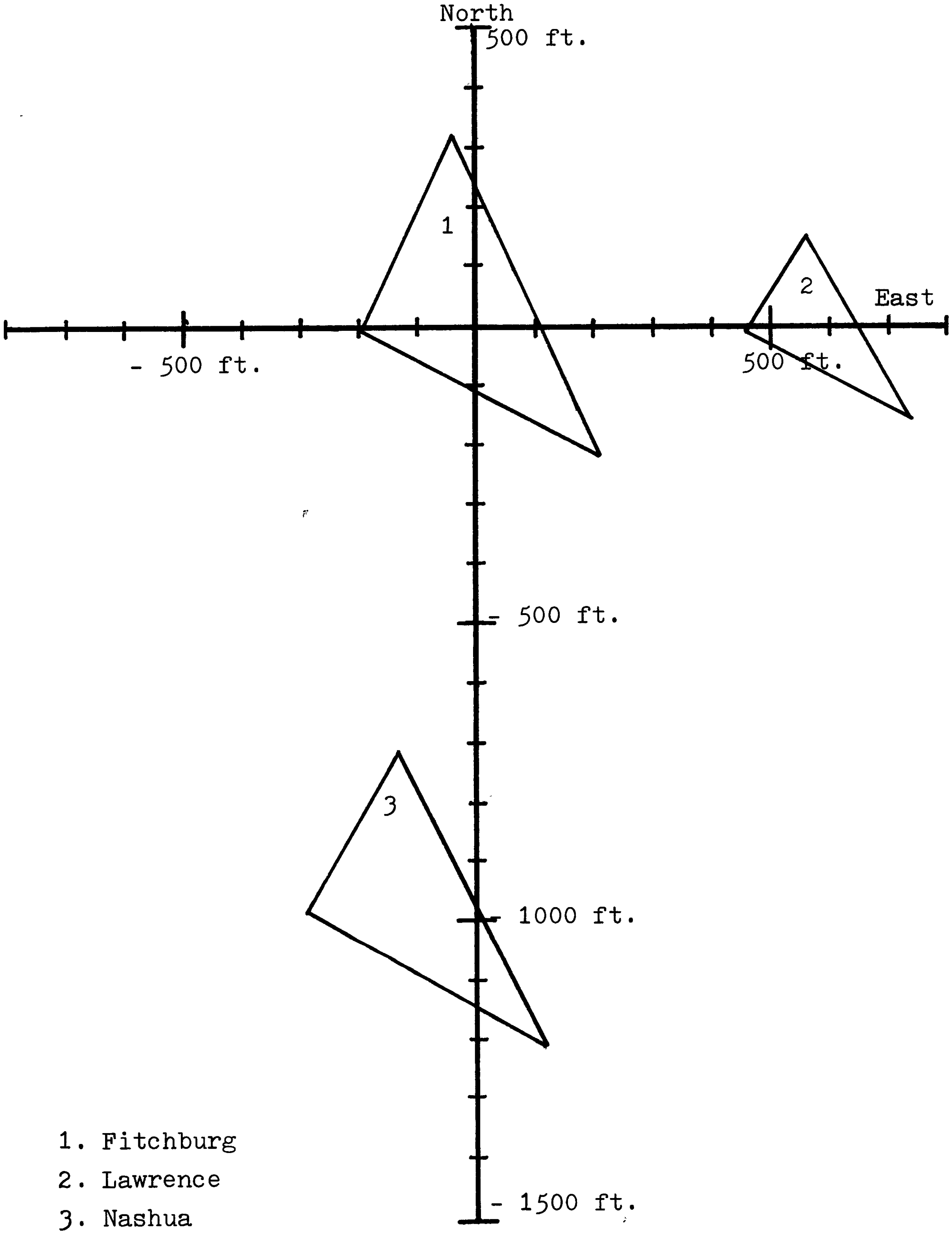


Figure 5.7
Position Corrections with Calibration

Single waypoint capability was inconvenient because of the inability to intercept a course. A minimum of 3 waypoints is needed for most navigation requirements.

The cross track error display used was adequate. However, its resolution (600 ft. end to end) was too fine for aircraft use during enroute flight. For approaches this resolution was good. A variable sensitivity cross track error display would be desireable for navigation during all phases of flight.

The receiver tracking loops were designed for boat speeds. As a result, the dynamic tracking ability was inadequate for airborne applications. This is not a fundamental problem, and can be easily corrected. Some steady state accuracy can be traded off for better dynamic performance.

With Loran-C there was no problem flying long legs directly between two waypoints. This made it unnecessary to follow less direct Victor airways. There were several instances in which upto 200 n.m. legs were sucessfully flown.

It was hard to check waypoint input blunders with this receiver. Some means of waypoint input verification is necessary. One means of achieving this is to display the bearing and distance to the next waypoint.

Apart from these minor difficulties the receiver worked very well in providing navigation and guidance information. This information was found to cross check very well against other navigation aids. In many cases Loran-C derived information was found to be more accurate than that from more conventional navigation aids.

5.1.5 Reliability Records

Reliability of the receiver was evaluated during 32.5 hours of total test time. Of this time 24.0 hours was test time in which an adequate antenna was used. An adequate antenna was one for which 2 time differences were received which had at least 0 dB SNR's. All the reliability estimates and the other qualitative observations were based on the time the adequate antenna were used.

For the 24.0 test hours there were no receiver failures (either hardware or software) or total signal outages. There were 4.5 minutes of time for which the receiver indicated incorrect cycle track. No transmitter blink indications were noted. Useful, reliable navigation information was available for 99.7% of the demanded time. Time for receiver lockup was not counted in the 24.0 hours.

Three waypoint input blunders were documented. These were waypoint errors which were undetected during entry. All of these errors were detected within 2 minutes after entry and corrected. None of these waypoint input errors were made during approach or terminal flight. All were made during enroute testing.

Approximately 2 hours of enroute and survey testing were done in the vicinity of thunderstorm activity. There was no significant reduction of the SNR's, no signal outages were observed. For the 24.0 hours of flight testing no problems with P-static or interference signals were noted.

5.1.6 Transmitter Proximity Test Results

Figure 5.8 shows the results of the flight tests. It is seen that the accuracy over the Loran-C transmitter is poorer than the accuracy test results stated in section 5.1.1. However, the accuracy over the consolant transmitter was consistent with the accuracy test results in section 5.1.1. This accuracy was within AC 90-45A limits. The definition of the various errors is the same as that in section 5.1.1.

The test tesults showed that the system accuracy degrades slightly with proximity to the Loran-C transmitter. Even directly above the transmitter the accuracy was still acceptable under AC 90-45A enroute accuracy specifications. For distances close to the transmitter there was no reduction in accuracy from the nominal accuracy values described in section 5.1.1. Another important result was that no receiver malfunction was observed with the aircraft close to the transmitter.

The ground survey results at Nantucket airport were processed as described in section 5.1.3. Here, corrections were calculated for the three time differences at each of the four survey points. The mean time difference corrections were then calculated for the airport. Three position corrections were calculated using these time difference corrections. The position corrections are shown in figure 5.6.

The magnitude of the correction at Nantucket is not significantly different from that of other airports. In fact, the scatter of the position correction is the same as that

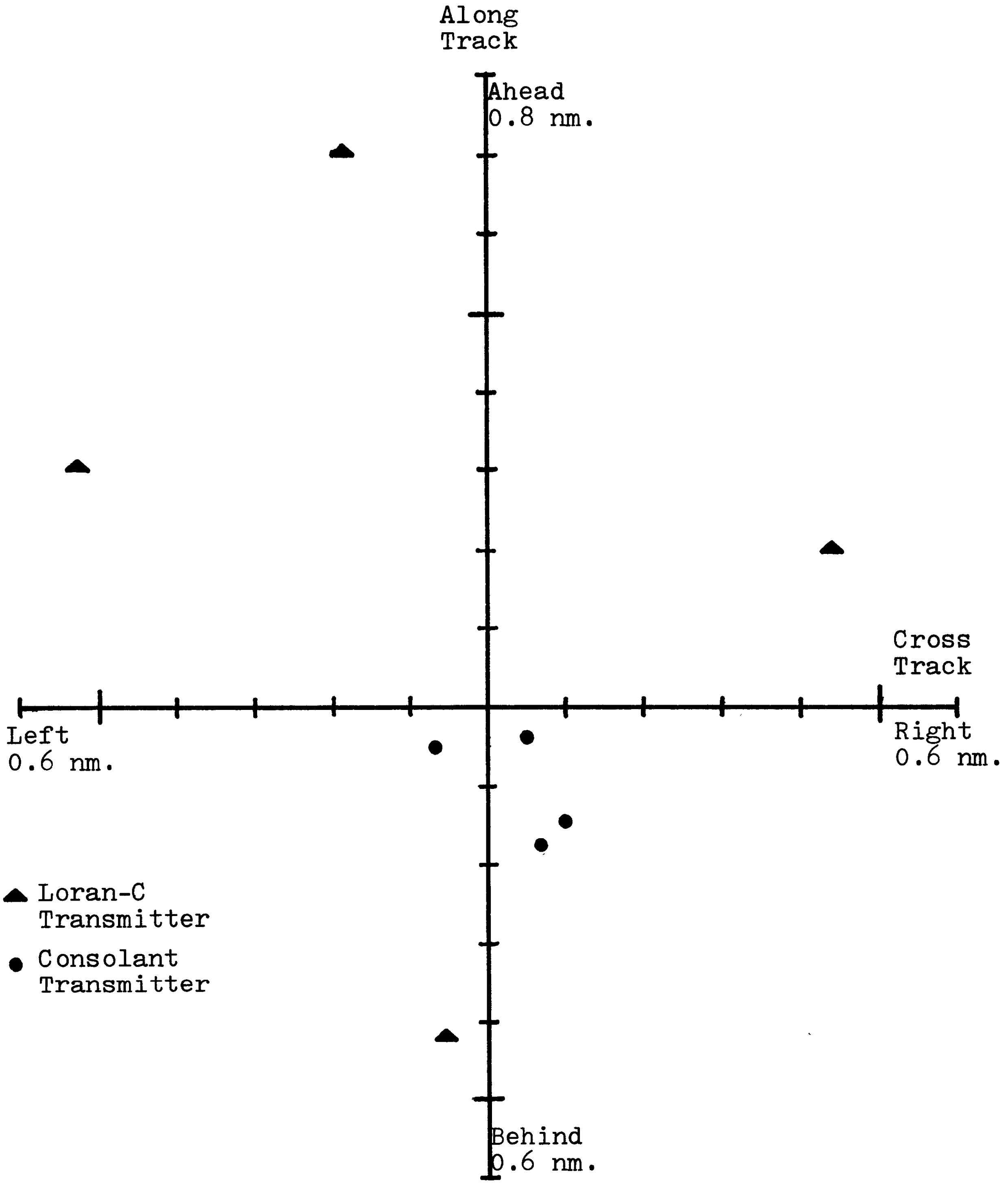


Figure 5.8
Transmitter Proximity Test Results

of the airports. Again, the airport survey test showed no degradation of Loran-C performance near the transmitter.

5.2 Ground Test Results

Grid stability was evaluated by taking averaged time difference data at a fixed location. This was done from April to October. All time difference measurements were made in the morning. Measurements were made for 51 days during the test period. The distribution of time differences 1 and 2 is shown in figure 5.9, the distribution for time differences 3 and 4 is shown in figure 5.10.

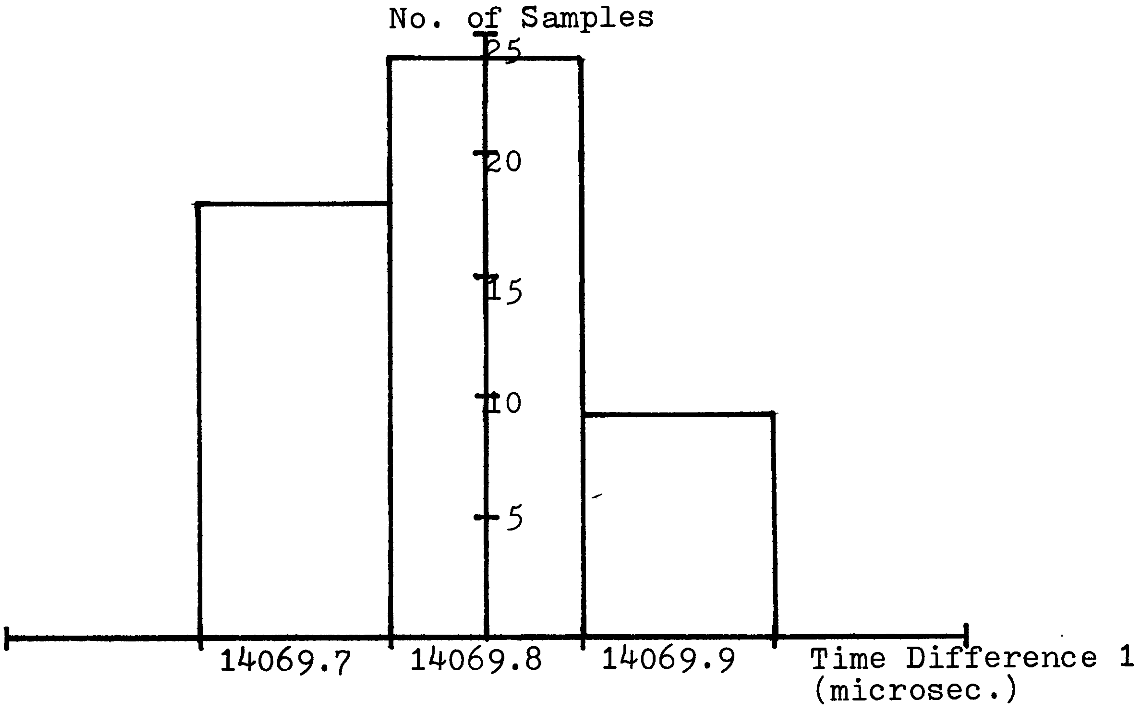
For time differences 1,2, and 3 the long term peak-to-peak variation was 0.3 microseconds. Time difference 4 had a peak-to-peak variation of 0.4 microseconds. No significant variation of time differences with rain, cloud cover, or thunderstorm activity was noticed.

5.3 Antenna Test Results

5.3.1 Ground Tests

Antenna ground tests are given in table 5.6. Here, the ADF and vertical whip antennas were tested. SNR's are given in terms of dB, signal strength is given in terms of relative numerical units, and is used for comparison purposes.

The ADF antenna was as good as or better than the vertical whip antenna. This result was in terms of SNR's for all the transmitters. Part of the reason for this was that



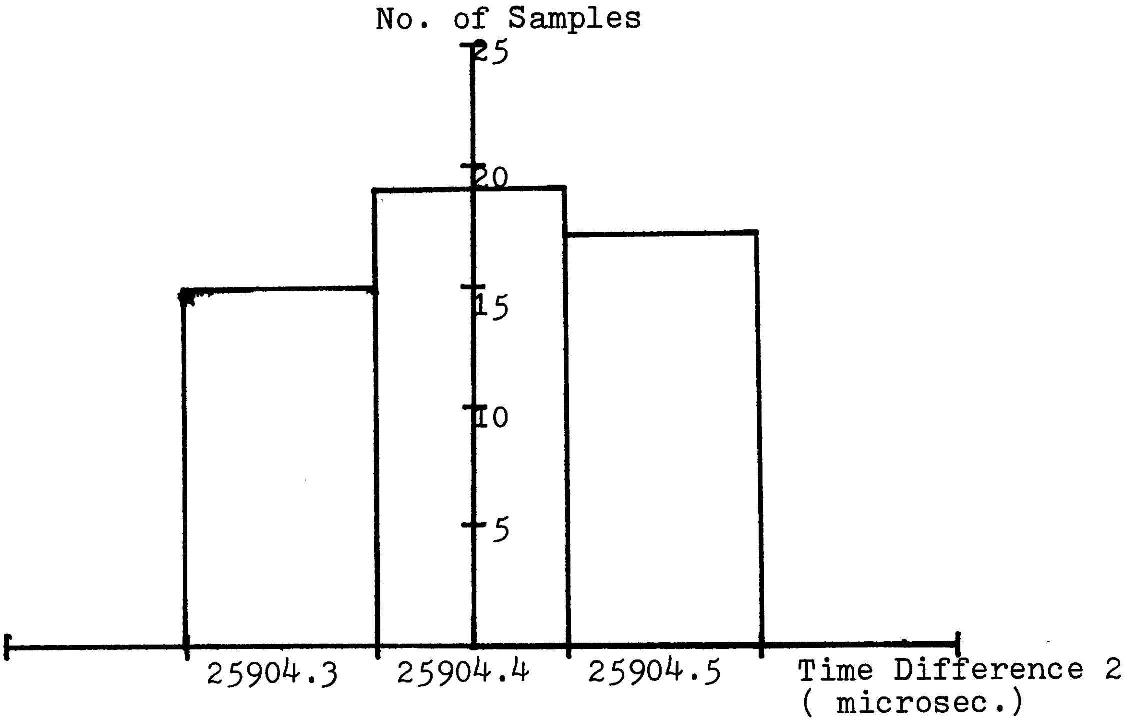
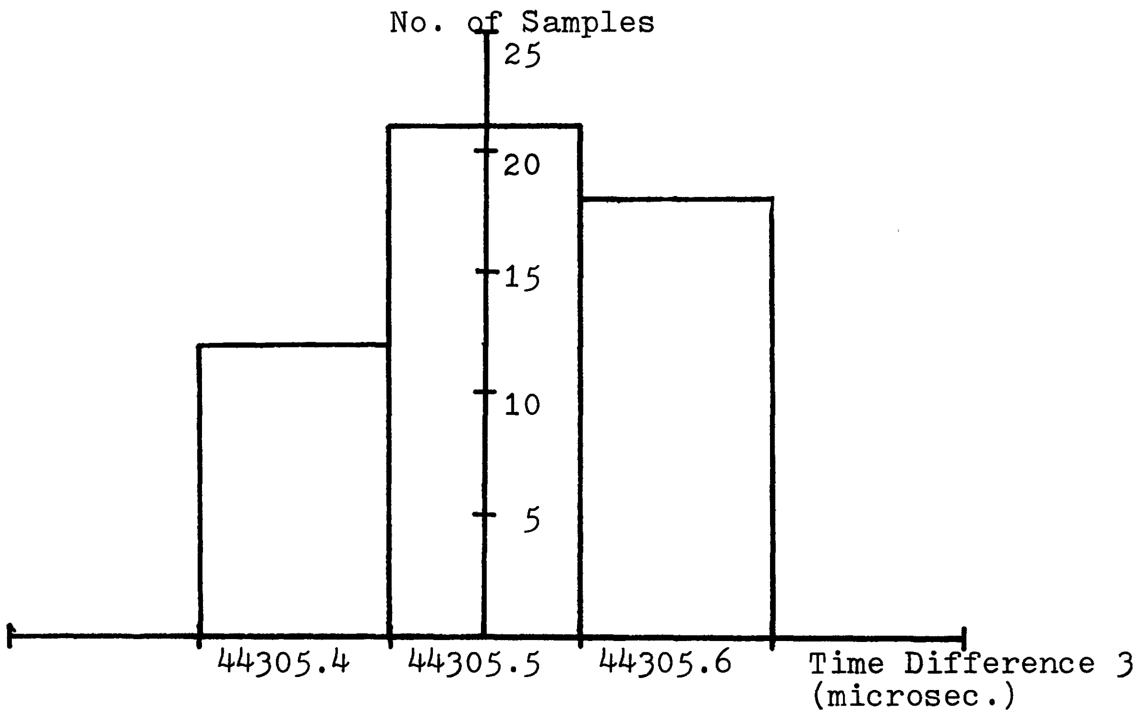


Figure 5.9

Grid Stability Test Results - Part 1



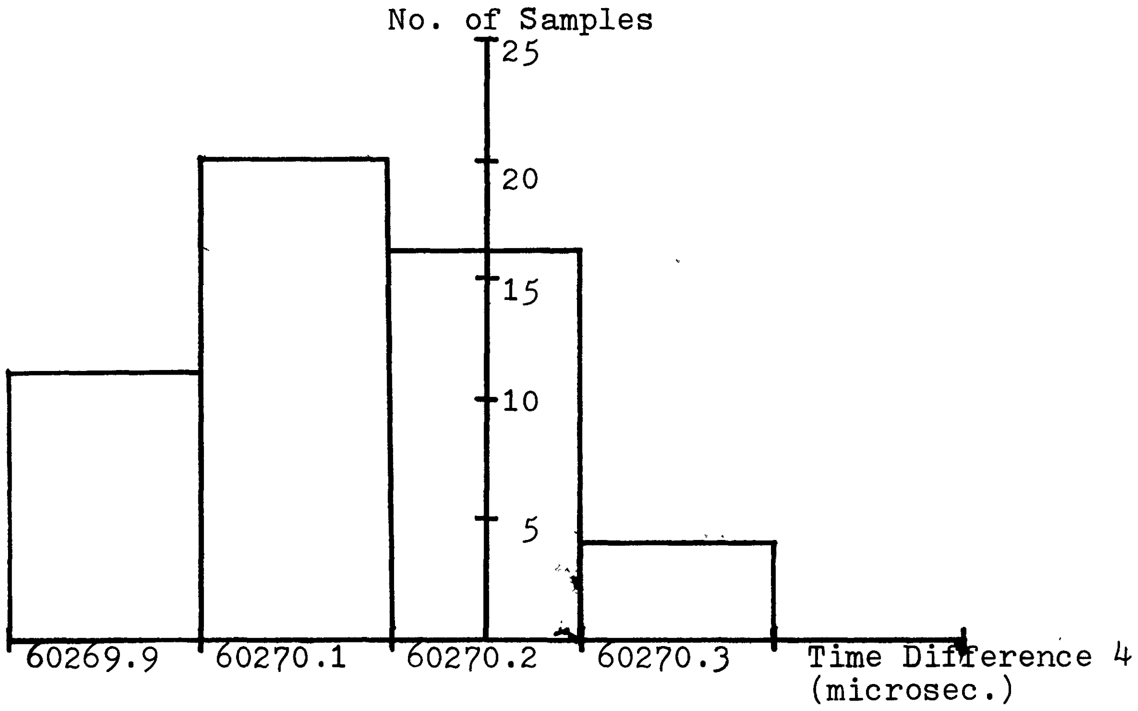


Figure 5.10

Grid Stability Test Results - Part 2

	Antenna	Relative Signal Strength	Signal / Noise Ratio (dB.)				
			Mas-ter	Sec. # 1	Sec. # 2	Sec. # 3	Sec. # 4
Engine and Avionics off.	ADF	3.0	4.5	1.5	4.5	-2.6	-13
	Vertical Whip	2.0	3.0	-4.5	4.5	-12	-18
Engine and Avionics on.	ADF	3.0	3.0	0.9	4.5	-3.4	-18
	Vertical Whip	3.0	-4.0	-11	2.0	-14	-19

Aircraft on Ground.

Antenna	Relative Signal Strength	Signal / Noise Ratio (dB.)				
		Mas-ter	Sec. # 1	Sec. # 2	Sec. # 3	Sec. # 4
ADF	3.0	4.5	1.5	4.5	-1.5	-9.4
Vertical Whip	3.0	-3.3	-12	0.5	-13	-19
Trailing Wire	3.0	3.7	-4.0	4.5	-6.3	-11

Aircraft in Flight.

Table 5.6

Antenna Test Results

the shorter vertical whip was mismatched to the antenna coupler. Engine noise in the Cessna drastically lowered the SNR's when the engine was running. The Mooney 201, used to test the ADF antenna, had a good engine noise suppression system. As a result, no significant reduction of SNR's was noticed with the engine running.

5.3.2 Flight Tests

Antenna flight test results are shown in table 5.6. The ADF, vertical whip, and trailing wire antennas were tested in the air. Units for the SNR's and signal strength are the same as before.

For the ADF and vertical whip antennas there was no appreciable change of SNR's or signal strength with altitude. The trailing wire antenna tested on the Cessna 172 performed better than the vertical whip. However, it was not as good as the ADF antenna on the Mooney 201. Again, this was due to poor engine ignition noise suppression in the Cessna.

The ADF antenna performed very well, with the master and 3 secondaries having SNR's greater than 0 dB. Proper ignition noise supression on the Cessna 172 would have improved the performance of the vertical whip and trailing wire antennas. Of the 3 antennas only the ADF and vertical whip antennas were suitable from a practical standpoint.

6.0 CONCLUSIONS

The various tests and their results lead to the following conclusions. These conclusions are meant to answer the detailed technical objectives of section 3.

1. Loran-C had the accuracy to meet AC90-45A accuracy specifications. The along and cross track errors were not significantly biased. Standard deviations were .09 n.m. along track and .13 n.m. cross track. The enroute cross track flight technical error had a bias of -.18 n.m. and a standard deviation of .24 n.m.

These test results can be compared to values obtained in the Vermont flight test program (Ref. 4). Here, typical values for the standard deviation of Loran-C errors were .07 n.m. along track and .08 n.m. cross track. Enroute cross track flight technical error had a standard deviation of .52 n.m.

2. With a good antenna receiver reliability was 99.7%. This was based on 24.0 hours of flight tests. During this test time no fatal receiver failures or signal outages were recorded.

3. P-static was not found to be a problem.when a good antenna was being used. The long term time difference variations were typically 0.3 microsecond peak-to-peak.

4. Without the use of corrections typical approach accuracies were 0.3 n.m. (2σ) along track and .25 n.m. (2σ) cross track. When corrections were used the approach accuracy improved significantly. Errors for thes case were 300 ft.

(2σ) along track and 100 ft. (2σ) cross track. Both the approach cross track errors given above include flight technical error.

5. Two suitable antenna configurations were found. These were the ADF and vertical whip antennas. The ADF antenna provided SNR's greater than 0 dB for the master and the W and X secondaries. The Y secondary had a -2.6 dB SNR.

Corresponding values for the vertical whip antenna were greater than 0 dB SNR for the master and the X secondary. The W secondary had an SNR of -4.5 dB, the Y secondary -12 dB.

6. Grid stabitity makes a one time airport correction feasable. Such corrections are in principle similar to altimeter settings.

If no corrections were used there was typically a .5 n.m. (2σ) uncertainity in locating a single point. When a single correction for a 20 n.m. by 30 n.m. area was used this uncertainity was reduced to .15 n.m. (2σ). With a correction for every test point this uncertainity becomes typically 200 ft. (2σ).

The correlation distance of these corrections was estimated to be less than 80 n.m.

7. Qualitative observations on cross country test flights indicated that Loran-C was practical for use on such flights. It was possible to fly 200 n.m. legs directly. No serious operational difficulties were encountered while using Loran-C for area navigation.

Appendix A

Description of Northstar 6000 Loran-C Receiver

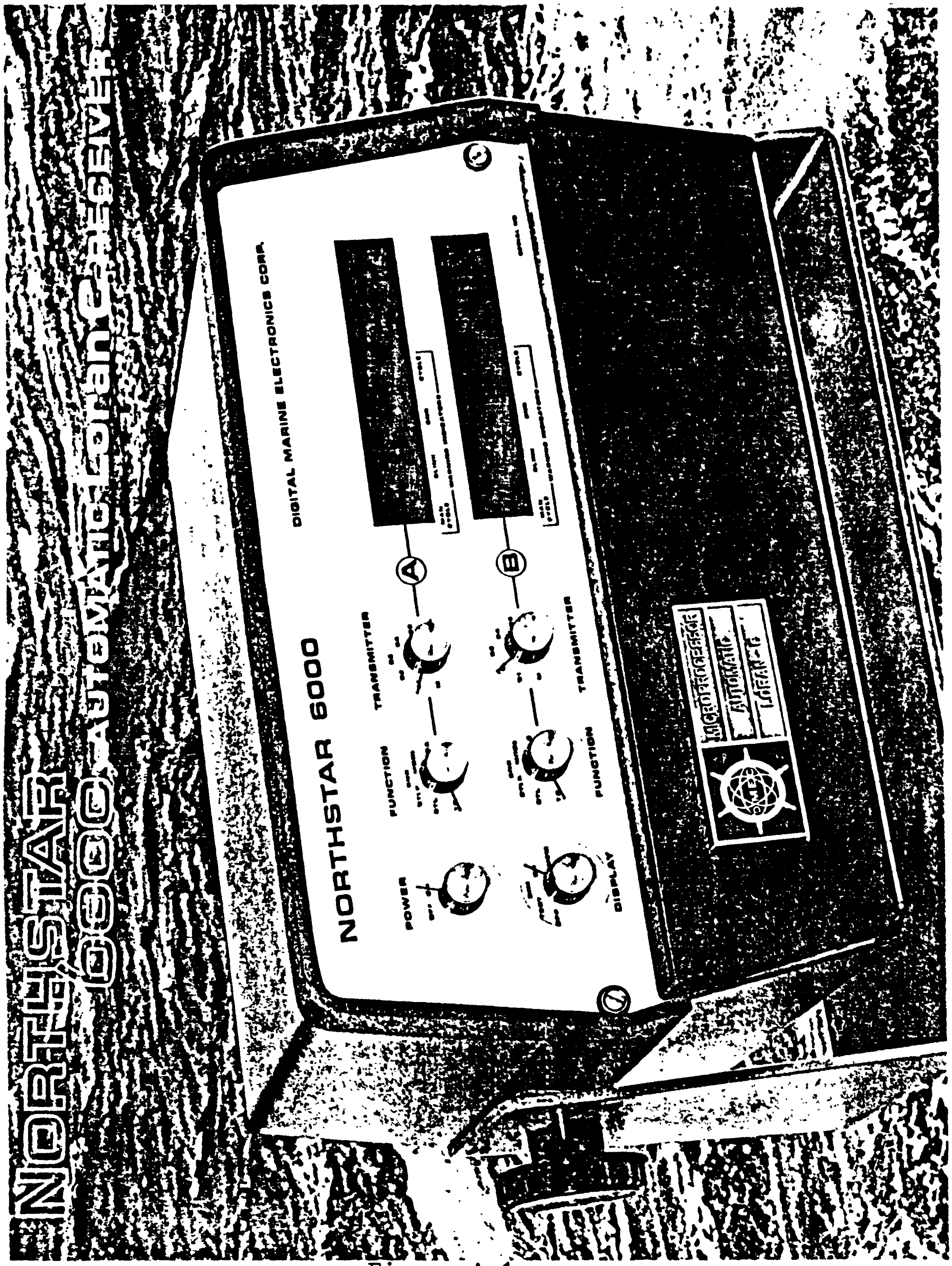


Figure A.1
Northstar 6000 Loran-C Receiver

FEATURES

Operation

Simple. Set all switches to Red position. Turn on power.

Automatic acquisition, cycle-selection and tracking.

No CRT necessary.

Tracks up to 5 Slaves simultaneously.

Signal quality information automatically calculated for all stations.

Warning lights for abnormal conditions.

Manual override controls for extended range operations in extreme fringe areas.

User may assign any Slave into any display position.

Exclusive STEER LOP format.

"ALL" displays tracked slaves sequentially.

Automatic adaptive tracking provides maximum display stability for any vehicle speed.

Uses new standard 4 digit GRI format.

Display

Bright, dual, LED readouts.

Contrast-enhancing filters.

Dim position for nighttime operation.

Stable readings - updated 10 times per second.

0.1 microsecond resolution.

Display test function.

Maintenance

100% modular construction.

High quality, conservatively rated components.

Fiberglass epoxy printed circuit boards.

Built-in test functions.

RF and Scope sync test jacks for easy dealer service/adjustment.

Optional Equipment

(Ground Isolating)
Power Supply, 110 vac.
Power Supply, 110 vdc.

Dual Readout Remote Display connects with standard RG-58 coaxial cable.

X/Y Plotter.

Latitude/longitude converter with speed/course information.

SPECIFICATIONS

Receiver Module

Integrated circuit design.

Wide bandwidth for maximum pulse fidelity.

Low noise - Wide dynamic range - 110 db.

Sensitivity - 0.8 μv

Four Notch Filters - two external - two internal.

Solid state LED type Interference Meter.

Antenna Coupler (included)

Permanently sealed in solid epoxy.

Minimum parts-count construction.

Connects to receiver with standard coaxial cable and plug.

Mounts with standard 1" - 14 hardware.

Length 7½" Weight 1¼ lbs.

Antenna (not included)

Fiberglass CB Whip (about 108") recommended.

3/8" - 24 mounting stud.

Electrical

Voltage 10 - 40 vdc standard

Optional 120 vdc or 120 vac adaptors available.

Power consumption 45 watts

Negative ground only. Ground isolating power supply required for positive ground or floating system.

Efficient switching regulator for low power consumption.

Automatic solid state fault protection.

Cabinet and Mounting

Rugged, welded, all-aluminum anodized and painted case and yoke. All fasteners stainless steel.

Serial number engraved on front panel for theft protection.

	Case Only	*Including Yoke*
Height	9½"	11½"
Width	16"	19-3/4"
Depth	11"	11"

Weight 25 lbs.

APPENDIX B

Data Reduction Procedure for Accuracy Tests

Figure B.1 shows the sign conventions used for the data processing calculations. A Loran-C fix was taken over every landmark. Radar track data was also available which was tagged with a time reference. The time of the Loran-C fix was also recorded.

The best estimate of position was taken as the point on the radar track closest to the landmark. A position error was calculated as the difference between the Loran-C fix and the best estimate of position. This was resolved into along and cross track components. The sign convention used was as follows:

Positive cross track error when the Loran-C fix was to the right of the aircraft.

Positive along track error whan the Loran-C fix was in front of the aircraft.

Positive cross track flight technical error when the landmark was to the right of the aircraft ground track.

The along track error included any time synchronization error between the Loran-C and DABS fixes. This error was estimated by taking the time of 11 Loran-C fixes and the time of closest approach to the landmark. A error was computed as the difference between Loran-C fix time and the time of closest approach. Statistics for this error were:

Mean error = 1.1 second

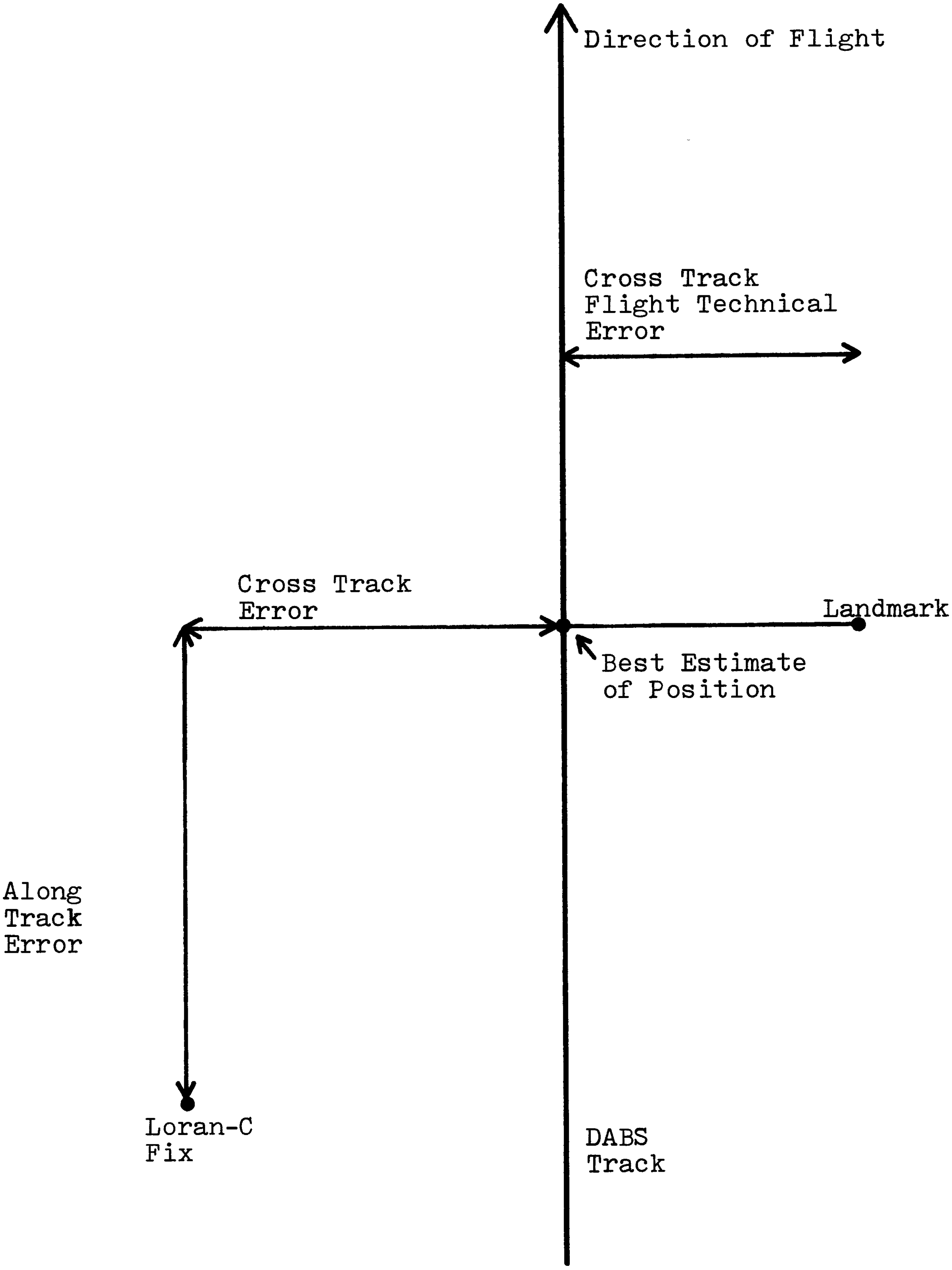


Figure B.1
Error Analysis Diagram for Flight Tests

Standard deviation = 6.4 second.

Using the groundspeed from the tracking radar this time uncertainity was converted to a position uncertainity with these statistics:

Mean error = 213 feet

Standard deviation = 1242 feet.

The actual Loran-C along track error was calculated as:

$$\sigma_{ATE} = \sqrt{(\sigma_M)^2 - (1242)^2}$$

σ_{ATE}= Standard deviation of the Loran-C error.

σ_M = Standard deviation of the measured along track error.

Figure B.2 is a flowchart of the data processing program. An elliptical earth model was used to convert the radar fix from range and bearing to latitude and longitude. This is described in appendix J of reference 10. A listing of the computer program used for the data analysis is also given.

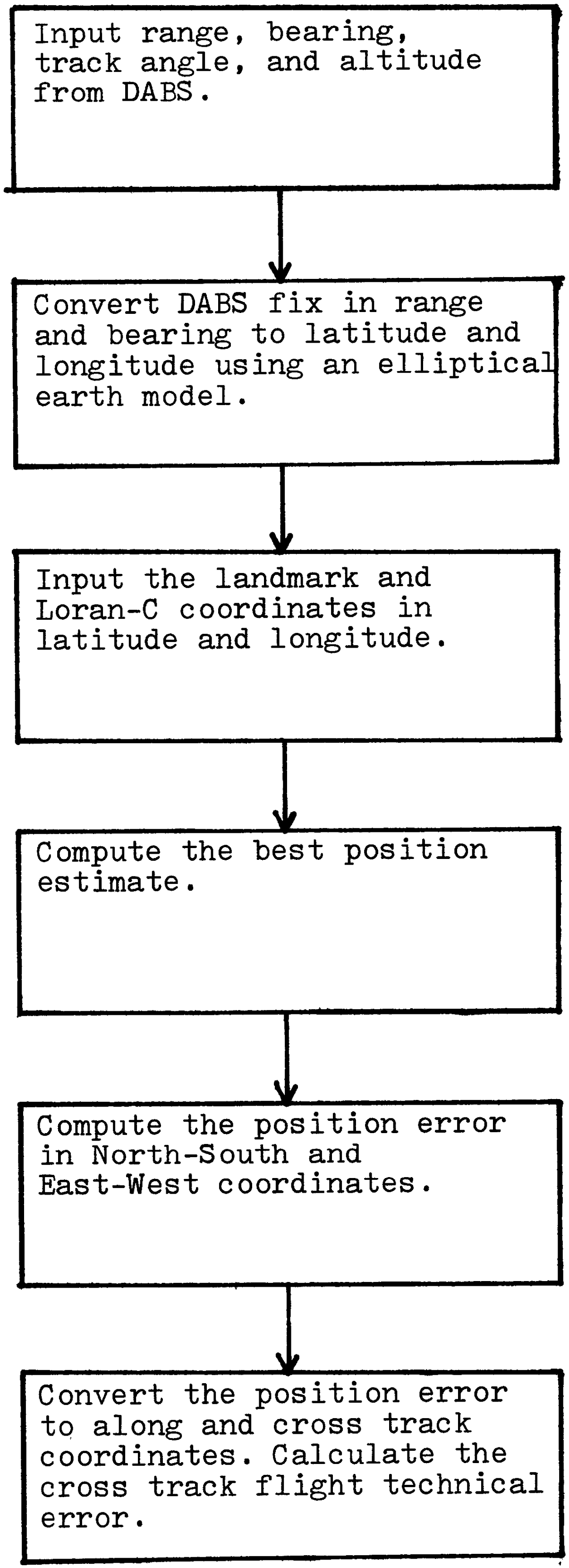


Figure B.2

Flowchart of Data Processing Program

```
10 REM     THIS PROGRAM PROCESSES LORAN TEST FLIGHT DATA.
20 REM     FOR DOCUMENTATION SEE NOTES.
30 DIM LO(3),L1(3),X(1),Y(1)
40 E=3443.96 \ LO(0)=.741006 \ L1(0)=1.24384
50 REM     INPUT DABS PARAMETERS.
60 PRINT 'INPUT RANGE IN NM.'
70 INPUT DO
80 IF DO=0 GO TO 650
90 PRINT 'INPUT BEARING IN DEGREES.'
100 INPUT D1
110 D1=D1*(PI/180)
120 PRINT 'INPUT TRACK ANGLE IN DEGREES.'
130 INPUT D2
140 D2=D2*(PI/180)
150 PRINT 'INPUT ALTITUDE IN FEET.'
160 INPUT D3
170 REM     CALCULATE DABS FIX.
180 R=SQR((DO^2)-((D3/6076.12)^2))
190 R=.0166932*R
200 B1=ATN(.99661*(SIN(LO(0))/COS(LO(0))))
210 BO=(COS(B1))*(SIN(D1))
220 B2=(SIN(B1)*COS(R))+(COS(B1)*COS(D1)*SIN(R))
230 B2=B2/(SQR(BO^2+(COS(R)*COS(B1)*COS(D1)-SIN(B1)*SIN(R))^2))
240 LO(1)=ATN(B2/.99661)
250 L3=SIN(R)*SIN(D1)
260 L3=L3/(COS(B1)*COS(R)-SIN(B1)*SIN(R)*COS(D1))
270 L3=ATN(L3)
280 IF (SIN(D1))<0 THEN L3=L3-PI
290 IF (SIN(D1))>=0 THEN L3=L3
300 L1(1)=L1(0)-L3
310 REM     INPUT LORAN AND LANDMARK.
320 PRINT 'INPUT LORAN LAT. AND LONG. IN DEC. DEG.'
330 INPUT LO(2),L1(2)
340 LO(2)=LO(2)*(PI/180)
350 L1(2)=L1(2)*(PI/180)
360 PRINT 'INPUT LANDMARK LAT. AND LONG. IN DEC. DEG.'
370 INPUT LO(3),L1(3)
380 LO(3)=LO(3)*(PI/180)
390 L1(3)=L1(3)*(PI/180)
400 REM     LINEARIZE AROUND LANDMARK.
410 E=E*6076.12
420 X(0)=(L1(3)-L1(2))*E*COS(LO(3))
430 Y(0)=(LO(2)-LO(3))*E
440 X(1)=(L1(3)-L1(1))*E*COS(LO(3))
450 Y(1)=(LO(1)-LO(3))*E
460 REM     FIND THE BEST POSITION ESTIMATE AND ERRORS.
470 H=(PI/2)-D2
480 M1=SIN(H)/COS(H)
490 C1=Y(1)-(M1*X(1))
```

```
500 M2=(-1)/M1
510 X=C1/(M2-M1)
520 Y=M2*X
530 C=SQR(X^2+Y^2)
540 C=C*SGN(X*COS(H+(PI/2))+Y*SIN(H+(PI/2)))
550 E0=X(0)-X
560 E1=Y(0)-Y
570 E2=E0*COS(H)+E1*SIN(H)
580 E3=E1*COS(H)-E0*SIN(H)
590 PRINT "NORTH-SOUTH ERROR IN FT. :",E1
600 PRINT "EAST-WEST ERROR IN FT. :",E0
610 PRINT "ALONG TRACK ERROR IN FT. :",E2
620 PRINT "CROSS TRACK ERROR IN FT. :",E3
630 PRINT "CROSS TRACK FTE IN FT. :",C
640 GO TO 10
650 END
```

APPENDIX C

Time Difference Prediction Algorithm

The time difference algorithm used is described in detail on pages 25 to 27 of reference 1. An elliptical earth model was used to calculate the arc length, which is the major component of the time differences. The following parameters were used in the time difference prediction calculation. No corrections of any kind were used.

c = Free space speed of light = 983.567 ft./microsec.
η = Atmospheric index of refraction = 1.000338
a = Semimajor axis of reference ellipsoid = 3443.93 n.m.
f = Flattening of the reference ellipsoid = 1/298.2 .

```
10 REM THIS PROGRAM CONVERTS LATITUDE AND LONGITUDE TO
20 REM TIME DIFFERENCES. THIS IS DONE FOR THE 9960
30 REM CHAIN. THE EQUATIONS USED HERE ARE GIVEN IN
40 REM KAYTON AND FREID PAGES 26 AND 27.
50 DIM R$(1),S0(4),S1(4),D(4),C(4),R(4),T(4)
60 DEF FNA(A$)=(VAL(SEG$(A$,6,7))*60+VAL(SEG$(A$,9,LEN(A$))))/3600
70 DEF FNB(A$)=(PI/180)*SGN(VAL(SEG$(A$,1,4)))*(VAL(SEG$(A$,2,4))+FNA(A$))
80 DEF FNC(A)=SIN(A)/COS(A)
100 REM LISTED BELOW IS DATA ON THE 9960 CHAIN.
110 A=21282.3 \ F=1/298.2
120 M0=.745501 \ M1=1.34087
130 S0(1)=.816946 \ S1(1)=1.18555
140 S0(2)=.720006 \ S1(2)=1.22134
150 S0(3)=.594508 \ S1(3)=1.35984
160 S0(4)=.69555 \ S1(4)=1.52693
170 D(1)=13797.2
180 D(2)=26969.9
190 D(3)=42221.6
200 D(4)=57162.1
210 PRINT "ENTER ALL NORTH LATITUDES AND WEST LONGITUDES AS POSITIVE."
220 PRINT "ENTER ALL SOUTH LATITUDES AND EAST LONGITUDES AS NEGATIVE."
230 PRINT "POSITIONS MUST BE ENTERED IN THE FORM +037:46:47.56 ."
240 PRINT "ENTER 0,0 TO QUIT."
250 PRINT ""
260 PRINT "ENTER RECEIVER'S LATITUDE AND LONGITUDE."
270 INPUT R$(0),R$(1)
280 IF R$(0)="0" THEN 1200
290 R0=FNB(R$(0)) \ R1=FNB(R$(1))
300 REM SECONDARY PHASE DIFFERENCES ARE CALCULATED.
500 REM CALCULATE THE FOUR TIME DIFFERENCES.
510 L=R0 \ L1=M0 \ D=R1-M1
520 GOSUB 1000
530 R(0)=R
540 FOR I=1 TO 4
550 L=R0 \ L1=S0(I) \ D=R1-S1(I)
560 GOSUB 1000
570 R(I)=R
580 T(I)=(R(I)-R(0))+D(I)+C(I)
590 PRINT USING "#####.#",T(I)
600 NEXT I
610 PRINT ""
620 PRINT ""
630 GO TO 260
1000 REM THIS IS THE ARC LENGTH COMPUTING SUBROUTINE.
1010 B=ATN((1-F)*FNC(L))
1020 B1=ATN((1-F)*FNC(L1))
1030 C1=COS(B1)*SIN(D)
1040 C2=(COS(B)*SIN(B1))-(SIN(B)*COS(B1)*COS(D))
1050 C3=(SIN(B)*SIN(B1))+(COS(B)*COS(B1)*COS(D))
1060 IF C2=0 THEN P=(PI/2)*SGN(C1)
1070 IF C2>0 THEN P=ATN(C1/C2)
```

```
1080 IF C2<0 THEN P=PI+ATN(C1/C2)
1090 IF C3=0 THEN T=PI/2
1100 IF C3>0 THEN T=ATN(((C2*COS(P))+(C1*SIN(P)))/C3)
1110 IF C3<0 THEN T=PI+ATN(((C2*COS(P))+(C1*SIN(P)))/C3)
1120 IF SIN(T)=0 THEN R=A*T
1130 IF SIN(T)=0 THEN 1190
1140 M=(SIN(B)+SIN(B1)) \ M=M*M
1150 N=((SIN(B)-SIN(B1))/SIN(T)) \ N=N*N
1160 U=((1-COS(T))/SIN(T))*((T-SIN(T))/SIN(T))
1170 V=(1+COS(T))*(T+SIN(T))
1180 R=A*(T-(F/4)*(M*U+N*V))
1190 RETURN
1200 END
```

APPENDIX D

Position Correction Calculation Algorithm

Calculation of position corrections from time difference residuals is discussed in pages 27 to 28 of reference 1. An elliptical earth model was used with the same parameters as in appendix C. To compute the position corrections time difference residuals were used two at a time. A listing of the computer program used is given below.

```
10 REM     THIS PROGRAM COMPUTES LATITUDE AND
20 REM     LONGITUDE CORRECTIONS FOR THE AIRPORT SURVEY.
30 DIM E(3),T0(3),T1(3),B(3),A(3),G(3)
40 T0(0)=.745501 \ T1(0)=1.34087
50 T0(1)=.816946 \ T1(1)=1.18555
60 T0(2)=.720006 \ T1(2)=1.22134
70 T0(3)=.594508 \ T1(3)=1.35984
80 C=983.567 \ F=1/298.2
90 PRINT "INPUT LAT. AND LONG. IN DEC RAD."
100 INPUT L0,L1
110 PRINT "INPUT CORRECTIONS IN MICROSEC."
120 INPUT E(1),E(2),E(3)
130 PRINT ""
140 PRINT ""
150 REM     COMPUTE BEARINGS TO TRANSMITTERS.
160 FOR I=0 TO 3
170 B=ATN((1-F)*(SIN(L0)/COS(L0)))
180 B1=ATN((1-F)*(SIN(T0(I))/COS(T0(I))))
190 D1=L1-T1(I)
200 C1=COS(B1)*SIN(D1)
210 C2=(COS(B)*SIN(B1))-(SIN(B)*COS(B1)*COS(D1))
220 IF C2>0 THEN B(I)=ATN(C1/C2)
230 IF C2<0 THEN B(I)=PI+ATN(C1/C2)
240 IF C2=0 THEN B(I)=(PI/2)*SGN(C1)
250 NEXT I
260 REM     NOW COMPUTE THE THREE CORRECTIONS.
270 FOR I=1 TO 2
280 FOR J=1 TO 3
290 IF J<=I THEN 390
300 A(I)=(COS(B(I))-COS(B(0)))/C
310 A(J)=(COS(B(J))-COS(B(0)))/C
320 G(I)=(SIN(B(I))-SIN(B(0)))/C
330 G(J)=(SIN(B(J))-SIN(B(0)))/C
340 D=A(I)*G(J)-A(J)*G(I)
350 N=(E(I)*G(J)-E(J)*G(I))/D
360 E=(E(J)*A(I)-E(I)*A(J))/D
370 PRINT "TD'S USED ARE :",I,J
380 PRINT "LAT. CORR. :",N,"LONG. CORR. :",E
390 NEXT J
400 NEXT I
410 END
```

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