NASA Conference Publication 2176

Joint University Program for Air Transportation Research - 1980

Proceedings of a conference held at
NASA Langley Research Center
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PREFACE

The Joint University Program for Air Transportation Research is a coordinated set of three grants, sponsored by NASA Langley Research Center, one each with Massachusetts Institute of Technology (NGL-22-009-640), Ohio University (NGR-36-009-017), and Princeton University (NGL-31-001-252) to support the training of students for the air transportation system. These grants, initiated in 1971, are intended to encourage the development of innovative curriculums and to support the establishment of graduate and undergraduate research assistantships and internships. A major element of the program is the participation of both undergraduate and graduate students working closely with faculty and staff on research programs.

A wide spectrum of navigation, guidance, control, and display research has been conducted. Recent emphasis has been on low-cost avionics concepts and hardware for general aviation aircraft. An important feature of this cooperative program is quarterly reviews, one held at each of the schools and a fourth held at NASA Langley Research Center. Attendance at these meetings includes student, faculty, and staff from all three schools and invited guests from government and industry.

This conference publication summarizes the research conducted under the grants during the 12 months preceding the conference. The majority of the material is the effort of the students supported by the grants. Three types of contributions are included. Completed works are represented by the full technical papers. Research previously published in the open literature, for example, theses or journal articles, are presented in an annotated bibliography. Status reports of ongoing research are represented by copies of viewgraphs augmented with a brief descriptive text.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by NASA.

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OHIO UNIVERSITY

PRINCETON UNIVERSITY

Massachusetts
Institute
of
Technology

INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY, 1980

Professor Robert W. Simpson
Director, Flight Transportation Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

INTRODUCTORY REMARKS

There have been three major areas of research sponsored by the Joint University Program at MIT during the past year: 1) Development of Automated Decision Making for Dynamic Scheduling of Runway Operations at a Major Airport; 2) Flight Evaluation of the Performance of Low Cost Loran-C Receivers; 3) Design of Micro-computer-Based Electronic Flight Displays for General Aviation Aircraft.

1. DYNAMIC SCHEDULING OF RUNWAY OPERATIONS

The activity in the first area has concentrated in the past year on building a real-time interactive ATC simulation at the MIT Joint Computer Facility. This has finally become operational. An experimenter can now view an ATC radar display similar to the current FAA Arts III display, and can also view an auxiliary display of terminal area flight information (such as the proposed TIPs or ETABS displays). On this auxiliary display, a continuously updated, dynamic schedule of proposed runway operations by takeoffs and landings is generated by software. The experimenter can manually control landing aircraft to try to achieve its scheduled arrival time. He should be able to rely on software-generated path commands soon. All computer-generated commands will be passed through the human controller who will signify his validation of them.

This ATC simulation facility, called TASIM, can work in a variety of modes from fast time to real time, and with varying degrees of automation of the decisionmaking in terminal area ATC. It has been designed to continue the investigation of human factors problems in introducing automated decisionmaking to terminal area ATC. The current research goals are to demonstrate in real time the potential reductions in delay from automated runway scheduling, first indicated by Dear's research (1977) sponsored by this program. We hope to finish this phase by June 1980.

2. FLIGHT EVALUATION OF LOW COST LORAN-C

A Northstar Loran-C receiver originally designed for marine use has been flown over the past year to evaluate its performance, and to study antenna problems in installing Loran-C in a typical GA aircraft. Of particular interest has been the possibility of using Loran-C for non-precision approaches to runways at small airports in the New England region. It would appear that this is feasible with these low-cost receivers if

Loran-C coordinates are available for each runway end. These coordinates show very little seasonal or short term variation: K. Natarajan reports on this work in a subsequent paper in this compilation.

3. LOW-COST ELECTRONIC FLIGHT DISPLAYS

Work in this area began two years ago with an attempt to use a low-cost commercially-available microcomputer to drive a television monitor display. This work is now being redirected, based on more recent developments in microcomputer technology and a set of commercially-available microcomputer boards and graphics software. We have renamed this project with the acronym P-POD for "Programmable - Pilot Oriented Display." The design, assembly, and programming of this device has just started, and is described by J. A. Littlefield in a subsequent paper in this compilation. We hope that it will provide us with a flexible device which we can use in laboratory simulation and flight test, and which can be used to study various formats for electronic ADI's, HSI's, and Flight Data displays.

There have also been two other areas of research which have received minor support from the Joint University Program in the past year. John Nordin has developed a fast-time simulation model for runway operations called "Flexsim" in a recent Ph.D. thesis. Jeff Katz finished his thesis work on IFR pilot workload with a series of experiments in the B-707 simulator, which were supported by JUP. Their work resulted in two theses which are described in the Annotated Bibliography.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

ANNOTATED BIBLIOGRAPHY

Swedish, William: Some Measures of Aircraft Performance on the Airport Surface. Flight Transportation Laboratory Report, R72-4, Department of Aeronautics and Astronautics, MIT, June 1972.

Field survey data were gathered at Boston Logan and Atlanta airports on aircraft operations on runways and taxiways. The data included: runway occupancy times for landings and takeoffs, touchdown distances and times, time to traverse a given length of taxiway, and delays in crossing taxiways or in initiating takeoff. Analysis of the data revealed that there was no difference in taxi speeds by aircraft type, but rather by location and length of taxiway segments. For landings, the times to exit did not vary by type, although the probability of leaving the runway varied by type and airline identity.

Sager, Dennis: Simulator Evaluation of Manually Flown Curved Instrument Approaches. Flight Transportation Laboratory Report, R73-1, Department of Aeronautics and Astronautics, MIT, January 1973.

Pilot performance in flying horizontally-curved instrument approaches was analyzed by having nine test subjects fly curved approaches in a fixed-base simulator. Approaches were flown without an autopilot and without a flight director. Evaluations were based on deviation measurements made at a number of points along the curved approach path and on subject questionnaires. Results indicate that pilots can fly curved approaches, though less accurately than straight-in approaches; that a moderate wind does not affect curve flying performance; and that there is no performance difference between 60° and 90° turns. A tradeoff of curved path parameters and a paper analysis of wind compensation were also made.

Dodge, Steven M.: A Comparative Analysis of Area Navigation Systems for General Aviation. Flight Transportation Laboratory Report, R74-1, Department of Aeronautics and Astronautics, MIT, June 1973.

A cost-effectiveness analysis of three area navigation systems was performed: 1) VORTAC; 2) LORAN-C; 3) Differential OMEGA. A set of system-cost sensitivity charts was developed which allows conclusions on the relative cost-effectiveness of candidate systems as a function of required navigation performance. The cost-effectiveness of the VORTAC system falls considerably short of that of both LORAN-C and OMEGA. LORAN-C offers the highest cost-effectiveness if navigation performance of less than 0.5 n. miles standard deviation is required.

Hengsbach, Gerd and Odoni, A.R.: Time Dependent Estimates of Delays and Delay Costs at Major Airports. Flight Transportation Laboratory Report, R75-4, Department of Aeronautics and Astronautics, MIT, January 1975.

Two queueing models appropriate for estimating time-dependent delays and delay costs at major airports are reviewed. The models use the demand and capacity profiles at any given airport as well as the number of runways there to compute bounds on queueing statistics. The bounds are obtained through the iterative solution of systems of equations describing the two models. This computational procedure is highly effective and inexpensive. The assumptions and limitations of the model are discussed.

Common characteristics and properties of delay profiles at major airports are illustrated through a detailed example. Potential applications to the exploration of the effect of air traffic control innovations on congestion and to the estimation of marginal delay costs are also described.

Hwoshinsky, Peter V.: Flight Test and Evaluation of Omega Navigation for General Aviation. Flight Transportation Laboratory Report, R75-5, Department of Aeronautics and Astronautics, MIT, June 1975 (also NASA CR-132677).

A 70-hour flight test program was accomplished to determine the suitability and accuracy of a low-cost Omega navigation receiver in a general-aviation aircraft. An analysis was made of signal availability in two widely-separated geographic areas. Comparison was made of the results of these flights with previous work focused on VOR/DME. Conclusions are drawn from the test experience that indicate developmental system improvement is necessary before a competent fail-safe or fail-soft navigation system is offered to general aviation. This report won the first annual student thesis competition for the Charles Jackson Prize offered by ARINC in 1976.

Kivestu, Peeter and Odoni, A.R.: A Handbook for the Estimation of Airside Delays at Major Airports (Quick Approximation Method). Flight Transportation Laboratory Report, R75-10, Department of Aeronautics and Astronautics, MIT, June 1976 (also NASA CR-2644)

The handbook contains a set of curves that allow estimation of the average number of total daily delay minutes at a major airport under a variety of conditions. Demand profiles at each airport are classified with respect to the number of daily peak periods, the percentage of daily flights during peak periods, and the number of peak period operations at the airport. When combined with the saturation capacity of the airport, these descriptions provide sufficient information to allow usage of the handbook.

Examples illustrating the use of the handbook are provided, as well as a brief review and description of the technical approach and of the computer package developed for this purpose.

Wischmeyer, C.E.: General Aviation Navigation in the National Airspace System. Flight Transportation Laboratory Report, R76-7, Department of Aeronautics and Astronautics, MIT, June 1976.

Based on flight test data and short-term noise measurements, mathematical models of Omega noise were developed. These allowed determination of the RMS error of differential Omega with variations in update rate, and consequently the path following errors using Omega. Various analytical models showed that differential Omega approaches could be flown with a standard deviation of less than 457 meters (1500 feet) in the presence of severe winds. The optimal time constants were of the order of 20 seconds.

Malherbe, Gerard: Modeling of Wind and Radar for Simulation in Four Dimensional Navigation Environments. Flight Transportation Laboratory Report, R76-8. Department of Aeronautics and Astronautics, MIT, September 1976.

Disturbances affecting time control precision in four-dimension navigation are modeled. Several models of wind and turbulence from the ground to 3048 meters (10,000 feet) are developed. A distinction is made between wind mean and turbulence and between the different layers of the troposphere. These models can be used for most cases of flight simulations. A selection of simple wind and radar models is made. Real-time computer programs using a mathematical model of a Boeing 707-320B are developed.

Dear, Roger G: The Dynamic Scheduling of Aircraft in the Near Terminal Area. Flight Transportation Report, R76-9, Department of Aeronautics and Astronautics, MIT, September 1976.

Aircraft arrive in a random fashion into a terminal area seeking to land at a given runway. The aircraft are differentiated by their landing velocities. All aircraft are required to maintain a prespecified minimum horizontal separation distance and also fly on a common final approach. As a consequence, the minimum interarrival time separation is interactive, i.e., a function of the landing velocities of the preceding and following aircraft as well as the separation minimum and final approach length.

The controller's decision-making problem in sequencing the aircraft, termed dynamic scheduling, is formulated in this dynamic environment. It is observed that the first-come, first-serve discipline is inefficient and the system properties employing optimality objectives of maximum throughput and minimum delay are investigated. The solutions must be updated with each new arrival and, as a result, the solutions employing these optimality objectives are shown to have undesirable properties, including 1) a priority structure with the potential for indefinite delay; 2) non-implementable updating assignments; 3) computationally-intractable solutions in real time.

As a consequence of this analysis, a decision methodology termed Constrained Position Shifting (CPS) is proposed to eliminate these undesirable properties. CPS prohibits an aircraft from being shifted more than a given number of positions from its first-come, first-serve position.

The CPS methodology is then shown via simulation to be practical, efficient and extremely flexible, with the following properties:

1. increases the runway throughput rate
2. treats individual aircraft equitably
3. treats aircraft velocity classes equitably
4. particularly successful during peak periods
5. well within the capabilities of today's computers.

The simulation is designed to compare identical arrival streams under various strategies. The simulation-aided analysis is then extended to include "heavy" jets (with aircraft-dependent separation minima) and also mixed operations (arrivals and departures). Even greater improvements in terminal area levels of service are demonstrated for these extensions.

(This report won the Dissertation Prize of the Transportation Science Section of the Operations Research Society of America, 1976.)

Francisco, Glen L.: A Study of Signal to Noise Ratio, Lane Counting, and Position Accuracy Using the Omega Navigation System. Flight Transportation Laboratory Report, R76-11, Department of Aeronautics and Astronautics, MIT, December 1976.

A 40-hour flight program was completed to study signal-to-noise ratio, lane counting and position accuracy using a low-cost Omega navigation system in a general aviation aircraft. Specific test objectives were developed to investigate signals both on the bench and in the air.

Signal-to-noise ratio and lane counting characteristics were investigated in a single frequency, uncorrected mode and in a pseudo-differential mode. It was learned that the received signal-to-noise ratio is highly correlated with lane counting characteristics and receiver navigability. The relationship between system accuracy and reliability was also examined.

The Omega navigation system's bias and position accuracy were investigated with the aid of the Discrete Address Beacon System (DABS). A circular probable error of 1067 meters (3500 feet) was observed.

It was also determined that certain necessary hardware and system improvements must be implemented before a completely usable Omega navigation system can be offered to the general aviation user.

Hsin, Cheng-Chung: An Analytical Study of Advanced Air Traffic Management and Control. Flight Transportation Laboratory Report, R76-13, Department of Aeronautics and Astronautics, MIT, September 1976.

This report gives a comprehensive study of the theory and practice of the advanced terminal area air traffic management and control. The entire terminal area ATM/C system has been formulated as a feedback control system, with individual subsystems identified and described. The ground control system, which is one of the two major control elements in the system, has been studied in detail. Definitions, purposes, input, output, and the processing steps of the control functions in the ground control system have been discussed. Automation of these functions has been recommended.

One of the control functions, namely, the path generation function, has been presented to demonstrate the automation implementation. Formulated as a two-point boundary values problem (TPBVP) of optimal control, solution techniques and numerical examples of the path generation problem have been presented. A Newton-Raphson method on trajectory optimization has been used to carry on the computer simulation. Finally, a one-degree-of-freedom, speed control final approach problem has been presented to demonstrate the application of parametric error analysis to ATM/C system performance evaluation.

(This dissertation won the third Charles Jackson Prize offered by ARINC in 1978.)

Durocher, Cort L.: Ground Controlled Precision Landing Delivery in the Presence of Radar Disturbances. Flight Transportation Laboratory Report, R77-2, Department of Aeronautics and Astronautics, MIT, May 1977.

This study examines the effect of radar disturbances on time-controlled precision landing delivery. A simulation was developed to model an aircraft on a Four-Dimensional Navigation terminal approach. During the flight, position information is estimated from noisy radar observations. Four radars were modeled and tested.

All experiments were conducted in a fixed-base cockpit simulator configured as a Boeing 707. Trained pilots flew a nominal approach following timed delivery commands from an initial approach fix to a final approach fix.

Three phases of testing were conducted to quantify the accuracy of a timed delivery algorithm with modifications in the flight commands. In all cases, the pilot was able to complete the approach safely. Time delivery was performed with great accuracy for all phases of testing. This was accomplished while keeping pilot workload at a low level.

Psaraftis, Harilaos N.: A Dynamic Programming Approach to the Aircraft Sequencing Problem. Flight Transportation Laboratory Report, R78-4, Department of Aeronautics and Astronautics, MIT, October 1978.

In this report, a number of Dynamic Programming algorithms for three versions of the Aircraft Sequencing problem are developed. In these, two alternative objectives are considered: How to land all of a prescribed set of airplanes as soon as possible, or alternatively, how to minimize the total passenger waiting time. All these three versions are "static", namely, no intermediate aircraft arrivals are accepted until our initial set of airplanes land. The versions examined are: a) the single runway-unconstrained case, b) the single runway-Constrained Position Shifting (CPS) case, and c) the two-runway-unconstrained case. In the unconstrained case, no priority considerations exist for the airplanes of our system. By contrast, CPS prohibits the shifting of any particular airplane by more than a prespecified number of positions (MPS) from its initial position in the queue. All three algorithms exploit the fact that the airplanes in our system can be classified into a relatively small number of distinct categories and thus realize drastic savings in computational effort, which is shown to be a polynomially bounded function of the number of airplanes per category. The CPS problem is formulated in version (b) in a recursive way, so that for any value of MPS, the computational effort remains polynomially bounded as described above.

All algorithms of this work are tested by various examples and the results are discussed. Implementation issues are considered and suggestions on how this work can be extended are made.

(This work won the annual Dissertation Prize of the Transportation Science Section of the Operations Research Society of America, 1978.)

Nordin, John P.: A Flexible Simulation Model of Airport Airside Operations. Ph.D. Thesis, Civil Engineering, MIT, September 1980.

A computer simulation model of landing and takeoff operations for multiple runways at a major airport is created which makes several contributions: a new method for describing the demands for service; a procedure for modeling landing operations as a function of exit locations; a realistic method of modeling aircraft separations; and a method to model changes in runway operating policies in response to weather and congestion. Numerous additional optional provisions in the design of the model and improved computational efficiency permit the analyst to quickly optimize airport operational strategies and airside geometries. The model was validated against operations at Logan Airport and results from other airside models.

Katz, Jeffrey G.: Pilot Workload in the Air Transport Environment: Measurement, Theory, and the Influence of Air Traffic Control. S.M. Thesis, Aeronautics and Astronautics, MIT, May 1980.

A multi-attribute, subjective assessment scale is presented as a method of gathering pilot ratings of workload in an air transport operational environment. It is copied from the Cooper-Harper Scale used to evaluate aircraft handling qualities where three major classes (Satisfactory, Acceptable, Unacceptable) are further subdivided into three ratings. A final class (Impossible) with a single rating makes a ten-point scale. The subject may be subsequently asked to explain his rating by selecting a level of workload on a five-point scale from three attributes of workload: Fraction of Time Busy; Mental Effort; Emotional Stress. Simulated IFR arrivals were flown in a fixed base B-707 simulator with eight subject pilots under varying ATC taskloads and turbulence levels. Consistent responses were obtained at low workload ratings, and subjects seemed receptive to using subjective assessment terminology.

USE OF LORAN-C FOR GENERAL AVIATION AIRCRAFT NAVIGATION

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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: air, ground, and antenna tests.

A Loran-C receiver was test-flown to evaluate 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 five different aircraft under various conditions.

As a part of the test program, 24 approaches to seven runways were flown to evaluate the capability of Loran-C to make non-precision approaches. Here, five 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 four 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 three types of E-field antennas. These were ADF (Automatic Direction Finding), vertical whip, and trailing wire antennas. All three types were evaluated in flight: the vertical whip and ADF antennas were also tested on the ground.

A complete description of the test program and results are presented in reference 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 (Table 1).

Qualitative and quantitative observations on the performance of Loran-C in aircraft were desired. The evaluation of Loran-C for both cross-country flights and non-precision approaches under simulated IFR (Instrument Flight Rules) conditions were of interest. 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.

3. EXPERIMENTAL PROCEDURE

The various tests carried out were divided into three 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 four hours of flight time. For these tests the aircraft was being tracked by the DABS (Discrete Address Beacon System) tracking radar at MIT's 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 1/2 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 uncorrected and corrected 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, seven survey points at three 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 three antenna configurations in flight. There 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 qualified in terms of SNR and relative signal strength.

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 (Table 2).

With a prior airport 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 problems with precipitation static were 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.

5. CONCLUSIONS

The various tests and their results led to the following conclusions:

1. Loran-C had the accuracy needed to meet FAA AC 90-45A accuracy specifications. The along- and cross-track errors were not significantly biased. Standard deviations were .09 nm along-track and .13 nm cross-track. The enroute cross-track flight technical error had a bias of -.18 nm and a standard deviation of .24 nm.

These test results can be compared to values obtained in the Vermont test flight program (ref. 2). Here, typical values for the standard deviation of Loran-C errors were .07 nm along-track and .08 nm cross-track. Enroute cross-track flight technical error had a standard deviation of .52 nm.

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 nm (2σ) along-track and .25 nm (2σ) cross-track. When corrections were used the approach accuracy improved significantly. Errors for this case were 91.44 m (300 ft) (2σ) along-track and 30.48 m (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's for the master and the X secondary. The W secondary had an SNR of -4.5 dB, the Y secondary -12 dB.

6. Grid stability makes a one-time airport correction feasible. Such corrections are in principle similar to altimeter settings.

If no corrections are used, there was typically a .5 nm (2σ) uncertainty in locating a single point. When a single correction for a 20 nm x 30 nm area was used, this uncertainty was reduced to .15 nm (2σ). With a correction for every test point, this uncertainty becomes typically 60.96 m (200 ft) (2σ).

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

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

REFERENCES

1. Natarajan, K., "Use of Loran-C for General Aviation Aircraft Navigation," MIT Master's Thesis, Department of Aeronautics and Astronautics, December 1980.

2. Polhemus, W.L., "Evaluation of Loran-C for Enroute Navigation and Non-Precision Approach Within the State of Vermont," Polhemus Associates Inc., for the Agency of Transportation, State of Vermont, March 1980.

TABLE 1.- FAA AC 90-45A ACCURACY SPECIFICATIONS

	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 2.- LORAN-C EQUIPMENT ERRORS

	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.

AN ANALYSIS OF THE ADAPTABILITY OF LORAN-C TO AIR NAVIGATION

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I. INTRODUCTION

With the advent of lower-cost receivers, Loran-C has become an attractive possibility as an air navigation system. The advantages of Loran-C are its high theoretic accuracy, large network of existing transmitters, and decreasing cost, combined with increasing quality in both the RF stages and digital hardware and software. These factors have led to a project dedicated to testing currently-available receivers to determine their suitability for further modification, eventually leading to a prototype Loran-based RNAV.

This work was dedicated to two objectives:

1. Identification of Loran errors, their point of entry into the system, and their elimination;
2. Development of a hardware and software test environment to implement objective 1 on a variety of commercially-available receivers.

Position errors can enter the system at several levels. There is a certain amount of warpage in the Loran hyperbolas due to variations in atmospheric conductivity. These variations are due to solar activity, daily or seasonal variations in the position of the ionosphere, and electrical properties of the atmosphere. A second class of error enters at the transmitter/receiver level. These errors involve factors such as antenna orientation effects, phase errors, ability of the receiver to accurately measure TD's, and saturation of RF stages due to excessive signal strength or onboard noise sources. A third type of error arises from the uncertainty associated with coordinate transformations, analog or digital filtering, and readout errors associated with the displays used to provide the information to the pilot. It is with these last two types of errors that most of this work has been concerned.

II. RESULTS

Figures 1-3 present flight test results for a modified Teledyne 711 receiver using the setup shown in Figure 4. The data is quite smooth except for two large errors in the upper left of the plot; these are due to software problems in the receiver and do not represent deviations in the raw Loran data. Transportation Systems Center, the group conducting the test, added some internal software to statistically remove bias errors in the Loran data. Malfunctions of this software caused the data jumps. Figure 1 is a radar track of the flight. DABSEF supplies a radar datum once every 4 seconds. To provide a larger number of points for statistical calculations, the radar data has been interpolated using the linear interpolation routines so that a radar fix is available once every second. On the plot, each data point visible represents one second of flight time. The next figure is an overlay plot of both the radar and Loran data. The Loran track is a lighter shade and is the outer track on the turns. As expected the receiver sensitivity to acceleration-induced error is evidenced by a lagging toward the outside of a turn.

Although only two test flights are discussed in this work, the data presented is consistent with the observed day-to-day performance of each receiver. The Teledyne 711 was accurate enough to warrant continued testing of Loran-C equipment for airborne navigation. These favorable test results have demonstrated that Loran-C is capable of providing a stable, repeatable position fix with sufficient accuracy for use in an airborne navigation system. This conclusion is supported by preliminary experience with the Northstar 6000. While the ratio of realized accuracy to theoretic accuracy of Loran-C is highly receiver-dependent, the actual performance of two commercial receivers, the Northstar and the Teledyne, has already approached the level of precision needed for general aviation aircraft.

REFERENCE

Littlefield, J., "An Analysis of the Adaptability of Loran-C to Air Navigation", Bachelor's Thesis, Aeronautics and Astronautics, MIT, May, 1980.

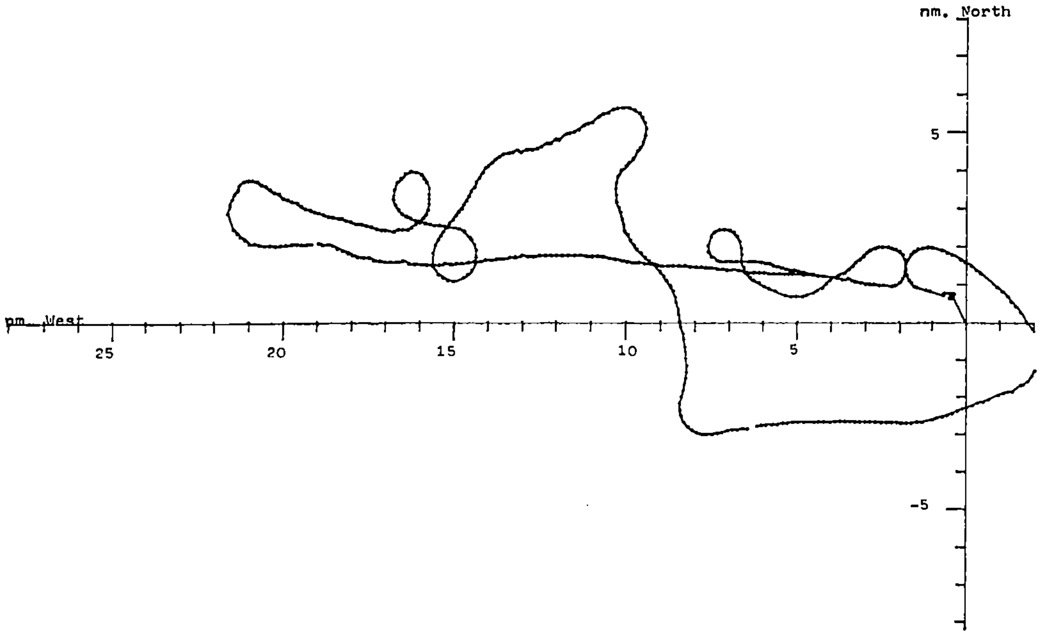


Figure 1.- Teledyne 711 flight of 9/20/79, Loran data plot. Radar track.

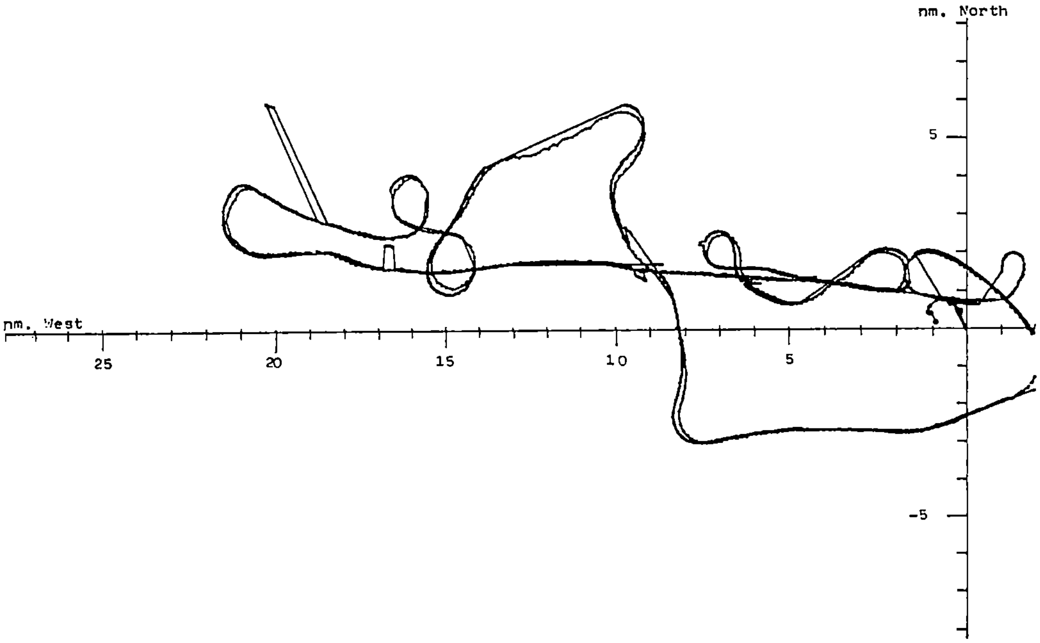


Figure 2.- Teledyne 711 flight of 9/20/79, radar data plot. Radar and Loran data.

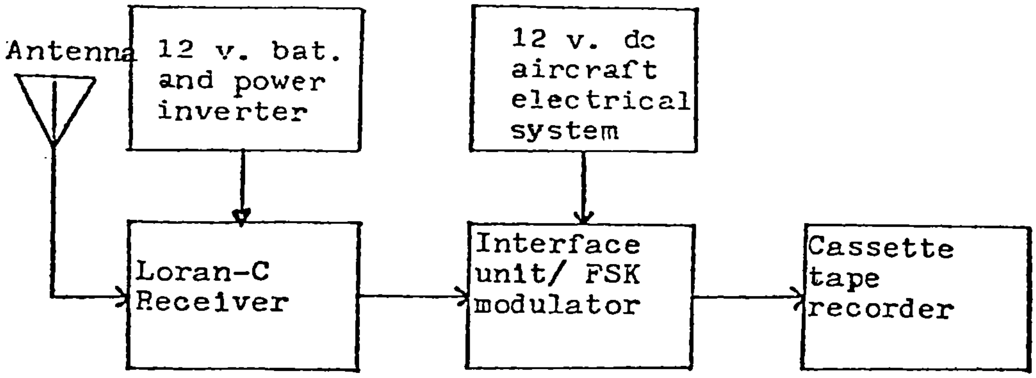
```
RUN


STAT1                01:48:00

THIS PROGRAM USES TWO SCRATCH FILES, SCRAT1.LST,SCRAT2.LST.
ENTER LORAN DATA FILE.
? L7LAC.DAT
ENTER RADAR DATA FILE.
? L7DAE1.DAT
ENTER TIME WHERE CALCULATION IS TO START.
? 403
MEAN E-W ERROR .0181376
MEAN N-S ERROR-.0278627
VARIANCE OF E-W ERROR IS     .0474749
VARIANCE OF N-S ERROR IS     .124491
STANDARD DEVIATION OF E-W ERROR IS         .217887
STANDARD DEVIATION OF N-S ERROR IS         .352832
MEAN SQUARE OF E-W ERROR IS  .0477753
MEAN SQUARE OF N-W ERROR IS  .125192
RMS E-W ERROR IS             .218576
RMS N-S ERROR IS             .353825
CROSS CORRELATION OF E-W AND N-S ERRORS IS-.0130942
CORRELATION COEFFICIENT OF E-W AND N-S ERRORS IS       -.170325

READY
```

Figure 3.- Statistics for 711 test flight.



AIRBORNE EQUIPMENT

HARDWARE BLOCK DIAGRAM

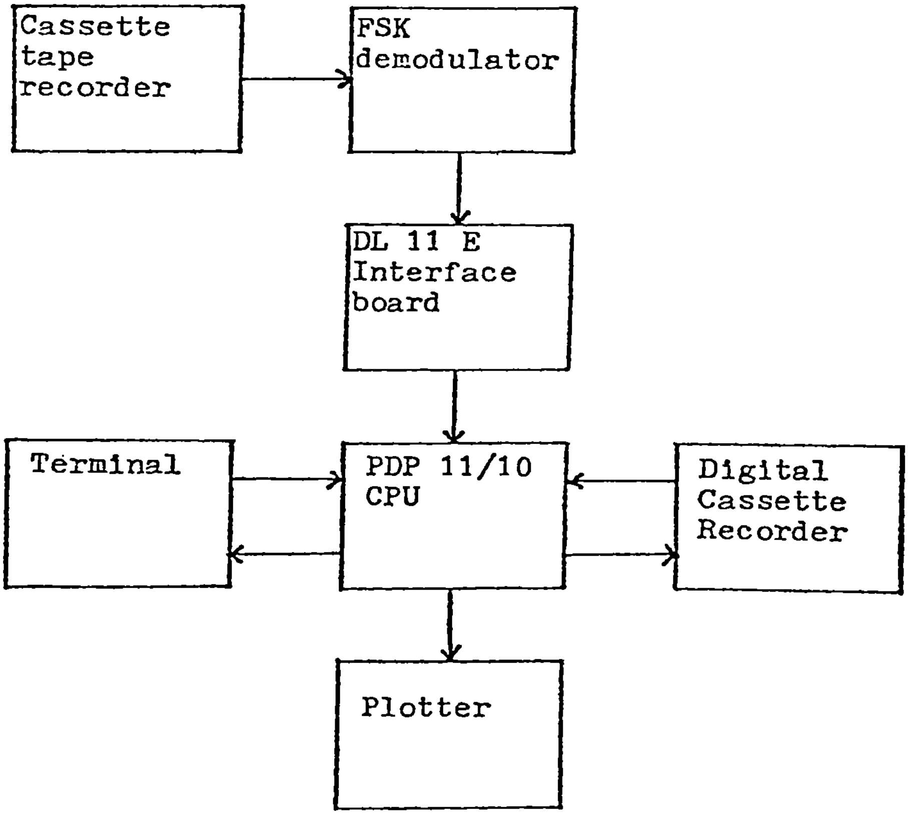


Figure 4.- Ground equipment.

TESTING OF LORAN-C FOR GENERAL AVIATION AIRCRAFT

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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 figure 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.

Figure 1.- AC 90-45A accuracy specifications.

FIGURE 1 SHOWS THE ACCURACY REQUIRED FOR LORAN-C CERTIFICATION UNDER FAA AC 90-45A ACCURACY SPECIFICATIONS. THE REQUIREMENTS ARE EXPRESSED IN 2σ LIMITS FOR ALL PHASES OF FLIGHT.

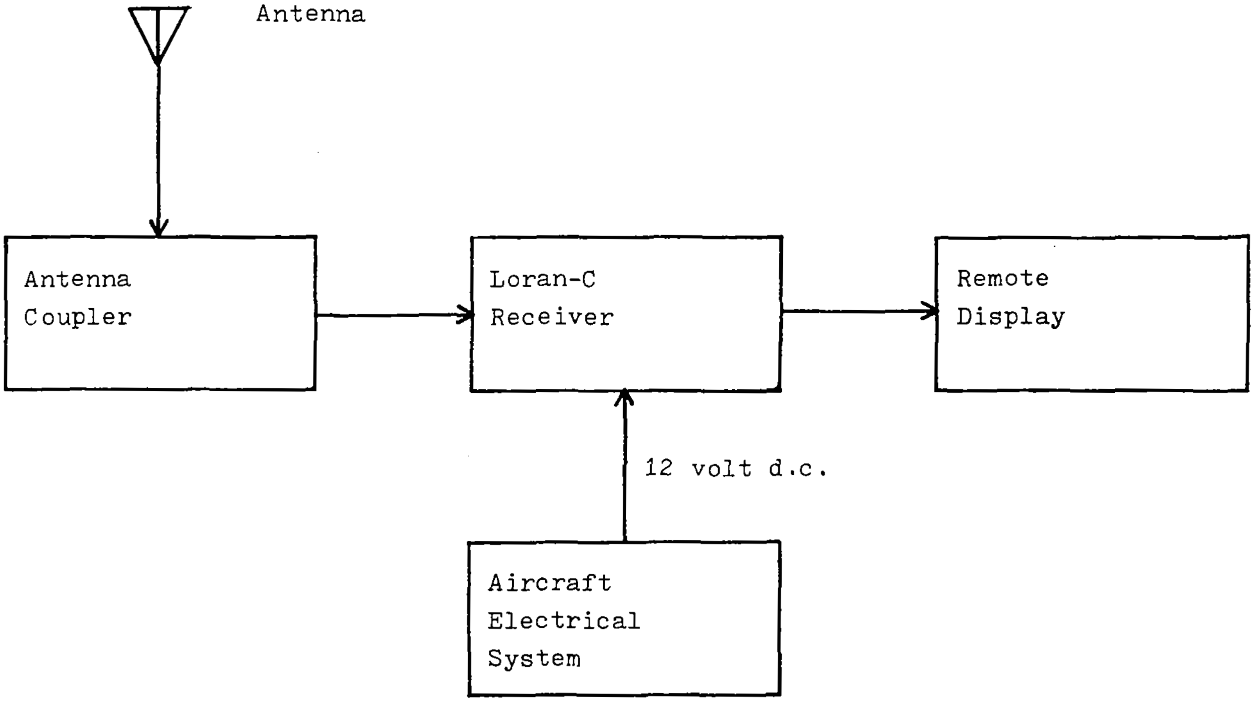


Figure 2.- Airborne equipment for accuracy tests.

FIGURE 2 SHOWS THE EQUIPMENT SETUP USED FOR THE ACCURACY AND OTHER TESTS. THIS SETUP CONSISTED OF SEVERAL COMPONENT PARTS.

FIRST OF ALL, THE ANTENNA USED WAS CONNECTED TO THE COUPLER. THE COUPLER WAS IN TURN CONNECTED TO THE LORAN-C RECEIVER. POWER FOR THE RECEIVER CAME FROM THE AIRCRAFT ELECTRICAL SYSTEM. A REMOTE DISPLAY WAS USED FOR PART OF THE FLIGHT TESTS.

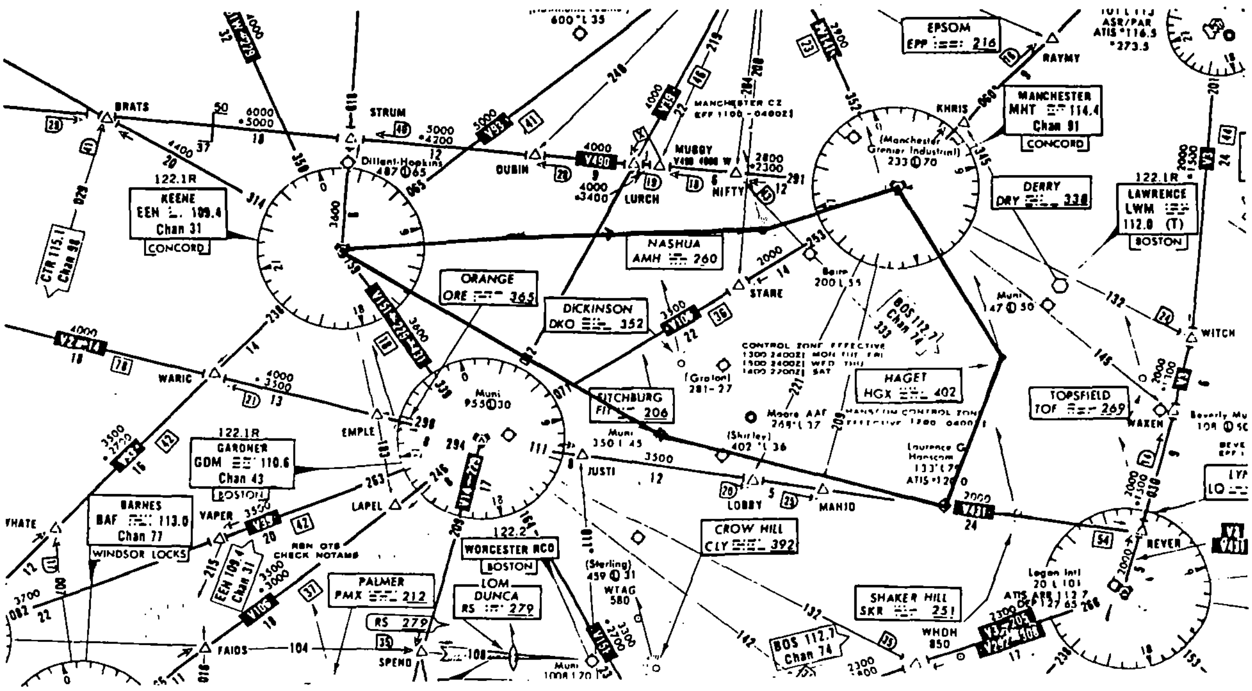


Figure 3.- Flight profile for accuracy tests.

THE FLIGHT PROFILE USED FOR THE ACCURACY TEST FLIGHTS IS SHOWN HERE. EACH LOOP OR CIRCUIT WAS FLOWN FOUR TIMES IN A COUNTERCLOCKWISE DIRECTION.

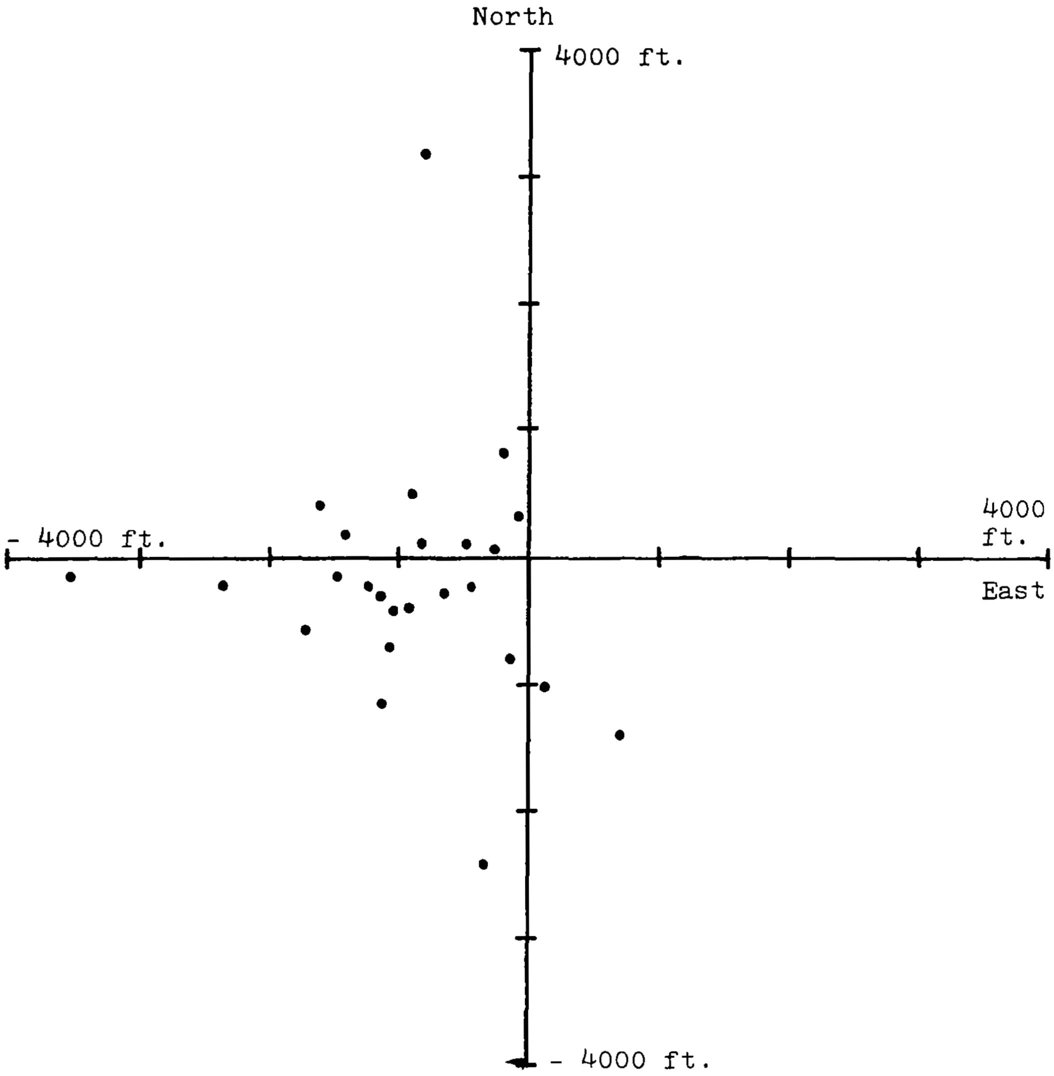


Figure 4.- Loran-C error plot. 1 ft. = 0.3048 m.

FIGURE 4 IS THE LORAN-C ERROR PLOT. LORAN-C ERRORS INCLUDE ANY TIME-SYNCHRONIZATION ERRORS. THE ORIGIN REPRESENTS THE ACTUAL AIRCRAFT POSITION. EACH DOT SHOWS THE LOCATION OF THE LORAN-C FIX RELATIVE TO THE AIRCRAFT POSITION. A NORTH-SOUTH AND EAST-WEST COORDINATE SYSTEM WAS USED.

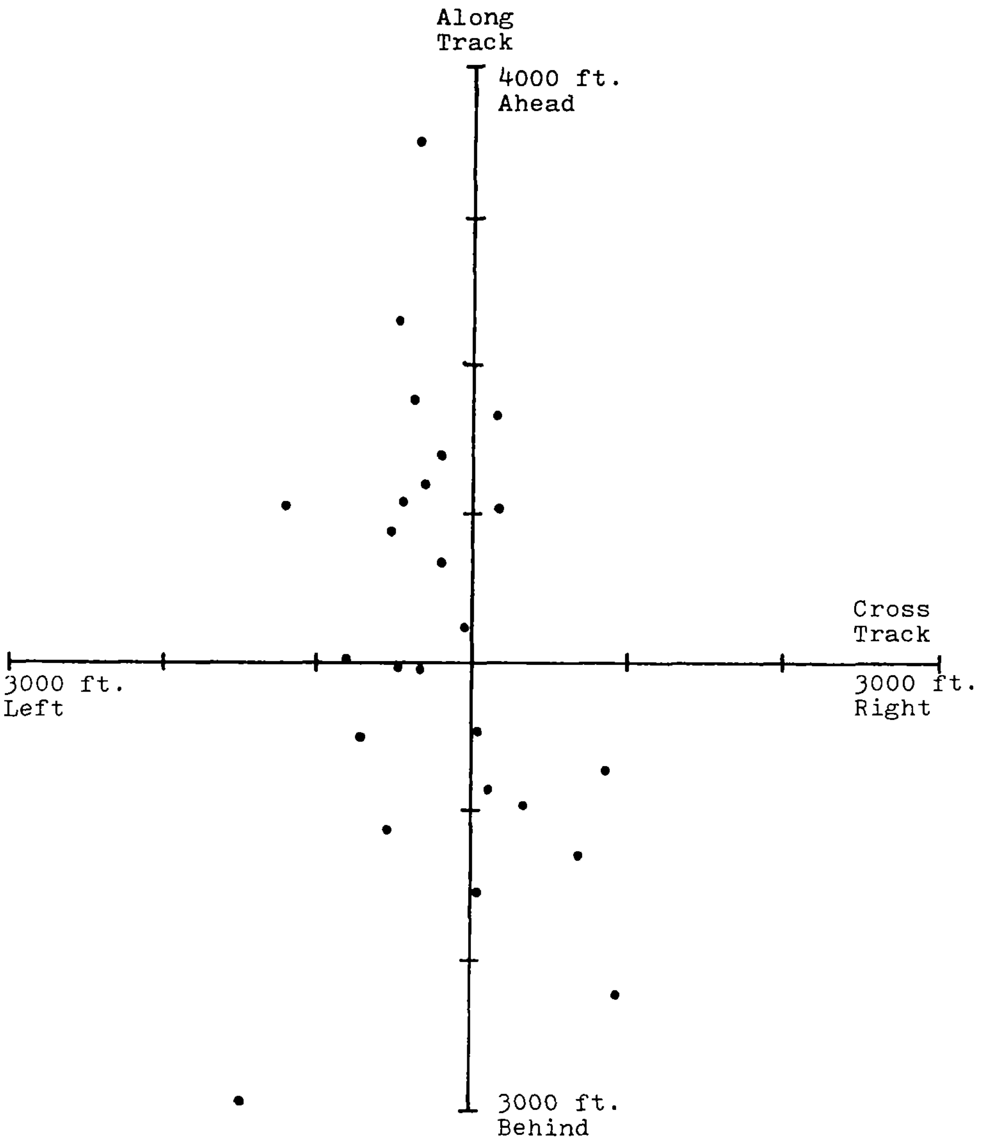


Figure 5.- Along and cross track error plot. 1 ft. = 0.3048 m.

FIGURE 5 SHOWS THE LORAN-C ERRORS OF FIGURE 4 IN ALONG- AND ACROSS-TRACK COORDINATES. AS BEFORE, THE ORIGIN REPRESENTS THE ACTUAL AIRCRAFT LOCATION. EACH DOT IS THE LORAN-C FIX RELATIVE TO THE ACTUAL AIRCRAFT LOCATION.

	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.

Figure 6.- Error statistics for flight test results.

This figure shows the Loran-C equipment error statistics. These statistics are corrected for any time-synchronization error. comparison with figure 1 shows that Loran-C meets FAA AC 90-45A accuracy specifications for all phases of flight.

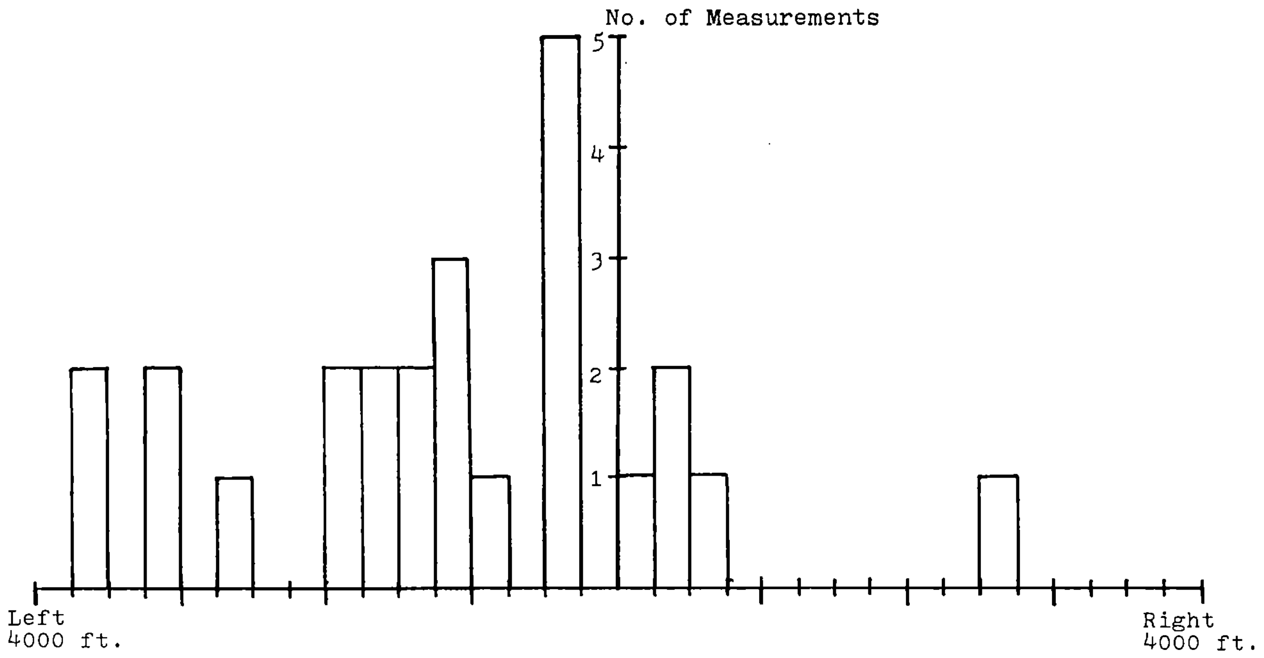
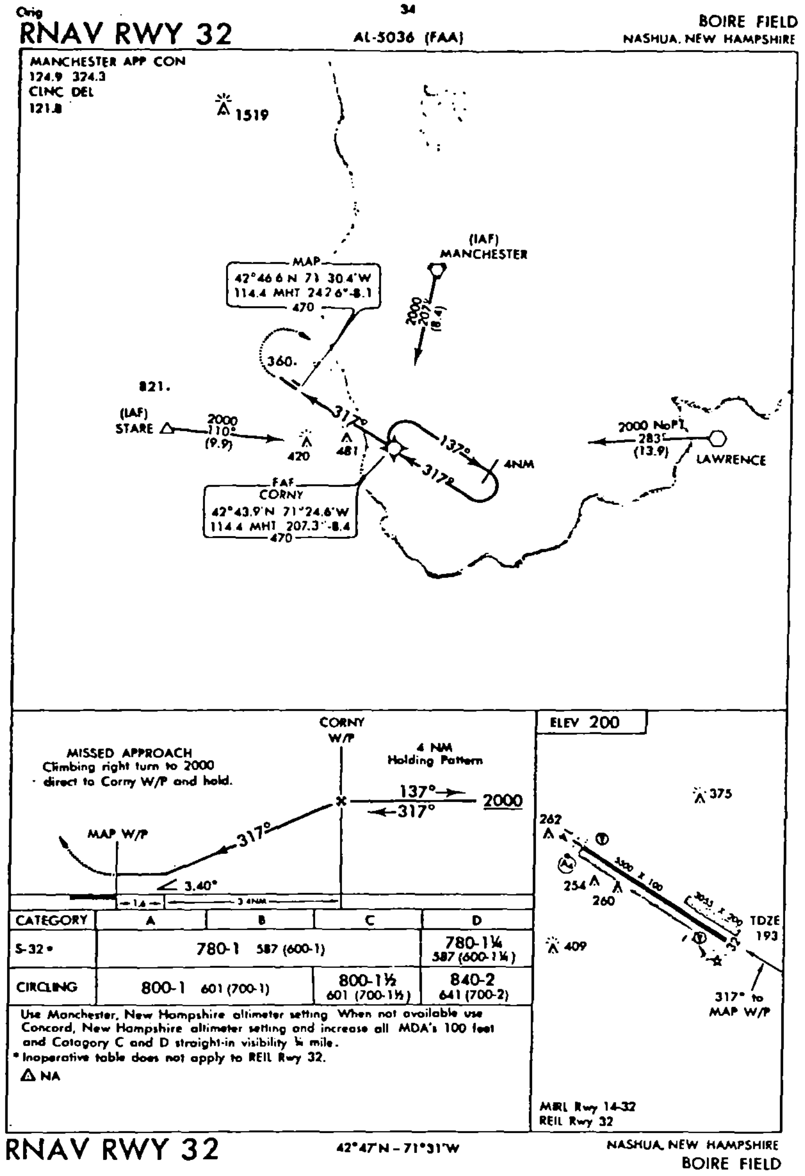


Figure 7.- Cross track flight technical error plot. 1 ft. = 0.3048 m.

FIGURE 7 SHOWS THE DISTRIBUTION OF THE CROSS TRACK FLIGHT TECHNICAL ERROR. THE CENTER OF THE HORIZONTAL AXIS REPRESENTS THE WAYPOINT LOCATION. THE CROSS TRACK FLIGHT TECHNICAL ERROR IS THE LEAST DISTANCE BETWEEN THE WAYPOINT AND THE AIRCRAFT GROUND TRACK.



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 8.- Boire runway 32 approach plate.

THIS FIGURE SHOWS A TYPICAL APPROACH PLATE USED IN THE APPROACH TESTS. THIS IS A STANDARD RNAV APPROACH TO A LOCAL AIRFIELD.

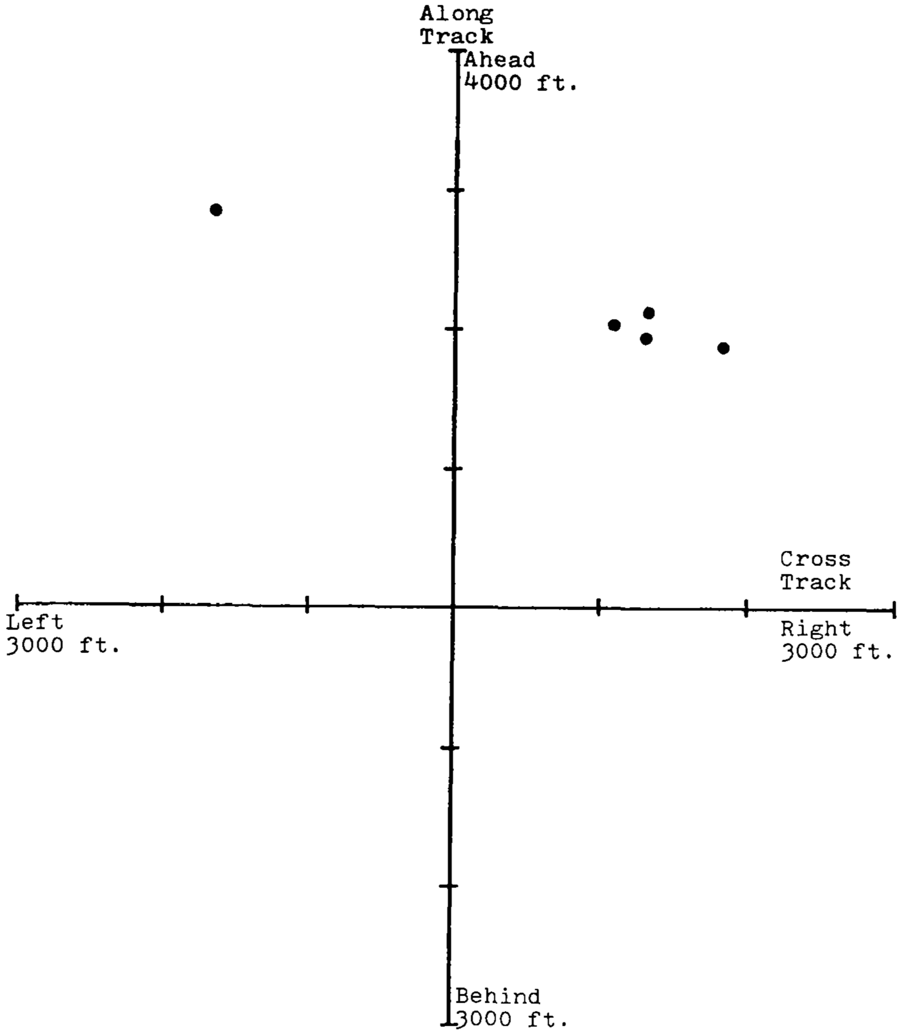


Figure 9.- Along and cross track errors with uncorrected coordinates. 1 ft = 0.3048 m.

THIS SHOWS THE RESULTS OF THE FIRST PART OF THE APPROACH TESTS. HERE APPROACHES WERE FLOWN USING PUBLISHED COORDINATES WITHOUT ANY CORRECTION. THE ORIGIN IS THE RUNWAY MISSED APPROACH POINT. EACH OF THE FIVE DOTS SHOWS THE POINT OF ARRIVAL WHEN USING LORAN-C DERIVED GUIDANCE INFORMATION.

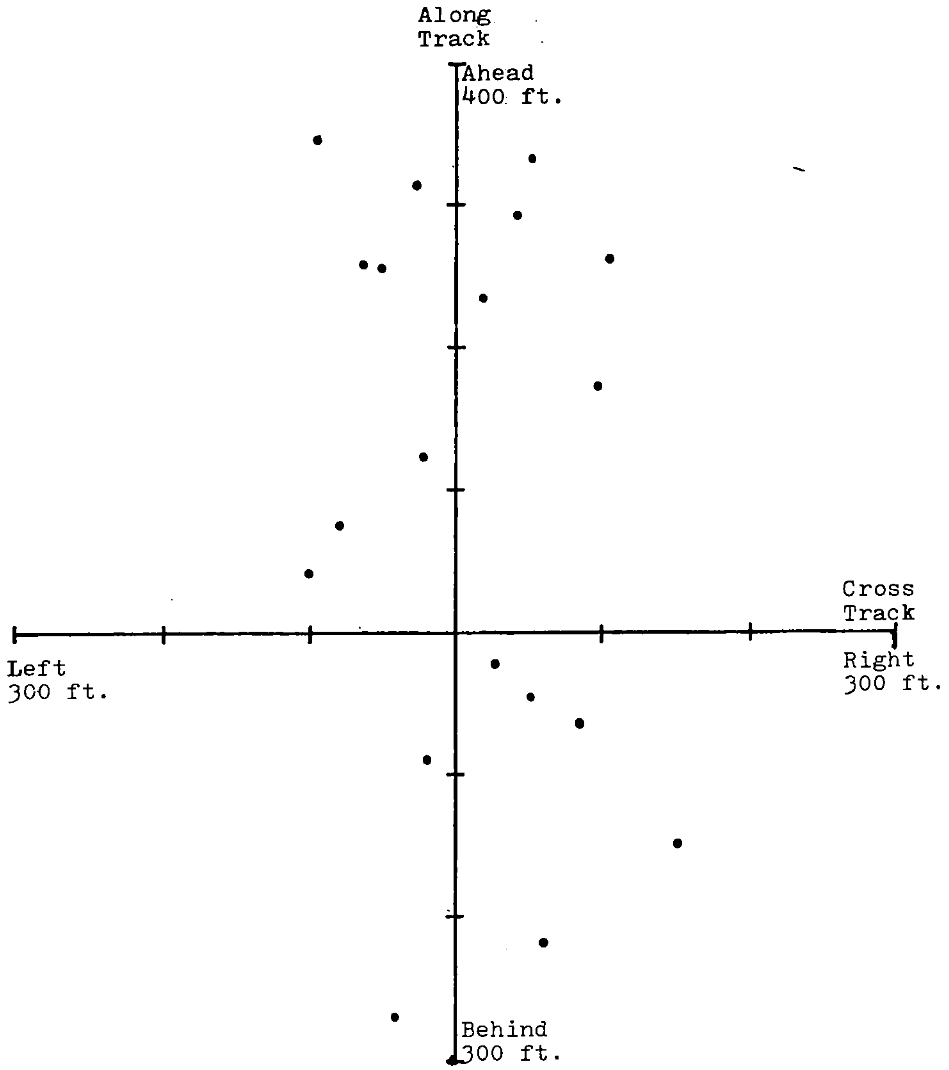


Figure 10.- Along and cross track errors with corrected coordinates. 1 ft. = 0.3048 m.

FIGURE 10 SHOWS THE APPROACH TEST RESULTS WHEN CORRECTED COORDINATES WERE USED. HERE, APPROACHES WERE FLOWN USING PREVIOUSLY MEASURED LORAN-C COORDINATES OF THE RUNWAY MISSED APPROACH POINT. AS IN FIGURE 9, THE ORIGIN IS THE RUNWAY MISSED APPROACH POINT. THE DOTS SHOW THE APPROACH ACCURACY ACHIEVED FOR EACH OF 19 APPROACHES.

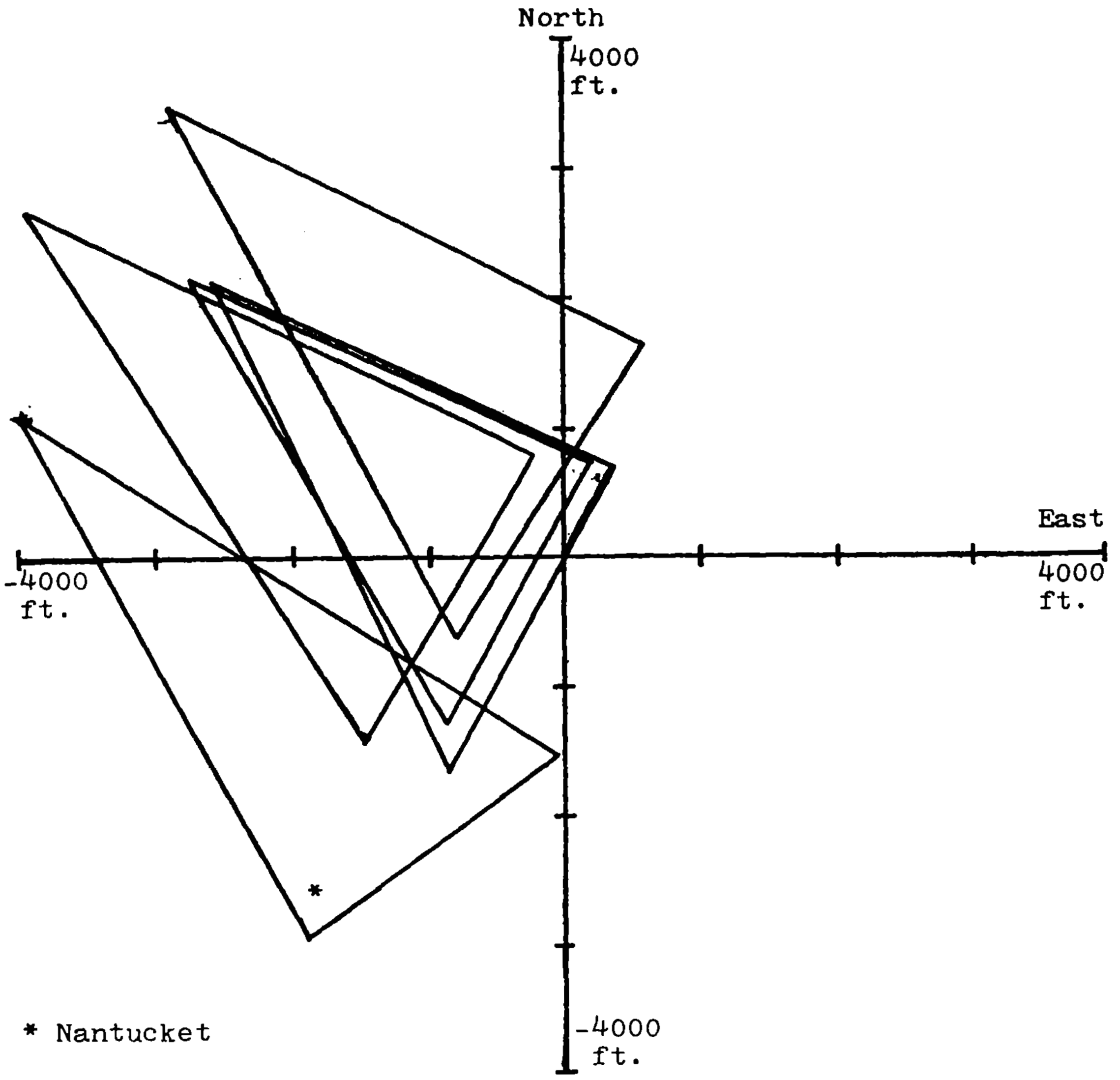


Figure 11.- Position corrections without calibration. 1 ft. = 0.3048 m.

FIGURE 11 SHOWS THE EXPECTED LORAN-C ACCURACY WHEN NO CALIBRATION IS USED. THE ORIGIN IS THE REFERENCE POINT FOR THE AIRPORT USED FOR THESE TESTS. EACH OF THE COCKED HATS SHOWN PICTORIALLY REPRESENTS THE CONFIDENCE WITH WHICH LORAN-C CAN BE USED TO DETERMINE POSITION.

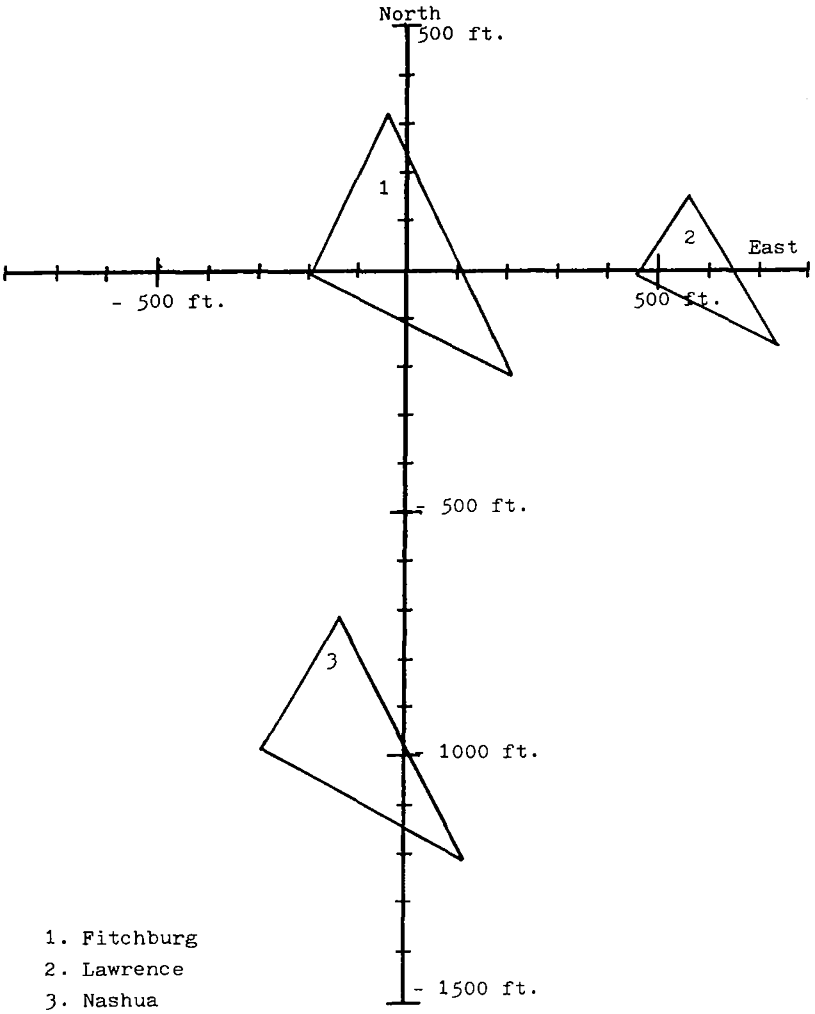


Figure 12.- Position corrections with calibration.
1 ft. = 0.3048 m.

Figure 12 is very similar to figure 11 except that calibration is used here. Here, a single calibration point was used for a 20 x 30 mm area. As before, the origin is the location of the airport reference point. The cocked hats again pictorially show the accuracy of Loran-C. It is seen that the use of a single calibration point improves accuracy by an order of magnitude.

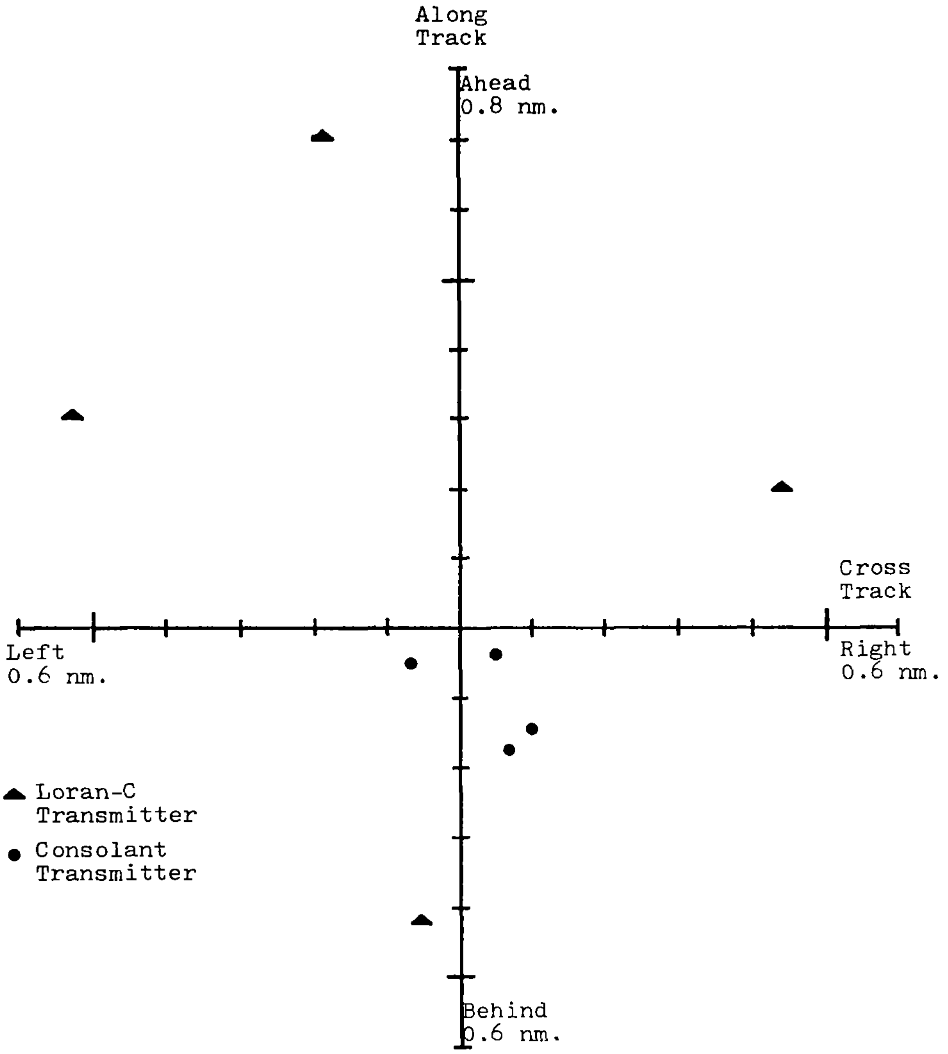
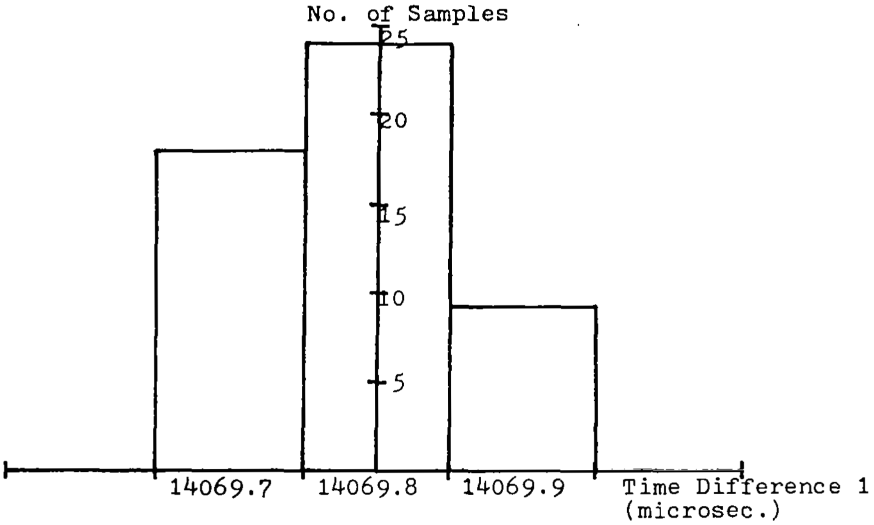


Figure 13.- Transmitter proximity test results.

THIS FIGURE SHOWS THE ACCURACY OBTAINED NEAR A LORAN-C TRANSMITTER. THE ORIGIN IS THE ACTUAL AIRCRAFT LOCATION. LORAN-C ERROR IS SHOWN RELATIVE TO THE ORGIN IN ALONG- AND ACROSS-TRACK COORDINATES. TWO LOCATIONS WERE USED FOR THESE ACCURACY TESTS. ONE WAS THE LORAN-C TRANSMITTER; THE OTHER, THE NANTUCKET CONSOLANT TRANSMITTER.



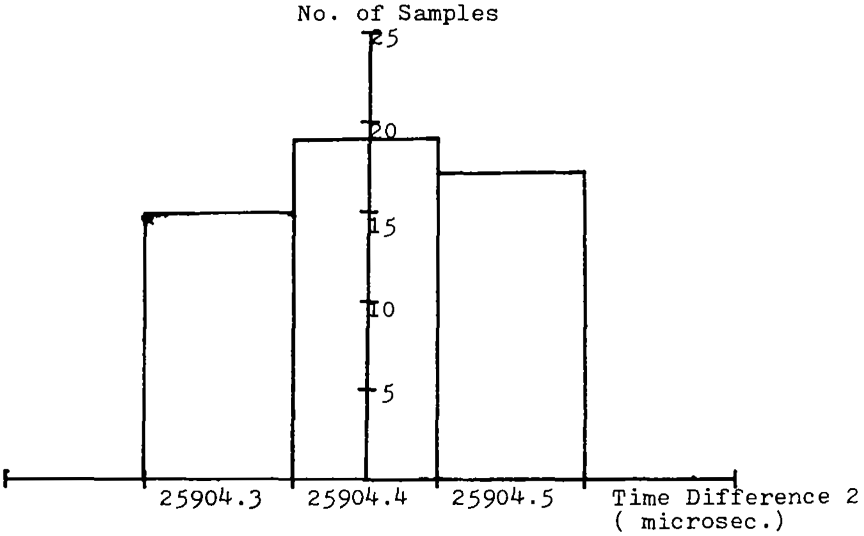


Figure 14.- Grid stability test results - part 1.

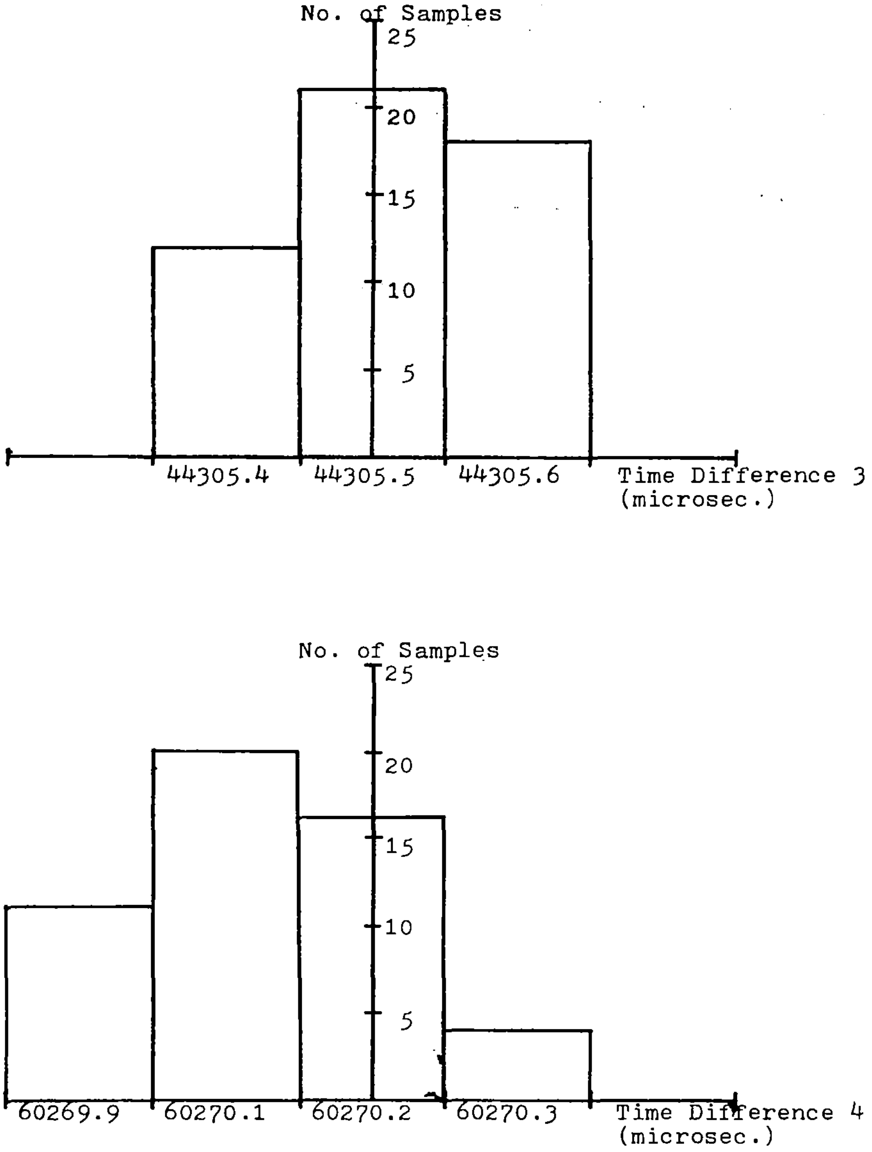


Figure 15.- Grid stability test results - part 2.

FIGURES 14 AND 15 SHOW THE LONG-TERM STABILITY OF THE LORAN-C GRID. EACH TIME DIFFERENCE WAS MEASURED 51 TIMES BETWEEN APRIL AND OCTOBER 1980. HISTOGRAMS OF THE TIME DIFFERENCE DISTRIBUTIONS SHOW ONLY A MAXIMUM 0.4 MICROSECOND PEAK-TO-PEAK TIME DIFFERENCE VARIATION.

FAA CONCERNS

1. Define minimum Loran-C receiver.
2. Notams service for Loran-C.
3. Routing airways around transmitters.
4. Station outages.
5. Primary and secondary triad for approach.
6. P-static problem.
7. Power line carrier interference.
8. Check for cycle slip before final approach.
9. Selection of alternate airport after Loran-C failure.
10. GRI change procedure.

THE P/POD PROJECT:
PROGRAMMABLE/PILOT ORIENTED DISPLAY

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P-POD PROGRAM OBJECTIVES

- USE MICROPROCESSORS/ADVANCED DISPLAYS IN GA AIRCRAFT TO REDUCE WORKLOAD IN SPIF ENVIRONMENT
- EMPHASIS WILL BE PLACED ON THE FLIGHT PROCEDURAL ASPECTS (HOW DO WE USE LORAN DATA)
- UTILIZE PROVEN LOW-COST HARDWARE/SOFTWARE TO REDUCE DEVELOPMENT COSTS
- PARALLEL DEVELOPMENT AND TESTING ON THE GROUND (SIMULATOR) AND IN THE AIR USING SAME HARDWARE
- PROGRESSIVE SOPHISTICATION

FIGURE 1

P-POD OPERATING ENVIRONMENT

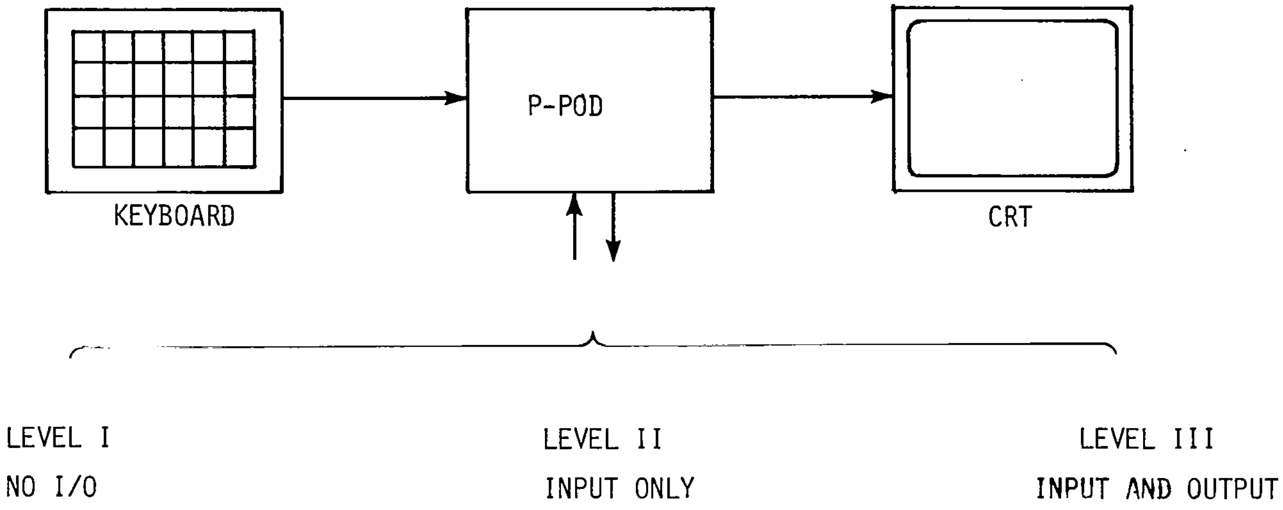

FIGURE 2

FIGURE 2 IS A BASIC (HARDWARE/SOFTWARE) BLOCK DIAGRAM. PILOT INPUT IS THROUGH THE KEY BOARD. THE P-POD UNIT ISSUES PROMPTS AND RESPONDS TO PILOT INQUIRY VIA THE CRT. ALSO ILLUSTRATED ARE THE THREE LEVELS OF SOFTWARE -- I/O SOPHISTICATION. THESE LEVELS ARE DETAILED IN FIGURES 3, 4, 5.

P-POD FUNCTIONAL CHARACTERISTICS - LEVEL I

1. REAL TIME CLOCK/PACER FUNCTIONS
   a) DELIVER PILOT PROMPTS ON A PRESET SCHEDULE DURING CRITICAL FLIGHT PHASES

2. TAKEOFF/LANDING, EMERGENCY CHECKLISTS
   a) AUTOMATIC CHECKLIST DISPLAY/VERIFY

3. STORAGE OF INFORMATION PERTAINING TO FLIGHT CONDITIONS OR DESTINATION (APPROACH PLATES)
   a) INFORMATION AVAILABLE AT OPERATOR REQUEST
   b) INFORMATION DISPLAYED AT SCHEDULED TIME

4. FLIGHT COMPUTER FUNCTIONS
   a) CRUISE PERFORMANCE TABLES, TAKEOFF DISTANCE, ETC.
   b) FLIGHT PLANNING COMPUTATIONS (FUEL CONSUMPTION, WIND CORRECTION, WEIGHT AND BALANCE COMPUTATIONS)

FIGURE 3

LEVEL I IS THE SIMPLEST P-POD CONFIGURATION. IN THE LEVEL I CONFIGURATION, P-POD WILL BE USED TO TEST METHODS OF WORKLOAD REDUCTION WHICH DO NOT INVOLVE EITHER P-POD OUTPUT TO THE AIRCRAFT OR INPUT FROM THE AIRCRAFT TO P-POD. ALL COMMUNICATION IS BETWEEN PILOT AND P-POD. AIRBORNE TESTING OF LEVEL I P-POD WILL NOT REQUIRE ANY MODIFICATION OF THE TEST PLANE.

P-POD FUNCTIONAL CHARACTERISTICS - LEVEL II

1. NAVIGATION
   - a) VOR, VOR/DME, LORAN-C, OTHER INTERFACE CAPABILITY
     - 1) P-POD AUTO-SELECTS FROM SEVERAL AVAILABLE NAVIGATION DATA SOURCES
     - 2) COORDINATE TRANSFORMATION AND DISPLAY FORMAT
   - b) MULTIPLE WAYPOINT STORAGE -- AUTOMATIC SWITCHOVER WHEN WAYPOINT IS REACHED
   - c) VARIABLE DISPLAY FORMAT
     - 1) MOVING MAP DISPLAY
     - 2) NORTH UP
     - 3) EXPANDED SCALE

2. FLIGHT STATUS WARNING
   - a) ENGINE/ELECTRONICS
   - b) AIRCRAFT CONFIGURATION
   - c) AIRSPEED, STALL
   - d) ALTITUDE ADVISORY
   - e) P-POD SYSTEM FAULT DETECTION

3. OTHER FUNCTIONS
   - a) KALMAN FILTERING OF NAVIGATION DATA
   - b) FUEL CALCULATIONS
   - c) DABS MESSAGE DISPLAY, WEATHER DATA
   - d) ENHANCED ILS DISPLAY MODES

FIGURE 4

LEVEL II REPRESENTS A STEP UP IN SYSTEM COMPLEXITY. IN ADDITION TO THE PILOT/ P-POD DATA LINK, LEVEL II P-POD WILL BE DIRECTLY COUPLED TO THE AIRCRAFT. THE LEVEL II CONFIGURATION ALLOWS P-POD TO MONITOR A NUMBER OF PARAMETERS AND INFORM THE PILOT OF ANY RELEVANT DATA VIA THE VIDEO MONITORS.

P-POD FUNCTIONAL CHARACTERISTICS - LEVEL III

1. P-POD - AUTOPILOT LINK FOR AUTOMATIC COURSE FOLLOWING

2. DOWN LINK MESSAGES VIA DABS

3. AVIONICS FREQUENCY/MODE CONTROL

FIGURE 5

LEVEL III, THE MOST SOPHISTICATED MODE, ALLOWS P-POD TO BOTH MONITOR AIRCRAFT STATUS AND EFFECT CHANGES IN THAT STATUS. THE LEVEL III CONFIGURATION EMPLOYS TWO-WAY DATA LINKS BETWEEN P-POD, PILOT, AND AIRCRAFT. BOTH LEVEL II AND LEVEL III P-POD CONFIGURATIONS REQUIRE EXTENSIVE INTERFACING BETWEEN P-POD I/O PORTS AND ON-BOARD TRANSDUCERS.

P-POD HARDWARE RESOURCES

1. PROCESSORS -- 2 Z-80s OPERATING AT 4 MHz

2. RAM -- 64K AVAILABLE TO FREE PROCESSOR
   -- 32K DEDICATED TO VIDEO PROCESSOR

3. ROM -- 4K DEDICATED TO VIDEO PROCESSOR
   32K ACCESSIBLE TO FREE PROCESSOR

4. ADDITIONAL FEATURES
   a) EPROM PROGRAMMING CAPABILITY BUILT IN
   b) LIGHT PEN INTERFACE TO VIDEO BOARD
   c) DISK CONTROLLER CAPABLE OF ADDRESSING TWO 8" FLOPPY DISKS OR AN INTELLIGENCE HARD DISK
   d) COMPOSITE OR DIRECT-DRIVE VIDEO OUTPUT
   e) EXPANSION SLOTS FOR TWO MORE S-100 BOARDS (PROTO-BOARD, HIGH-SPEED ARITHMETIC UNIT)

FIGURE 6

FIGURE 6 IS AN OUTLINE OF THE HARDWARE RESOURCES. IN ADDITION, SEVERAL PIECES OF MANUFACTURER-WRITTEN SOFTWARE ARE INCLUDED. COMPLETE VIDEO MONITOR SOFTWARE AND A 30-COMMAND GRAPHICS LANGUAGE ARE INCLUDED IN THE VIDEO BOARD PACKAGE.

P-POD PROJECT: ADDITIONAL CONSIDERATIONS

1. HARDWARE WILL SUPPORT CP/M 2.2 OPERATING SYSTEM
2. A HIGH-LEVEL LANGUAGE (PL/1) WILL BE USED FOR SOFTWARE DEVELOPMENT
3. P-POD WILL BE CONFIGURED TO OPERATE AIRBORNE OR WITH THE PDP-11/10 SIMULATOR
4. P-POD HARDWARE/SOFTWARE CONTAINS THE BASIC ELEMENTS OF A MICROPROCESSOR DEVELOPMENT SYSTEM

FIGURE 7

FEATURES MENTIONED IN FIGURE 7 WILL TRANSLATE TO SIGNIFICANTLY REDUCED COSTS INVOLVED IN DEVELOPMENT/RECONFIGURATION OF THE P-POD SYSTEM.

Ohio University

INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY
AT OHIO UNIVERSITY, 1980

Professor Richard H. McFarland

Avionics Engineering Center
Department of Electrical Engineering
Ohio University
Athens, Ohio 45701

INTRODUCTORY REMARKS

During the calendar year 1980 the Joint University Program underway at Ohio University progressed well. Emphasis is now being placed on moving from the radio frequency processors technology to the processing of navigation information and making it available to the general aviation cockpit. Much effort in the past several years has been devoted to obtaining the best signal from Omega and Loran in spite of heavy noise contamination in those VLF and LF bands.

With the RF signal processing reasonably well in hand the major attention has been given to extracting the best navigational data from these signals and demonstrating this principally through digital processing of the Loran-C signal information. It is exciting work due in a large part because the results can be quantified and assessed rather objectively. The program effort has not only dealt with the theory for improved processing but has allowed the opportunity for computer simulation, fabrication of hardware and flight measurements with good references to allow thorough determination of the quality of engineering results.

At the completion of the last calendar year the timing was such that several reports were issued which are not included in this CY 1980 but they serve as very valuable background and are listed in the bibliography.

Two major report contributions were made during this year. These are a doctoral dissertation on digital phase-locked loops as applied to navigation receivers such as Omega, and completion of the analysis of the first flight test of the Ohio University Loran-C receiver in comparison with the DABS radar. Specifically:

Digital Phase-Locked Loops

The Digital Phase-Locked Loop (DPLL) work begun four years ago was completed by Paul R. Blasche with his research paper being accepted as a doctoral dissertation by the Department of Electrical Engineering in March of 1980. This work presents a rigorous error analysis of digital hardware that can be directly applied to Omega receiver processor designs. The DPLL hardware techniques can also be applied to other navigation processors such as VLF and possibly Loran-C. Dr. Blasche now has a position with the Charles Stark Draper Laboratories working on related processors for the NAVSTAR satellite navigation system. His dissertation has been reproduced as OU NASA TM 75 and contains 119 pages with 45 illustrations. A brief summary follows:

Specific configurations of first and second order all digital phase-locked loops were analyzed for both ideal and additive gaussian noise inputs. In addition, a design for a hardware digital phase-locked loop capable of either first or second order operation was presented along with appropriate experimental data obtained from testing of the hardware loop. All parameters chosen for the analysis and the design of the digital phase-locked loop were consistent with an application to an Omega navigation receiver although neither the analysis nor the design are limited to this application. For all cases tested, the experimental data showed close agreement with the analytical results indicating that the Markov chain model for first and second order DPLL's are valid.

Ideal inputs were considered for both first and second order DPLL's with the objective of classifying the time response of the loops. For both loops it was found that the phase error response was given by a non-linear difference equation for which no direct solution was found. However, partial response characteristics of phase error were determined for both first and second order DPLL's when the frequency of the input signal is identical to that of the loop's quiescent frequency. Also, expressions for the frequency range for which a second order DPLL can achieve phase lock in minimum time were derived. In both cases it was found that the frequency range was directly dependent upon the number of distinct phase states of the reference clock. As would be expected, it was found that the frequency range for which a second order DPLL will achieve phase lock, even with the constraint of minimum time to lock, is significantly greater than the frequency range over which a first order DPLL will achieve phase lock.

Specific first and second order DPLL's were also analyzed for stochastic inputs by means of a Markov chain model. From this Markov chain model, the steady state phase error and mean transient response were determined. The loop configurations used for the noise analysis were specifically chosen to both match the general loop model and to be realized in hardware by standard binary logic families. For both first and second order loops it was found that the usual tradeoff between steady state error and transient response existed. That is, the steady state error can be decreased only with the cost of a longer transient response and the transient response can be decreased only with an increase in steady state error.

For the data presented several specific points are worth noting. First, in comparing the transient response of the first and second order DPLL it is found that the first order DPLL will achieve phase lock in less expected time than the second order DPLL for initial phase offsets less than approximately $\pi/8$. Also, for a second order DPLL, the steady state phase error degrades rapidly as the signal-to-noise ratio decreases below 0.0 dB. Thus for an application such as an Omega receiver, if the initial phase error as the received signal is gated on is expected to be small then a first order DPLL will perform in a superior manner over a second order DPLL. However, if the signal-to-noise ratio can be expected to be in excess of 0.0 dB and the initial phase error is unknown then the second order DPLL will give superior performance.

Completion of the goals of this paper also points to areas in which further research would be of use. In particular, for the case of an ideal input, it would be of great utility if the determination of the phase error response characteristics were extended to include the case of frequency offsets. This extension would then allow the determination of time required to lock for an initial frequency offset without the necessity of performing a simulation. For the case of stochastic inputs, further research on several points is recommended. First, concepts presented should be extended to determine pertinent statistics on loop cycle-slippage. Secondly, it would be useful to develop a comparison of the DPLL's transient response to the standard loop bandwidth used to characterize APLL's (analog phase-locked loops). Finally, because of the transient response/steady state error tradeoff previously mentioned, research into adaptive loops could provide an optimum relationship between these two parameters.

Loran-C Versus DABS Test Results

Reports on the data analysis software and the final results of the first Loran-C flight test conducted in June 1979 with the DABS radar at Lincoln Labs were completed. The data show a very well-behaved consistency but an offset due to a signal amplitude problem previously mentioned. The preliminary conclusion is that quarter-mile precision is a feasible goal with a simplified receiver which depends mostly on envelope processing hardware and software methods for Loran-C, if a somewhat improved RF front-end can be achieved. (OU NASA TM72, TM74)

Other work accomplished during this period is as follows:

OU Loran-C Receiver Errors

A report on the analysis of systematic errors due to the RF front-end processor used in the first model of the Ohio University design of digital envelope processor for Loran-C was completed (OU NASA TM 73). The results showed a signal amplitude error effect. An improved model of the receiver front-end was designed during the year to cure this problem. This revised receiver is still being evaluated.

Loop Antennas for Airborne Loran-C

Work on experimental designs of loop antennas for Loran-C was completed during the year with the conclusion that many new and novel antenna systems might be applied to Loran-C receivers, but that the complexity of the receiver processor is inherently increased, making such designs less cost-effective from the standpoint of a simplified Loran-C navigation system for general aviation users. However, for some special uses such as in reducing precipitation static and for low-profile antennas, magnetic field loop antennas may be worthwhile in the future. Loop antenna systems are also very useful in ground-based measurement systems for locating interference to Loran-C and other VLF navigation systems. No further work is planned for loop antennas at the present time. (OU NASA TM71)

Software-Based Data and Navigation Processor for Loran-C

A new area of work was started this year aimed at an all-software system for simplified Loran-C airborne receivers which would accomplish both the sensor processing and navigation processing using microprocessor-based hardware, instead of random-logic digital hardware and hybrid analog-digital loop methods. An experimental prototype of a software-based sensor for Loran-C was test flown with mixed results on the second DABS test flight of September 1980. The results of this work are still being analyzed and the DABS data from the test flight has not yet been received in usable form from Lincoln Labs. A number of problems in the aircraft power systems, having nothing to do with the software processor, resulted in interference to the Loran-C processing results. Post flight analysis also detected a software error, which has now been corrected. Ongoing experiments are presently being conducted to help solve this problem. The expectation is that a software sensor processor combined with direct navigation readout will eventually be less costly and of greater utility and precision than previous digital or hybrid analog-digital sensors tested.

The locked-loop software design for this sensor follows past work accomplished under the Joint University Program while emphasizing Omega navigation receiver design (OU NASA TM47, 49, 75, 19, 15). The loop operates as a Memory-Aided Phase-Locked Loop (MAPLL), commutated among available Loran-C stations. The only user action required is Loran-C chain selection at receiver power-up. The software, in its present form, searches for available master and slave stations at the specified GRI, tracks each station and produces time-difference outputs at one-second intervals.

Present effort is concentrated on optimization of loop parameters for best signal-to-noise improvement, insuring appropriate operation at typical general aviation velocities, and determination whether second-order loop operation will be required. The preliminary results of this work have been presented at the NASA quarterly meetings held at MIT, Princeton, and Ohio University during the past year, and some of the ongoing work is presented in this compilation.

Active Antennas for VLF and Loran-C

A continuing effort over the past 5 years at Ohio University has been a concern for developing relatively simple E-field antenna systems usable for Omega, VLF, or Loran-C navigation receivers. At each quarterly meeting during this period some new form of active antenna and preamplifier system has been presented. There are a great many possible alternative circuits which can be devised for this purpose. The aim of the work has been to obtain a very good experimental understanding of the details of short antenna systems used for these low-frequency signals. The most recent example presented is a multiple-use circuit board which can be configured to operate either as a wide band VLF thru HF antenna preamplifier, as a low-pass amplifier for Omega-Loran-C E-field sensing, as a tuned circuit H-field loop antenna system for narrowband signal reception, or as a low-pass Omega thru Loran-C loop antenna preamplifier. Data on the sensitivity, signal-to-noise ratios, intermodulation distortion, and usable gain is being collected in a number of ground-based antenna installations for later presentation on the general state-of-the-art in active VLF-HF antenna systems.

Inquiry Listings

The technical memoranda and published results prepared by the Avionics Engineering Center of Ohio University on the NASA sponsored work here has resulted in a number of inquiries from industry, government, and individuals for more information and copies of the reports. The project has established a catalog listing with annotated bibliography which is sent to interested persons and a nominal copying charge for mailing complete copies of reports requested. During 1980 requests were received from Saudi Arabia, France, Quebec, Alaska, Hong Kong and a great many from California where work is being considered for microprocessor-based navigation systems. The average number of inquiries has been at a rate of about 40 per year during the past three years on both the Omega and Loran-C navigation receiver accomplishments.

The reports referred to as OU NASA TMXX in the papers and in the annotated bibliography are the work of Ohio University. Although this work was sponsored by NASA, these TM's are not to be confused with the NASA TM series of reports which are represented by five digit numbers (NASA TM-XXXXX). The OU NASA TM's may be obtained from Ohio University.

ANNOTATED BIBLIOGRAPHY

1 SIMULTANEOUS PAIR OMEGA RECEIVER, Ralph W. Burhans, August 4, 1972.

A new concept of OMEGA receiver operation is presented. The simultaneous comparison of 13.6 and 10.2 KHz in a single time slot results in 3.4 KHz, 10.2 KHz, and phantom 40.8 KHz difference pair lanes. Direct lane count without intermediate storage or sequential feedback loops is possible. Small boat receivers using low cost recorders such as a Rustrak might be possible at $300 market prices. Completely digital readout devices for general aviation use could become $500 instruments. Even with restricted lane pair use this could provide low cost navigation aids for over half of the U.S.A. and all of the coastal areas including most of the Great Lakes.

2 SIMPLE BAND PASS FILTERS, Ralph W. Burhans, December 28, 1972.

A single power source operational amplifier provides tunable-high Q band pass resonators of possible utility for OMEGA VLF receiver input processors and other audio frequency applications.

3 LOW BIT SINE WAVE APPROXIMATIONS FOR AUDIO SIGNAL SOURCES, Ralph W. Burhans, January, 1973.

Special purpose sine wave sources are easily obtained using digital counting-decoder-filter methods with second harmonic distortion less than 1%. Good frequency stability and reasonable variety in choice of output frequency results when the input clock signal is derived from a crystal oscillator through programmable divider chains. The resulting sine wave output would be suitable for applications such as the 90 and 150 Hz modulation frequencies of ILS transmitters, as well as other limited range audio frequency use.

4 SIMPLIFIED OMEGA RECEIVERS, Ralph W. Burhans, March, 1974.

Circuit details are presented for a low cost OMEGA receiver being developed for general aviation use. Some novel processing methods, not used in commercial systems, have been demonstrated in experimental bench processors. An airborne model is being designed.

5 BINARY PHASE LOCK LOOPS FOR SIMPLIFIED OMEGA RECEIVERS, Ralph W. Burhans, March, 1974.

A sampled binary phase lock loop is proposed for periodically correcting OMEGA receiver internal clocks. The circuit is particularly simple to implement and provides a means of generating long range 3.4 KHz difference frequency lanes from simultaneous pair measurements.

6 PHASE LOCK LOOP SYNTHESIZER FOR OMEGA REFERENCE FREQUENCIES, Kent A. Chamberlin, April, 1974.

An OMEGA reference frequency of 4080 KHz is provided by a single loop VCXO circuit driven from an atomic clock or stable crystal standard. The circuit is used to provide OMEGA frequencies for direct ranging, differential correction monitoring, or as a laboratory source for calibrating OMEGA receivers.

7 SIMULTANEOUS MASTER-SLAVE OMEGA PAIRS, Ralph W. Burhans, April, 1974.

Master-Slave sequence ordering of the OMEGA system is suggested as a method of improving the pair geometry for low cost receiver user benefit. The sequence change will not affect present sophisticated processor users other than require new labels for some pair combinations, but may require worldwide transmitter operators to slightly alter their long range synchronizing techniques.

8 SELECTED BIBLIOGRAPHY OF OMEGA, VLF and LF TECHNIQUES APPLIED TO AIRCRAFT NAVIGATION SYSTEMS, NASA Project Staff, August, 1974.

A bibliography of references collected during the first three years of the NASA Tri-University Program in Air Transportation Systems.

9 LOW-COST OMEGA NAVIGATION RECEIVER, Robert W. Lilley, October, 1974.

The status of Ohio University's efforts toward specifying a low-cost Omega receiver is reviewed, at the onset of the fourth-year program under the NASA Tri-University Program in Air Transportation Systems.

10 BINARY PROCESSING CONCEPTS FOR OMEGA RECEIVERS, Robert W. Lilley, November, 1974.

Preprint of paper presented at the Second Omega Symposium, sponsored by the Institute of Navigation, Washington, D. C., November 7, 1974.

11 THE MEMORY-AIDED DIGITAL PHASE-LOCKED LOOP, Kent A. Chamberlin, November, 1974.

Preprint of paper presented at the Second Omega Symposium, sponsored by the Institute of Navigation, Washington, D. C., November 7, 1974.

12 OMEGA FLIGHT-TEST DATA REDUCTION SEQUENCE, Robert W. Lilley, November, 1974.

A series of FORTRAN computer programs for preparation and summary of flight-test data obtained from the Ohio University Omega Receiver.

13 FLIGHT EVALUATION: OHIO UNIVERSITY OMEGA RECEIVER BASE, Kent A. Chamberlin, R. W. Lilley, and Richard J. Salter, November, 1974.

A description is given of the data-collection flight, round-trip from Athens, Ohio to Langley Field, Virginia, during which Omega data was collected on machine-readable media for use in the Tri-University Program in Air Transportation.

14 COMPUTER PROGRAM CORDET, R. A. Palkovic, November, 1974.

A simulation tool is described for use in the design and analysis of digital phase-locked loops, with specific application to the DPLL in the Ohio University Omega receiver base.

15 A SIMULATION ANALYSIS OF PHASE PROCESSING CIRCUITRY IN THE OHIO UNIVERSITY OMEGA RECEIVER PROTOTYPE, R. A. Palkovic, June, 1975. (NASA CR-132707) (Master's Thesis)

A first-order digital phase-lock loop is modeled on the computer. Loop response to signal phase in noise is evaluated. Optimum integration time is determined. Phase jitter in a frequency synthesizer used as the local oscillator is quantified, and design is optimized. Design rules for use of synchronous rate multipliers are presented. Overall system response is discussed.

16 GANGED SERIES POTENTIOMETER MIXER NETWORKS, Ralph W. Burhans, December, 1974.

A ganged potentiometer with a single linear section and two opposite log tapered sections is rediscovered for providing a simple series resistor control element for mixing of audio frequency signals. An application is for bench evaluation of detector signal to noise ratios with Omega receivers.

17 COMMON ANTENNA PREAMPLIFIER-ISOLATOR FOR VLF-LF RECEIVERS, Ralph W. Burhans, July, 1975.

An improved high impedance preamplifier circuit provides outputs to drive an Omega-VLF receiver and an ADF-LF receiver from a common antenna such as the ADF sense antenna on general aviation aircraft. The preamplifier has been evaluated with fixed ground station receivers and is anticipated for use in the second generation prototype Ohio University, Omega receiver design.

18 LOW COST, HIGH-PERFORMANCE, VLF RECEIVER FRONT-END, Ralph W. Burhans, September, 1975.

A VLF receiver front-end has been designed using standard linear integrated circuits. The basic methods have been evaluated extensively on the Omega 10.2 KHz channel but are readily adaptable to any other VLF frequency in the 10.2 KHz to 20 KHz region. Applications for the modules exist in position location, time-frequency measurements, and signal propagation. The set provides control gates, zero crossing signals, and analog outputs to interface with any type of digital logic, microprocessor, or analog signal processor.

19 DIGITAL CORRELATION DETECTOR FOR LOW-COST OMEGA NAVIGATION, Kent A. Chamberlin, February, 1976.
(NASA CR-144956) (Master's Thesis)

This report describes the background information on the research that led to the development of the memory-aided phase-locked loop (MAPLL) which is an all-digital correlation device that is capable of determining the phase of extremely noisy fixed-frequency signals. This design is of special interest for Omega or other phase sensitive VLF navigation purposes since it is relatively inexpensive, maintenance-free, and can operate in a time-multiplexed fashion.

20 THE MINI-O, A DIGITAL SUPERHET, OR A TRULY LOW-COST OMEGA NAVIGATION RECEIVER, Ralph W. Burhans, November, 1975.
(NASA CR-144923)

A quartz tuning fork filter circuit and some unique CMOS clock logic methods provide a very simple OMEGA-VLF receiver with true hyperbolic station pair phase difference outputs. An experimental system has been implemented on a single battery-operated circuit board requiring only an external antenna preamplifier, and LOP output recorder. A bench evaluation and preliminary navigation tests indicate the technique is viable and can provide very low-cost OMEGA measurement systems. The method is promising for marine use with small boats in the present form, but might be implemented in conjunction with digital microprocessors for airborne navigation aids.

21 FLIGHT TEST OF 4-HZ AND 30-HZ OMEGA RECEIVER FRONT-END
Lee Wright, February 1976.

A test flight in a DC-3 aircraft was conducted to evaluate the performance of a 4-Hz ultra-narrowband, Omega receiver front-end compared to a more conventional 30-Hz bandwidth receiver. Results indicate that the 4-Hz front-end has superior signal-to-noise performance. Other interesting results obtained during the test flight were recordings of the sunset noise effects on amplitude, and the attenuation of signal levels when flying through clouds.

22 POSSIBLE METHODS FOR USSR-VLF NAVIGATION RECEIVERS
Ralph W. Burhans, March 1976.

A brief study of the USSR-VLF navigation system indicates that very low-cost digital techniques might be applied to receiver systems. The transmitted signal format is of interest for application to other VLF systems in the future. Some possible circuits for simplified receiver processors are presented.

23 A PROPOSED MICROCOMPUTER IMPLEMENTATION OF AN OMEGA NAVIGATION PROCESSOR, John D. Abel, March 1976.

Documentation of current status of research pertaining to a microprocessor-based Omega navigation processor to be used in conjunction with the Ohio University Avionics Engineering Center Omega sensor processor is presented.

24 IMPROVEMENTS FOR OMEGA RF PREAMPLIFIERS, Lee Wright, April 1976.

An Omega preamplifier with no phase shift over the ADF band but with bandpass filtering and gain at the Omega-VLF band has been designed, built, and tested. This is expected to be useful principally in planned work at MIT and Princeton involving the use of the Ohio University Omega Sensor Processor Receiver.

25 NARROW BAND BINARY PHASE LOCKED LOOPS, R.W. Burhans, April 1976.

Very high Q digital filtering circuits for audio frequencies in the range of 1 Hz to 15 KHz are implemented in simple CMOS hardware using a binary local reference clock frequency. The circuits have application to VLF navigation receivers and other narrow band audio range tracking problems.

26 SIMULATION ANALYSIS OF A MICROCOMPUTER-BASED, LOW-COST OMEGA NAVIGATION SYSTEM, Robert W. Lilley, Richard J. Salter, Jr., May, 1976.

Preprint of paper presented at the Bicentennial National Symposium of the Institute of Navigation, Warminster, Pennsylvania, April 28, 1976.

27 AUTOMATIC NOISE LIMITER-BLANKER, R. W. Burhans, May, 1976.

Modifications of an audio noise limiter circuit, used in WW II era radio communications receivers, provides a noise limiter-blanker for narrow bandwidth low-level audio signals. The method has been evaluated for noise blanking with OMEGA-VLF navigation receivers but is adaptable to more general audio frequency processing systems.

28 SMALL-AIRCRAFT FLIGHT EVALUATION OF RUSTRAK CHART RECORDER, Richard J. Salter, Jr. and Robert W. Lilley, May 1976.

In support of the NASA Omega Prototype Receiver project, three short flight evaluations of the RUSTRAK chart recorder were flown.

29 DIGITAL TIME SLOT DISPLAY FOR OMEGA RECEIVER, Ralph E. Smith, July, 1976.

Variations of circuits to display the Omega sequence letters A through H have been designed, breadboarded, and tested. One of these is suggested as an alternative station display method for the Ohio University Omega sensor processor systems.

30 LOW-COST MECHANICAL FILTERS FOR OMEGA RECEIVERS, R. W. Burhans, June, 1976.

A set of mechanical filter assemblies has been obtained for possible use in the RF front-end of an OMEGA navigation receiver. The resonators provide very narrow bandwidth performance with good skirt selectivity in a simple two-stage circuit. It is recommended that these filters be used in a complete receiver system for long-term evaluation on reception of low-level OMEGA signals.

31 A MEMORY-MAPPED OUTPUT INTERFACE: OMEGA NAVIGATION OUTPUT DATA FROM THE JOLT(TM) MICROCOMPUTER, R.W. Lilley, August, 1976.

A hardware interface which allows both digital and analog data output from the JOLT microcomputer is described in context of the Ohio University software-based Omega Navigation Receiver.

32 A MICROPROCESSOR INTERFACE FOR THE OHIO UNIVERSITY PROTOTYPE OMEGA NAVIGATION RECEIVER, R. W. Lilley, August, 1976.

A hardware interface is described which allows a microcomputer to obtain data and interrupt signals from the Ohio University Omega Receiver Prototype.

33 TEST PROGRAM FOR 4-K MEMORY CARD, JOLT MICROPROCESSOR, R. W. Lilley, August, 1976.

A memory test program is described for use with the JOLT microcomputer memory board used in development of the Ohio University Omega navigation receiver.

34 A MICROCOMPUTER-BASED LOW-COST OMEGA NAVIGATION SYSTEM, R. W. Lilley, R.J. Salter, Jr., August, 1976.

Preprint of paper presented at the First Annual Meeting, International Omega Association, Arlington, Virginia, July 27-29, 1976.

35 MINI-O, SIMPLE OMEGA RECEIVER HARDWARE FOR USER EDUCATION, R.W. Burhans, August, 1976.

Preprint of paper presented at the First Annual Meeting, International Omega Association, Arlington, Virginia, July 27-29, 1976.

36 OPERATING INSTRUCTIONS: KENNEDY TEST FIXTURE, Donald P. Seyler, September, 1976

A unit for testing the integrity of data and control circuits of the Kennedy 1600/360 Incremental Tape Recorders is described.

37 OPERATING INSTRUCTIONS: MEMODYNE/KENNEDY INTERFACE UNIT, Donald P. Seyler, January 1977.

A unit for transcribing incremental data from magnetic cassette tapes to magnetic reel-to-reel tapes is described. This includes integral testing for validity of data.

38 KIM-1 INTERFACE ADAPTER TO 3-WIRE TELETYPE SYSTEMS, R. W. Burhans, August, 1976

This brief technical note has been submitted to the KIM-1 microcomputer group publication, KIM User Notes. It is of interest to others who have 3-wire ASR-33 teletype systems in using microcomputer hardware with the Ohio University Prototype Omega Sensor Receivers.

39 OMEGA DISTRIBUTION AMPLIFIER WITH FOUR CHANNEL INDEPENDENT LEVEL CONTROL, Donald P. Seyler, September, 1976

A portable unit for distributing a single small signal source to a maximum of four loads, with independent source level control for each load, is described.

40 MEASURING CLOCK OFFSETS FOR MINI-O WITH KIM-1, R. W. Burhans, September, 1976

The previous MINI-O Omega receiver system required adjustment of the local clock to a low offset for proper operation. Single station tracking loop software provides an easy way of determining the offset prior to experimental navigation tests. A second order software tracking loop is suggested to eliminate the local clock error problem.

41-Mod 1 IMPROVED ANALOG OUTPUT CIRCUITS FOR OHIO UNIVERSITY PROTOTYPE OMEGA NAVIGATION RECEIVERS, Lee Wright, October, 1976.

A minor hardware change is described which provides a more accurate analog output from the Ohio University Omega Prototype Receivers.

42 DIURNAL MEASUREMENTS WITH PROTOTYPE CMOS OMEGA RECEIVERS, R. W. Burhans, November, 1976.

The Ohio University Prototype CMOS Omega Sensor Processor is capable of receiving all eight Omega channels on 10.2 KHz. Diurnal recordings of selected station pairs made during the period October-November 1976, demonstrate the receiver performance and illustrate limitations for navigation using diurnal corrections.

43 DEMONSTRATION PROGRAM FOR OMEGA RECEIVER PROTOTYPE MICROCOMPUTER DATA PROCESSING, R.W. Lilley, November, 1976.

Using the prototype Omega receiver developed for the NASA Joint University Program plus a digital interface to a commercial microcomputer, a software routine to demonstrate receiver operation is described.

44 AN ASSEMBLER FOR THE MOS TECHNOLOGY 6502 MICROPROCESSOR AS IMPLEMENTED IN JOLT (TM) AND KIM-1 (TM), Robert W. Lilley, November 1976.

The 6502 Assembler implemented at Ohio University for support of microprocessor program development in the Tri-University Program is described.

45 INTERACTIVE OMEGA PROPAGATION CORRECTIONS, Robert W. Lilley, January 1977.

An implementation of Coast Guard computer programs for Omega propagation corrections is described.

46 ANALYSIS OF A FIRST ORDER PHASE LOCKED LOOP IN THE PRESENCE OF GAUSSIAN NOISE, Paul R. Blasche, March, 1977

A first-order digital phase locked loop is analyzed by application of a Markov chain model. Steady-state loop error probabilities, phase standard deviation and mean loop transient times are determined for various input signal-to-noise ratios. In addition, results for direct loop simulation are presented for comparison.

47 A MICROCOMPUTER-BASED LOW-COST OMEGA SENSOR PROCESSOR, Richard J. Salter, Jr., February 1977, Master's Thesis.

48 MINI-L LORAN-C RECEIVER, R. W. Burhans, March 1977

A low-cost prototype Loran-C receiver front-end has been designed and bench-tested. This receiver concept provides outputs to interface with a microcomputer system. The development of sensor and navigation software for use with the Mini-L system is underway.

49 SIMULATION OF DIGITAL PHASE-LOCKED LOOPS, Paul R. Blasche, April 1977

This technical memorandum deals with development of simulation equations for first-and second-order digital phase-locked loops. In addition, examples of loop simulation are given to determine loop performance with respect to several loop parameters.

50 A KEYBOARD INTERFACE FOR THE JOLT MICROPROCESSOR, Lee Wright, May 1977

The Ohio University Microprocessor Navigation Receiver Base utilizes the JOLT(TM) microcomputer. This keyboard interface is designed to allow data input without use of a teleprinter.

51 A FOUR DIGIT MEMORY-MAPPED DISPLAY, Ralph E. Smith, May 1977

An interface board has been fabricated for the Ohio University Microcomputer-Based Navigation Receiver to display data from the microprocessor.

52 INTERACTIVE LORAN-C TO GEOGRAPHIC AND GEOGRAPHIC-TO-LORAN-C COMPUTATION, Lynn M. Piecuch and Robert W. Lilley, August 1977

An implementation of Naval Oceanographic Office computer software for Loran-C is presented.

53 CIRCUIT METHODS FOR VLF ANTENNA COUPLERS, R.W. Burhans, September 1977

A summary of E-field antenna preamplifiers developed during the course of the NASA Tri-University Program studies on VLF methods for general aviation is presented. The circuit techniques provide useful alternative methods for Loran-Omega receiver system designers.

54 LORAN-C DIGITAL WORD GENERATOR FOR USE WITH A KIM-1 MICROPROCESSOR SYSTEM, James D. Nickum, December 1977

The digital word generator used with Mini-L front end to develop a Loran sensor processor at Ohio University is described.

55 MICROPROCESSOR-TO-SYSTEM/370 INTERFACE, Robert W. Lilley, February, 1978

A hardware interface is described which allows direct memory load of a microprocessor from the host System/370 computer, eliminating paper tape handling.

56 STAND-ALONE DEVELOPMENT SYSTEM USING A KIM-1 MICROCOMPUTER MODULE, James Nickum, March 1978

Documentation of the stand-alone microprocessor development system used in the navigation sensor processor research at Ohio University is described.

57 A LOW-COST LORAN-C ENVELOPE PROCESSOR (The Mini-L Loran-C Receiver), R.W. Burhans, April 1978

A reprint of published article on the Mini-L Loran-C receiver front-end is presented. Complete circuit details are given with a basic introduction to Loran-C navigation and time-frequency standard uses. The Mini-L concept is of particular interest to the low-budget experimenter as an RF signal interface for more sophisticated end use.

58 A VIDEO DISPLAY INTERFACE FOR THE LORAN-C NAVIGATION RECEIVER DEVELOPMENT SYSTEM, Joseph P. Fischer and Robert W. Lilley, May 1978

A character-mode video unit is described which allows microprocessor-controlled display of program and navigation data with a small investment in logic.

59 COMPUTING LORAN TIME DIFFERENCES WITH AN HP-25 HAND CALCULATOR, Edwin D. Jones, August 1978

Accurate LORAN-C time differences can be calculated from known transmitter and receiver positions using the program described.

60 PHASE-LOCKED TRACKING LOOPS FOR LORAN-C, R. W. Burhans, August 1978

Two, portable, battery-operated LORAN-C receivers have been fabricated to evaluate simple envelope detector methods with hybrid analog-digital phase-locked loop sensor processors. The receivers are being used to evaluate LORAN-C in general aviation applications. Complete circuit details are given for the experimental sensor and readout system.

61 LORAN-C FLIGHT TEST SOFTWARE, James D. Nickum, August 1978.

Described is the software package developed for the KIM-1 Micro-System and the Mini-L PLL receiver to simplify taking flight test data at Ohio University.

62 PREAMPLIFIER NOISE IN VLF RECEIVERS, R. W. Burhans September 1978.

Rapid methods of estimating antenna preamplifier noise contribution to receiver performance are presented for JFET or CMOS transistors. An improved CMOS preamplifier circuit is suggested.

63 LORAN-C TIME DIFFERENCE CALCULATIONS, Joseph P. Fischer, October, 1978.

A simplified approach to calculate Loran-C time differences from a given geographic location is presented.

64 INITIAL FLIGHT TEST OF A LORAN-C RECEIVER/DATA COLLECTION SYSTEM, Joseph P. Fischer, James D. Nickum November, 1978.

Described are the flight test results of a Loran-C navigation receiver/data collection system designed at Ohio University.

65 ACTIVE ANTENNA FOR THE VLF TO HF OBSERVER, R. W. Burhans, February 1979.

This report is a prepublication manuscript submitted to one of the contemporary electronics magazines as part of a series on VLF-LF signal reception problems. The report presents a simple and low-cost method of fabricating an active antenna preamplifier system covering the range of 10 KHz to 10 MHz, for use with tunable communications receivers. The same type of preamplifier system can be used with airborne VLF navigation receivers.

66 ANALYSIS AND DESIGN OF A SECOND-ORDER DIGITAL PHASE-LOCKED LOOP, Paul R. Blasche, March 1979.

A second-order digital phase-locked loop is analyzed by application of a Markov chain model with alternatives. Steady-state loop error statistics and mean transient time are determined for various loop parameters. In addition, a hardware digital phase-locked loop was constructed and tested to demonstrate the applicability of the Markov chain mode.

67 LORAN-C FLIGHT DATA BASE, Robert W. Lilley, February 1979.

A large file of Loran-C data to be used in receiver design and testing is documented.

68 RESULTS OF THE SECOND FLIGHT TEST OF THE LORAN-C RECEIVER/DATA COLLECTION SYSTEM, Joseph P. Fischer, March 1979.

Reported are the results of a second flight test of the LORAN-C system under development at Ohio University using a variation of the techniques used for the first flight test.

69 DIGITAL PHASE-LOCKED LOOP DEVELOPMENT AND APPLICATION TO LORAN-C, Daryl L. McCall, September 1979.

A digital phase-locked loop has been developed and implemented for use in a low-cost Loran-C receiver. This paper documents the DPLL design and application to Loran-C.

70 ACTIVE ANTENNA COUPLER FOR VLF, Ralph W. Burhans, November 1979.

A reprint of a paper published in the "Ham Radio Magazine", Volume 12, Number 10, October 1979, is presented. The circuit designs are applicable to a variety of VLF-HF active antenna receiving systems including Omega and Loran-C for airborne and marine users.

71 EXPERIMENTAL LOOP ANTENNAS FOR 60 KHz to 200 KHz, Ralph W. Burhans, December 1979.

A series of loop antennas have been fabricated and evaluated for possible use with Loran-C and other VLF to LF band receivers. A companion low noise and very high gain preamplifier circuit has been devised to operate the loop antennas remote from the receiver. Further work is suggested on the multiple loop antenna systems to provide omni-directional coverage and reduce E-field noise pickup in navigation or communications systems.

72 DATA REDUCTION SOFTWARE FOR LORAN-C FLIGHT TEST EVALUATION, Joseph P. Fischer, December 1979.

This paper describes a set of programs written for use on Ohio University's 370 computer for reducing and analyzing flight test data.

73 LORAN DIGITAL PHASE-LOCKED LOOP AND RF FRONT-END SYSTEM ERROR ANALYSIS, Daryl L. McCall, December 1979.

Various experiments have been performed to determine the system error of the DPLLs and RF front-end currently being used in a Loran receiver prototype. This paper documents those experiments and their results.

74 RESULTS OF A LORAN-C FLIGHT TEST USING AN ABSOLUTE DATA REFERENCE, Joseph P. Fischer, January 1980.

The results of a flight test using the Loran-C receiver and data collection system developed at Ohio University are described in this paper. An absolute data reference was provided by the Lincoln Laboratories DABS (Discrete Address Beacon System) facility.

75 ANALYSIS OF FIRST AND SECOND ORDER BINARY QUANTIZED DIGITAL PHASE-LOCKED LOOPS FOR IDEAL AND WHITE GAUSSIAN NOISE INPUTS, Paul R. Blasche, March 1980 (Dissertation)

Specific configurations of first and second order all digital phase-locked loops are analyzed for both ideal and additive white gaussian noise inputs. In addition, a design for a hardware digital phase-locked loop capable of either first or second order operation is presented along with appropriate experimental data obtained from testing of the hardware loop. All parameters chosen for the analysis and the design of the digital phase-locked loop are consistent with an application to an Omega navigation receiver although neither the analysis nor the design are limited to this application.

RESULTS OF A LORAN-C FLIGHT TEST
USING AN ABSOLUTE DATA REFERENCE

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I. INTRODUCTION

A closed circuit flight test was conducted on June 18 and 19, 1979 in the Boston area using VORs and NDBs as reference points. The Loran-C data collected during the flight was then compared against a reference provided by the Discrete Address Beacon System (DABS) facility at Lincoln Laboratories. This flight was a cooperative venture with the Massachusetts Institute of Technology. The MIT crew used a commercial receiver and recorded Loran-C time differences which would also be compared with the data provided by the DABS facility and eventually with the data collected by Ohio University.

The Ohio University low-cost receiver [1] [2] was used for this test which was conducted in the Ohio University DC-3 flying laboratory. The Loran-C time-difference data was recorded with a microcomputer data collection system and stored on magnetic tape for subsequent analysis. The MIT receiver was also on board the DC-3, and recorded its data on a cassette tape which was later used by the MIT crew for data analysis.

This paper presents information on the equipment configuration in the aircraft, the flight procedure and the results obtained from the data collected with Ohio University's receiver and recording system.

II. DISCUSSION

The flight test was planned for June 18 and 19, 1979 in the Boston area. Ohio University's DC-3 Flying Laboratory N7AP was used for this test. The flight was conducted using Victor airways and VOR navigation during the flight from Athens to Boston. Figure 1 shows a flight plan used by the crew responsible for the data collection and shows the VORs along the route, their latitude and longitude and the expected time differences over these VORs. This was used by the crew to insure that the data collection system was tracking correctly, and also was used as a reference for entering event marks on the data tape.

The actual flight test was conducted by flying a closed circuit in the Boston area with the data collection system in operation. An absolute reference was provided by the DABS radar facility at the Lincoln Laboratories. The data collected for this test then consisted of a tape containing the time differences recorded by the data collection system and a tape recorded by the DABS computer containing range and azimuth information relative to the DABS facility. The flight path was chosen to include several land references which would be noted on the data tape for later analysis; the flight path is shown in Figure 2.

The ADF sense antenna on the DC-3 was used in the Loran-C experiment along with a special preamplifier developed by Burhans. [3] This preamplifier contains filters to help minimize interference from broadcast band and other signals at frequencies above Loran-C. This preamplifier also contains outputs to drive several receivers and was used for both Ohio University's receiver and MIT's receiver. A block diagram of the data collection system as installed on the DC-3 is shown in Figure 3.

The U. S. East Coast Loran-C chain, 99600, was used in this flight test with Seneca, N.Y. as the master and Caribou, Maine (W) as the first secondary and Nantucket (X) as the second secondary station.

III. POST-FLIGHT PROCESSING AND RESULTS

All data recorded by the microcomputer consisted of GRI index numbers and the time differences for the two station pairs. The GRI index is initialized to zero at the start of the flight test and is incremented by one each time a Loran-C group repetition pulse is received, or equivalently, the index is incremented upon receiving the master pulses. By this method, each data point may be noted as being received at some time after the data recording operation began. All the TDs recorded are raw data, i.e., no averaging or smoothing was applied by the micro-program. In subsequent post-processing done on the main computing facility, no filtering was done; all plots shown in this paper are the raw data received and show rather good stability. Since the recorded data is in time-difference format, post-processing included the conversion of the TDs to latitude/longitude and also rho/theta (range-azimuth) relative to the DABS facility. Post-processing was conducted on the Ohio University IBM System/370 computer using procedures described in a previous report. [4]

The Loran-C flight test data was recorded on magnetic tape using the Kennedy 1600 digital recorder. The data was separated into three separate files: the flight to Boston, the flight test with the DABS facility, and the return flight to Athens. The unformatted data from the microcomputer was first converted to a more convenient format and stored on a second tape volume; following this, the data was scanned for bad data points and converted to lat/long and rho/theta which was stored on a disk volume for plotting.

For the discussion on the plotted results to follow, it should be noted that the scale for each plot is the same. The tick mark nearest the point marked "BED" is the location of the DABS radar facility and represents the origin. Each tick mark to the left of the origin is five nautical miles in the west direction; each tick mark above the origin is five nautical miles in the north direction. The rho/theta information obtained from the data reduction job is plotted on this scale with each point being the distance in nautical miles and bearing in degrees from the DABS facility. The data obtained from the DABS tape was already in rho/theta format; no post-flight filtering was applied to the DABS data.

Figure 4 is a plot of the DABS data for the first test pass on the 18th. This shows the flight path starting at the airport and continuing out in a counter-clockwise direction, then circling and landing at the airport. Some jitter in the data can be noted at the farthest distance (near Keene) and can be attributed to the few hits made by the radar at this range. Figure 5 is a plot of the raw data collected by the microcomputer. Here it may be noted that the plot follows nearly the DABS track but seems to exhibit a bias of approximately one nautical mile. This will be explained later. Much of this flight path was done in a thunderstorm and the receiver lost lock temporarily due to lightning static as evidenced by the broken plot near the Fitchburg NDB. The data shows good consistency even though the receiver was operating in an unusually high noisy environment. This first flight pass was designed mainly to serve as a preliminary trial to insure that all systems would work correctly for the next day's tests.

The tests made on the next day (June 19) were in good weather conditions allowing the VORs and NDBs used as events marks to be spotted visually in most instances. A power supply problem developed during the flight test and caused the data collection system to fail several times, after which it was then necessary to reload the control program. This also caused the data collection tape to have several blank gaps in it which subsequently caused a great deal of trouble in recovering the data during the data reduction process. As a result, all of one flight circuit was lost and half of another was lost. However, enough data was recovered for useful analysis.

Figure 6 is a plot of the DABS data for the second pass on the second day (June 19). Again, some jitter is evident at the farthest point due to the conditions discussed earlier. Some other small glitches can be seen in these DABS plots which are due mainly to changes entered in the DABS computer for tape changes, and ATC transponder code changes. Figure 7 is the corresponding plot of the data collected by the microcomputer for the second pass. Much of the data is missing because of the power problem already mentioned. As with the previous microcomputer plot, this is raw data and the data is fairly stable, although the southward bias is evident.

The last pass made on the second day was made in the reverse direction, i.e., in a clockwise direction. Figure 8 is a plot of the DABS data for this pass, and the microcomputer data is shown in Figure 9. The microcomputer data is quite stable as can be seen in this plot.

In all the microcomputer plots shown up to this point, the data appears to have a fixed bias to the south. After analysis of the plots and printed listings, it was found that the microcomputer plots could be made to correspond more exactly to the DABS plots by adding 18 microseconds to the second TD number (Nantucket). Upon further checking, it was noted that the Nantucket secondary Loran-C station is approximately 100 miles from the Boston area and provides a very strong signal, particularly while in the air. It was then decided that such a strong signal was overloading the envelope processor in the front-end of the test-flight receiver. A study has been made into the effect of various signal and noise levels on the receiver and has been reported by McCall. [5] Further studies on envelope processing and front-end processing is ongoing.

Figures 10, 11, and 12 show the microcomputer data plotted with the 18 microsecond offset added for the first pass on June 18, the second pass on June 19, and the last pass on June 19, respectively. It can be seen that the microcomputer data follows the flight path to a much greater extent. Simultaneous plots of the DABS data with the microcomputer data for the three flight test passes are shown in Figures 13, 14, and 15. It should be noted that some of the DABS data is missing in these plots near the Keene VOR because of the far distance from the radar involved and also because the aircraft flew below the minimum altitude the radar requires for good accuracy at this distance.

IV. SUMMARY

The opportunity to conduct a flight test with an absolute reference was valuable in that it allowed a more detailed analysis of the performance of the Loran-C receiver. Although a definite bias was found in the data, the stability and repeatability of the receiver was very good. The results of this test will be an aid to further development of front-end processors for low-cost Loran-C receivers.

Several factors for future work came out of this flight test. These include: continued work on optimum antenna/preamplifier designs for use in conjunction with various receiving setups to minimize noise and overloading problems, evaluation of reliable power sources for the data collection equipment to eliminate power supply noise, and low voltage and voltage drop-out problems, and continued work on implementing coordinate conversion techniques for use on the microcomputer.

V. ACKNOWLEDGEMENTS

Much of the organization for this flight test was handled by Dr. R. H. McFarland, Director at Ohio University and Professors R. Simpson and W. Hollister, Project Directors at MIT. Other support was rendered by R.W. Burhans, Project Engineer at Ohio University and Mr. Carter Pfaelzer of MIT who were in charge of setting up the receivers and antenna/preamplifier systems; Mr. Daryl McCall of Ohio University and Mr. Allen Littlefield of MIT who were primarily responsible for the operation of the receivers during the flight test; and Mr. D.G. Pullins who was the co-pilot of the DC-3. General assistance in organizing the flight test and post-flight analysis was given by Dr. R. W. Lilley, project advisor at Ohio University. The personnel at the DABS facility were very helpful in organizing the radar data and clarifying some interpretations of the plots in this paper.

VI. REFERENCES

[1] Burhans, R.W., "A Low-Cost Loran-C Envelope Processor", OU NASA TM-57, Avionics Engineering Center, Department of Electrical Engineering, Ohio University, Athens, Ohio, April 1978.

[2] McCall, Daryl L., "Digital Phase-Locked Loop Development and Application to Loran-C", OU NASA TM-69, Avionics Engineering Center, Department of Electrical Engineering, Ohio University, Athens, Ohio, September 1979.

[3] Burhans, R.W., "Active Antenna for the VLF to HF Observer", OU NASA TM-65, Avionics Engineering Center, Department of Electrical Engineering, Ohio Unversity, Athens, Ohio, February 1979.

[4] Fischer, Joseph P., "Data Reduction Software for Loran-C Flight Test Evaluation", OU NASA TM-72, Avionics Engineering Center, Department of Electrical Engineering, Ohio University, Athens, Ohio, December 1979.

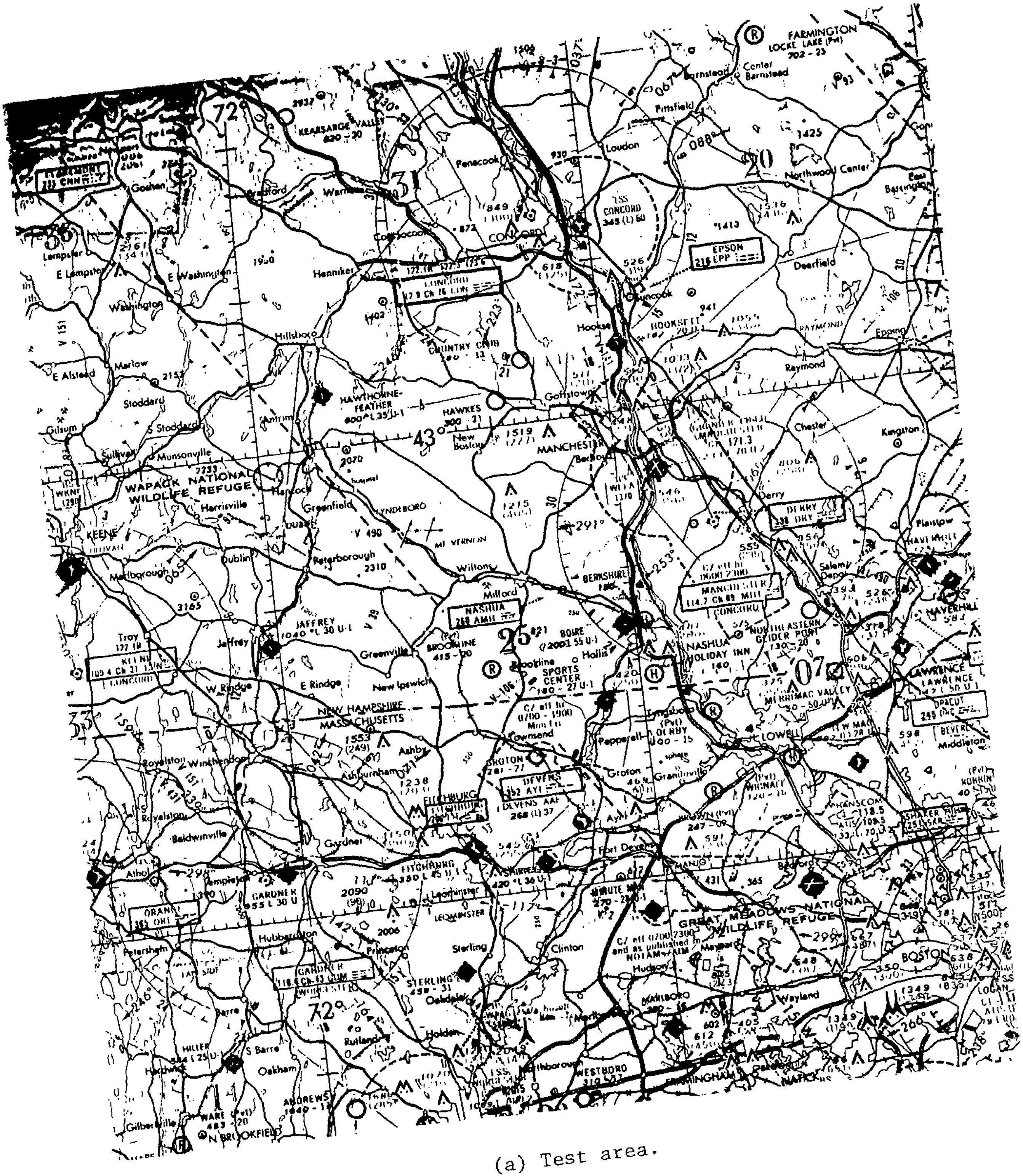
[5] McCall, Daryl L., "Loran Digital Phase-Locked Loop and RF Front-End System Error Analysis", OU NASA TM-73, Avionics Engineering Center, Department of Electrical Engineering, Ohio University, Athens, Ohio, December 1979.

U.S. NORTHEAST CHAIN 99600

VORTAC	LATITUDE			LONGITUDE			W	X	Y	Z
PKB	39°	26'	28"	81°	22'	30"	16588.50	28508.72	42704.69	57159.06
IHD	39°	58'	27"	79°	21'	31"	16550.57	28423.10	43215.58	58243.96
JST	40°	19'	00"	78°	50'	04"	16542.46	28438.35	43504.49	58580.39
TON	40°	44'	06"	78°	19'	54"	16538.50	28479.05	43852.42	58935.59
PSB	40°	54'	58"	77°	59'	35"	16526.29	28480.07	44020.10	59139.67
IPT	41°	20'	19"	76°	46'	31"	16400.51	28360.23	44428.13	59726.56
LHY	41°	28'	33"	75°	28'	59"	16030.45	27919.42	44469.48	60010.74
PWL	41°	46'	11"	73°	36'	04"	15244.73	27042.65	44389.41	60178.07
BAF	42°	09'	43"	72°	43'	00"	14791.26	26655.08	44437.87	60245.15
GDM	42°	32'	45"	72°	03'	31"	14412.18	26412.71	44491.10	60283.00
BOS	42°	21'	28"	70°	59'	38"	14032.40	25862.50	44294.04	60267.28

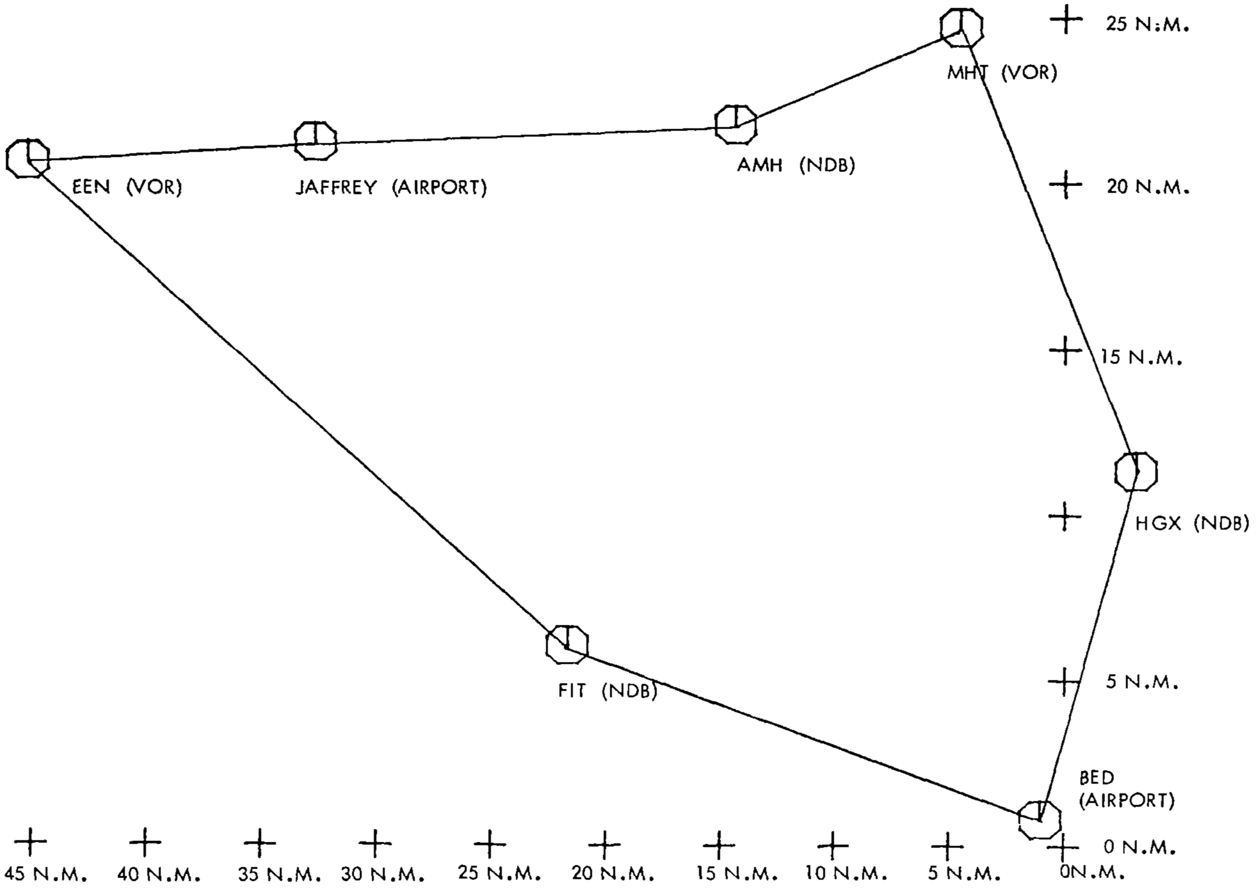
ALBANY TO BOSTON VOR CHECKPOINTS

Figure 1.- Checkpoints for trip to Boston and trip from Boston.



(a) Test area.

Figure 2.- DABS test flight path.



(b) Flight path geometry.

Figure 2.- Concluded.

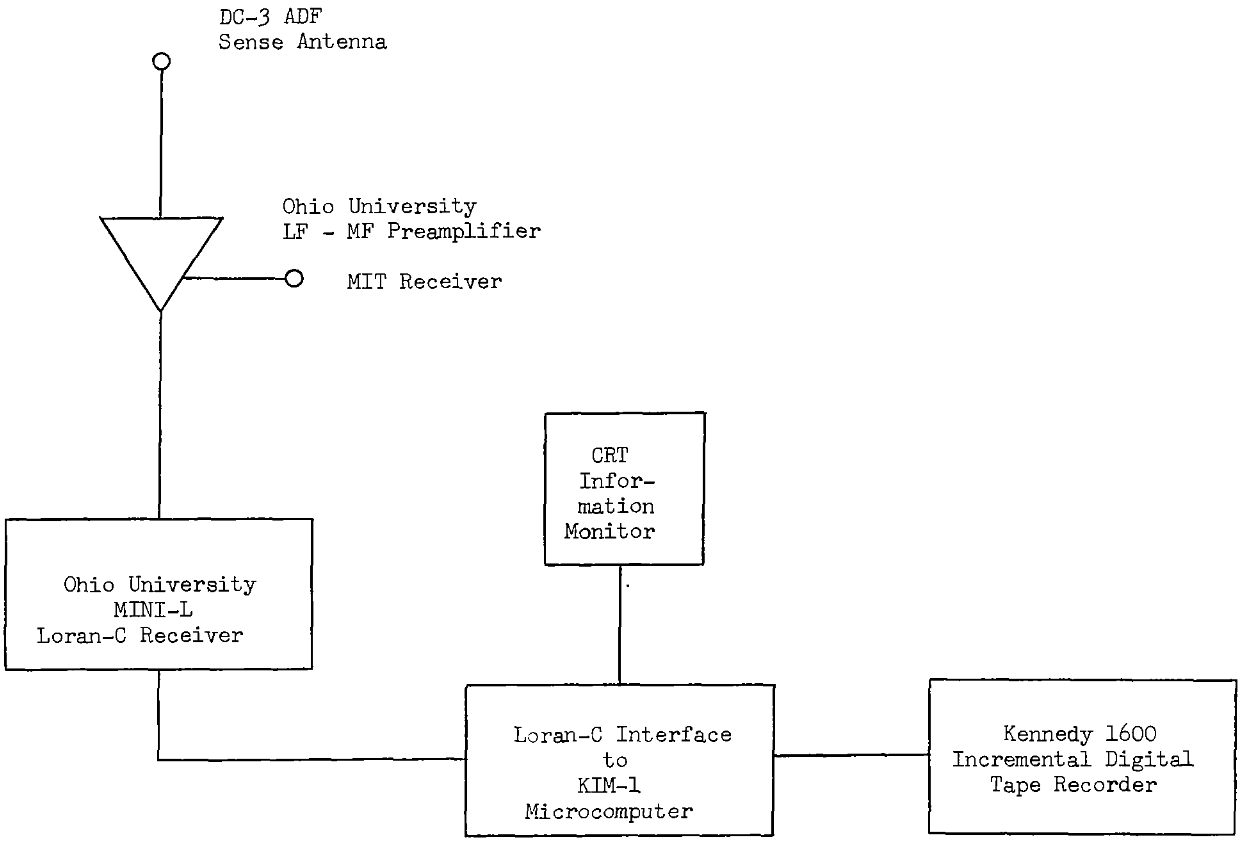


Figure 3.- Flight test equipment configuration.

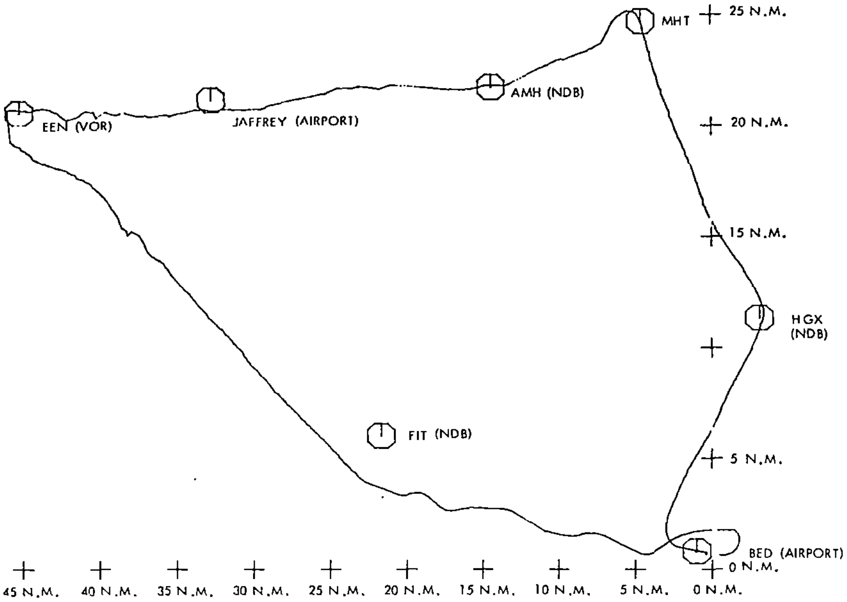


Figure 4.- DABS data plot for flight test on June 18.

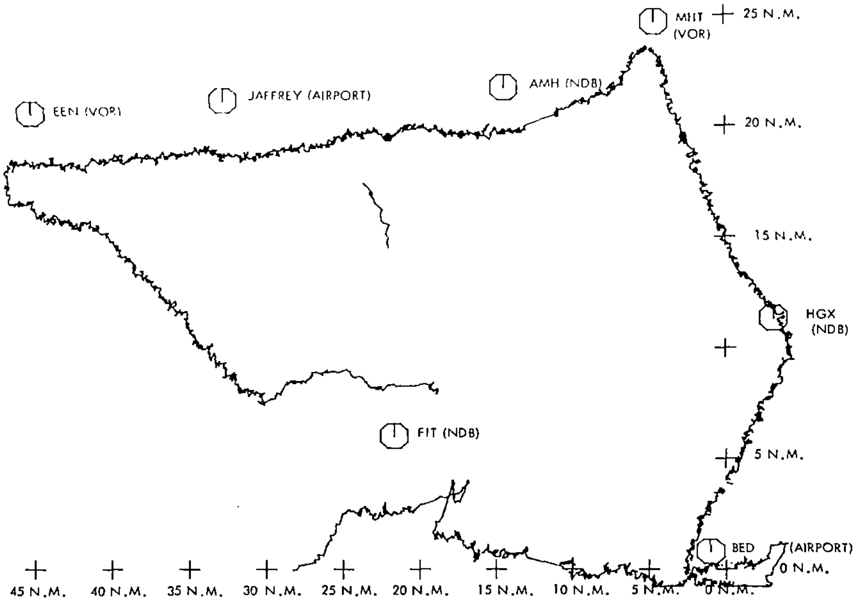


Figure 5.- Microcomputer data plot for flight test on June 18.

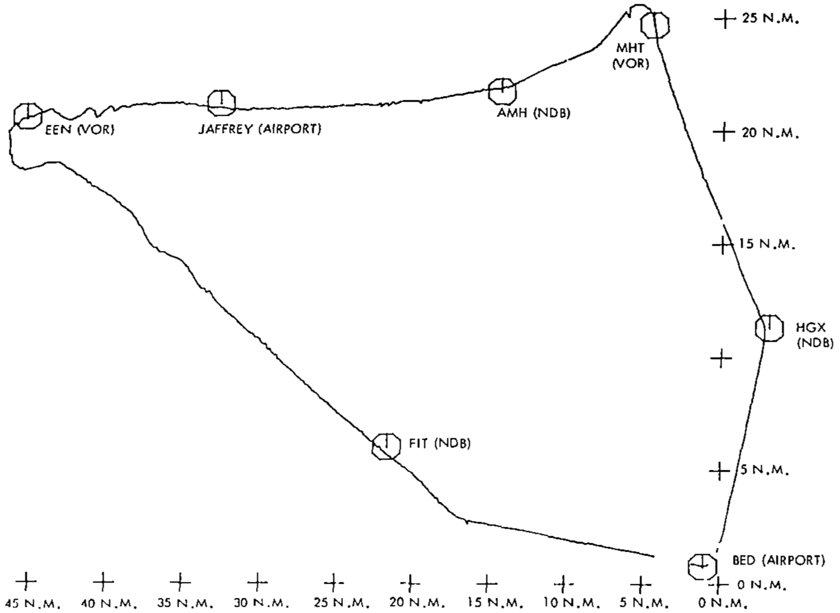


Figure 6.- DABS data plot for second flight pass on June 19.

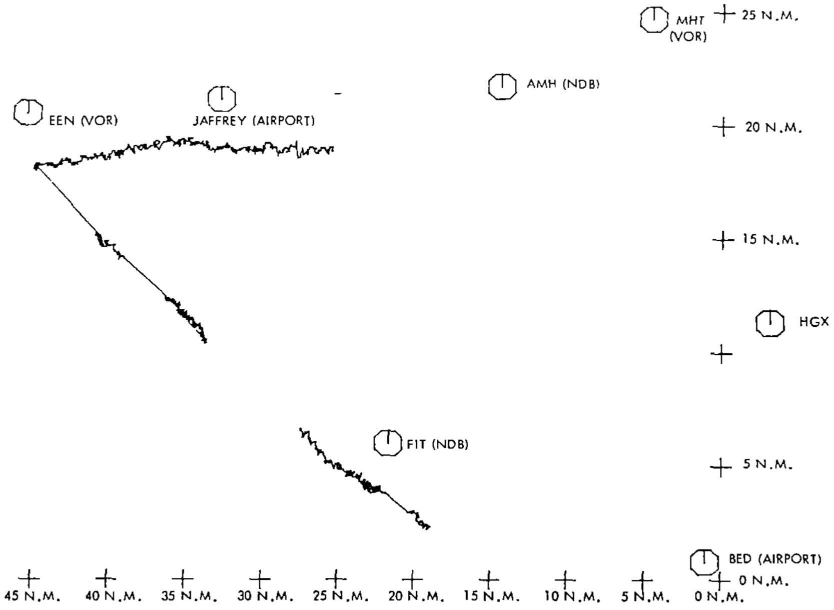


Figure 7.- Microcomputer data plot for second flight pass on June 19.

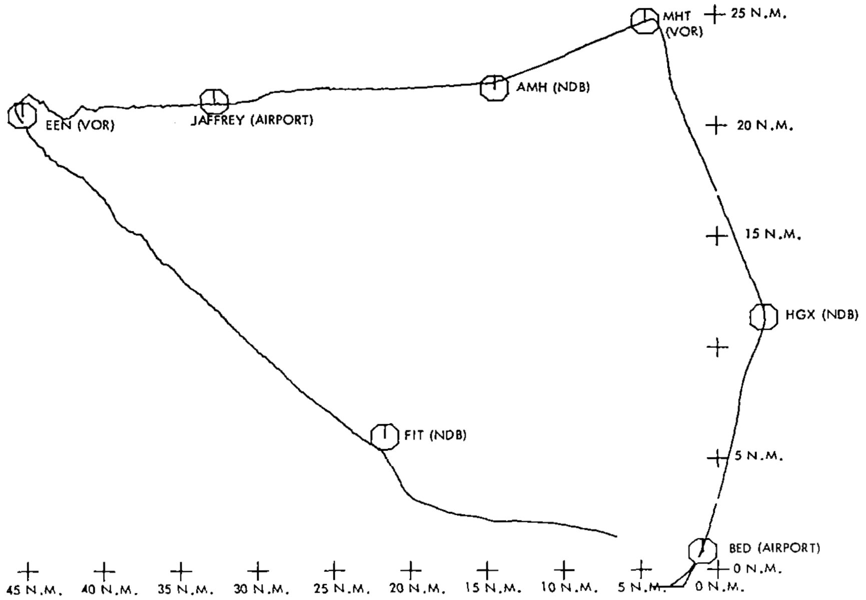


Figure 8.- DABS data plot for third (last) flight pass on June 19.

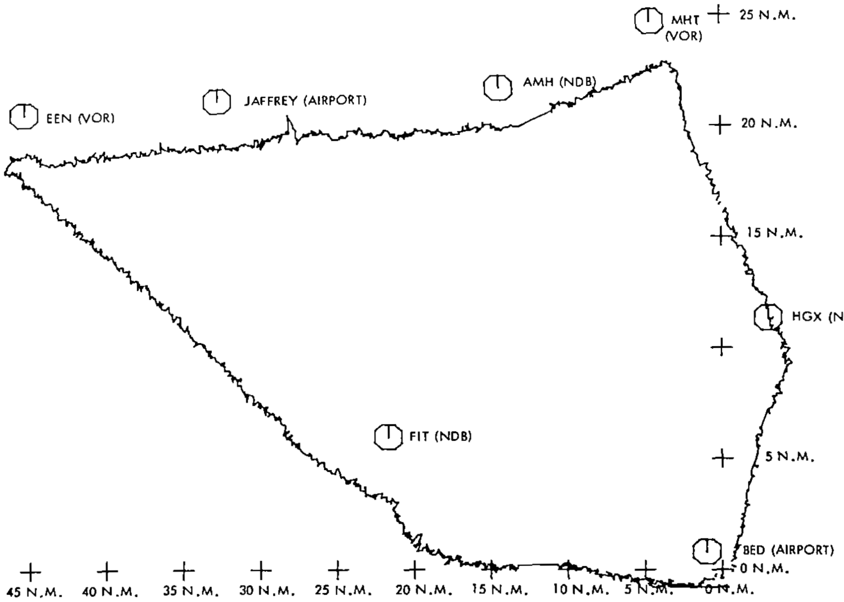


Figure 9.- Microcomputer data plot for third (last) flight pass on June 19.

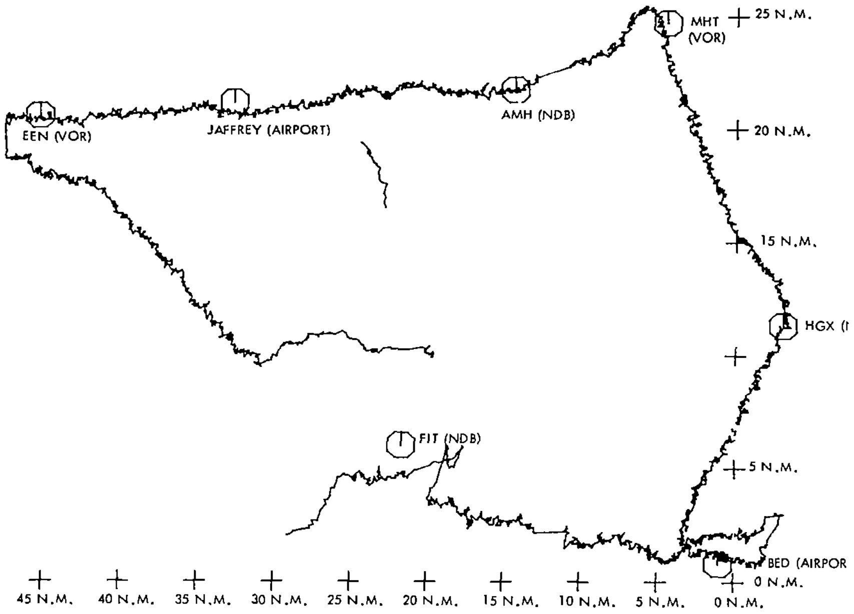


Figure 10.- Microcomputer data plot of flight test on June 18 with 18 μs. offset added to pair X.

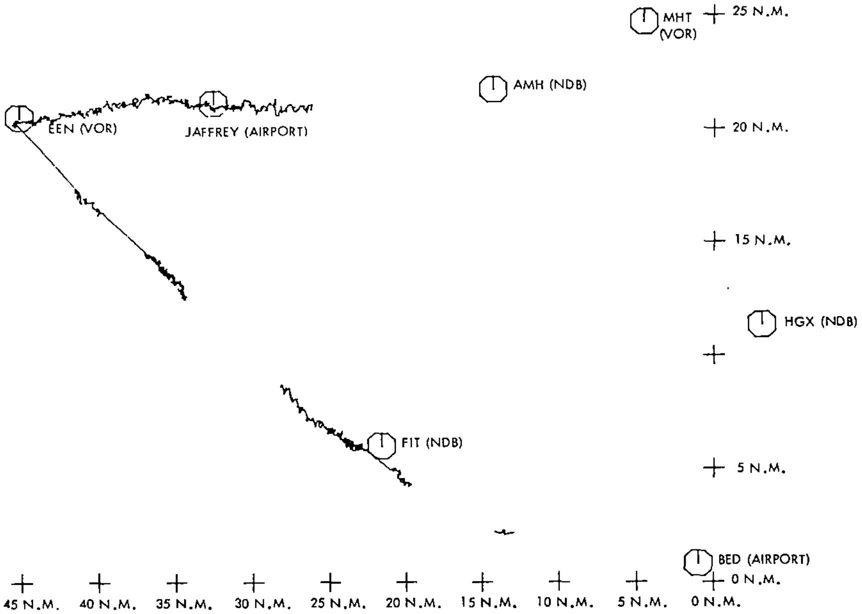


Figure 11.- Microcomputer data plot of second pass on June 19 with 18 μs. offset added to pair X.

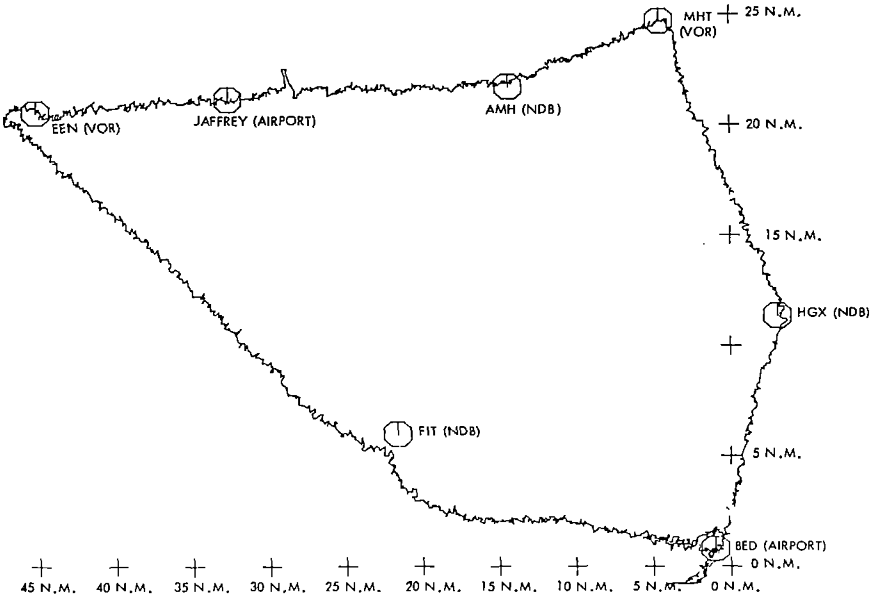


Figure 12.- Microcomputer data plot of third pass on June 19 with 18 μs. offset added to pair X.

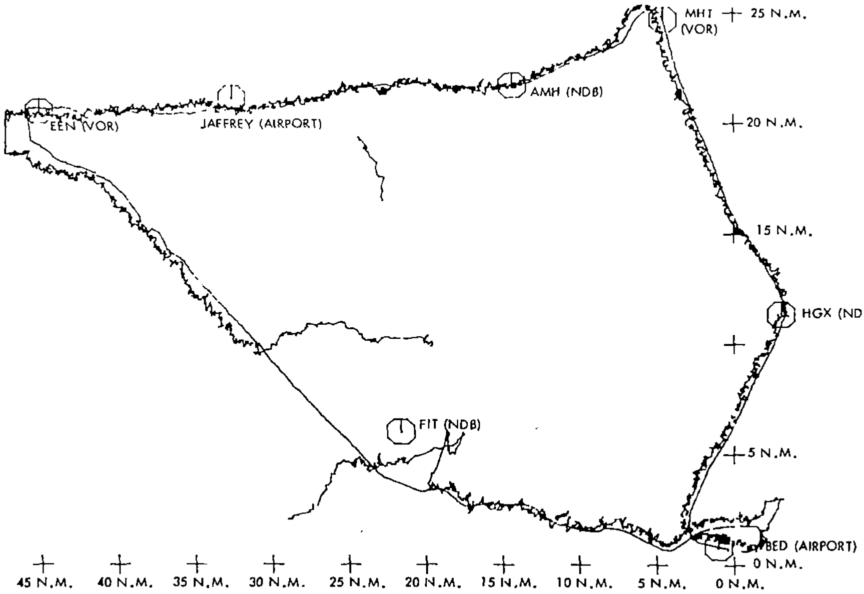


Figure 13.- Combined data plots of DABS and microcomputer data for June 18, with 18 μs. offset added.

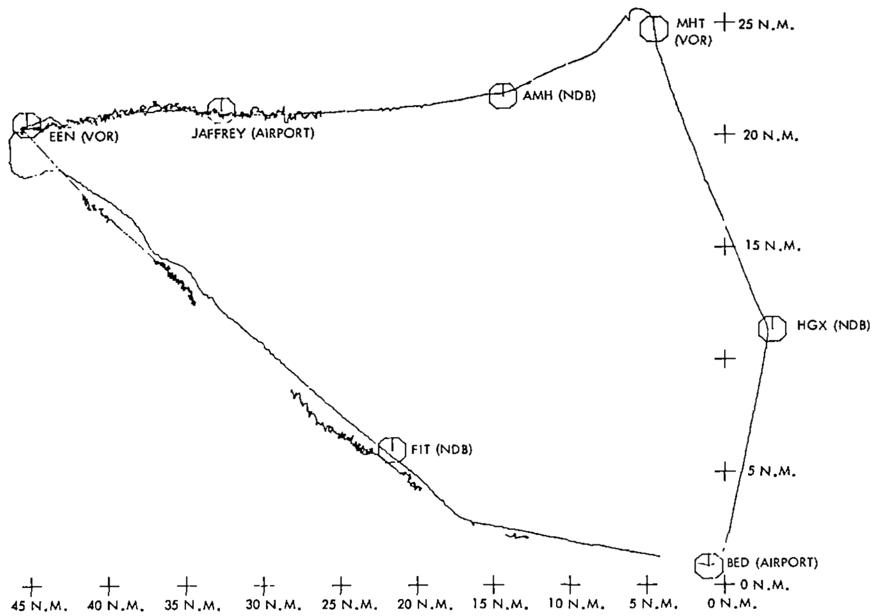


Figure 14.- Combined data plots of DABS and microcomputer data for second pass, June 19, with 18 μs. offset.

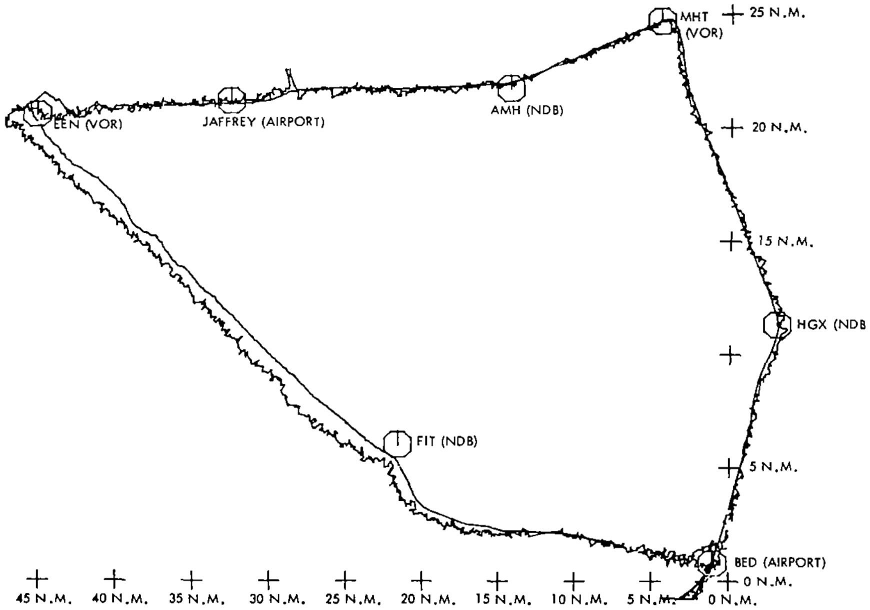
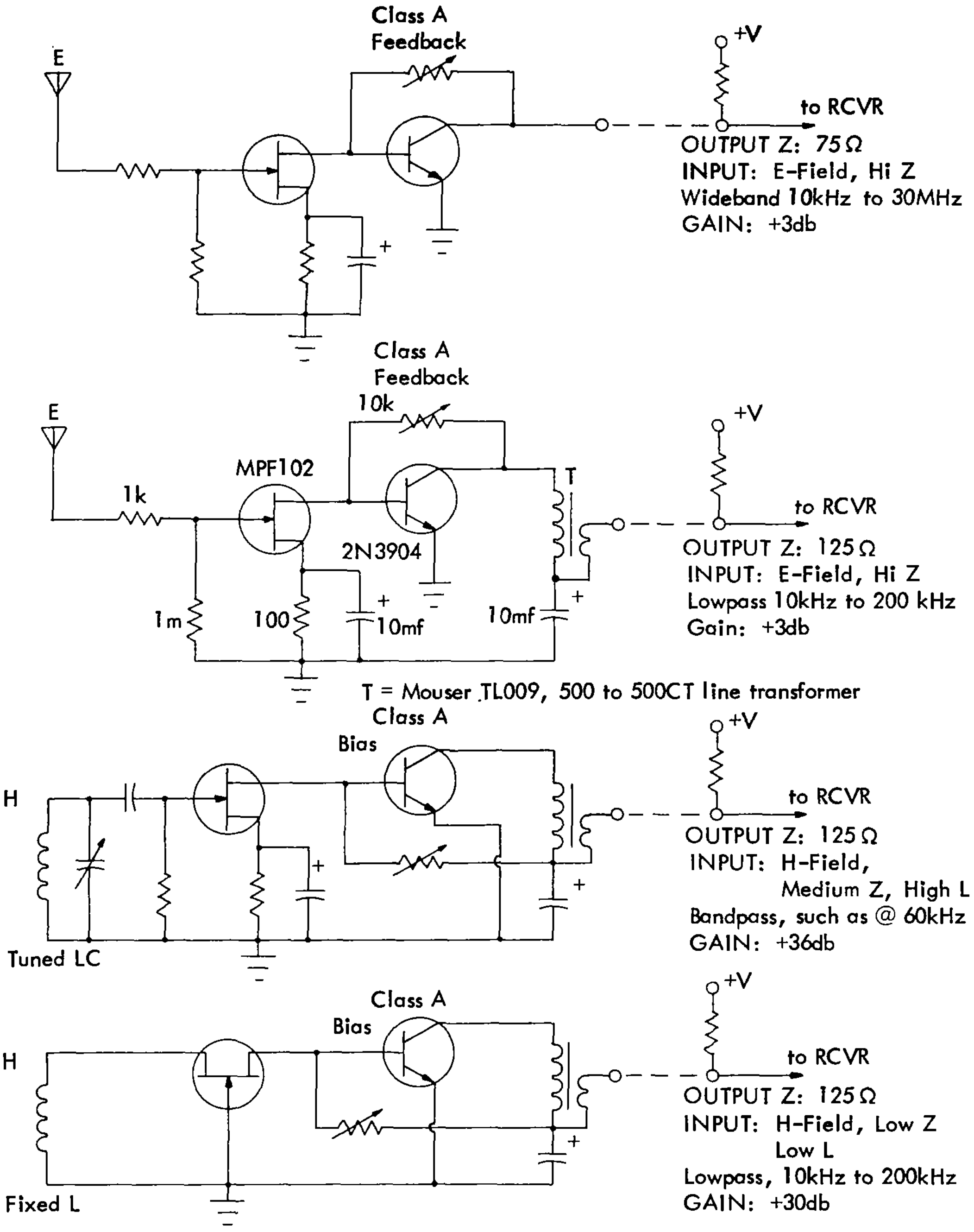


Figure 15.- Combined data plots of DABS and microcomputer data for third pass, June 19, with 18 μs. offset.

RF CIRCUITRY

Professor Ralph W. Burhans

Avionics Engineering Center
Department of Electrical Engineering
Ohio University



OUTPUT Z: 75Ω
INPUT: E-Field, Hi Z
Wideband 10kHz to 30MHz
GAIN: +3db

OUTPUT Z: 125Ω
INPUT: E-Field, Hi Z
Lowpass 10kHz to 200 kHz
Gain: +3db

T = Mouser .TL009, 500 to 500CT line transformer

OUTPUT Z: 125Ω
INPUT: H-Field,
Medium Z, High L
Bandpass, such as @ 60kHz
GAIN: +36db

OUTPUT Z: 125Ω
INPUT: H-Field, Low Z
Low L
Lowpass, 10kHz to 200kHz
GAIN: +30db

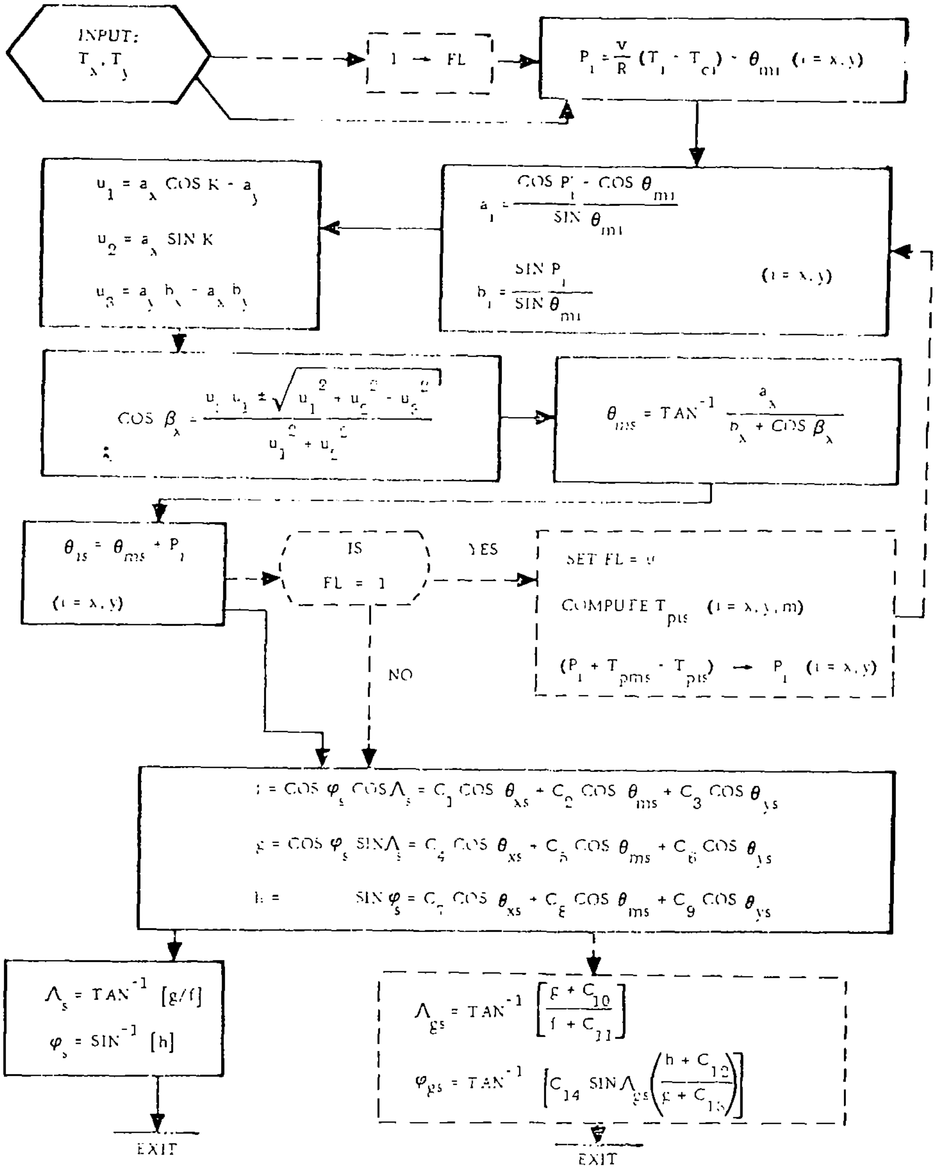
4-FUNCTION ACTIVE ANTENNA PREAMPLIFIER

Standard preamp circuit modified for multi-purpose use with single circuit board layout. Useful for: Omega, VLF, Loran-C, LF, MF, HF, E-field whips, H-field loops, airborne, mobile, or fixed station monitors.

NAVIGATION PROCESSING FOR LORAN-C

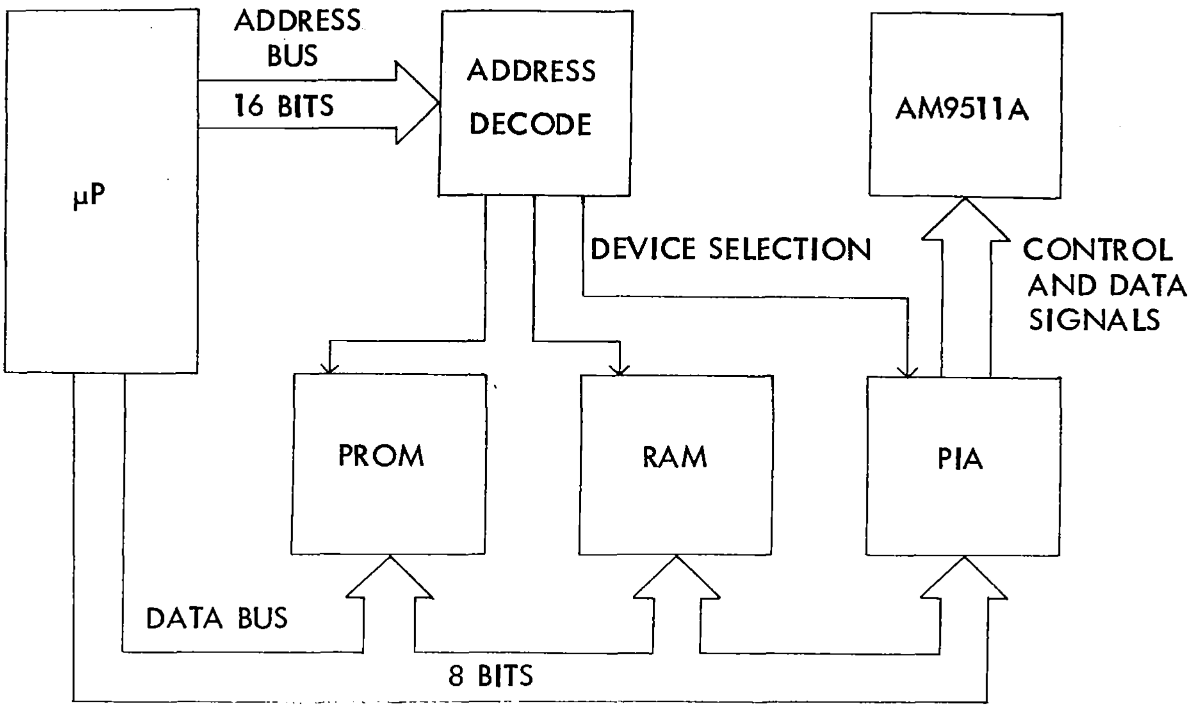
Joseph P. Fischer

Avionics Engineering Center
Department of Electrical Engineering
Ohio University



FLOW CHART OF EXPLICIT SOLUTION

This flow-chart shows the steps involved in calculating a position fix given the measured TD's. Note that this is an explicit, non-iterative solution. The constants C1 through C9 relate the spherical arc angles to the standard latitude-longitude coordinate system; these nine constants need be computed only once for any particular Loran chain. This flow-chart was reproduced from an Institute of Navigation article written by Razin (Vol. 14, No. 3, Fall 1967). A development of the computation of the constants was presented by Fell in the same Journal (Vol. 22, No. 2, Summer 1975).



BLOCK DIAGRAM OF AM9511 INTERFACE

This is the block diagram of the hardware interface between the microcomputer and the Am9511A math chip. The address decoding block recognizes a particular range of addresses from the microcomputer and uses these to select a device; i.e., the PROM, the RAM or the math chip indirectly through the PIA. The PIA handles all interfacing between the math chip and the microcomputer. The PIA is used to process handshake signals from the math chip and present data to the math chip when commanded to do so by the microcomputer.

Extra space has been reserved for additional ROM and/or RAM in addition to that on the microcomputer. This may be used to contain interface software for the math chip and scratch space for calculations.

Lat/Long	TD's	DEXLRN	Basic Program
39° 19' 23" 82° 5' 58"	42590.2 56774.5	39° 19' 23.4" 82° 5' 57.9"	39° 19' 14.3" 82° 5' 53.8"
37° 0' 82° 0'	41285.0 56494.3	37° 0' 42.2" 81° 59' 58.9"	37° 0' 34.1" 81° 59' 56.4"
38° 0' 79° 0'	41860.4 57855.1	38° 0' 20.0" 78° 59' 38.3"	38° 0' 13.4" 78° 59' 33.8"

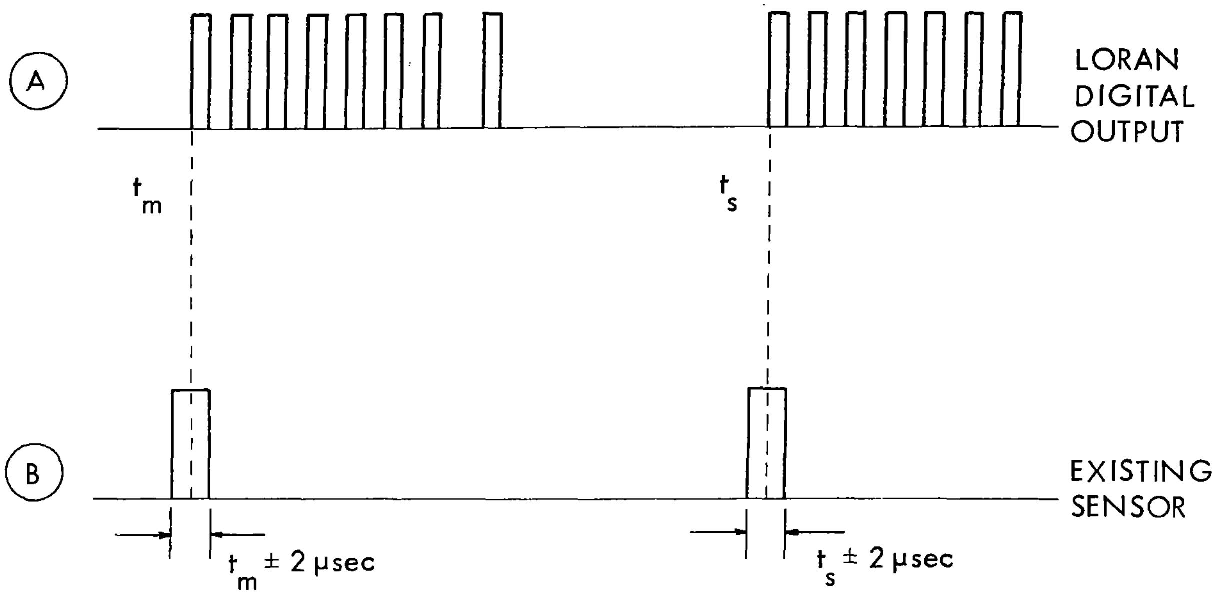
ACCURACY OF EXPLICIT SOLUTION

The table above shows the accuracy of the explicit solution using two procedures. The numbers under "DEXLRN" were calculated by a program written in FORTRAN-IV and run on an IBM 370. The numbers in the column under "Basic Program" were calculated by a program written in BASIC and run on a Rockwell AIM-65 microcomputer, calculation time was approximately two seconds. In both cases, the nine constants C1 to C9 were calculated beforehand and used as data constants in the program. A test program using the math chip setup shown in the block diagram is being tested with the same program. It is expected to yield similar accuracy as above and in less time than the Basic program. The accuracy of the explicit solution was found to be generally good to approximately one kilometer or better, the maximum error noted was 2.5 kilometers near the edge of the coverage region for the Loran chain tested.

MICROCOMPUTER PROCESSING FOR LORAN-C

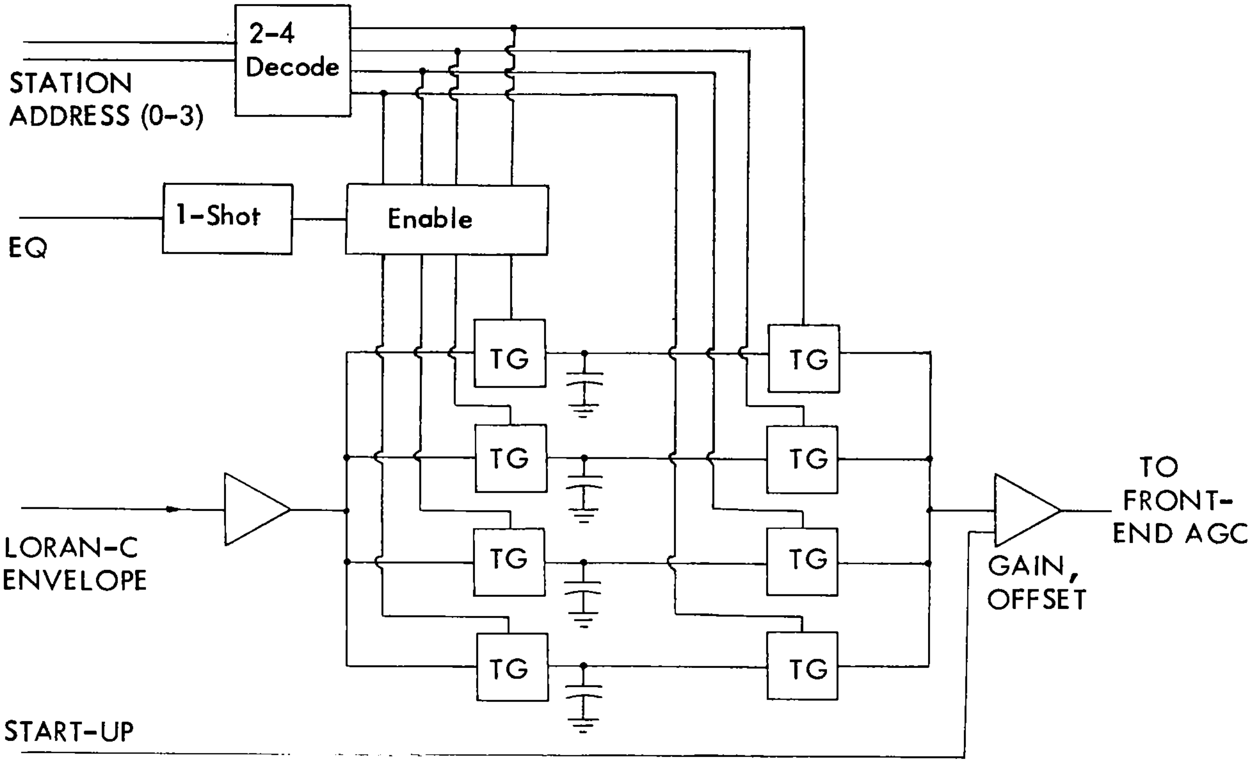
Professor Robert W. Lilley
Daryl L. McCall
Stanley M. Novacki III

Avionics Engineering Center
Department of Electrical Engineering
Ohio University



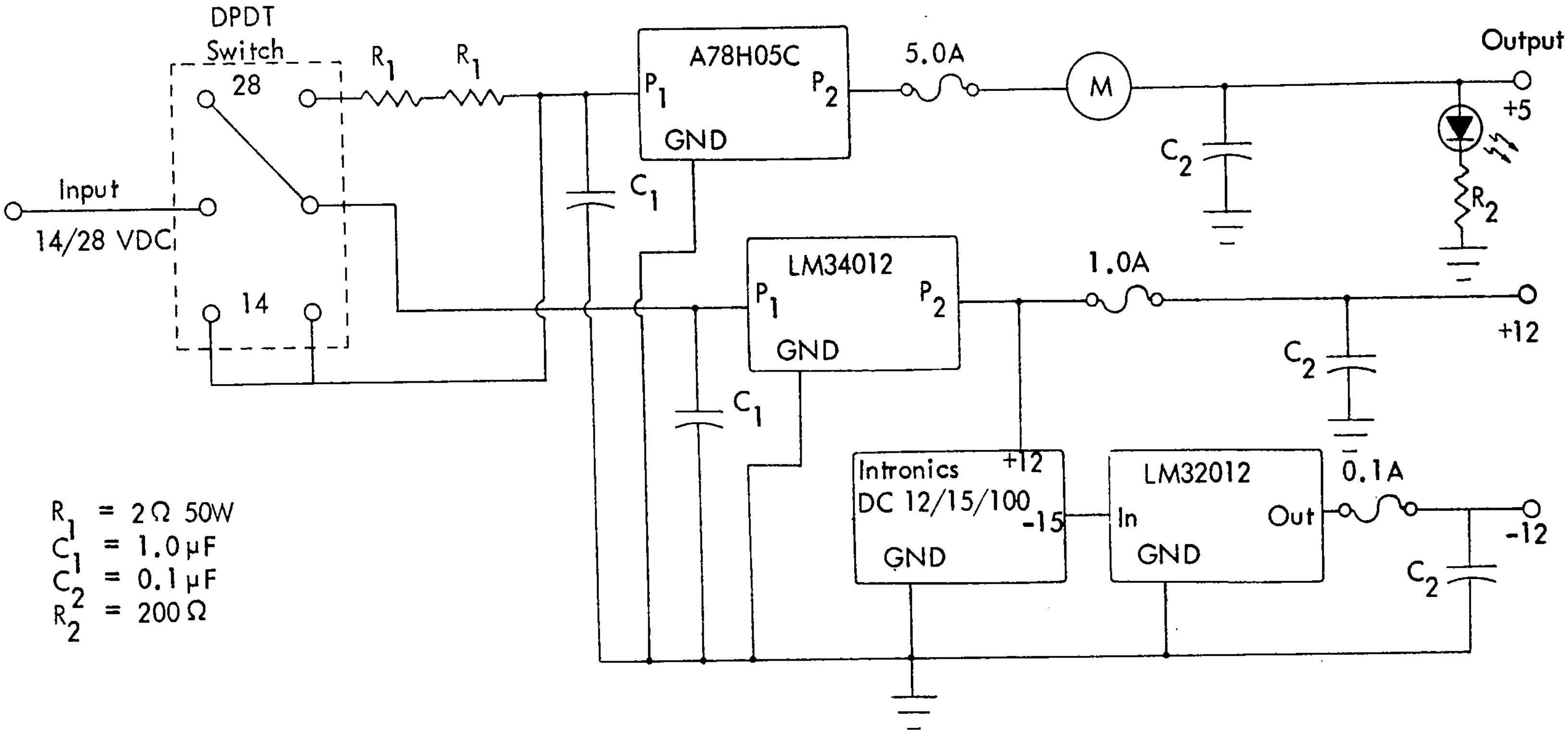
MICROCOMPUTER LORAN-C LOOP IMPROVEMENTS

- Existing Sensor Loop Uses only the First Loran-C Pulse
- Series of Experiments
  - Expand Loop Operation to All 8 Loran-C Pulses
  - Either with or without Loran-C Phase Code
  - Reduce Tracking Increment from 2 μsec to 1 μsec.
- Measure Loop S/N Improvement Using the Above Parameters
- Requires only Software Changes in Existing Receiver
- Increases Receiver Sample Speed by 7X
- May Increase Output Data Rate by Permitting Less TD Filtering



LORAN-C RECEIVER COMMUTATED AGC

- To be Added to Loran-C Low-Cost Prototype
- Commutated, Sampled AGC
- Avoids Front-End Phase Shift Problem
- Five Chips Required for Breadboard
- Permits Present AGC for Search Mode
- Minimum Load on Computer



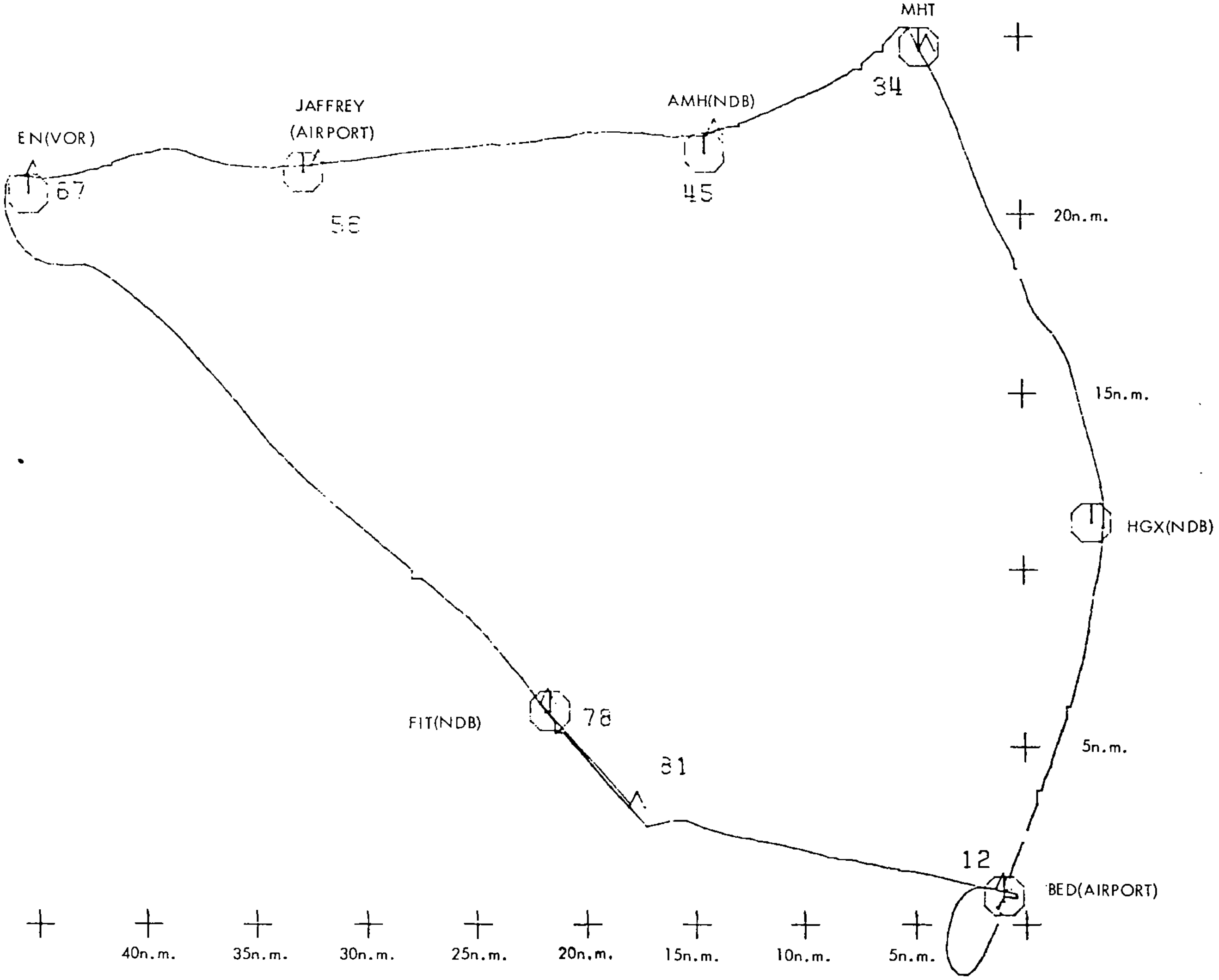
SCHEMATIC FOR DC-DC POWER SUPPLY

The power supply represented above was specifically designed to operate the Ohio University Loran-C receiver and signal processor. The supply was designed to operate directly from an aircraft's electrical system, hence the input of 28 or 14 volts DC. The outputs are respectively: +5V at 5A, +12V at 1A, -12V at 0.1A. The DPDT switch allows the 2 ohm resistors to be connected in series with the 5 volt regulator for 28 volt operation, bypasses the resistors for 14V operation (the maximum input voltage of the regulator is 24V), and serves as a power off switch.

PRELIMINARY RESULTS FROM SEPTEMBER 11, 1980
LORAN-C TEST FLIGHT

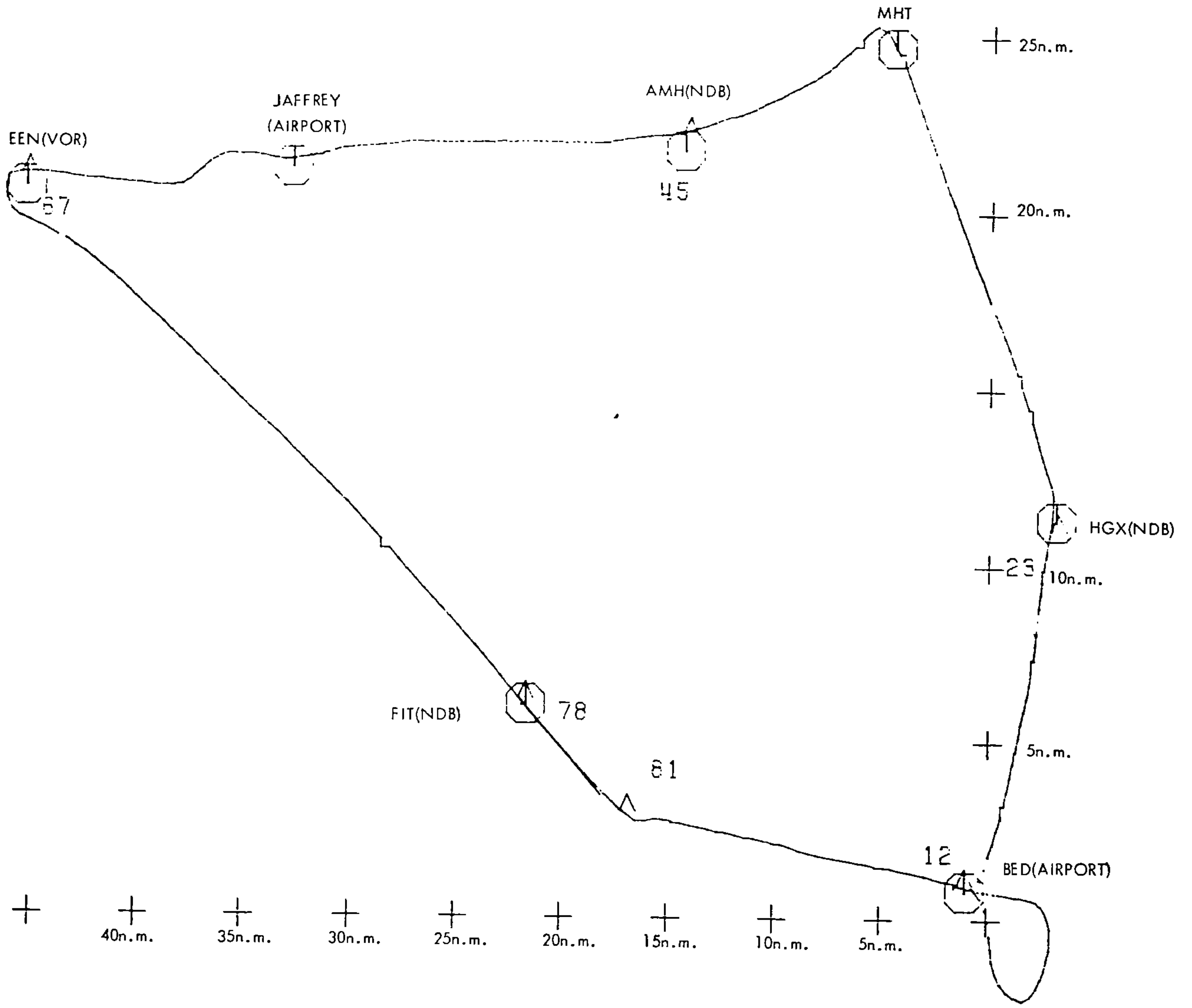
James P. Roman
Kim T. Constantikes

Avionics Engineering Center
Department of Electrical Engineering
Ohio University



PLOT OF TD-711 DATA - FIRST CIRCUIT

The first circuit of a test flight over the Boston area, in the Ohio University DC-3 Flying Laboratory, on September 11, 1980. The data was collected on a TD-711 receiver, and plotted against known positions.



PLOT OF TD-711 DATA - SECOND CIRCUIT

The second circuit of a test flight over the Boston area, in the Ohio University DC-3 Flying Laboratory, on September 11, 1980. The data was collected on a TD-711 receiver, and plotted against known positions.

Princeton University

INVESTIGATION OF AIR TRANSPORTATION TECHNOLOGY AT PRINCETON UNIVERSITY, 1980

Professor Robert F. Stengel
Department of Mechanical and Aerospace Engineering
Princeton University
Princeton, N.J. 08544

SUMMARY OF RESEARCH

The Air Transportation Technology Program at Princeton University has proceeded along six avenues during the past year:

- Evaluation of an OMEGA-Dead Reckoning Hybrid Navigation System
- Implementation of a Microprocessor-Controlled Flight Research Ground Station
- Investigation of Fuel-Use Characteristics of General Aviation Aircraft
- Investigation of a Dead-Reckoning Concept Incorporating a Fluidic Rate Sensor
- Experimentation Related to Ultrasonic Altimetry
- Concept Development for a Laser-Based Collision Avoidance System

In previous years, Princeton's research activities focussed on the analysis of OMEGA navigation, the design of a hybrid OMEGA-dead reckoning system, and the testing of such a system in flight. This project has culminated with the work of Janet Lepanto and Ralph Nichols. Ms. Lepanto's work has led to an M.S.E. thesis, which is abstracted in the attached bibliography. Mr. Nichols's M.S.E. thesis is in its final stages of preparation. It reports on the development of the hybrid system's hardware and software, flight test procedures, the theoretical background for analysis, and the results of flight experiments.

The development of a microprocessor-controlled telemetry decommutator-demodulator by Mark Title, an undergraduate who was recently awarded the degree of Bachelor of Science in engineering physics, also is abstracted here. The particular significance of this work is that it is an inexpensive and highly reliable realization of pulse-duration modulation (PDM) telemetry, which is somewhat simpler than the pulse-code modulation (PCM) systems currently in use. In demonstrating this approach, Mr. Title used one microprocessor single-board computer plus seven IC chips to perform the same functions that previously required two full-length, standard 48.26 cm (19-in) racks of electronic equipment. The engineering approach for this development was conceived by George E. Miller, member of the Princeton Flight Research Laboratory's senior technical staff.

The navigation research conducted earlier provided a logical stepping stone to consideration of flight management systems for general aviation aircraft, including fuel-minimizing guidance between origin and destination points. The effectiveness of such guidance logic is, of course, dependent on the accuracy of aircraft fuel-use models, and this, in turn, requires adequate mathematical descriptions of engine characteristics. In his doctoral research, Richard Parkinson has developed a cruise performance model that can be developed from operating handbook data, and he is developing a detailed mathematical model of the fuel-use characteristics of a turbocharged reciprocating engine. A status report on this work is contained in this compilation.

The study of low-cost navigation systems for general aviation aircraft has shifted from hybrid systems to an even simpler approach for precision dead reckoning. Robert Ellis is investigating alternate mechanizations in which a fluidic angular rate sensor is used to correct the northerly turning error of conventional flux gate magnetic compasses. (The northerly turning error results from the effect of "dip angle" on sensed magnetic heading when the aircraft is banked to turn.) Mr. Ellis has found that a simple filter which assumes that the aircraft performs coordinated turns and which uses a second-order Runge-Kutta integration to perform dead reckoning provides a practical navigation solution. This navigation technique will be tested in flight. The finished work will be reported in Mr. Ellis's M.S.E. thesis, and a status report appears below.

Amy Snyder, a junior in mechanical and aerospace engineering, has recently begun to investigate the feasibility of using an ultrasonic transducer as an altimeter for the landing approach through touchdown. The transducer initially was developed as an automatic range-finding component for a camera; it is commercially available at very low cost, and it possesses better than 1% accuracy for ranges of 0.27 to 10.67 m (0.9 to 35 ft). There are a number of technological barriers to be understood (and possibly overcome), including the echo shift at typical approach speeds (75 KIAS) and very-high-frequency noise (50 to 60 kHz) from the airstream and engine. Nevertheless, the potential benefits of the technology are large.

A status report will be presented at an upcoming Joint University Program quarterly review.

Students Edward Wong and Maged Tomeh have begun to study the application of low-power lasers in air-to-air tracking and collision avoidance under the guidance of co-principal investigators Prof. Larry Sweet and Prof. Richard Miles. While it might appear that an optical collision avoidance system would be compromised by inclement weather, accident statistics indicate that well over 95% of the mid-air collisions occur in visual flight conditions. An introduction to this project is included here.

ANNOTATED BIBLIOGRAPHY

The remainder of this report is dedicated to an annotated bibliography of the principal publications to date sponsored in whole or part by this grant.

Dunstan Graham, "Technology for Terminal Area Traffic Guidance and Control", Air Transportation and Society, Vol. II, American Institute of Aeronautics and Astronautics, Sept 1971, pp. 171-179.

Problems of air traffic control capacity are reviewed, and three technologies which show promise for improving the safety, flexibility, and approach success of IFR operations are discussed. Phased-array radar could allow substantial reduction in longitudinal and lateral separation standards. Guidance for curved approaches would permit an additional flexibility of operations and would tend to minimize the length of the common path for mixed categories of aircraft. "Windproofing" control of the approach and landing, in conjunction with a microwave landing system, would be essential to the achievement of a high degree of regularity in operations under conditions of low visibility.

Donald L. Flick, "An Investigation of the Optimal Combination of Omega and Air Data", Princeton M.S.E. Thesis, Aug 1973.

This thesis investigates the potential of a hybrid navigator for use by general aviation users. The navigator forms a "best' estimate of position by combining information from very low frequency Omega signals and Air Data (heading and true airspeed) by means of a Kalman filter. The estimate thus formed is optimal in the least-squared sense. The filter equations are developed, and the resulting navigator is tested by use of Monte Carlo simulations to gain indications of system performance.

B. Jay Bagdis, "An Aircraft Wind Response Model for Use in Air Traffic Control Simulations", Princeton M.S.E. Thesis, Sept 1973.

An aircraft wind response model for longitudinal and lateral motions is presented for incorporation into simulations of the Air Traffic Control system. The transfer functions of the aircraft along with its various navigation, guidance, and control subsystems are developed using multiple-loop feedback analysis techniques. The aircraft is then subjected to stochastic disturbance inputs, and an assessment of the overall system performance is made. A method is then developed for use in determining a simple response model for any type of aircraft.

This method is specifically applied to the DC-8 aircraft, and the approximate results are compared with true responses. It can be shown that for Air Traffic Control system simulation requirements, a simple first-order filter approximation for aircraft longitudinal motions resulting from gust inputs is adequate. Furthermore, lateral perturbations resulting from gusts are sufficiently small as to prove negligible.

Richard V. Cox, "The Analysis and Design of Air Traffic Control Algorithms in the Near Terminal Area", Princeton Ph.D. Thesis, Feb 1974.

This thesis deals with the analysis and design of air traffic control algorithms. Emphasis is placed on the interaction between the practical and theoretical aspects of the problem.

After reviewing previous FAA studies and some theoretical work, we discuss the problem of the optimal control of a string of moving vehicles. A first-order model is used to describe the system, and a more appropriate cost functional is proposed. The resulting optimal control law is computationally simpler than the quadratic cost control law. A 1:1 transformation from optimal speed control to two-dimensional path control is also given.

The statistical properties of the optimal control law, when applied to a shifted exponential process, are investigated. It is shown that a bunching phenomenon results which reduces the infinite string problem to an infinite number of finite string problems. This means that the control law can be easily applied. The bunching phenomenon and the steady state are investigated, and the results of Pearcey, Oliver, et al are found to describe the statistical behavior of the system under the optimal control law. This investigation also shows the need for delay capability in any actual algorithm.

In developing an algorithm, the work of Porter and Schatz is reviewed in detail. Both of their algorithms are essentially one dimensional in nature and do not take advantage of the approach geometry. The algorithm of Schatz does not have sufficient delay capability. Porter included a set of optimal delay maneuvers which are unacceptable to pilots. An ATC merging algorithm is presented, and its components discussed. It attempts to use all the available controls and implement the control ideas developed earlier.

The simulation of ATC algorithms is then treated. Models for the radar errors and pilot errors are discussed. A wind response model is referenced for use in the simulations and the problem of tracking filters discussed in an appendix. An algorithm for delays of less than 2 minutes based on the 1:1 transformation is implemented. The sensitivity of this algorithm and Porter's maneuvers to radar-tracking filter errors and pilot errors is investigated. Since the Porter maneuvers were found objectionable, the 1:1 transformation may be better.

Arthouros K. Zervos, "A Performance Simulation of a Potential Class of Low Cost Omega/Air Data Navigation Systems", Princeton University M.S.E. Thesis, Sept 1975.

Omega is a very low frequency (VLF), very long range radio navigation system with the potential of providing worldwide coverage. However, the application of Omega VLF navigation to general aviation is hindered by the high cost of Omega receivers that are accurate and free from signal loss due to precipitation static and high levels of atmospheric noise.

Three years ago the Joint University Program on Air Traffic Control Systems was initiated under the sponsorship of NASA. The major topic of the program is low-cost navigation, with special emphasis on Omega. Under this program, research at Princeton has looked into methods of combining Omega position data and air data (heading and airspeed). Preliminary computer simulations of Kalman and exponential filter algorithms, which were investigated for the implementation of this concept, indicated feasibility of the approach.

In this thesis, Omega data collected by Ohio University's low-cost receiver are analyzed, and the characteristics of the Omega errors are derived. Then, an Omega/Air Data navigation computer is conceptually designed and its performance is tested by use of a digital computer simulation. Several simulations are performed over a range of input conditions in order to find the effect of the design parameters on the performance of the navigation system.

Jean-Luc Hidalgo, "The Statistical Effects of Wind Gusts on Aircraft Flight Time", Princeton University M.S.E. Thesis, Sept 1976.

The statistical effect of wind gusts on aircraft flights and transit time is examined for one-leg flight paths, then extended to an n-leg geometry. A close look is taken at the variation, Δt, in aircraft trip time resulting from the effect of the gusts, specifically its statistical parameters. Expressions that provide both the mean and variance of Δt are derived for one-leg trajectories, as well as n-leg flight paths. These equations are used to formulate strategies for terminal navigation of aircraft.

Specifically, the problem is the following: an aircraft flies over a fixed point, A, at a certain time, and it is desired to have it fly over another fixed point, B, at another specified time such that the total time for the flight from A to B is greater than is required to fly the straight line course AB. This thesis examines the option for multiple leg flight paths from A to B where it is desired to cross point B as close to, but not before, a specified time as possible. The problem is treated as a chance-constrained optimization problem.

A chance-constrained optimization is applied in the case of two-leg flight paths; then, using variational techniques, it is shown that the two-leg geometry is not locally optimal, and that a three-leg path allows for an improvement. The performance function gain is not, in general, significant enough to justify a systematic three-leg approach to the problem. The results obtained should provide a foundation for continuing the development of simulations of the Air Traffic Control system.

Mark A. Title, "Design and Operation of the Microprocessor-Controlled Telemetry Ground Station at the Princeton University Flight Research Laboratory", Princeton Senior Independent Work Report, May 1980.

This report describes the configuration and operation of the Microprocessor-Controlled Telemetry Ground Station, designed for use in flight experiments at the Princeton University Flight Research Laboratory. This station was developed to replace the obsolete, existing telemetry system, consisting of several bulky racks of vacuum-tube electronics with huge power and maintenance demands. The digital nature of this new system increases both our capability and flexibility in the display and analysis of our flight data, with a microprocessor coordinating all operations through a single console terminal. Additional advantages of the system include the decreased space and power requirements and increased reliability inherent in a microprocessor-based system.

Described in this report are the hardware elements of the Ground Station itself, the software of the microprocessor Telemetry Control Program, and instructions for operation of the telemetry system. Test results obtained in the development of the microprocessor system are also included.

Janet A. Lepanto, "Omega Coordinate Transformations and Propagation Corrections", Princeton University M.S.E. Thesis, Sept 1980.

The low cost, general aviation hybrid navigator, conceptualized and designed at Princeton University under NASA sponsorship, combines very-low-frequency Omega radio signals with air data to provide position information. The navigation software is based upon a flat-earth model and a linearization of Omega's hyperbolic-elliptic coordinate system. This approximation to the theoretical Omega lane structure ignores the lane variations that can result from very-low-frequency propagation anomalies.

This thesis proposes a non-linear earth model for the coordinate transformations from Omega phase differences (which constitute a grid of hyperbolae and ellipses) to latitude and longitude, and from latitude and longitude to range and bearing to a known waypoint. In addition, Omega propagation corrections, as predicted by Coast Guard software, are studied to ascertain the feasibility of condensing the corrections information for storage in the navigation computer and inflight implementation. A simulation of a short range flight is presented to demonstrate the need for propagation corrections in general aviation applications of Omega. Finally, there is a discussion of unpredicted ionosphere disturbances which can seriously degrade any Omega based navigation system.

PRINCIPAL INVESTIGATORS

Professor Dunstan Graham was principal investigator for this program until his retirement in January, 1980. At that time, Prof. H. C. Curtiss, L. M. Sweet, and R. F. Stengel became co-principal investigators for the program; Prof. Stengel has been delegated the corresponding investigator.

LASER BEACON COLLISION AVOIDANCE SYSTEMS

PROFESSOR L. M. SWEET, PROFESSOR R. B. MILES,
E. WONG, AND M. TOMEH

OBJECTIVES

LONG-TERM OBJECTIVES:

- DEVELOP FUNDAMENTAL TECHNOLOGY AND PERFORMANCE LIMITS FOR LASER-BASED LOW-COST COLLISION AVOIDANCE SYSTEMS SUITABLE FOR GENERAL AVIATION

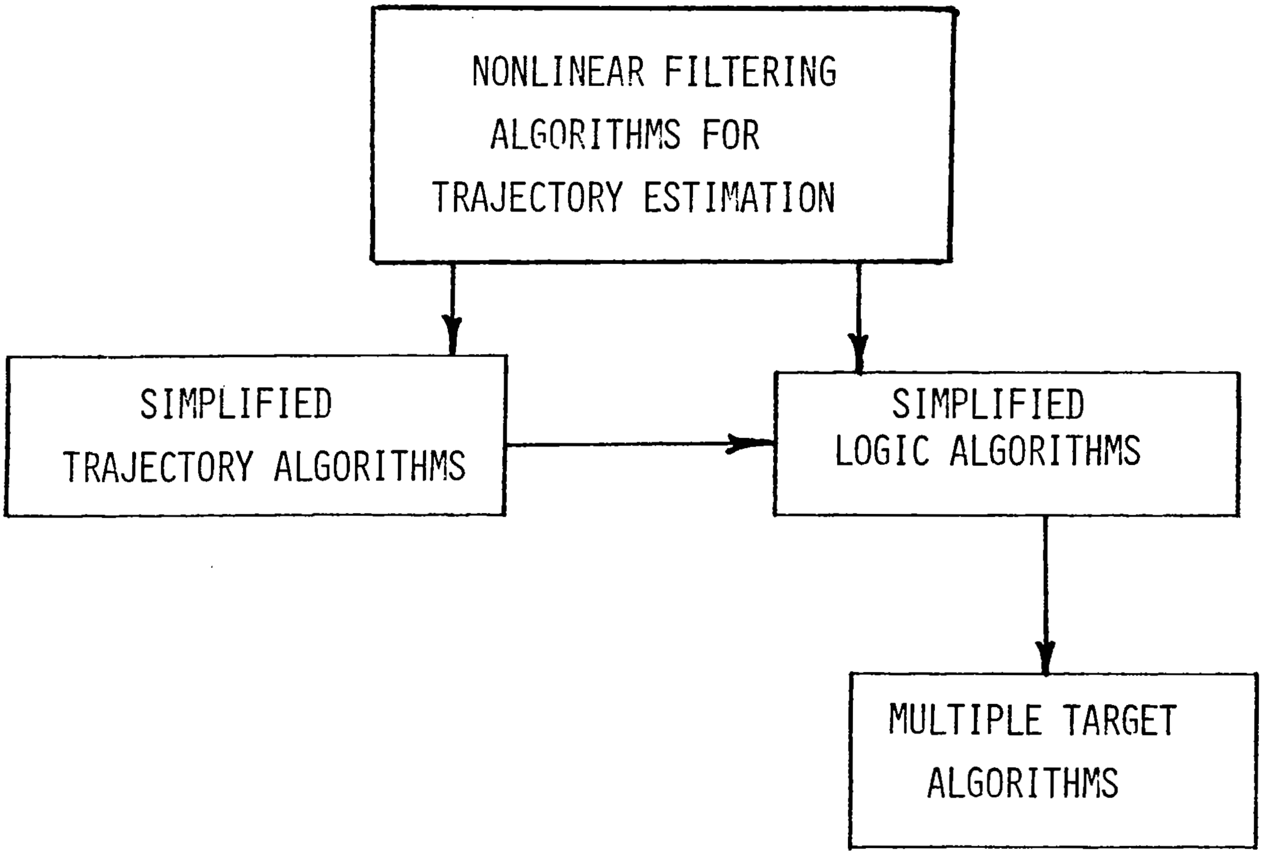
TRI-UNIVERSITY PROGRAM OBJECTIVES:

- DEVELOP TECHNIQUES FOR PROCESSING LASER BEACON-DERIVED INFORMATION FOR COLLISION AVOIDANCE

- ESTABLISH FUNDAMENTAL TRADEOFFS IN ACHIEVABLE SYSTEM PRECISION AND DESIGN PARAMETERS

- DEVELOP TECHNIQUES FOR SEPARATION OF MULTIPLE AIRCRAFT

COLLISION AVOIDANCE ALGORITHM DEVELOPMENT



MEASUREMENTS AVAILABLE TO COLLISION AVOIDANCE SYSTEM

LATERAL SWEEP ONLY:

HORIZONTAL COMPONENT OF RANGE

BEARING TO TARGET AIRCRAFT

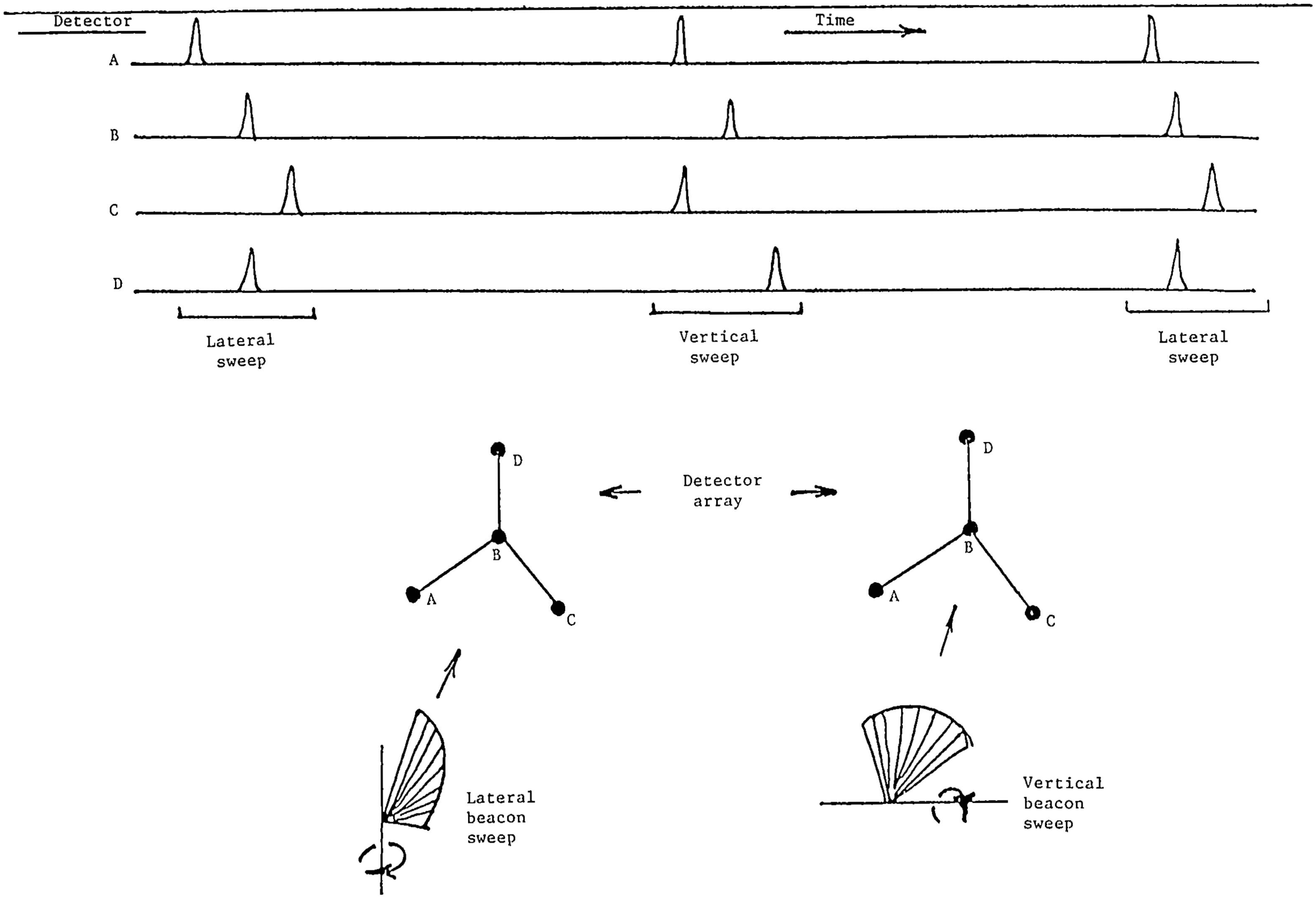
RELATIVE HEADING OF TARGET AIRCRAFT

LATERAL PLUS VERTICAL SWEEP:

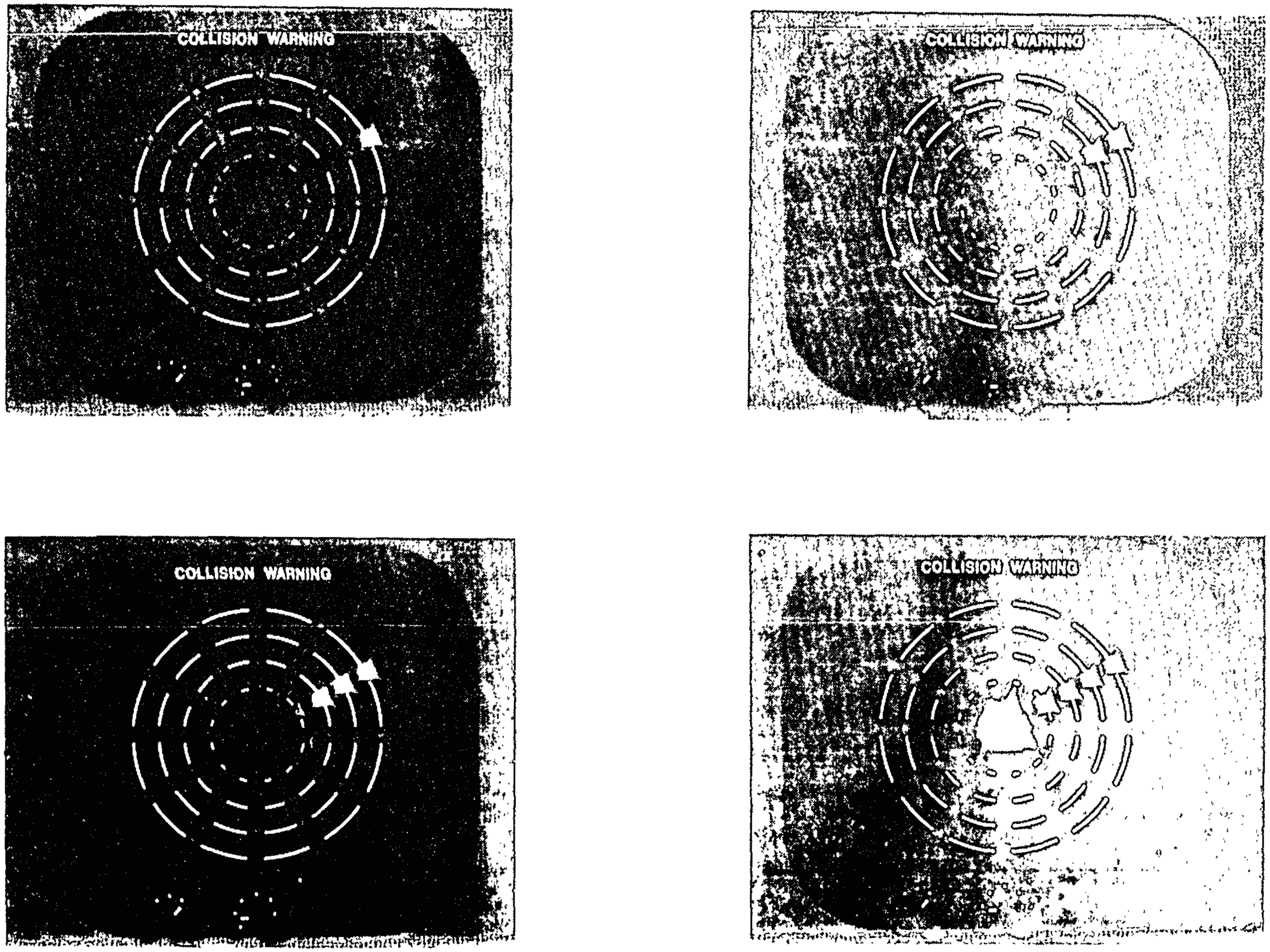
RELATIVE ALTITUDE BEARING
TO TARGET AIRCRAFT RELATIVE
HEADING OF TARGET AIRCRAFT

PROGRAM HISTORY

PERIOD	ACTIVITIES	SPONSORSHIP
1978-1980	CONCEPT DEVELOPMENT	PRINCETON UNIVERSITY
	PRELIMINARY RANGE ESTIMATES	NEW INITIATIVES FUND
1980-1981	HELICOPTER POSITION ESTIMATION	NASA/AMES
	BEACON AND DETECTOR TECHNOLOGY	
	ON-BOARD POSITION ESTIMATION	
1980-1982	COLLISION AVOIDANCE ALGORITHMS	NASA/TRI
	SEPARATION OF MULTIPLE BEACON SOURCES	UNIVERSITY PROGRAM

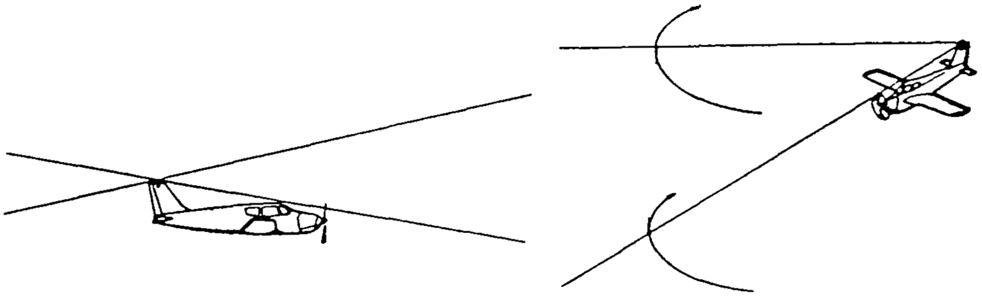


Pulse patterns generated by vertical and lateral sweeps of laser beacon past detector array.

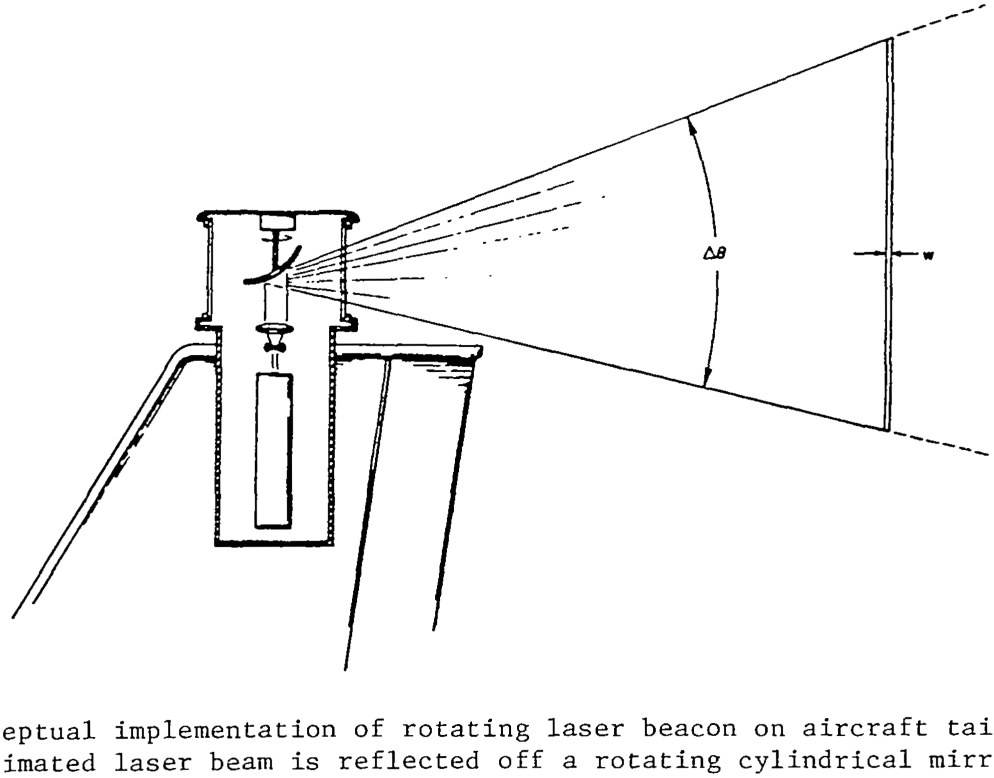


CONCEPTUAL COCKPIT DISPLAY OF POTENTIAL COLLISION HAZARD

DIAGRAM OF AIRCRAFT BEACON (RIGHT) FIELD OF ILLUMINATION AND AIRCRAFT DETECTION SYSTEM (LEFT) FIELD OF VIEW



LASER BEACON OPTICS AND BEAM PROFILE; $\Delta\theta$ IS VERTICAL DIVERGENCE, AND ω IS HORIZONTAL BEAMWIDTH



Conceptual implementation of rotating laser beacon on aircraft tail. Collimated laser beam is reflected off a rotating cylindrical mirror to produce a "Japanese fan" sweeping through the sky.

Range of Various Detector Configurations when the Visibility is 1.9 km Calculated for SNR = 5 (Left-Hand Value) and SNR = 0.5 (Right-Hand Value)

	10^{-2} sr (km)		10^{-1} sr (km)		1 sr (km)	
1-GHz filter						
Direct sunlight	1.30	2.10	1.30	2.10	1.30	2.10
Sunlit cloud	2.50	3.40	2.00	2.90	1.60	2.50
Sky (observed horizontally)	2.70	3.60	2.30	3.20	1.80	2.70
3-Å filter (225 GHz)						
Direct sunlight	0.47	1.20	0.47	1.20	0.47	1.20
Sunlit cloud	1.50	2.30	1.10	1.90	0.72	1.50
Sky (observed horizontally)	1.70	2.60	1.30	2.10	0.90	1.70
10-Å filter (749 GHz)						
Direct sunlight	0.34	1.00	0.34	1.00	0.34	1.00
Sunlit cloud	1.30	2.10	0.88	1.70	0.55	1.30
Sky (observed horizontally)	1.50	2.30	1.10	1.90	0.71	1.50
100-Å (7490 GHz)						
Direct sunlight	0.15	0.61	0.15	0.61	0.15	0.61
Sunlit cloud	0.88	1.70	0.55	1.30	0.29	0.90
Sky (observed horizontally)	1.10	1.90	0.71	1.50	0.42	1.10

Theoretical predictions of system range under conditions of limited visibility for various detector configurations. Calculations assume a 1-mW laser beacon. (Ref: Miles, R.B., "Laser beacon system for aircraft collision hazard determination." Applied Optics, Vol. 19, p. 2098, July 1980.)

DEAD RECKONER NAVIGATION PROJECT

R. ELLIS AND PROFESSOR L. SWEET
PRINCETON UNIVERSITY

THIS PROJECT IS PART OF THE CONTINUING EFFORT TO CREATE A LOW-COST, RELIABLE DEAD RECKONING NAVIGATION SYSTEM FOR USE IN GA AIRCRAFT, WITH POSSIBLE APPLICATION IN A HYBRID LORAN/DR NAVIGATOR.

A PREVIOUS DEAD RECKONER USED IN THE RESEARCH AT PRINCETON INVOLVED A CLASSICAL GYROCOMPASS, A HEWLETT-PACKARD MINICOMPUTER, AND A TRUE AIRSPEED SENSOR. IN AN EFFORT TO BRING THE COST OF THIS SYSTEM MORE IN LINE WITH THE REALITIES OF GENERAL AVIATION, RECENT WORK HAS BEEN DONE ON REPLACING THE MINICOMPUTER WITH A MICROCOMPUTER AND IMPLEMENTING A FLUIDIC RATE SENSOR IN THE COMPASS SYSTEM IN PLACE OF THE DIRECTIONAL GYRO.

<u>OBJECTIVES SINCE JUNE 1980</u>

- CHOOSE NUMERICAL INTEGRATION ROUTINE FOR CALCULATING POSITION FROM VELOCITY
- SET UP MICROCOMPUTER SYSTEM
- PROGRAM NUMERICAL INTEGRATION ROUTINE AND OTHER NECESSARY SOFTWARE IN MACHINE CODE
- INTERFACE SENSORS TO MICROCOMPUTER SYSTEM

NUMERICAL INTEGRATION ROUTINE

$\dot{\underline{X}} = \underline{F}\ (T, \underline{X})$

CRITICAL FACTORS INVOLVED IN THE CHOICE:

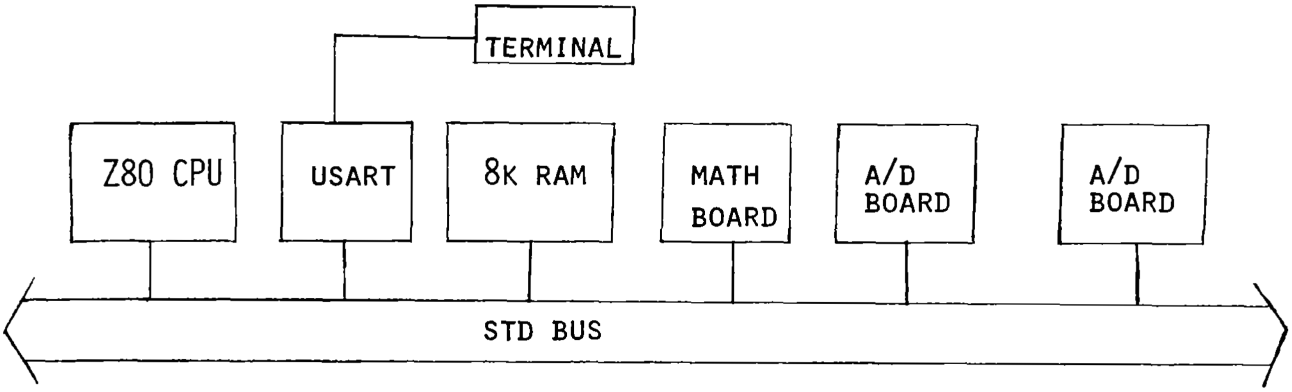
- NUMBER OF FUNCTION EVALUATIONS
- ACCURACY
- MEMORY AREA NEEDED FOR PROGRAM

MULTISTEP, SINGLE STEP MEHTODS BY ADAMS, GEAR, RUNGE-KUTTA WERE LOOKED AT. SECOND ORDER RUNGE-KUTTA WAS SELECTED AS THE BEST COMPROMISE FOR THE FOLLOWING REASONS:

- ACCURACY IS EXCELLENT FOR THE CASE WHERE ACCELERATIONS VARY SLOWLY
- ONLY 2 FUNCTION EVALUATIONS REQUIRED PER TIME STEP
- LESS PROGRAMMING EFFORT REQUIRED - IF A MULTISTEP METHOD HAD BEEN USED, IT WOULD HAVE BEEN NECESSARY TO PROGRAM A RUNGE-KUTTA METHOD ANYWAY TO GENERATE THE FIRST TIME STEPS.

MICROCOMPUTER SYSTEM

- Z80 CPU BOARD WITH 8K PROM SPACE, 4K RAM SPACE
- 4 CHANNEL USART BOARD WITH INTERRUPT CONTROLLER
- RAM CARD WITH SPACE FOR UP TO 16K
- FLOATING POINT MATH PROCESSING UNIT (AM9511ADC CHIP)
- 2 A/D INPUT BOARDS
- TERMINAL, MONITOR SOFTWARE
- UTILITY SOFTWARE FOR INTERFACING MATH BOARD AND A/D BOARDS TO CUP



REAL-TIME SOFTWARE

- WRITE A SECOND ORDER RUNGE-KUTTA ROUTINE IN 3 VARIABLES IN MACHINE CODE
  1. USE DATA FROM SENSORS TO CALCULATE PARAMETERS USED IN EVALUATION OF DERIVATIVE
  2. EVALUATE DERIVATIVES
  3. USE DERIVATIVES TO CALCULATE VALUES AT NEXT TIME STEP
- ABOVE SOFTWARE WRITTEN AND TESTED
- INTEGRATION ROUTINE IS FAST ENOUGH TO ALLOW A TIME STEP OF AROUND ONE SECOND - THIS IS ROUGHLY THE SAME VALUE USED IN PREVIOUS DR WORK AT PRINCETON
- WORK IS IN PROGRESS ON SOFTWARE TO ACQUIRE MEASUREMENTS FROM SENSORS
- RECORDING DATA -

  CURRENT PLAN IS TO STORE DATA ON CASETTES FOR HP2644 TERMINAL
  EACH CASETTE HOLDS ≈ 10^5 BYTES; TERMINAL HOLDS 2 CASETTES
  WORK UNDERWAY ON PROGRAMS TO ACCOMPLISH THIS
- ANALYZING DATA -

  DATA FROM CASETTES IS TRANSFERRED TO MICROCOMPUTER MEMORY, THEN TO DISK ON 3033

INTERFACING SENSORS TO MICROCOMPUTER SYSTEM

- SENSORS USED

  1) J-TEC TAS INDICATOR-VOLTAGE PROPORTIONAL TO TAS
  2) FLUXGATE DETECTOR-SYNCHRO SIGNAL
  3) FLUIDIC RATE SENSOR-VOLTAGE PROPORTIONAL TO ANGULAR RATE
  4) (DIRECTIONAL GYRO) - SYNCHRO SIGNAL

- NEED TO PERFORM A/D CONVERSION

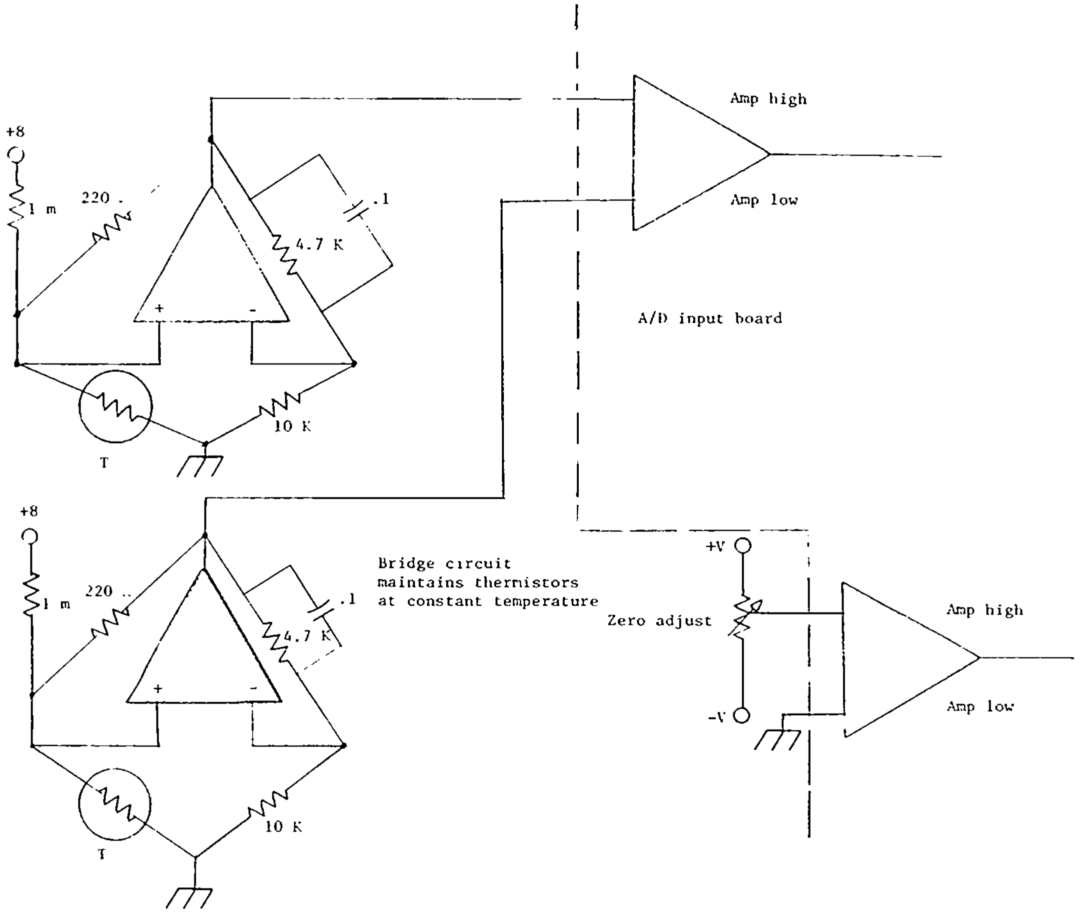
  A/D BOARDS ASSOCIATED WITH MICROCOMPUTER WILL BE USED AS OPPOSED TO SEPARATE BOARDS FOR EACH SENSOR FOR FOLLOWING REASONS

  1) MINIMIZE EQUIPMENT NEEDED
  2) LESS INTERFACE WORK
  3) EASIER TO CONTROL TIME AT WHICH CONVERSION IS DONE

WORK ON RATE SENSOR

- CIRCUIT TO KEEP THERMISTORS AT CONSTANT TEMPERATURE BUILT (SEE SCHEMATIC)

- FOR THE DIFFERENTIAL AMPLIFIER SECTION, CURRENT PLAN IS TO USE A/D BOARD IN DUAL INPUT CONFIGURATION THIS WILL ALSO PROVIDE THE HIGH COMMON MODE REJECTION WHICH IS IMPORTANT TO THE OPERATION OF THE SENSOR ZERO ADJUSTMENT WILL BE DONE BY A POTENTIOMETER CONNECTED TO ANOTHER INPUT CHANNEL ON A/D BOARD (SEE DIAGRAM) NO GAIN ADJUSTMENT - A/D BOARD DOES NOT PERMIT THIS



Bridge circuit maintains thermistors at constant temperature

RESOLVING SYNCHRO SIGNAL

- FLUXGATE TRANSMITS ITS ANGULAR READING AS A SYNCHRO SIGNAL MUST CONVERT IT TO DIGITAL

  2 CHOICES:

  1) USE SYNCHRO-DIGITAL CONVERTER CHIP AND ASSOCIATED ELECTRONICS

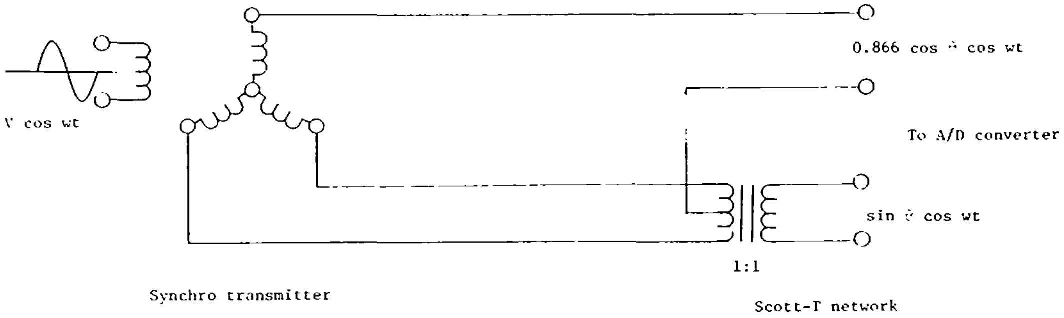
     - SYNCHRO-DIGITAL CONVERTER IS EXPENSIVE
     - SYNCHRO-DIGITAL CONVERTER WOULD REQUIRE INTERFACING TO BE COMPATIBLE WITH THE I/O ADDRESS SPACE OF THE COMPUTER

  2) USE A/D BOARDS TO PERFORM CONVERSION

     - USE SCOTT-T TRANSFORMER TO RESOLVE 3 VOLTAGES INTO 2 VOLTAGES PROPORTIONAL TO SIN θ AND COS θ (SEE DIAGRAM)

     - USE THE RATIO OF THESE VOLTAGES TO DETERMINE θ (WRITE AN ALGORITHM)

     - FLUXGATE USES 400 HZ CARRIER



Resolution of Synchro Signals

TAS INDICATOR

- CONNECT TO A/D BOARD A LOW PASS FILTER MAY BE REQUIRED TO PREVENT "ALIASING" IN THE REAL-TIME SOFTWARE

GENERAL AVIATION AIRPLANE FUEL ECONOMY SYSTEM MODEL

Professor L. Sweet and Professor H. Curtis, R. Parkinson
Princeton University

NOMENCLATURE

c	engine brake specific fuel consumption, lb/BHP·hr (1 lb/BHP·hr = 0.608 g/W·hr)
$\bar{c}$	wing mean aerodynamic chord, ft (1 ft = 0.3048 m)
D	airframe power-off drag, lb (1 lb = 0.138 N)
$h\bar{c}$	longitudinal center of gravity position, ft
L	lift, lb
MAP	engine inlet manifold absolute pressure, inches Hg (1 in. Hg = 3.39 kPa)
$\dot{m}_f$	fuel flow rate, lb/hr (1 lb/hr = 0.453 kg/hr)
N	propeller shaft speed, RPM
N_E	engine shaft speed, RPM
P_a	atmospheric ambient pressure, inches Hg
P_e	engine exhaust back pressure, inches Hg
P_R	airframe power required (power-off), horsepower (1 HP = 0.746 kW)
Q_a	propeller shaft torque (incompressible aerodynamics), lb·ft (1 lb·ft = 1.36 J)
Q_E	engine shaft torque, lb·ft
R^*	specific range, ground nautical miles/lb (1 n. mi./lb = 2.2 n. mi./kg)
S^*	$= R^*/c$
T_a	atmospheric ambient temperature, ^{o}K
T_m	engine inlet manifold temperature, ^{o}K
T_p	propulsive thrust, lb

V_E	equivalent airspeed EAS, knots
V_T	true airspeed, knots
V_w	wind component along track, knots
W	gross weight, lb
W_o	reference gross weight, lb
X	corrected EAS, knots
Y	corrected propeller RPM, RPM
Z	corrected propeller shaft torque, lb·ft
β	propeller blade angle, degrees
γ	climb angle, degrees
ψ	heading, degrees
σ	density ratio
η_p	propulsive efficiency

SYSTEM BLOCK DIAGRAM FOR R* ANALYSIS

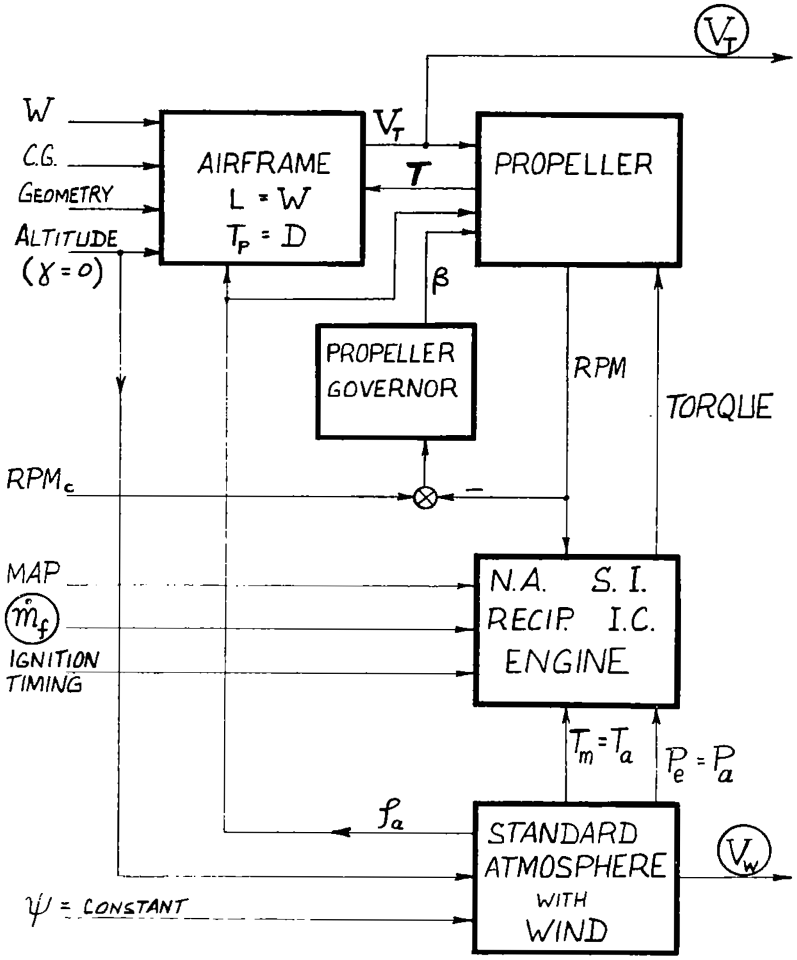


Figure 1

Figure 1 is a block diagram of the naturally aspirated engine-propeller-airframe-atmosphere model used in this study of R^*: Inputs to the system appear at the left, and outputs at the right. The value of R^* is given by:

$$R^* = \frac{V_T + V_w}{\dot{m}_f}$$

To optimize R^*, we must optimize the performance of the entire system and not just individual blocks shown in figure 1.

AIRFRAME-PROPELLER

- ZERO WIND
- FIXED C.G. POSITION
- NO COMPRESSIBILITY EFFECTS

$$R^* = \frac{V_T}{P_R}\,\frac{\eta_P}{C} = \frac{S^*}{C}$$

$$S^* = \frac{V_T\ \eta_P}{P_R} = \frac{5252.1\ V_E}{E\ N\ Q\sqrt{\sigma}}$$ where E = number of engines

LET $X = V_E\sqrt{\frac{W_0}{W}}$ CORRECTED EAS

$Y = N\sqrt{\frac{W_0\,\sigma}{W}}$ CORRECTED RPM

$Z = Q\ \frac{W_0}{W}$ CORRECTED TORQUE

THEN

$$S^* = \frac{5252.1}{E}\ \frac{X(W_0/W)}{YZ}$$

Figure 2

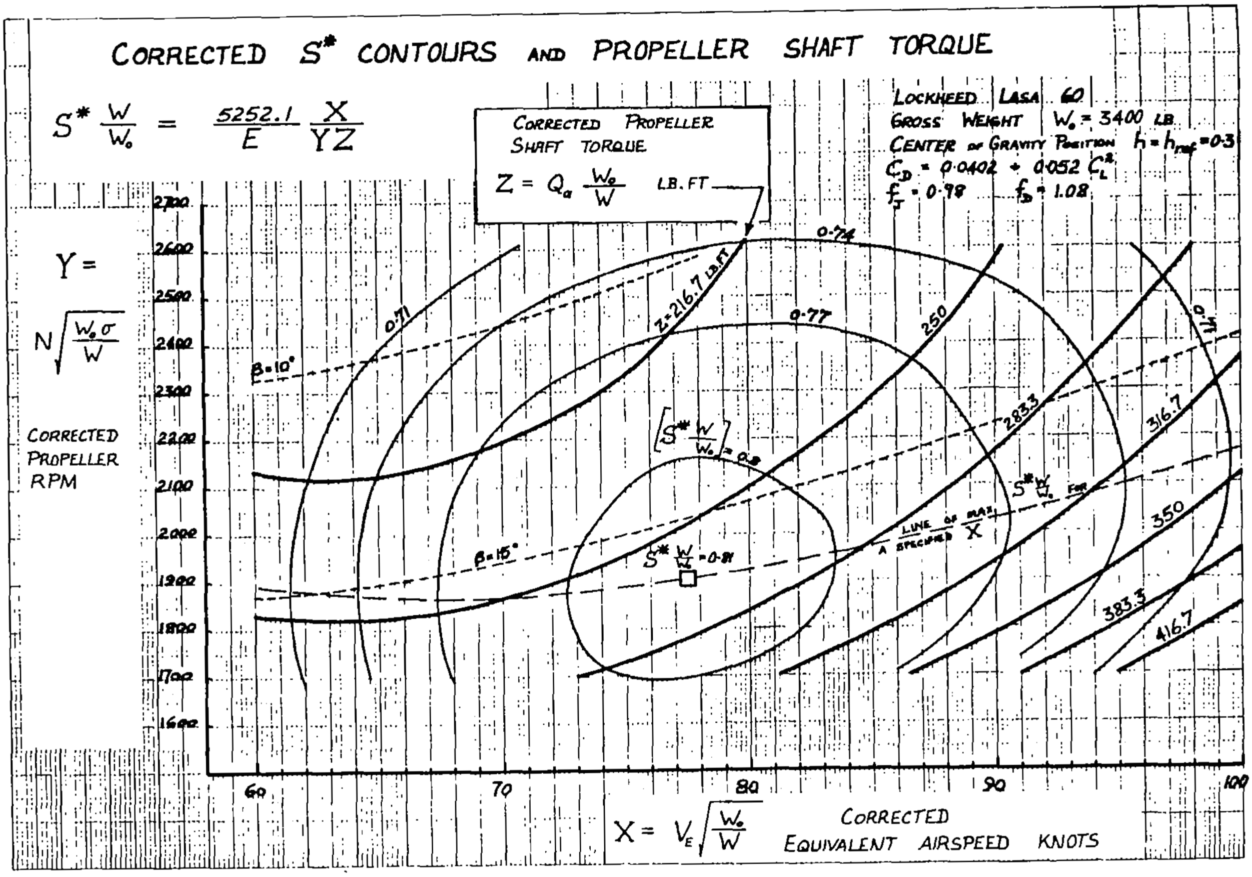


Figure 3

A plot of $\{X,Y,Z,S^*\}$ is given in figure 3 for the LASA 60 Airplane. Such a plot may be constructed from propeller shaft torque data, and yields S^* for all values of

- Equivalent airspeed
- Gross weight
- Propeller RPM
- Altitude

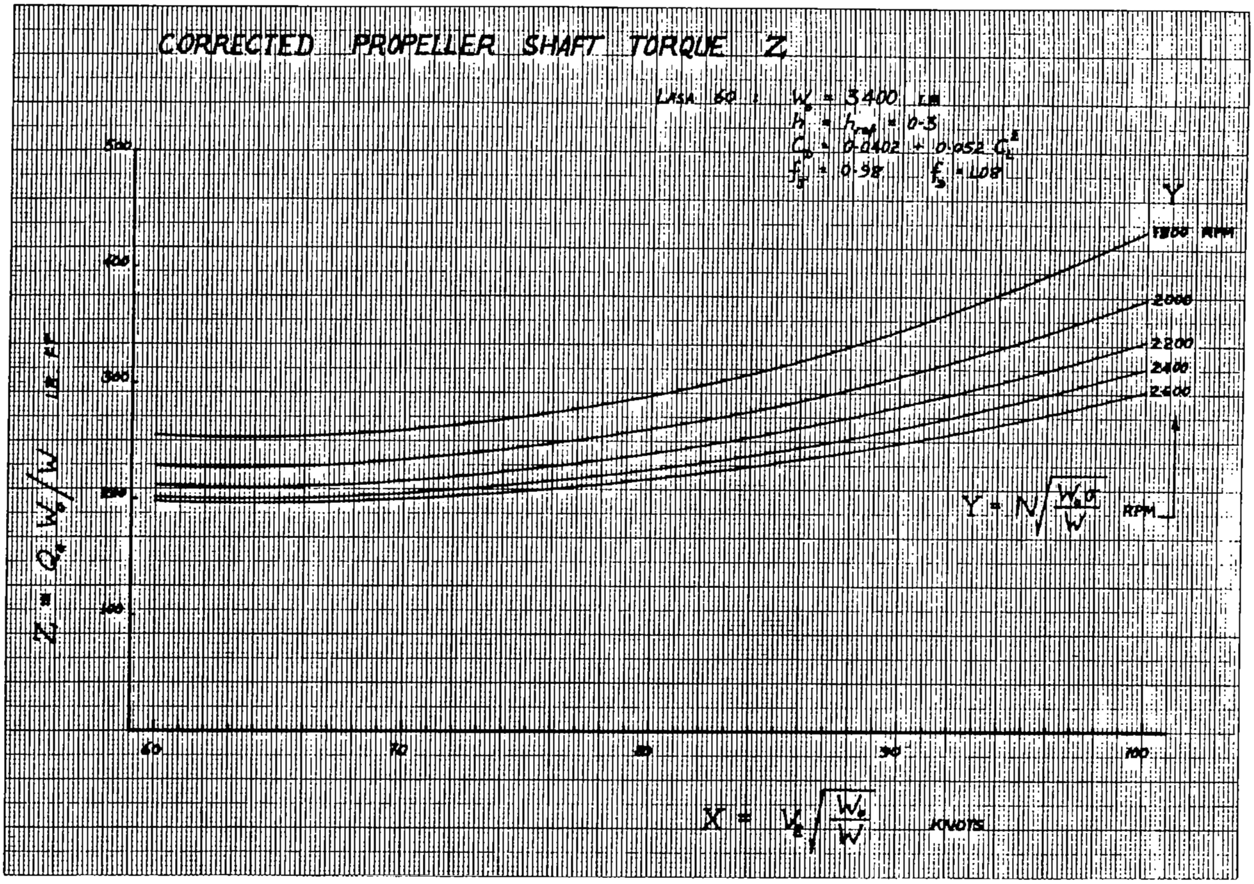
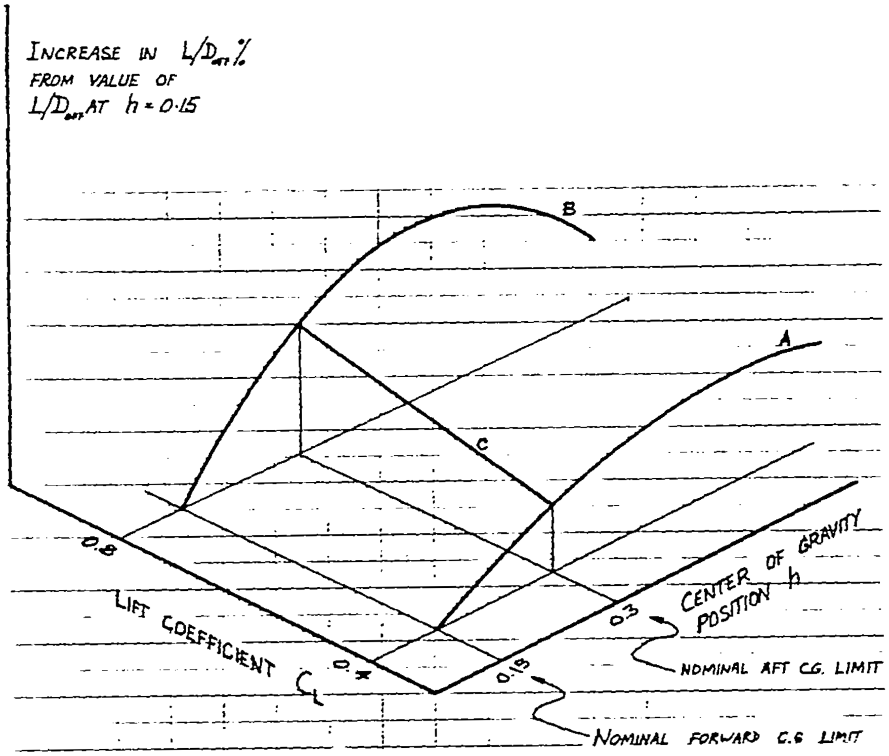


Figure 4

Figure 4 shows the form in which the torque data would be collected and stored in a microprocessor for airborne computations.

SCHEMATIC VARIATION OF AIRPLANE L/D_{OFF} WITH h AND C_L



h	c.g. position
h_{ref}	Reference c.g. position
$dh =$	$h - h_{ref}$
ξ	Positive constant
C_L	Lift coefficient

Surface height is a function of the geometric and aerodynamic characteristics of the airplane. In the usual range of c.g. position, this surface indicates that

$$R^*_h = R^*_{h_{ref}}(1 + \xi C_L\ dh)$$

Figure 5

COMPLETE SYSTEM

$$R^* = \left[1 + \frac{V_W\sqrt{\sigma}}{V_E}\right] \frac{(1 + \xi C_L dh)\,\eta_{COMP}\, S^*}{C}$$

WHERE

$$\eta_{COMP} = \frac{\eta_P \text{ COMPRESSIBLE}}{\eta_P \text{ INCOMPRESSIBLE}}$$

ENGINE PARAMETERS

$$N_E = G.\, N$$

$$Q_E = \frac{WZ}{W_0\,(1 + \xi C_L dh)\,\eta_{COMP}\; G}$$

G = Gear ratio

Figure 6

The engine parameters, simply computed in figure 6, are used to enter the brake specific fuel consumption curves to determine

- MAP required
- BSFC

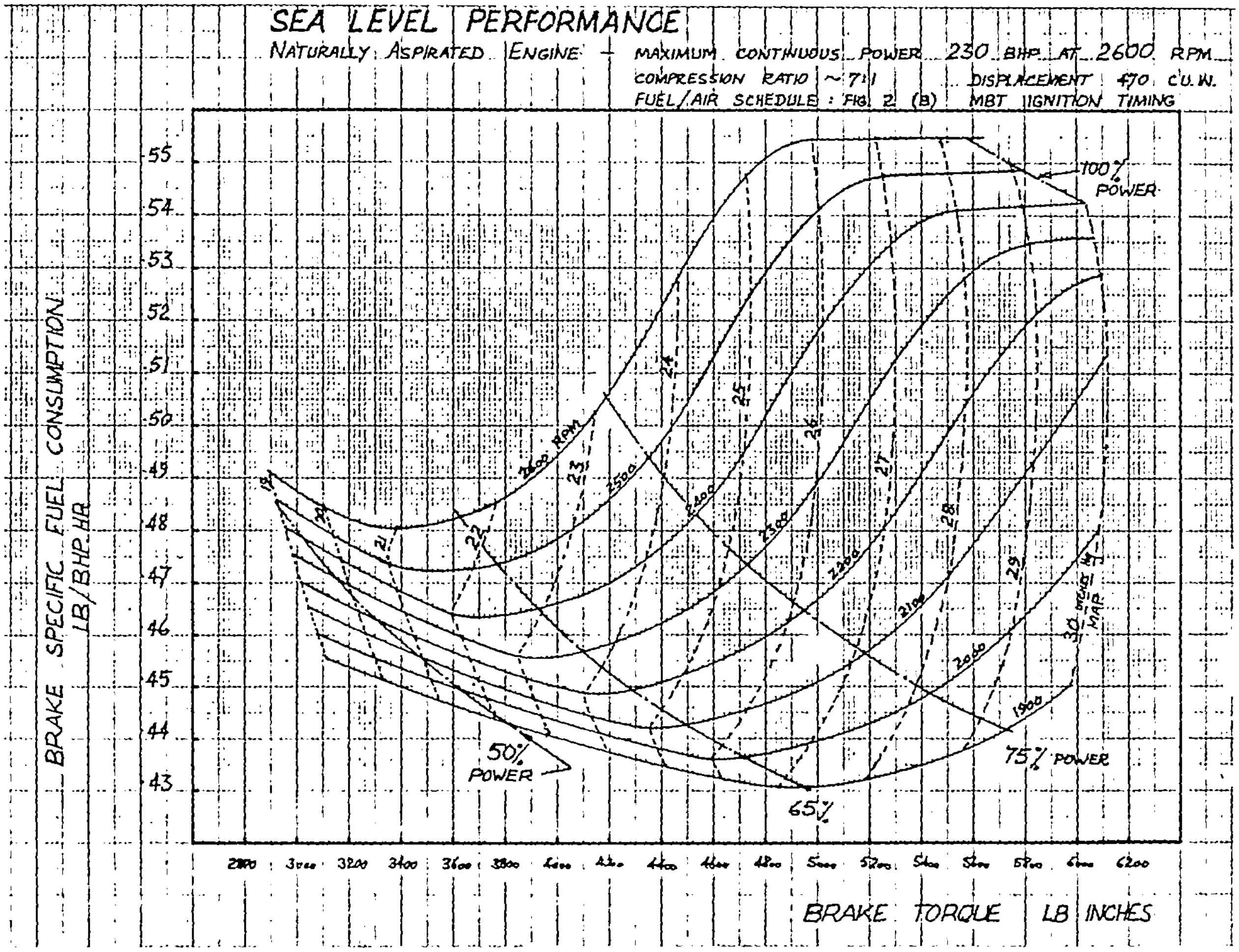


Figure 7

A sample BSFC plot is shown in figure 7 which illustrates, for a typical naturally aspirated engine at sea level, the relationships between:

- MAP
- Torque } Power
- RPM
- BSFC

for a certain Fuel/Air ratio schedule. Similar plots for different altitudes show the influence of altitude on this set of relationships.

CONCLUSIONS

1. POH DATA INADEQUATE
2. MUST OPTIMIZE SYSTEM PERFORMANCE
3. AIRFRAME - PROPELLER R* PERFORMANCE
   - ONE SET OF CORRECTED TORQUE CURVES
   - COMPRESSIBILITY CORRECTIONS TO PROPULSIVE EFFICIENCY
   - ONE EQUATION FOR R* (FIGURE 6)
4. ENGINE PERFORMANCE
   - FORM OF BSFC CURVES
   - EFFECTS OF F/A

     P_M
     RPM

     ALTITUDE
   - FUEL ECONOMY BENEFITS OF TURBOCHARGING
5. HAVE A COMPACT MODEL SUITABLE FOR MICROPROCESSOR APPLICATIONS, WHICH
   - MAY BE SIMPLY CONSTRUCTED FROM EXPERIMENT
   - PROVIDES BASIS FOR OPTIMIZING R* AND TRIP FUEL CONSUMPTION

Figure 8

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