Quarterly Technical Summary

Air Traffic Control

15 February 1971

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

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ii

INTRODUCTION

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Other members of the group are continuing with their studies on Beacon System improvements, signal processing, and the Cockpit Display Concept. The Boston Harbor laser experiment is now collecting test data.

22 February 1971

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CONTENTS

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AIR TRAFFIC CONTROL

I. SUMMARY

The Lincoln Laboratory Air Traffic Control program includes investigations related to the development of improved surveillance and communications capability to support the needs of the automated air traffic control system. Recent work on the beacon system and on tracking studies is reported in Sec. II.

Under the sponsorship of the Transportation Systems Center of DOT we are engaged in technical studies on Fourth Generation Air Traffic Control System Concepts. Our activities in this area are reported in Sec. III.

New studies, sponsored by the Federal Aviation Administration, on the Discrete Address Beacon System (DABS) have commenced. A technical development plan for the DABS is being prepared; its scope is described in Sec. IV.

The simulation studies and system planning of an airborne traffic situation display which will provide pilots with a suitably edited and formatted display of traffic information in the terminal area are continuing. Details of this work are found in Sec. V.

Field testing is proceeding on a prototype laser warning system which has been designed to alert the tower controllers at Logan Airport of the presence of a ship with a tall mast in the shipping channel which crosses the approach path to Runway 4R. This test program is supported by the Massachusetts Port Authority and is reported in Sec. VI.

II. SURVEILLANCE TECHNOLOGY

While the focus of our activity during the past quarter has been on topics related to ATCRBS and tracking, we continue to apply the results of other programs under way at Lincoln Laboratory to the solution of the surveillance problems of the air traffic control systems. For example, the performance of a high resolution, electronically scanned radar system currently being assembled by the MTI Radar Group will be evaluated in detecting aircraft in flight and on the ground in the presence of heavy ground clutter. This class of radar could serve as an all-weather, clutter-free monitor for traffic on closely spaced parallel runways. In addition to the electronically scanned antenna, the radar employs an advanced, fast digital processing terminal for extracting Doppler information and rejecting clutter.

Plans are being developed for a demonstration of the surveillance capability of this system, including its utility in monitoring V/STOL traffic.

A. ATC Radar-Beacon System Development

1. ATCRBS Interrogator Antenna

The preliminary analytical work related to upgrading the performance of the mechanically rotated ATCRBS antennas has been completed. Further effort in this area is contingent upon the interest and support received from the sponsoring agencies.

Antenna modifications have been investigated which could improve performance at the present interrogator sites. This work was reported in our last quarterly technical summary, (15 November 1970). Further improvement could be achieved through the development of new antennas and especially through better siting of the beacon antennas.

It has been shown that multipath problems which manifest themselves through missed replies, false replies, and azimuth angle errors, can be reduced substantially by siting the ATCRBS antennas above interferring structures. High siting also increases the probability that reflections from the ground will be diffuse rather than specular, thus reducing the magnitude of the vertical lobing. Presently, many interrogators are located at airports where large structures interfere with the antenna beam. For example, at Logan Airport in Boston, structures around the airport, and in the city have elevation angles of as much as 4 degrees when viewed from the interrogator site. Reflections from these structures can produce false replies. Diffraction effects can produce significant azimuth angle errors as shown in Fig. 1, which is representative of one of the "worst case" situations studied.
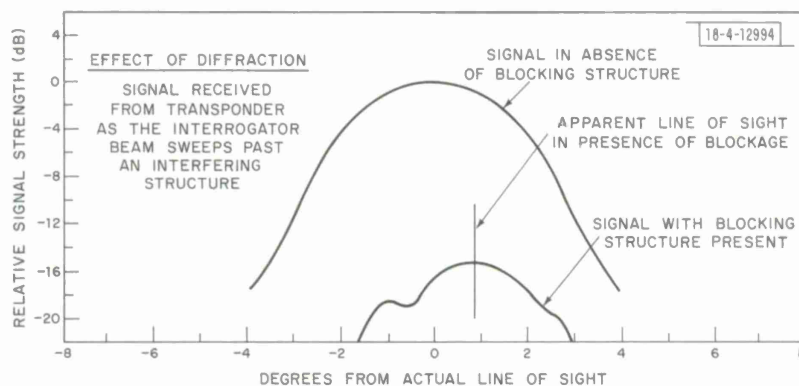

Fig. 1. Estimated effects of diffraction on signal strength received from ATCRBS transponder as interrogator antenna sweeps past interfering structures. Obstruction profile based on topography of Logan Airport, Boston, Massachusetts.

During this reporting period, our effort has been concentrated on the analysis of the performance of a cylindrical array which meets the objectives of the recently released FAA specification for an electronic scan antenna. A computer program was developed which conveniently calculates and plots the far-field radiation patterns for the above array for a variety of parameter values. Pattern calculations and plots were made for planes at various elevation angles above the "principal plane" and show pattern distortions not expected by simple analogy with columns of a linear array. The results of the calculations to date approximate the FAA requirements in part, and it is believed that by further parameter variation a closer approximation to those requirements could be achieved. Both the monopulse sum-and-difference patterns and an appropriately superimposed omnidirectional pattern for improved sidelobe suppression were examined. In addition, the specific hardware required to physically realize the associated feed circuit was considered.

A synthesis technique for circular arcs has been developed which has the following features:

(a) The directional patterns of the elements are taken into account.

(b) The effects of a cylindrical reflector are taken into account explicitly, although alternatively this may be treated at part of (a).

2

(c) The method holds for general patterns, including those with even or odd symmetry so that monopulse operation may be considered.

(d) No matrix inversion is required; instead explicit closed-form solutions are derived.

2. ATCRBS Interference

During the past quarter we have worked on analysis of a model of ATCRBS interference and on evaluation of the performance of current commercial transponders. These studies were instigated in order to develop a better understanding of the interference problem which exists in the operation of the contemporary ATCRBS and of the problems which may arise if present frequencies and signaling waveforms are adopted for the proposed Discrete Address Beacon System.

a. Interference Model

The sources of ATCRBS interference result from separate physical phenomena on the uplink and downlink channels. On the uplink channel, several interrogators may attempt to access a single transponder. Since each interrogation initiates a dead-time interval, some interrogations will not elicit replies. For this reason the round reliability is less than unity. However, round reliability is presently based on a long-term average. Consequently, it is inadequate to describe the likelihood that some fraction of a sequence of contiguous interrogations from a particular interrogator (i.e., 18 for a terminal interrogator) will elicit replies. A more explicit measurement of reliability is important for adequate characterization of the channel with respect to the performance of the receiver signal processing algorithms (i.e., detection, angle estimation, etc.). We define the uplink reliability to be the probability that of n pulses from a particular interrogator, exactly j of them will elicit replies, $j = 0, 1, 2, \ldots, n$. Although we have made some progress in computing this performance measure, the problem is not completely solved. Since the computation is quite complicated, we feel that upper and lower bounds for it should be computed. The latter are considerably easier to obtain.

Once a reply signal has been elicited from the transponder, it is still possible that it will not be correctly received at the intended interrogator receiver because of the presence of undesired fruit replies. These arise from the ensemble of transponders emitting signals to other interrogators which are inadvertently received by the interrogator under study. We define the downlink reliability to be the probability that a signal from a particular transponder is correctly received by the intended interrogator. Although related to the notion of fruit per scan, it represents a more detailed characterization of the downlink channel which, when combined with the uplink reliability, permits an overall characterization of the ATCRBS communication channel. It is the downlink model which was described in the preceding quarterly technical summary; a computer block diagram has been developed for it. Programming and evaluation will begin in the next quarter.

The downlink model can also be used to describe the ATCRBS interference which will be seen by a discrete-address interrogator operating at the same frequency; hence, it will be a useful tool for the signal format study.

b. Transponder Studies

The characteristics of the modulation employed in the up and downlinks of ATCRBS have been examined with regard to their compatibility with a Discrete Address Beacon System (DABS)

3

which utilizes the same frequency band and waveforms. Particular emphasis has been devoted to the problem of false triggering of the present generation of transponders by DABS interrogations. Two methods for preventing false replies from ATCRBS transponders when they receive DABS interrogation messages were studied. The first inhibits the transponder by means of the sidelobe suppression code; the second employs a DABS code which is free of the pulse combinations used in the current interrogation format. In this latter scheme, random false triggering of sidelobe suppression is allowed to occur. The major effects of these two solutions on the surveillance system have been analyzed and possible means for implementing them on typical transponders have been outlined.

To arrive at a model for a typical ATCRBS transponder, a detailed examination of the maintenance and operating manuals of a number of commercially available transponders was undertaken. In addition, it was found necessary to investigate experimentally the performance of transponders in order to determine their specific response to nonstandard inputs.

The first transponder selected for testing was typical of the less expensive units which are reported to be selling in significant quantities to the general aviation market. Some of the reasons for the choice of such units for the initial tests are:

(1) General aviation aircraft are the most numerous users of the airspace, and as more of them become transponder equipped they will become the major source of ATCRBS replies.

(2) Cost factors are quite important to general aviation owners and the lower cost transponders are expected to increase in use.

(3) It was assumed that the more complex, higher cost transponders designed for the commercial airline markets were more likely to conform to the letter and intent of the ATCRBS national standard, and therefore discrepancies in transponders were more likely to show up in the lower priced units. Nonetheless, we shall also test the higher priced units at an early date.

Initial tests were run to determine sensitivity to certain parameters of interest. Following the initial testing of one of the units, it was put through the test routine specified by the RTCA SC-116B in document DO-144 "Minimum Operational Characteristics for Airborne ATC Transponder Systems."

Two particularly significant facts were learned which were not obvious from a study of the transponder circuit diagram. The unit was found to emit spurious responses upon receipt of a CW signal of only 10 dB less intensity than a correctly coded pulsed signal and to exhibit a dead time of a millisecond or more following the transmission of a reply. The sensitivity of the unit for both correct and CW signal interrogations is illustrated in Fig. 2.

Experience with the initial transponder tested clearly indicated the difficulty of predicting its performance from circuit diagrams alone, and therefore it is important to ascertain performance experimentally. Tests on this unit and other transponders will continue.

B. Tracking Studies

At the level of automation represented by ARTS-III and NAS Stage A, the chief function of tracking is to maintain target identity, while the most accurate estimate available of target
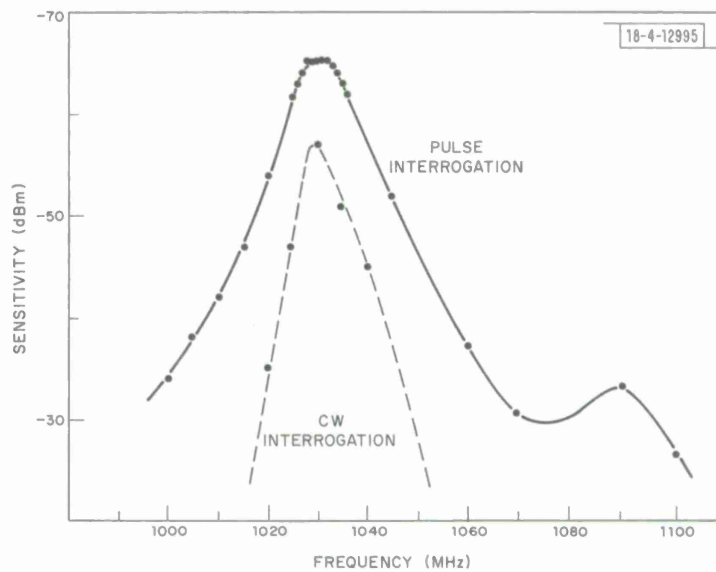
Fig. 2. Transponder sensitivity to pulsed and CW signals
as a function of frequency.

position will usually be the raw surveillance data from the most recent scan. At higher levels of automation, including metering and sequencing, collision-avoidance and approach monitoring functions, the computer will be totally dependent on tracking for target velocity and this will place definite and generally more severe requirements on the accuracy of both track position and track velocity. The accuracy of the tracker is governed by the accuracy and data rate of the raw surveillance data and the degree of immunity of the tracker to maneuvers it was not designed to follow. Surveillance data errors tend to be reduced by smoothing over a long tracking window, while errors due to maneuver tend to increase. An analysis of this trade-off relationship in some simple cases has led to a useful method for evaluating the effects of maneuver on various trackers, and for choosing a reasonable window length in terms of data accuracy and maneuver limits.

To model the maneuver it is assumed that any acceleration profile is possible, so long as the acceleration itself does not exceed a fixed bound. This model is also used in the analysis of hazard regions in the collision-avoidance problem. We have studied expanding and sliding window, least-squares trackers of various types and find that it is possible to express the errors in tracked position and velocity in the form of integrals over the acceleration profile. From these expressions one can deduce the worst-case profile, subject to the bounds assumed, and hence evaluate the corresponding worst-case tracker errors. Errors due to maneuver are essentially biases in the estimates of track position and velocity, while surveillance data errors cause a random component. By fixing the ratio of bias due to maneuver to the standard deviation of the random component, we can solve for the appropriate tracking window length.

For a simple least-squares tracker (expanding or sliding window) designed to follow constant-velocity motion, the worst-case maneuver is a constant acceleration, and we obtain the following expression for the tracking window length, T

$$\frac{T}{\Delta} = \gamma \left(\frac{\sigma}{A\Delta^2/2}\right)^{2/5} \quad ,$$

where Δ is the scan time, σ is the standard deviation of raw position error, A is the bound on acceleration and γ is the coefficient dependent on assumed ratio of maneuver bias to standard deviation of random error. The ratio T/Δ is simply the number of scans in the tracking window. To illustrate this formula, let us require the maneuver bias in tracked position to equal the random position error, which results in $\gamma = 2.7$. For the enroute situation, we take

$$\sigma = 3000 \text{ ft}$$
$$\Delta = 10 \text{ sec}$$
$$A = 0.1 \text{ g},$$

and find

$$\frac{T}{\Delta} \approx 9 \text{ scans}.$$

For the terminal area, we choose

$$\sigma = 1000 \text{ ft}$$
$$\Delta = 4 \text{ sec}$$
$$A = 0.5 \text{ g},$$

and find

$$\frac{T}{\Delta} \approx 6 \text{ scans}.$$

The numbers we have used here are only representative values, but the general conclusion that track smoothing should be held to a very modest number of scans is probably valid.

A least-squares tracker designed to follow constant acceleration motion was also studied. The worst-case maneuvers now have maximum acceleration with an abrupt reversal of sign near the middle of the window. Maneuvers consisting of maximum acceleration during roughly half the window, followed or preceded by zero acceleration are nearly as serious and will often occur when the tracking window includes the start or end of a turn. This tracker develops a smaller worst-case bias than the simple (constant velocity) tracker for a given window length, hence longer windows are possible. However, longer windows are required to achieve the same smoothing (reduction of random errors) as the simple tracker, and the two effects almost exactly cancel.

This analysis and the complementary work reported in the last quarterly technical summary on the application of modern filter theory and sensor netting to the tracking problems in air traffic control systems, point the way to effecting system improvement using the present sensor system. Further applications of these techniques will be investigated.

III. FOURTH GENERATION ATC CONCEPT STUDY

On 1 February 1971, we began a study of Fourth Generation ATC concepts sponsored by the Transportation Systems Center of the Department of Transportation. Our initial effort

will concentrate on the area of "control" in the context of the ATC system. Topics to be addressed include: What degree of automation of the controller function is feasible and desirable, what level of distributed management versus centralized management is beneficial, how should the airspace and airport surface be structured, and what rule and procedural changes are needed in light of advancing technology and increasing demand.

IV. DISCRETE ADDRESS BEACON SYSTEM (DABS)

In support of the Office of Systems Engineering Management of the FAA, we have commenced the preparation of a comprehensive Technical Development Plan for the design, evaluation and implementation of a Discrete Address Beacon System which is intended to meet future requirements for improved surveillance and communications in the ATC environment. This study extends and complements the previous work in this area reported by the Department of Transportation Air Traffic Control Advisory Committee.*

The Technical Development Plan will summarize the major technical and operational issues which influence the design of the DABS and will identify topics which are unresolved and consequently in need of further investigation. The various design options available for the development of the proposed system will be described. A system block diagram will be configured and supported by descriptions of subsystem components and technical parameters.

In addition, the Technical Development Plan will include a comprehensive program plan for developing and evaluating the discrete address beacon and an overall management plan to guide the utilization of governmental and industrial resources, to monitor and evaluate progress, and to integrate civil and military aviation requirements.

V. AIRBORNE TRAFFIC SITUATION DISPLAY

During the past quarter our program to develop an airborne traffic situation display of NAS/ARTS data resulted in a proposal for the development of brassboard equipment. While awaiting a response to this proposal, both design and simulation work continued and have now reached the stage at which fabrication of equipment can commence.

This device will provide pilots with a display of adjacent aircraft as well as symbols and lines to represent fixes, airways, localizers, etc. It is viewed as a natural outgrowth of and an adjunct to the NAS/ARTS equipments currently being installed.

A. Design Studies

Work continued on the design of an experimental airborne display consisting of a message processing computer located at the ARTS facility, a narrowband datalink, an airborne situation display terminal and a ground monitor. The monitor will be linked to the message processing computer via telephone lines to facilitate system design, checkout, and experimental data gathering.

A preliminary design of an interface between an ARTS computer and a candidate message processing computer has been completed; the final design will be dependent upon the specific computer selected and the details regarding the ARTS input-output channel hardware. The ARTS software and controller input-output equipment involved in generating displays were reviewed as part of the work. This study revealed that the controller can exercise considerable

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* Report of the Department of Transportation Air Traffic Control Advisory Committee, December 1969 (GPO 1970-0-375-448).

discretion over the alphanumerics appearing on his console. This freedom will complicate the experimental testing of the system, unless a spare console is available which can be dedicated to the experiment.

The computer software and display data channel converters for the airborne equipment were blocked out. The computer will handle the tasks of interfacing with a VHF datalink, sorting the uplinked aircraft messages, tracking up to 8 aircraft, generating the display file of traffic and map information, reading experimental data on tape and monitoring the pilot display control. Adequate capacity has been reserved for performing area navigation calculations at a later date, if desired.

Design has started on the display indicator and waveform generator portions of the ground monitor. The indicator will use a high-brightness CRT. Three digitally controlled gray levels will be available for alphanumerics and vectors. The indicator will be driven by a waveform generator consisting of symbol generator, vector generator, rotation array, and translation adders. A hybrid rotation array and digital adders will be used to translate the center of the display to aircraft coordinates and rotate the display to aircraft headings. Digital inputs to rotation array and translation adder will have 12-bit precision. The vector generator inputs will have 10-bit precision. Design has also started on the interface between the waveform generator and a candidate processor.

B. Display Simulation (Electronic Systems Laboratory, Flight Transportation Laboratory, Man-Vehicle Laboratory)

The integration of the Boeing cockpit mockup with the display simulator has now been accomplished and a very useful tool created for current and future programs on Air Traffic Control (see Fig. 3). Tests are under way to assess the usefulness of an air traffic situation display for
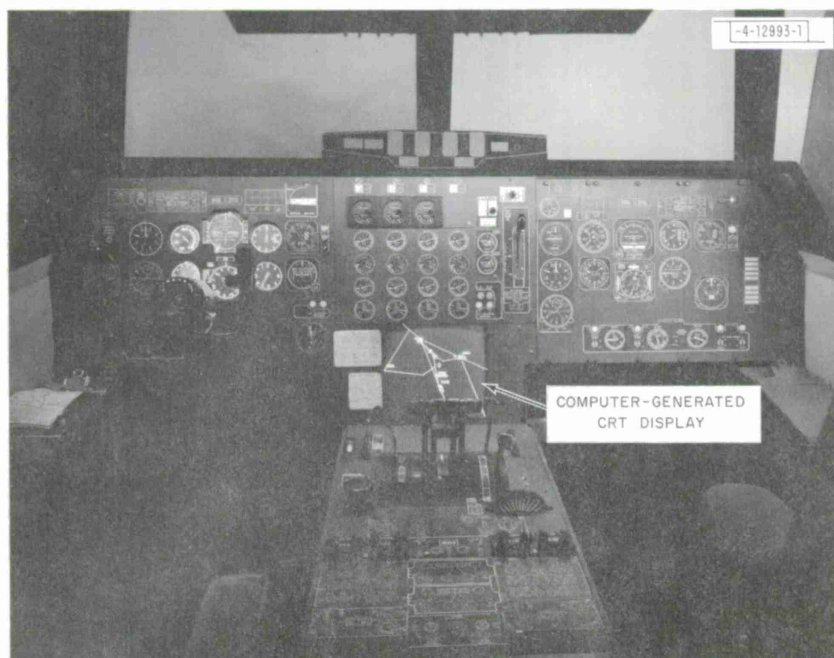

Fig. 3. Cockpit simulator.

maneuvering in the terminal area. Three candidate models have been selected in which the pilot will attempt to:

    (1) Track a "box" moving at constant speed (a wind model will be included in the dynamics)

    (2) Merge into a straightline trail formation with and without commands from a controller

    (3) Execute a curved pursuit merging maneuver.

Two reports are in preparation: the first will discuss the potential contribution of an airborne air traffic situation display in increasing the capacity of terminal areas, the second will evaluate techniques for measuring pilot workload. This will lead to studies of the impact of an airborne air traffic situation display upon the workload of pilots using the device in an operational environment.

VI. WARNING SYSTEM FOR RUNWAY 4R AT LOGAN AIRPORT

The program to evaluate a laser-gate alerting system for the detection of ships entering the approach zone of Runway 4R at Logan Airport was funded by the Massachusetts Port Authority on 1 December 1970. The installation of test hardware is complete and data taking has commenced. Initial test results have been favorable; ship masts have been detected under conditions where visibility was reduced to less than three quarters of a mile by a snowstorm.

Since this type of system would be unique within the FAA, a task force of FAA personnel, representing each major operating division, has been designated to study the requirements for opening the full length of Runway 4R for night landings. Weather criteria, controller and pilot procedures, and acceptance criteria for the laser system are actively under study. A close working relationship with these officials has been established.

A description of the test installation was included in the last quarterly technical summary (15 November 1970).

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13. ABSTRACT

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14. KEY WORDS

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