Quarterly Technical Summary

Air Traffic Control

15 May 1972

Prepared under Electronic Systems Division Contract F19628-70-C-0230 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

Quarterly Technical Summary

Air Traffic Control

15 May 1972

Issued 20 June 1972

Prepared under Electronic Systems Division Contract F19628-70-C-0230 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, with the support of the Department of the Air Force under Contract F19628-70-C-0230.

INTRODUCTION

This report summarizes the progress on the Air Traffic Control tasks funded by the Air Force during the period 1 February through 30 April 1972. A total of seven staff is engaged in these activities, and the principal effort has been directed toward reaching a status which will permit the presentation of tentative conclusions and reports because several of the tasks must be terminated in FY 72. The radar MTI study effort will continue under FAA sponsorship, and the analysis of microwave landing guidance systems will be maintained for the Air Force. Discussions are under way concerning the scope and level of future Air Force-supported effort on airborne graphical displays and CNI system performance analysis.

H. G. Weiss
Head, Division 4

15 May 1972

Accepted for the Air Force
Joseph R. Waterman, Lt. Col., USAF
Chief, Lincoln Laboratory Project Office

CONTENTS

AIR TRAFFIC CONTROL

I. SUMMARY

The Air Traffic Control (ATC) program at Lincoln Laboratory was initiated by the Air Force in fiscal year 1971. Its objective was to explore areas of interest to the military, particularly those involving interaction with the Federal Aviation Administration (FAA) ATC system. Within the past nine months, major tasks have been funded by the FAA; however, several small-scale efforts continue to address specific military ATC-related problems.

This Quarterly Technical Summary reports the progress in tasks undertaken for the Air Force.

II. SURVEILLANCE TECHNOLOGY

A theoretical analysis of the M-pulse staggered prf signal design problem has been completed. A Technical Note documenting the results of the study is in process. It was shown that the stagger sequence used in the ASR-7 resulted in significant improvement in the detection performance at the former blind speeds, but that the ability to resolve Doppler was poor. If velocity resolution is important, therefore, it is proposed that the stagger sequence be chosen on the basis of the associated Doppler ambiguity function. The design problem is similar to specifying antenna patterns using nonuniformly spaced array elements.

The major limitations in utilizing the full potential of the ASR radars for ATC are due to scanning ground clutter and weather clutter. In an attempt to determine whether sophisticated signal processing could eliminate these effects, an optimal MTI processor was derived. In addition to providing some improvement in eliminating receiver noise, it was found that significant improvements in clutter rejection capability were possible. Furthermore, the processor could be implemented using state-of-the-art digital signal processing techniques.

Utilizing the theoretical foundations used to derive the optimum receiver, it was possible to explore the question of blind speed elimination through the use of staggered prf's. A new, thorough, theoretical understanding of this concept has been documented from which it can be shown that resolution of velocity ambiguity is possible.

Although this work will no longer be funded by the Air Force, it is continuing under FAA sponsorship as part of a program to determine the ultimate performance that is possible using the S-band radars. An MTI processor has been implemented on the FDP, and work is under way to specify an experiment that will feed real-world radar data directly into the test setup. Further theoretical work is continuing to determine an optimum stagger sequence, and these concepts will also be explored experimentally.

III. AIRBORNE TRAFFIC SITUATION DISPLAYS (ATSD)

Computer and display hardware for a demonstration ATSD has been completed; Fig. 1 is a photograph of a test picture. This equipment is suitable for: (a) installation in an aircraft simulator, (b) a stand-alone demonstrator, and (c) installation in an aircraft with some repackaging.

The display hardware has been designed on a modular basis and connects to the digital computer via a boss-type interface. The present equipment incorporates all the design options, with the exception of color. Actual airborne equipment would probably not contain all these options.

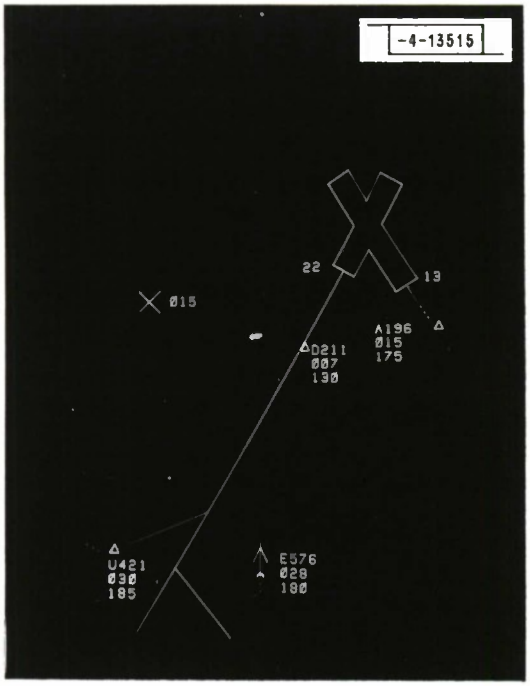

Fig. 1. Test display of ATSD.

Work is continuing to develop software for a stand-alone demonstrator and hardware for permitting the computer to test the integrity of the display equipment. Also, commercially available equipment, e.g., airborne computers, display indicator boxes, and beacon interrogators, are being reviewed to assess their utility in an experimental ATSD evaluation.

A study has been completed for the Aviation Advisory Commission to show the utility of the ATSD in the ATC system of the 1980's. One recommendation of this study is to conduct an experimental evaluation of the ATSD. This study also revealed that several critical technical and operational problems relating to the role of an ATSD should be evaluated through a flight-test program.

IV. COMMUNICATIONS, NAVIGATION, AND IDENTIFICATION SYSTEM

Under the sponsorship of the Air Force Electronic Systems Division, a study to understand the impact of propagation phenomena on the choice of a modulation scheme for use in CNI systems is nearing completion. A variety of links, including air-to-air and air-to-ground, are being investigated along with the combination of operating modes and propagation effects.

To identify critical (but not sufficiently well understood) aspects of the channel, we have evolved a propagation model to account for ground reflection multipath based in part on theoretical analysis and in part on previously obtained experimental results. Certain aspects of the model are described in Sec. A below. Section B describes the results of an analysis of the performance degradation on spread spectrum signaling schemes due to ground reflection multipath.

A. Propagation Model

Using the propagation model described in the previous Quarterly Technical Summary,[1] we can estimate the region of operating parameters over which severe multipath fading can be experienced. Here, we shall concentrate on describing the regions in which destructive interference due to specular reflection from the ground can cause fades in excess of 10 dB. We shall consider two cases: smooth dry land, and smooth sea. We restrict attention to vertical polarization – most aircraft antennas are vertically polarized, especially near the horizon. For simplicity, we assume omnidirectional antenna patterns.

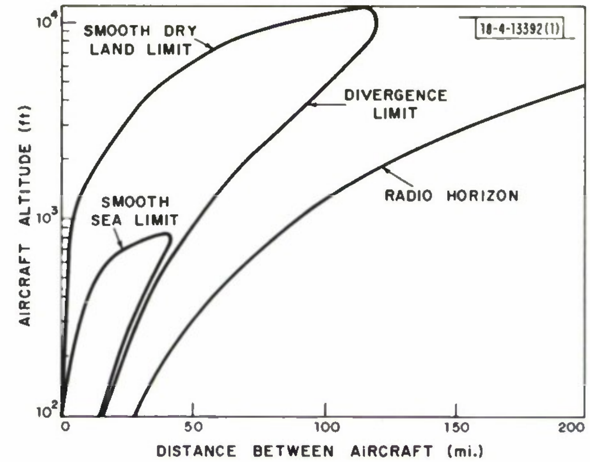

Fig. 2. Regions of airspace with possible fades in excess of 10 dB caused by destructive interference due to specular reflection from ground for two aircraft at same altitude, using vertical polarization.

In Fig. 2, these regions are plotted assuming both aircraft are at the same altitude. The difference between the two curves results from the lower reflection coefficient of sea water vs dry land. Clearly, at altitudes in excess of 12,000 feet, losses in excess of 10 dB will not be experienced. Over the sea, this limit reduces to 800 feet and, in fact, makes up a significantly smaller fraction of the airspace.

By way of contrast, we plot similar curves in Fig. 3, assuming our aircraft at an altitude of 50,000 feet and the other aircraft altitude being a variable. The corresponding curves are lower than those of Fig. 2, a result from the effect of the divergence factor, i.e., the reduction in reflected power due to the effect of the curvature of the earth. Clearly, fades in excess of 10 dB are absent at altitudes in excess of 5000 feet.

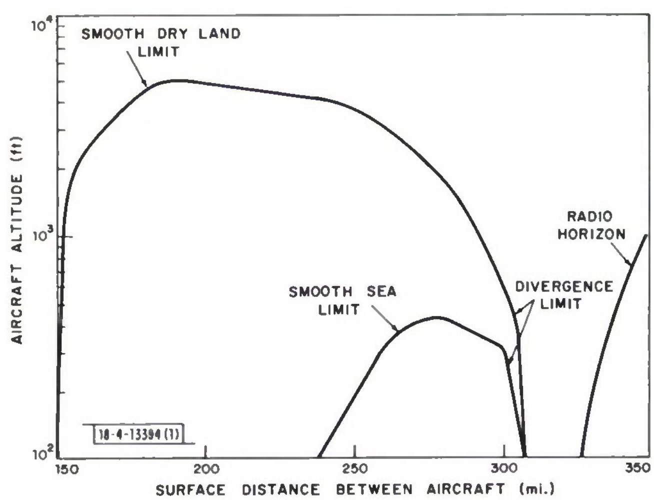

Fig. 3. Regions of airspace with fades in excess of 10 dB caused by destructive interference due to specular reflection from ground with our aircraft at 50,000 feet, using vertical polarization.

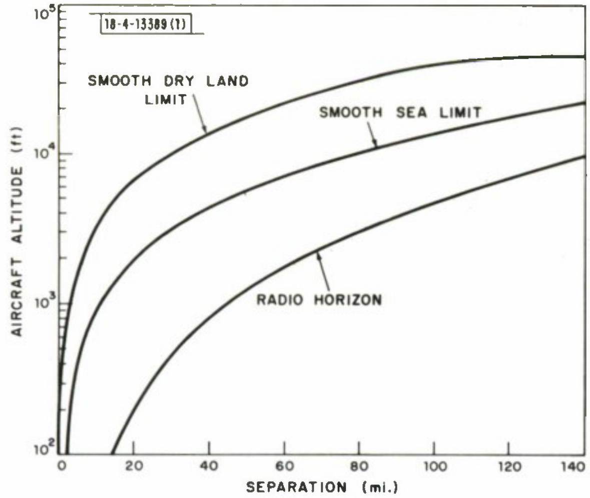

Fig. 4. Regions of oirspace with fodes in excess of 10 dB coused by destructive interference due to speculor reflection from ground with one terminol close to ground (<50 feet).

Figure 4 is a plot of the regions under the condition that one terminal is close to the ground, i.e., below 50 feet. In this case, fading in excess of 10 dB can be experienced over an extensive fraction of the airspace. In practice, if one of the terminals is located on the ground, significantly reduced regions can be obtained by appropriate sighting and by judicious use of antenna gain.

B. Performance Degradation

We have been assessing in detail the impact of reflection multipath on two classes of wide-band spread spectrum modulation techniques operating over an additive white Gaussian noise channel. The techniques under study are frequency hopping-frequency shift keying (FH/FSK) and pseudo noise-phase shift keying (PN/PSK). Details of how these modulation techniques operate can be found for FH/FSK in Ref. 2, and for PN/PSK in Ref. 3. Our results indicate that both FH/FSK with coding and PN/PSK modulation can be effective in reducing the performance degradation due to multipath.

We have chosen two measures of performance for the modulation techniques under consideration. An error probability measure is employed with uncoded signaling schemes. As described in the last Quarterly Technical Summary,[1] the efficiency factor defined by

$$\eta = \frac{E_c/N_o}{R_o(E_c/N_o)}$$

is utilized with coded waveforms, where E_c is received energy per code digit* over the direct path, N_o is the (single-sided) background noise power density, and $R_o(\cdot)$ is the computational cutoff rate.[4]

In the analysis of both the FH/PSK or PN/PSK modulation techniques, the value $\tau W = 1$ represents a critical performance threshold, where τ is the differential time delay between the

*The demodulator is envisioned as a device which accepts an analog signal and produces a digital output. Thia digital output ia used as an input to the decoder. E_c is the energy per digit at the input to the decoder; E_b corresponds to the energy per information bit.

direct and specularly reflected paths, and W is the spread spectrum bandwidth. As expected, both PN/PSK and coded FH/FSK are effective in combating specular multipath if $\tau W > 1$, but are less effective for smaller values of τW.

For coded FH/FSK with multipath present, system performance is primarily a function of the delay-bandwidth product τW and the strength of the reflected signal. Performance generally deteriorated monotonically with the delay bandwidth product. The increases in η due to multipath, which corresponds to a loss in system performance, are shown in Fig. 5 for $E_c/N_o = 6$ dB and $R_c/W << 1$, where R_c is the encoder rate in bauds. There is further increase in η as E_c/N_o is decreased below 6 dB. However, with $\tau W \geqslant 1$, multipath is not detrimental to performance and in some cases actually improved performance by as much as 3 dB for low E_c/N_o, as described in the last Quarterly Technical Summary.[1]

The degradation due to multipath for uncoded binary FH/FSK for $R/W << 1$ where R is the data rate in bits per second shown in Fig. 6 is considerably more severe. Since the detection process is based on the matched filter output after an interval of $1/R$ seconds, the multipath signal is present in this same filter for a period corresponding to $(1/R) - \tau$; hence, τR is an important system parameter. Thus, the resulting bit decision is strongly influenced by both the direct and multipath signals. In computing the error probability averaged over all phase differences between direct and reflected signals, we find that the destructive phase condition dominates the average error probability, thus accounting for the poor performance.

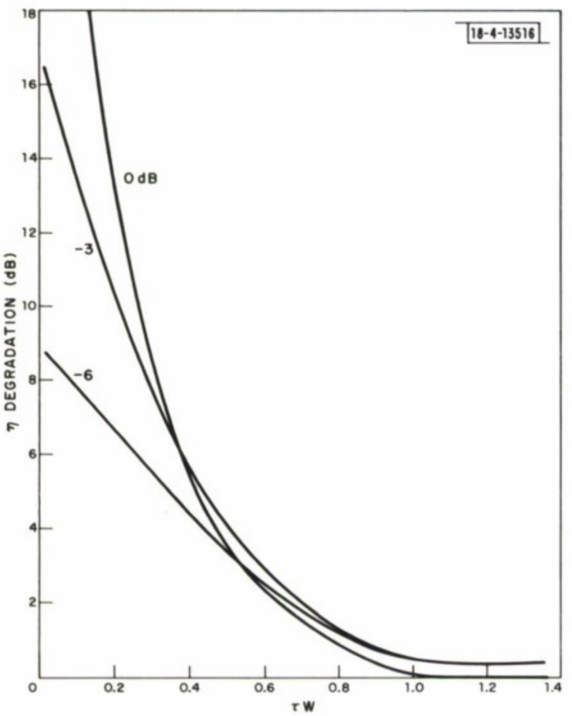

Fig. 5. Decrease in efficiency η for indicated power ratios between direct and reflected paths assuming 8-ary FH/FSK modulation with coding $E_c/N_o = 6$ dB and $R/W << 1$.

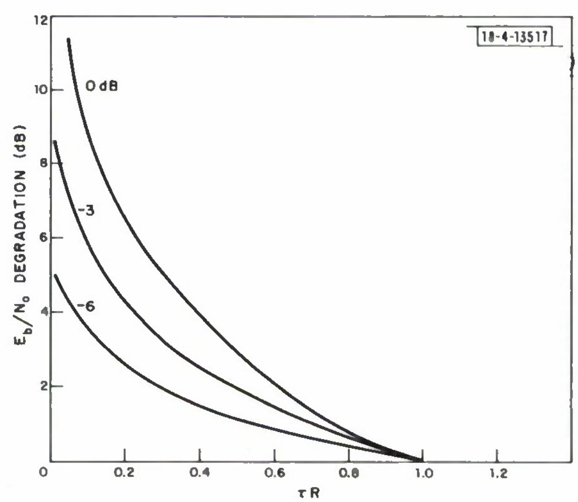

Fig. 6. Loss in E_b/N_o at an error probability of 10^{-5} for uncoded binary FH/FSK for indicated power ratio between direct and specularly reflected paths and $R/W << 1$.

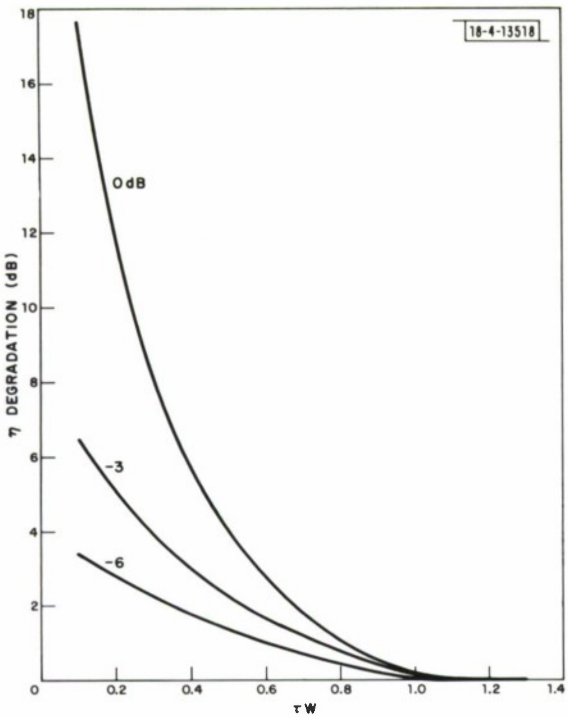

Fig. 7. Decreases in efficiency η for indicated power ratios between direct and reflected paths assuming PN/PSK modulation with coding E_c/N_o = 3 dB and R/W << 1.

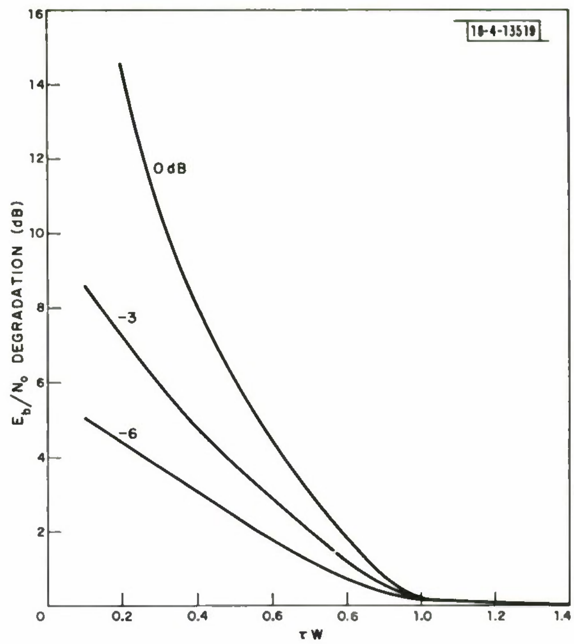

Fig. 8. Loss in E_b/N_o at error probability of 10^{-5} for uncoded binary PN/PSK for indicated power ratios between direct and specularly reflected paths.

Results for coded PN/PSK (Fig. 7) are comparable to those for FH/FSK when $\tau W \geqslant 1$, except in no case did the multipath improve performance. The performance of coded PN/PSK degrades more slowly than with coded FH/FSK, as τW gets smaller.

The degradation in performance due to multipath of uncoded binary PN/PSK for R/W << 1, as shown in Fig. 8, is considerably better than for uncoded FH/FSK. We see from Fig. 8 that to communicate with binary uncoded PN/PSK at a 10^{-5} error probability and $\tau W > 1$, there is effectively no degradation. For $\tau W < 1$, we have considered the worst-case situation in which the reflected signal is directly out of phase with the direct signal.

Regardless of the modulation technique, synchronization in receiver timing function is fundamental to the operation of both FH/FSK and PN/PSK systems. In the results presented here, it is assumed that accurate synchronization is maintained throughout the signaling interval. Although performance of synchronization circuits is beyond the scope of this study, it is reasonable to expect that, under severe multipath conditions, the detection problem will be further compounded by degradation in synchronization performance.

V. MICROWAVE LANDING GUIDANCE SYSTEM

Work is continuing on the microwave landing guidance system (MLGS) with emphasis on assessing the sensitivity of various techniques to multipath reflection. The Radio Technical Commission for Aeronautics (RTCA) Special Committee No. 117 proposed[5] two possible techniques for the MLGS: a scanning beam system, and a Doppler scan system. Although it was known that the two techniques are quite similar in most respects,* it has been suggested† that the Doppler system has a "unique capability..., whereby discrimination between the direct and ground reflected signals can be affected." Below, we summarize the key arguments in our result that appropriate versions of the two systems are entirely analogous in this respect also, so that the extensive experimental data gathered to date for scanning beam systems can be utilized for analyzing the Doppler scan system.

A. Observations

The two specific systems we shall consider are the time reference scanning beam system shown in Fig. 9, and the idealized Doppler scan system shown in Fig. 10. We now consider how ground reflection modifies the two figures under the following assumptions:

(1) The phase of the reflected wave is 180° with respect to the incident wave [this assumption, made only to simplify the figures, is generally quite good for horizontal polarization and reasonable for vertical polarization of the angles of interest ($\Theta \leqslant 3°$)].

(2) The amplitude of the reflected wave is α ($\leqslant 1.0$).

(3) Both systems have a suitable reference which is not affected by the reflection (this will be examined in Sec. B below).

(4) An additional phase factor corresponding to mean antenna height may be neglected (this factor will affect both systems in an identical manner).

(5) The scanned beam is a uniformly illuminated rectangular aperture of length L: the Doppler scan antenna radiates at constant amplitude over a vertical distance L (this assumption produces equivalent beam patterns; both systems may be readily modified to obtain other equivalent sidelobe patterns).

With these assumptions, it may readily be verified‡ that the Fourier transform of the received Doppler scan system is the sum of the two waveforms shown in Fig. 11. Note that:

(1) As a consequence of the coherence of the direct and reflected signals, the spectrum of the received signal is not the sum of the individual spectra. This point (which has been overlooked by some Doppler system proponents) means that significant distortion of the received signal spectrum will occur at Doppler shifts $f_d \leqslant \frac{1}{2} T_S$, i.e., elevation angles $\Theta \leqslant \lambda/2L$ where T_s is the Doppler scan period.

(2) Since the reflected signal shows up primarily, but not entirely, at negative Doppler frequencies, a high-pass filter with a sharp cutoff at f_0 could largely remove the reflected signal. As $T_S = L/v \rightarrow \infty$, the reflected signal would be completely rejected by such a high-pass filter.

* A readable summary of the two systems that stresses the similarities is contained in the paper of Redlein and Masek.[6] We may loosely describe the overall relationship as follows: (1) time aspects of the scanning beam (e.g., beamshape and angle estimation) appear as frequency aspects of the Doppler system, i.e., the systems act as a transform pair; (2) the Doppler system substitutes high scan rates for low directivity (i.e., antenna gain) to achieve theoretically equivalent angle estimation accuracy; and (3) although the "optimal" angle estimator structures form a transform pair, commonly used suboptimal schemes apparently are not duals.

† See p. 61 in Vol. I of Ref. 5.

‡ By noting that the ground reflection corresponds to an "image" antenna which is moving downward at velocity v. The sidelobe structure arises from the "time window" of $T_s = L/v$ over which the signal is observed. The reflected signal has a negative peak as a consequence of the 180° phase shift on reflection [incorporating the antenna average height h would add a lag of $4\pi(h/\lambda) \sin \theta$ to the reflected signal phase].

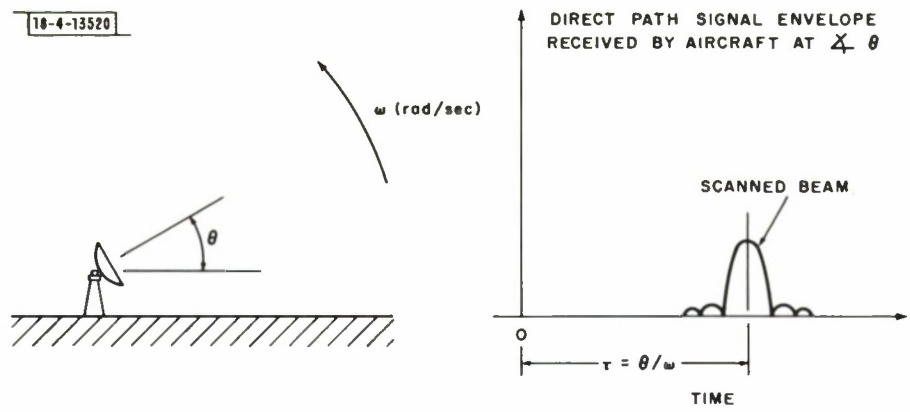

Fig. 9. Time reference scanning beam system.

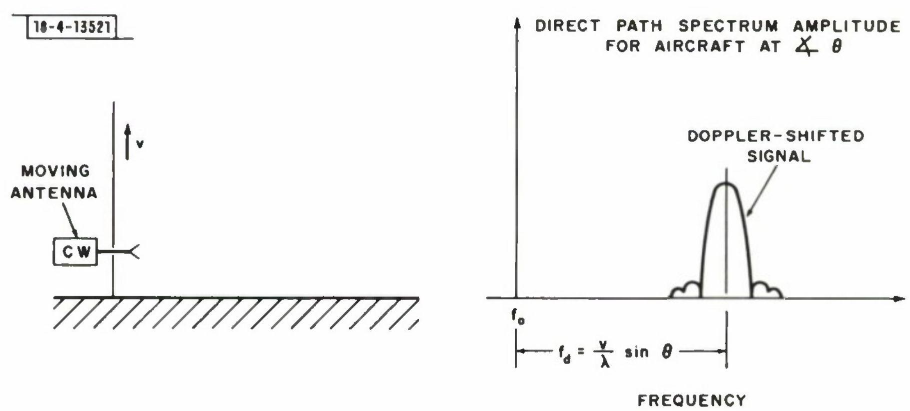

Fig. 10. Doppler scan system.

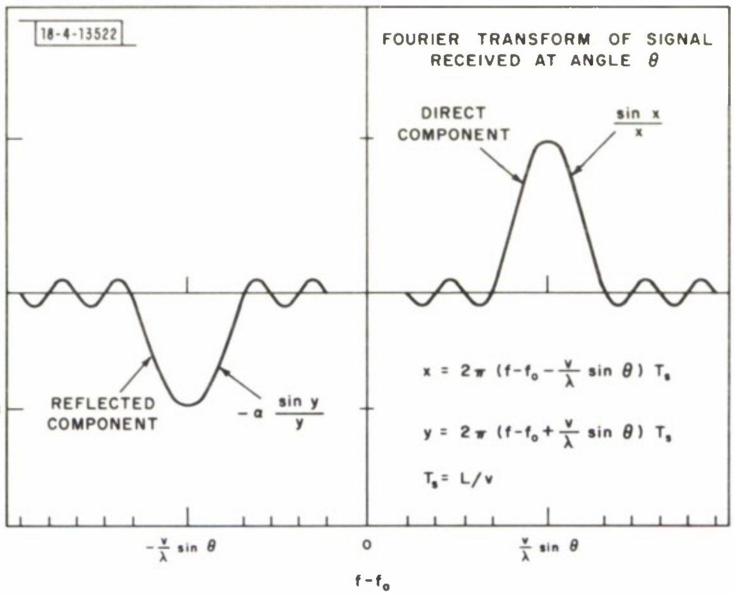

Fig. 11. Fourier transform of received Doppler scan signal components.

One would expect that the scanning beam system should have a similar offset of direct and reflected signals in time. However, at first inspection this is not the case, since the path length differences between the direct and reflected signals is too small to be resolved in the bandwidth allocated to the landing system. This fact provides the basis for the statement that the Doppler system has a "unique capability" to reject ground reflections.

We now show that such an offset in time does exist for the scanning beam system and is identical in nature to that shown in Fig. 11 for the Doppler system. The key to our observation is the recognition that, although the ground reflection indeed arrives essentially simultaneously in time with the direct signal (in either system), in the scanning beam system the reflected signal is markedly reduced in amplitude at time $\tau = \Theta/\omega$ (where, from Fig. 9, Θ = elevation angle

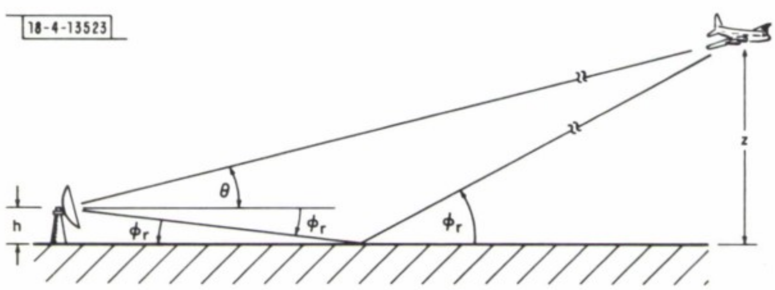

Fig. 12. Geometry of ground reflection for scanning beam system.

of the aircraft and ω is the antenna scan rate) because it is radiated through a sidelobe of the scanning antenna as shown in Fig. 12. For example, in Fig. 12 we see that when the scanning beam is directly pointed at the target, the ratio R of ground-reflected signal amplitude to direct signal amplitude is

$$R = \alpha \frac{G(\Theta + \varphi_r)}{G(0)}$$

where G(·) is the antenna broadside gain [$= \sin(\pi \frac{L}{\lambda} \sin\eta)/\pi(\frac{L}{\lambda}) \sin\eta$] for our assumed aperture distribution.

When the aircraft altitude z is very much greater than the antenna height h in Fig. 12, the reflection angle is $\varphi_r \approx \Theta$.* We now assume that the antenna is initially pointed downward at a large angle and scans upward at rate ω, passing through zero at time $t = 0$.† With this assumption and straightforward use of Fig. 12, we find that the received signal by an aircraft at angle Θ

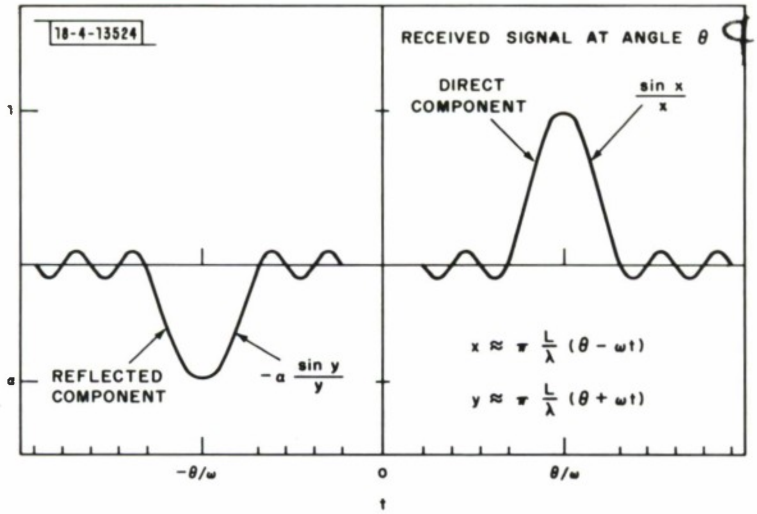

Fig. 13. Received signal components for scanning beam system.

is given by the sum of the two signals shown in Fig. 13. The analogous nature of Figs. 11 and 13 is obvious. For example, significant distortion of the signal envelope will occur at time shifts $\tau \leqslant \lambda/2\omega L$ (i.e., $\Theta \leqslant \lambda/2L$).

B. Concluding Comments

We have demonstrated the equivalence of certain versions of the scanning beam and Doppler scan landing guidance systems insofar as ground reflection is concerned. A few comments are in order regarding the relation of these particular versions to proposed systems:

(1) A practical Doppler system also has a reference frequency radiated from a stationary omnidirectional antenna at a frequency near f_0 to allow the removal of the aircraft velocity-induced Doppler as well as to avoid carrying a highly stable onboard local oscillator. This reference is subject to nulls at certain angles due to the ground reflection. Similarly, the "time reference" scanning beam system radiates an omni-pulse at the start of a scan to avoid having the aircraft carry a high accuracy synchronized clock. This omni-pulse is subject to nulls due to ground reflections at the same angles and in the same degree that the Doppler reference would be affected.

* If the assumption $\phi_r \approx \theta$ does not hold, then the peak of the reflected wave occurs at a time $-\phi_r/\omega$ in the scanning beam system and at a frequency $f_o - v \sin \phi_r/\lambda$ in the Doppler scan system.

† In practice, one normally scans downward at $t = 0$ from a large positive angle, in which case the similarity of Figs. 11 and 13 is not quite as obvious.

(2) The RTCA-proposed scanning beam system[5] carries the time reference on the beam as an FM waveform, thus avoiding the reference nulling problem. However, it still has the envelope distortion problem given in Fig. 13. An interesting, but as yet unanswered question, is whether the Doppler scan system can be modified (presumably by some time modulation) to also carry the reference information on the "beam."

(3) From Figs. 11 and 13, it is clear that for a fixed aperture L, both systems degrade at essentially the same angle. A question under current investigation is whether the Doppler data from a number of scans* can be coherently combined to lead to an effective T_s in Fig. 11 that is considerably larger than L/v. From Fig. 11, it is clear that increasing the effective T_s would give the Doppler system a reflection rejection capability somewhat better than that achieved in the scanning beam system. The corresponding option would be hard to achieve in the RTCA scanning beam system, since the available spectrum there is largely utilized in providing the time reference data on the beam.

REFERENCES

1. Air Traffic Control, Quarterly Technical Summary, Lincoln Laboratory, M.I.T. (15 February 1972), DDC AD-740877.
2. P.R. Drouilhet, Jr. and S.L. Bernstein, "TATS – A Bandspread Modulation-Demodulation System for Multiple Access Tactical Satellite Communication," paper presented at NATO TACSATCOM Scientific Group Meeting, London, 15-19 September 1969.
3. J.J. Stiffler, Theory of Synchronous Communication (Prentice-Hall, New York, 1971).
4. J.M. Wozencraft and I.M. Jacobs, Principles of Communication Engineering (Wiley, New York, 1965).
5. "A New Guidance System for Approach and Landing – Volume I," Document No. NO-148, prepared by SC-117 of the Radio Technical Commission for Aeronautics, 18 December 1970.
6. H.W. Redlein and R.J. Masek, "Doppler Scanning Landing Guidance System Development," presented to National Air Meeting of Institute of Navigation, Saddlebrook, New Jersey, 15 April 1971.

* Recall that the Doppler scan system uses a high scan rate to offset the low directivity gain as far as SNR is concerned.

DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None

3. REPORT TITLE

Air Traffic Control

4. OESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Quarterly Technical Summary, 1 February through 30 April 1972

5. AUTHOR(S) *(Last name, first name, initial)*

Weiss, Herbert G.

6. REPORT OATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 May 1972	16	6

8a. CONTRACT OR GRANT NO. F19628-70-C-0230	9a. ORIGINATOR'S REPORT NUMBER(S) Air Traffic Control QTS, 15 May 1972
b. PROJECT NO. 649L	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TR-72-86
c.	
d.	

10. AVAILABILITY/LIMITATION NOTICES

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
None	Air Force Systems Command, USAF

13. ABSTRACT

This report summarizes the progress on the Air Traffic Control tasks funded by the Air Force during the period 1 February through 30 April 1972. A total of seven staff is engaged in these activities, and the principal effort has been directed toward reaching a status which will permit the presentation of tentative conclusions and reports because several of the tasks must be terminated in FY 72. The radar MTI study effort will continue under FAA sponsorship, and the analysis of microwave landing guidance systems will be maintained for the Air Force. Discussions are under way concerning the scope and level of future Air Force-supported effort on airborne graphical displays and CNI system performance analysis.

14. KEY WORDS

air traffic control
moving target indication (MTI)
airborne graphical displays
communications, navigation and identification systems (CNI)
microwave landing guidance systems (MLGS)
Federal Aviation Administration (FAA)