REPORT NO. DOT-TSC-FAA-71-26

ACCURATE SURVEILLANCE IN THE TERMINAL AREA

BERNHARD KULKE
ROBERT T. MINKOFF
GEORGE G. HAROULES
TRANSPORTATION SYSTEMS CENTER
55 BROADWAY
CAMBRIDGE, MA. 02142

SEPTEMBER 1971
FINAL REPORT

Prepared for
DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
WASHINGTON,D.C. 20546

1. Report No. DOT-TSC-FAA-71-26	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Accurate Surveillance in the Terminal Area		5. Report Date Sept 1971
		6. Performing Organization Code TER
7. Author(s) B. Kulke, R.T. Minkoff, G.G. Haroules		8. Performing Organization Report No.
9. Performing Organization Name and Address Transportation Systems Center 55 Broadway Cambridge, Mass. 02142		10. Work Unit No. R2132
		11. Contract or Grant No. FA09
12. Sponsoring Agency Name and Address Federal Aviation Administration 800 Independence Ave. S.W. Washington, D.C.		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The problem of deriving surveillance information from the MLS has been analyzed in terms of the available air-to-ground communication links. The results of this study indicate that the use of this approach is feasible and it is recommended that the configuration based on the DABS data link be included in the upgraded third-generation design to meet the high-density terminal-area surveillance requirements.

17. Key Words	18. Distribution Statement
Approach Surveillance Air-derived data Parallel-runway spacing	Availability is Unlimited. Document may be Released To the National Technical Information Service, Springfield, Virginia 22151, for Sale to the Public.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	43	

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

This report is in response to PPA FA-09, "Tradeoff Study of Updated Microwave Landing System vs. UATCRBS for the Transition, Final Approach and Departure Surveillance." The objective is to determine to what extent the precise antenna beams of the MLS can be used to supplement the beacon system so that approach surveillance can be accomplished most effectively, particularly for parallel-runway situations. The use of the Discrete-Address Beacon System (DABS) to monitor parallel ILS approaches in order to maintain safe separation has been proposed in the ATCAC Report (Ref. 1) and is discussed herein.

Highly accurate surveillance data in principle could be obtained by increasing the aperture of the DABS antenna (e.g., a phased array of some 80 feet in diameter). Cost considerations would limit such a system to perhaps the five or six busiest airports. Because of its size, such an antenna could not be colocated with the primary radar, and the cost and complexity of correlating the primary and the beacon data would increase, probably by a significant amount.

On the other hand, as the MLS possesses the required accuracy for both navigation and surveillance on simultaneous close-spaced parallel approaches that are perhaps as little as 2500 feet apart, and as this new system must be carried for such approaches, it appears well worthwhile to investigate the use of the MLS-derived position data in conjunction with DABS data of lower accuracy. That is, if surveillance information of sufficient precision were readily available from the MLS, this would remove the burden of accurate approach monitoring from the DABS and thus would free the latter for the less dedicated task of terminal area surveillance, with a consequent possible relaxation of design constraints and/or an improvement in quality of service.

In accordance with the instructions received at a meeting with cognizant personnel at FAA Headquarters on 6 May 1971, the body of this report will be confined to a detailed consideration of a number of methods by which surveillance information can be derived from the MLS. The impact on failure modes and equipment complexity also will be considered.

As part of our effort over the last quarter, the parameters that enter into the safe operation of parallel runways have been analyzed in terms of given mathematical models, and this work is included in Appendix A. Also included are considerations affecting the along-track spacing of descending aircraft, and hence, the accuracy required for assuring that separation.

APPROACH SURVEILLANCE WITH THE MICROWAVE LANDING SYSTEM (MLS)

In this Section a number of options will be discussed that in principle could be employed to derive surveillance information from the MLS. The proposed use of the MLS will allow simultaneous approaches to close-spaced parallel runways. Thus a surveillance system of comparable accuracy becomes necessary to monitor these approaches. The coarse azimuth guidance accuracy of the MLS, configuration K, will be $2\sigma = 0.085$ degrees or 9 feet per nautical mile (Ref. 2). This number is derived as the root-sum-of-squares of the bias error ($2\sigma = 0.072^{\circ}$) and the noise error ($2\sigma = 0.045^{\circ}$).

On page 64 of Ref. 1 it is stated that "the current four-degree (ATCRBS) beam can be centermarked to an accuracy of 0.25 to 0.4 degree. However, the FAA presently does not use centermarking for separation service because of poor accuracies caused by garbling and reliability". The actual accuracy therefore is not as good. Assuming that the above implies $\sigma = 0.25$ degrees, or 27 feet per nautical mile, it is clear that even with centermarking the existing ATCRBS could not approach the MLS accuracy, where σ would be less than five feet per nautical mile.

It is expected that DABS will be capable of improved accuracy with $\sigma = 0.2$ degrees or 22 feet per nautical mile, but this is still not comparable to the MLS accuracy. At the same time, the MLS design also calls for a range (DME) accuracy of $\sigma = 20$ feet rms, while present ATCRBS performance only gives $\sigma = 380$ feet, and DABS is only expected to improve this to $\sigma = 100$ feet. The superior accuracy of the MLS therefore is evident. It may be of interest to note that for the purposes of approach surveillance, the azimuthal accuracy is of relatively greater importance than the range accuracy, because for parallel-runway approaches, the cross-track separation of incoming aircraft is much smaller than the along-track separation, and the cross-track separation imposes a requirement mainly on the azimuthal accuracy of the monitoring system.

Throughout this report, the emphasis is placed on approach surveillance, because this appears to be the most critical part of the overall surveillance task. It is tacitly assumed that a system that is proved capable of effective approach surveillance can easily be modified or extended to provide back-course and departure surveillance as well, over the same angular sectors as the MLS from which the surveillance information is derived.

SURVEY OF DIFFERENT METHODS

The guidance and surveillance design problem in the terminal area can be viewed as one of optimizing the information flow

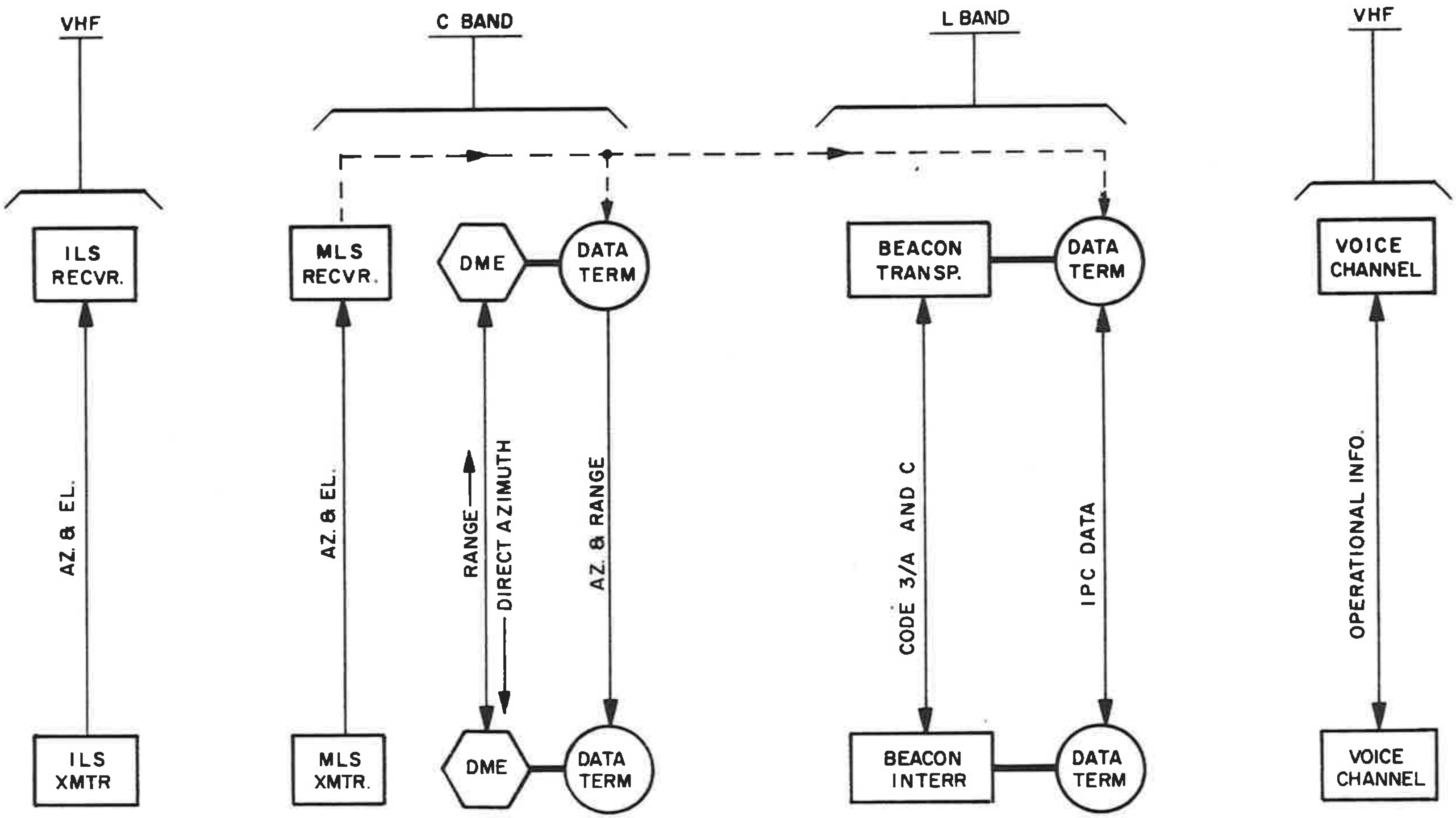


Figure 1. Communication Links in the DABS/MLS Environment

from ground to air and back. This process is illustrated in Figure 1. Given certain equipment, information is or can be exchanged as shown by the arrows.

At present, guidance during final approach is provided by the ILS, with fixed-path localizer and glide-slope beams operating near 100 MHz and 300 MHz, respectively. The proposed microwave scanning-beam system will improve upon ILS performance by offering curved-path guidance with higher accuracy and integrity than is possible with the ILS. In either case, there is a one-way flow of position information from the ground to the aircraft, i.e., azimuth and elevation for the ILS, and the same plus range information for the MLS. As will be shown, the C-band DME associated with the MLS could be modified to serve as an air-to-ground data link.

The L-band beacon transponder automatically transmits altitude and flight identity information to the ground, in addition to supplying the range and azimuth data inherent in the beacon operation. With the advent of DABS, a mandatory ground-to-air data link will be superimposed to accommodate IPC messages, while air-to-ground data capability will be optional.

Finally, a two-way flow of information takes place over the VHF voice channels. While certain military users are equipped with data link capability in the VHF/UHF band, an addition of such capability for general usage is not contemplated. Current planning foresees the following:

(a) IPC and ATC control and surveillance messages will be transmitted over the DABS data link, in real time.

(b) For users equipped (for other reasons) with VHF/UHF data link, non-real time clearance and meterological data services <u>may</u> be provided.

(c) Clearance changes to aircraft aloft will be given by voice or, in coded form, over the DABS data link.

The following methods can be identified by which surveillance information could be derived from the MLS operation:

First, it is possible to derive aircraft azimuth, within a certain error, by synchronizing the DME interrogation with the MLS azimuth beam. That is, the C-band DME interrogation could be triggered by the azimuth guidance beam, so that a beacon transponder-like operation would result. With this method it would not be practical to derive range information, because of the uncertainty in the time reference, (i.e., the time when the azimuth beam illuminates the aircraft).

Second, the air-derived position information may be transmitted in suitably encoded form over an appropriate air-to-ground data link. Candidate systems are the C-band DME channel and the DABS data link. The existing L-band DME channel, used in VOR/DME ranging, is a less likely candidate because it would be far simpler to adapt the proposed C-band DME design, rather than to modify the existing on-board L-band equipment.

A remark is in order concerning the use of primary radar for surveillance purposes. At present, ASR surveillance is routinely being used during the final-approach phase between the outer marker and touchdown. Also, if mechanically-scanned antennas were used in the MLS, a skin-track surveillance mode could be superimposed on the MLS. However, primary radar surveillance is susceptible to rain clutter, and thus becomes least reliable when it is needed the most. For this reason, primary-radar surveillance will not be considered. The other methods will be discussed in detail in the following paragraphs.

DETAILS OF METHODS

SYNCHRONIZED C-BAND DME USED AS A PSEUDO-TRANSPONDER

The MLS signal format, as proposed by RTCA-SC-117, does not require synchronization of the DME function with the angle data functions. If the DME function were synchronized with, say, the azimuth scanning beam, (i.e., if the DME interrogation were triggered when the aircraft is illuminated by this beam), then a beacon-transponder type of operation would result. By correlating the DME interrogation with the known azimuth of the guidance antenna, azimuth can be determined. The resulting cost in terms of increased system complexity is significant, however.

First, a slight modification in the DME signal format becomes necessary. The proposed DME interrogation rate is 60/sec during search and 40/sec after lock-on. These numbers correspond to the expected value of search time (320 msec) and data smoothing interval (200 msec). However, the scan rate of the MLS azimuth beam is 5/sec. If only one DME interrogation were triggered per azimuth scan (i.e., if the DME rate were decreased to 5/sec), then the search time would increase to nearly 4 sec, which clearly is intolerable. Alternatively, the DME pulse train could be synchronized with the azimuth beam illumination once every eight (or twelve) interrogations, and any range ambiguities could be eliminated by giving the one synchronized pulse pair a special label, (i.e., spacing) for recognition by the ground transponder. This label would have to be compatible with the pulse spacings identifying the DME channel at a given frequency. These are 10, 12, 14,...28 μsec spacings, so one could arbitrarily assign an 8μsec spacing, for example, to the synchronized pulse pair.

Second, a suitable detection algorithm must be incorporated with the ground transponder in order to accommodate an incoming train of 8 interrogations, (i.e., to interpret it as a target at the azimuth defined by the position of the antenna mount at the time of arrival of the first, labeled interrogating pulse pair).

Third, the airborne interrogator becomes very complex. A labeled pulse pair must be launched at the precise instant when the aircraft is at the center of the azimuth beam, in order to achieve consistent tracking. Center marking already would be done by the MLS receiver as part of the angle decoding process, but this process is not instantaneous because of internal circuit delays. Therefore, in order to achieve the required synchronism, information on beam width and threshold level must be stored from the previous scan (i.e., the transmit command from the logic circuitry must precede the actual instant of transmission by a preset interval in order to allow for built-in delays). These built-in delays in turn must be held to tight specifications. In addition, a special buffer unit is required to transmit the center marking data from the azimuth receiver to the DME interrogator.

Fourth, a significant error arises from the fact that by the time the DME pulse reaches the ground transponder, the azimuth beam will have advanced to a new position. This error is calculated as follows: assuming a slant range R, the signal delay in space will be

$$\Delta t = \frac{R}{c}$$

where c = velocity of light. Given a rate of beam advance of ω radians/sec, the angle error then will be

$$\theta = \omega \Delta t = \omega \frac{R}{c}$$

and the corresponding arc length error will be

$$\varepsilon = R\theta = R^2 \frac{\omega}{c}$$

For configuration K, the rate of beam advance is 80 degrees/ 88.8 msec or 0.9 degrees/msec. With a signal delay in free space of 983 feet/µsec, the arc error due to beam advance then is:

$$\text{arc error (in feet)} = 0.6R^2$$

where R denotes the range, in nautical miles. Thus the arc error at 20 n.m. would be 240 feet.

Finally, the synchronized DME method cannot supply ground-derived range information, as there is no time reference available that would allow the ground transponder to derive range from the received, synchronzied pulse pair. The lack of such a time reference is, of course, responsible also for the arc error discussed in the preceding paragraph.

To complete this discussion, a sketch of a possible block diagram for a synchronized DME scheme is shown in Figure 2., which is essentially an enlarged and detailed portion of Figure 1. The ground-based MLS transmitters provide the guidance information which is received and decoded by the airborne receiver unit. A (new) airborne buffer unit serves to convert the analog position information received from the MLS, into analog or digital code that would be transmitted as part of the DME interrogation. The (new) memory and logic unit would serve to synchronize the DME pulse train with the azimuth beam center mark. The (new) ground-based buffers serve as interface units between the MLS azimuth transmitter, and the DME transponder, and the surveillance data processing unit. The airborne DME interrogator would have to be built to tight specifications on those internal delay times which govern the instant of transmission of the labeled interrogator pulse. Thus, this scheme would require a total of three new buffer or interface units, a new memory and logic unit, and tightened specifications on the airborne DME interrogator.

In summary, a scheme has been discussed whereby the aircraft azimuth would be derived on the ground by observing the azimuth beam position at the time when a triggered, specially labeled DME interrogation is received. This scheme suffers from an azimuth arc error that is proportional to the square of the range; it does not permit range determination; and it is costly in terms of the necessary modifications in equipment and in signal format.

C-BAND DME USED AS DATA LINK

In normal DME operation, as envisioned by RTCA-SC-117, the airborne interrogator transmits a pair of pulses at the rate of 40/sec (60/sec in the search mode), at a frequency and with a spacing that identify one of 200 distinct channels, and hence, convey the interrogating aircraft's identity to the ground transponder. The latter, after a calibrated delay, responds with a pulse pair of its own. The response-channel characteristics bear a fixed relation to those of the interrogating channel, except that by encoding fixed, small departures from the expected spacing on successive pulse pairs, ground transponder

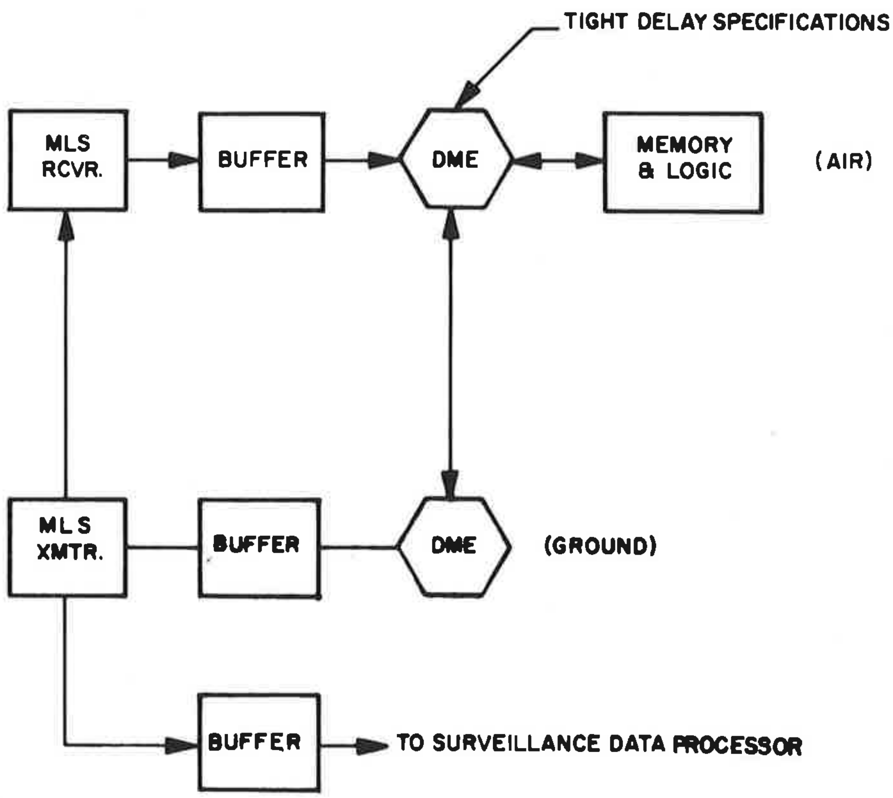


Figure 2. Equipment Configuration for Synchronized DME

(and hence, runway) identity may be conveyed to the aircraft, at the slow but adequate rate of 5 bits/sec. As the transponder has a limited average-power capability, which might be exceeded by too many aircraft interrogating it at the same time, a "dead interval" occurs after each transmission, and this limits the average PRF, as well as the information renewal rate for any given aircraft.

The possibility suggests itself of using modulation of the pulse-pair spacing to transmit airborne data to the ground, but clearly, the data rate achieved in this manner is far too slow to transmit fast-changing information such as aircraft position data. However, by adding two or more pulses with variable spacing to the interrogating pulse pair, one could analog-encode a four-digit number corresponding to range, using existing levels of precision in reading pulse spacings.

A similar argument holds for encoding the airborne azimuth data. A simple solution seems to be to add a few more pulses to the DME format, which would convey the azimuth information in analog form by variable pulse spacings. Four-digit accuracy probably could be obtained by using two additional pulses, with a minimum of other modifications to the planned C-band DME equipment.

A drawback to analog encoding of the airborne data is that, once received by the ground transponder, they must still be decoded and translated into digital language, in order to interface with the surveillance data processing system.

Alternatively, range and azimuth information could be encoded directly in binary form and added as a pulse train to each DME interrogation. This would require a larger number of pulses, however, as follows. If azimuth is resolved into 0.02 degree increments over a 120 degree sector, this is equivalent to 13 bits of digital data. Similarly, if an eight-mile distance beyond the runway threshold is resolved to the 1σ accuracy of the DME (σ = 22 feet), this corresponds to 11 bits. After adding parity and framing bits, an estimated 30 bits will be required to transmit the air-derived range and azimuth information to the ground transponder. This method has been diagrammed in Figure 3. Additional equipment required would be an airborne digital encoder (buffer), interfacing both with the MLS receiver and the DME interrogator. The ground-based transponder would have to be redesigned to accomodate the decoding function. Data from the transponder would be buffered into the surveillance data processing system. It should be noted that since precision surveillance need only take place during final approach, aircraft identity can be "coasted" on the ARTS III beacon label, (i.e., identity information need not be refreshed during final approach, and thus the burden on the data link is lessened).

DABS DATA LINK

The data link associated with the proposed DABS is briefly described in Ref. 1, p. 61. "The data link transmits air traffic control separation messages to the aircraft and receives altitude and control-acknowledgement messages in reply.

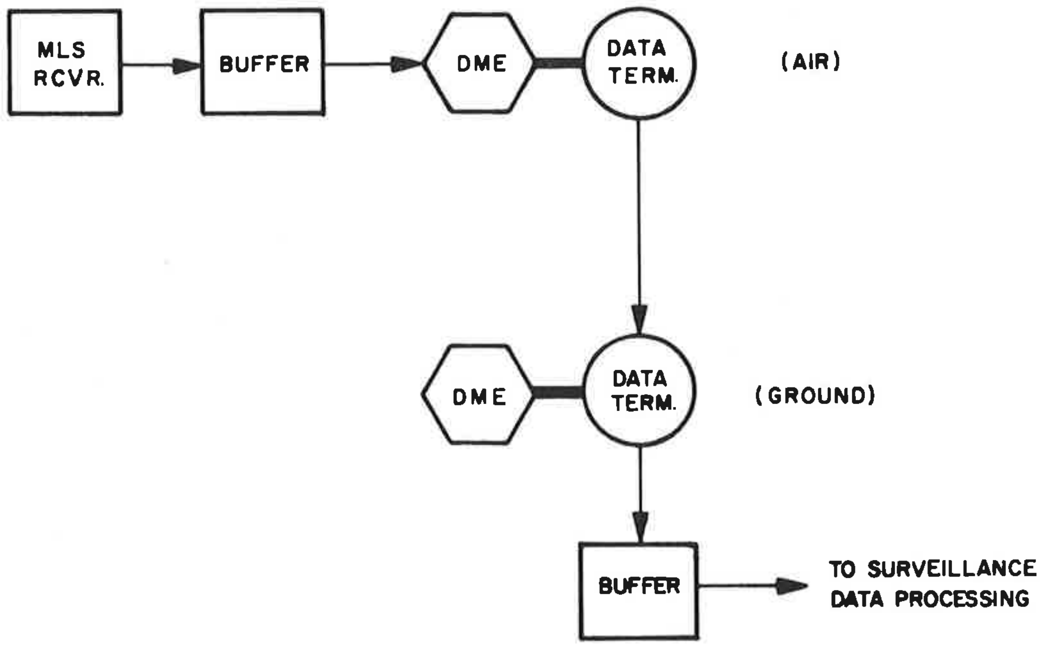


Figure 3. Equipment Configuration for DME Data Link.

Replies are also used to determine the position of the aircraft. Assignment of aircraft to particular data acquisition sites is by the terminal or en route center computers. The appropriate computer orders the surveillance and data link messages to be transmitted to the aircraft."

Current estimates are that each interrogator will transmit up to 5000 data-link messages per second, of length 50 bits each at a rate of one bit per microsecond. As a firm design is not yet available either for the data code or for the message format and interleaving scheme, it is somewhat difficult to judge the impact that 30 bits of air-derived azimuth and range information would have when superimposed on this data flow, but no problems are anticipated.

An important fact is that the flow of surveillance data would be air-to-ground, and thus must compete for receiving time at the ground interrogator along with Mode 3/A and C replies and with replies to other up-link data commands. However, interference is minimized by soliciting air-derived position information from DABS-equipped aircraft only once every three seconds. The aircraft would then transmit, in reply, 20 bits of identity information followed by 30 bits of position information.

As the DABS data link capability will exist regardless of the method by which precision surveillance is accomplished, it appears that its use for the transmission of air-derived position data would constitute a very economical, piggy-back type of solution. The only additional equipment required would be an airborne buffer unit between the MLS receiver and the transponder.

A summary is given in Table I of the additional equipment and/or functions required to implement each of the above-mentioned approaches for deriving surveillance data from the MLS.

FAILURE MODES

In discussing the possible failure modes of an approach surveillance system, it is important to bear in mind a clear picture of what functions the system is designed to perform. The basic function of ATC surveillance is to provide separation assurance. The "precision" surveillance which might be derived from the MLS, becomes essential on final approach, at the point where altitude separation no longer exists. For example, for the two-runway situation at O'Hare airport in Chicago this point is 11 miles out. For a situation where three runways are operated in parallel it would be 15 miles out. Obviously surveillance is also required on departure routes and in missed-approach corridors, but because approach surveillance is the most critical, it is being emphasized here to illustrate the system tradeoffs.

The main function of precision surveillance thus is to monitor the approach of incoming aircraft and when necessary, to generate off-course warnings of high integrity. Present planning is to transmit such warnings to the aircraft via the IPC system which would be mandatory equipment for all aircraft.

Any surveillance information that is derived from the MLS will necessarily be subject to failure or degradation if and when the MLS fails. The worst case would be an MLS failure during the final approach, shortly before touchdown in a CAT III (zero decision height) landing. For this case, if there is time to go around, (i.e., execute a missed approach), the pilot will do so upon realizing that the MLS has failed (i.e., presumably in response to an automatic warning signal). Back-course guidance would then be given by PVOR-DME supplemented by voice communication and data link, based on DABS surveillance data.

Table I

Additional equipment and/or functions required for candidate systems.

System	Additional Equipment Required
Synchronized DME	Airborne: buffer, memory & logic unit modified DME and DME message format Ground: MLS/DME buffer MLS/DABS buffer
DME data link	Airborne: buffer, data terminal (modified DME) DME message format modified Ground: Data terminal (modified DME), DME/DABS buffer
DABS data link	Airborne: MLS/Beacon transponder buffer

A failure of only the precision surveillance function could be precipitated anywhere in the data stream from the MLS receiver through the data link to the surveillance data processor on the ground.

For the method using synchronized DME in a pseudo-transponder mode, failure of the synchronizing logic, failure of the DME itself, or failure of the ground decoding logic would precipitate loss of precision surveillance, and an ATC go-around command would be generated. Again it is assumed that PVOR, DABS and MLS-based back-course guidance can be given.

The important case where independent approaches along parallel runways are monitored, requires one independent MLS per runway. Only one out of several MLS's need be used at the time to produce precision surveillance data. In case of failure of one system another could fulfill this function, so that surveillance is never interrupted, even if for any given aircraft the guidance function were to fail, resulting in a missed approach.

In summary, either a failure of the MLS itself or a failure of the MLS-based surveillance data link would only constitute a "soft" failure of the landing guidance system as a whole, because only a missed approach would result, with back-course guidance given by PVOR, DABS advisories, or by MLS back-course guidance in case that still functions.

CONCLUSIONS AND RECOMMENDATIONS

The problem of deriving surveillance information from the MLS can be analyzed in terms of the available air-to-ground communication links.

In one scheme, the aircraft azimuth would be derived on the ground by observing the MLS azimuth beam position at the time when a triggered DME interrogation is received. A significant azimuth error, a lack of range information, and considerably increased system complexity make this approach undesirable.

The remaining approaches differ only in terms of the characteristics of the data link that would be used to transmit the air-derived surveillance data to the ground. A data link may be superimposed on DABS, by using the proposed pulse code exchange between the ground interrogator and the airborne transponder. Alternatively, the C-band DME signal format could be modified to permit air-to-ground transmission of surveillance data.

The simplest approach technologically appears to be the one based on the DABS data link. A detailed tradeoff here will be possible once the signal format has been defined.

Any surveillance information that is derived from the MLS will be subject to failure if and when the MLS approach guidance fails. However, only a missed approach would result, and back-course guidance would still be given either by the MLS back-course function or, in case of complete MLS failure, by PVOR and DABS surveillance-based advisories.

REFERENCES

1. Report of DOT-ATCAC, December 1969.

2. Microwave Scanning Landing Guidance System, SFDT Report to SC-117, Washington, D. C., September 5, 1970.

APPENDIX A
ACCURACY REQUIREMENTS

In considering the accuracy required for approach surveillance it is evident that the constraints differ sharply depending on whether cross-track or along-track separation of aircraft must be assured. Cross-track separation is involved in parallel-runway operation, where the spacing may be as little as 2500 feet. Along-track separation, on the other hand, will typically be several miles, as dictated by aircraft speed differences, vortex avoidance, and runway design.

A somewhat analogous difference exists between the azimuthal and range accuracies of the beacon surveillance system. The projected azimuthal accuracy for DABS is $\sigma = \pm 0.2$ degrees or 22 feet per nautical mile, with a constant range accuracy of $\sigma = 380$ feet. The planning objective is a range accuracy corresponding to $\sigma = 100$ feet. For this planned system, the azimuthal and range accuracies would be equal to a target range of 4.5 miles, and inside this radius the azimuthal accuracy would increasingly be better than the range accuracy. If the range accuracy should correspond to σ greater than 100 feet, the crossover point would lie at a correspondingly greater range.

In order to take advantage of the difference in required accuracy, the surveillance therefore should be done from a location close to the runway center line, (e.g., colocated with the ILS localizer). However, even if the placement is not ideal, some relaxation of constraints on the surveillance system can perhaps be derived from the obvious difference between the required cross-track and along-track precision. Some factors that influence this precision are discussed below.

A.1 SPEED DIFFERENCES ON FINAL APPROACH

This section will consider the effect of differences in aircraft speed during the final approach, in the minimum practical along-track spacing, and hence, on the required surveillance accuracy. Under current procedures, the final approach speed is selected by the pilot within the limits of aircraft performance, and may vary from 60 knots for a Class I light aircraft, to 180 knots for a Class IV craft such as a 747 (Ref. A1). In order to maximize the runway acceptance rate, a sequencing and spacing function must be performed at some waypoint prior to passage over the outer marker, which takes into account differences in speed class, so that the final approach run (inside the outer marker) can be performed at a constant speed and with assured separation. Methods have been developed to achieve such spacing either by means of direct speed control

(Ref. A2) or by using a variable time-to-turn geometry without speed control (Ref. A3). Regardless of how the spacing is achieved, efficient sequencing for optimum landing rates will require a grouping of aircraft according to speed class, at least for runways dedicated to arrival-only traffic. From the viewpoint of surveillance to assure along-track separation during the landing phase, the smaller, slower aircraft hold the greatest interest, because they can be spaced more closely without being endangered by vortex wakes. As will be shown, large jet aircraft, under certain conditions, must be kept apart by as much as five miles to avoid vortices, (i.e., by distances that are much greater than the error envelope of even the present ATCRBS).

The operational minima for aircraft separation are rigidly governed by FAA standards. Current standards permit enroute longitudinal separation as low as 3-5 miles, under radar surveillance, depending on location. These standards may be changed, of course, from time to time in order to allow for different conditions of aircraft operation. Clearly, this great a separation can easily be monitored even with the existing ATCRBS system.

A.2 VORTEX AVOIDANCE

Every airplane generates a wake while in flight that takes the form of a pair of counter-rotating vortices trailing from the wing tips. The vortex strength increases with aircraft weight and wing span loading, with tangential velocities of as much as 90 knots. Aircraft caught in a vortex tend to roll with that vortex, and the consequent possible loss of control is a serious hazard. With heavy aircraft, the diameter of the vortex core ranges from 25 to 50 feet.

Vortices tend to sink, and with an aircraft in final approach the vortices will first sink towards the ground and then will drift in a cross track direction, and this motion may be aided or opposed by a cross wind. Vortices in the touchdown area constitute a serious hazard, and thus vortex avoidance procedures must be incorporated into the runway operation. Present thinking (Ref. A4) considers parallel runways that are spaced not less than 2500 feet apart, to be safe from cross-track vortices, so that independent parallel runway operation should still be possible. However, the along-track spacing of landing aircraft clearly must assure vortex avoidance.

Experimental results are available on vortex sink profile, (Ref. A5), and a sink slope of 100 feet per mile under calm wind conditions, is considered typical at landing approach speeds. Two aircraft that are due to land at 2 minute intervals, with an approach speed of 165 knots, would be spaced 5.5 miles apart, and the second aircraft thus would fly at least 600 feet above the vortex wake of the first. The question is whether a 2 minute headway is sufficient to allow adequate vortex dissipation in the touchdown area. Vortex persistence tests indicate that the vortices generated by a landing aircraft, with flaps fully down, tend to break up within 1-2 minutes into less dangerous, random air turbulence. Artificial means to accelerate vortex dissipation on the ground have been considered (Ref. A6). Wake turbulence sensors such as acoustic radars appear to be useable to determine those conditions under which aircraft spacings on approach should be increased to allow time for vortex dissipation. At these times, alternate arrival-departure use of each runway can recover some of the capacity.

In summary, vortex persistence in the touchdown area is an important constraint on the runway acceptance rate and hence, on the along-track spacing of aircraft in final approach.

A.3 PARALLEL RUNWAY SPACING

An important feature of the proposed microwave landing system (MLS) will be its ability to provide guidance for simultaneous approaches to close-spaced parallel runways. At present, parallel runways with 5000-foot spacings are being operated independently and it has been assumed generally that once the proposed MLS becomes operational, the spacing can be reduced to as little as 2500 feet. As will be shown below, however, this assumption must be subjected to close scrutiny in terms of several important operational parameters.

As the possibility that the risk of collision will be increased presents a deterrent to reducing parallel runway separation, considerable effort has been expended previously in determining the probability of a collision for such reduced runway separation (Ref. A7, A8, A9).

While collision risk can lead to rejection of a particular runway configuration, acceptably small collision risk is not in itself an adequate basis for accepting a particular system. Such a decision must be based on the performance of the system with a particular configuration. Probably there is no one performance measure which in itself would adequately serve this purpose, but in addition to collision risk, three closely related measures of performance have been derived which, taken together with collision risk, may provide the basis for rational system design.

These three measures are: (1) false alarm probability, the probability that an aircraft not requiring a maneuver command will be given one; (2) undetected excursion probability, the probability that an aircraft requiring a maneuver command will not be given one; (3) the probability that an aircraft requires a maneuver command.

For the proposed configuration of Figure A-1, false alarm probability will be defined as the probability that an aircraft within the normal operating zone (NOZ) will be observed by the system as being outside the NOZ. This is a significant measure of system performance for two main reasons: (1) presumably this type of situation will generate maneuver commands, and there is a definite limit on the number of such commands the system can generate and still perform efficiently; (2) the receipt of a large number of such commands, particularly when they are not necessary, will probably lead to a loss of confidence in the system by the user, which could increase the risk of collision due to a pilot ignoring a valid maneuver command.

To determine the probability of a false alarm, we need to make some basic assumptions. As we are concerned here with only the problem of lateral separation, we will deal only with lateral position of the aircraft. For each aircraft there are two positions, its true position, x_1, and the position observed by the landing system, x_2. The observed position will be equal to the true position of the aircraft plus an error term p, which is due to the surveillance system errors. Figure A-1 shows the relationship between x_1, x_2, and p. While the pilot of an aircraft using the landing system will attempt to fly along the centerline of the NOZ, he will not always be able to do this because of aircraft response, wind, and human errors, to mention the major causes.

Our analysis will assume that the flying errors are normally distributed with a zero mean and a standard deviation of σ_x. The assumption of zero mean is not necessary to the analysis, but it appears to be the most logical assumption that can be made. Similarly, the observation errors are assumed to be normally distributed with zero mean and standard deviation σ_p. These assumptions are consistent with those made in other analyses of the microwave landing system.

For a false alarm, as stated previously, the true lateral position, x_1, of the aircraft must be $-D<x_1<D$, where D is half the width of the NOZ, while the observed position x_1+p must be $-D>(x_1+p)>D$, where p is the observation error. Then, the probability of a false alarm is the product of two probabilities P_1, the probability that $-D<x_1<D$, and P_2, the probability that $-D>(x_1+p)>D$. Because the geometry is perfectly symmetrical and the distributions have zero means, the probability that $(x+p)>D$ is equal to the probability that $(x+p)<-D$, so that the probability, P, of a false alarm is $2P_1P_2'$ where P_2' is the probability that $(x_1+p)>D$.

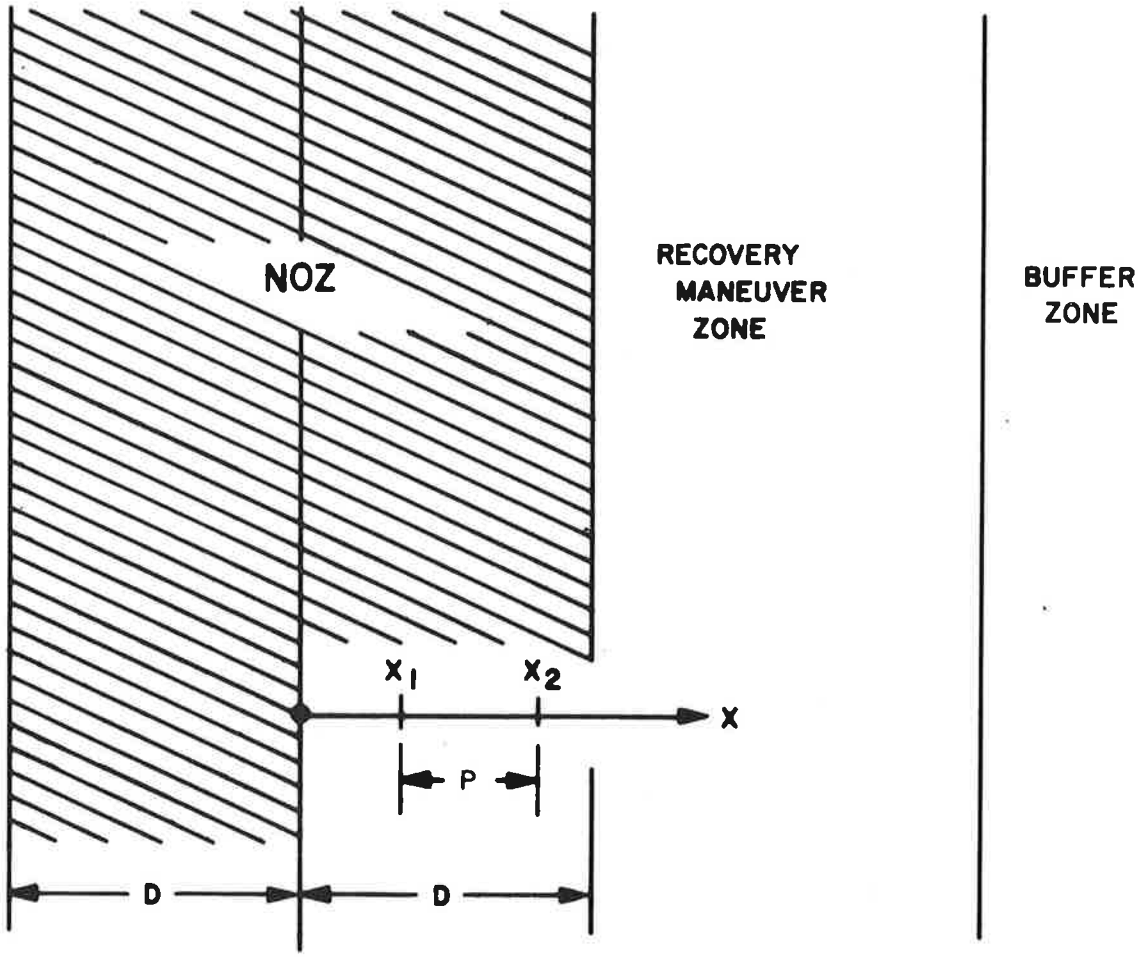


Figure A-1. Runway Geometry

Referring to Figure A-1, x_1, must be in the cross-hatched region and (x_1+p) must be to the right of D. The probability that x_1 is in the cross-hatched area is

$$P_1 = \int_{-D}^{D} f_1(x)\,dx$$

For $(x_1+p)>D$, $p>(D-x_1)$. Let the probability that $p>(D-x_1)$ be

$$P_2' = \int_{D-x_1}^{\infty} f_2(p)\,dp$$

This latter integral is a function of x_1, so that

$$P = 2\int_{-D}^{D} f_1(x_1)\int_{D-x_1}^{\infty} f_2(p)\,dx_1 dp$$

where

$$f_1(x_1) = \frac{1}{\sigma x_1\sqrt{2\pi}} \exp\left(-\frac{x_1^2}{2\sigma x_1^{\,2}}\right)$$

and

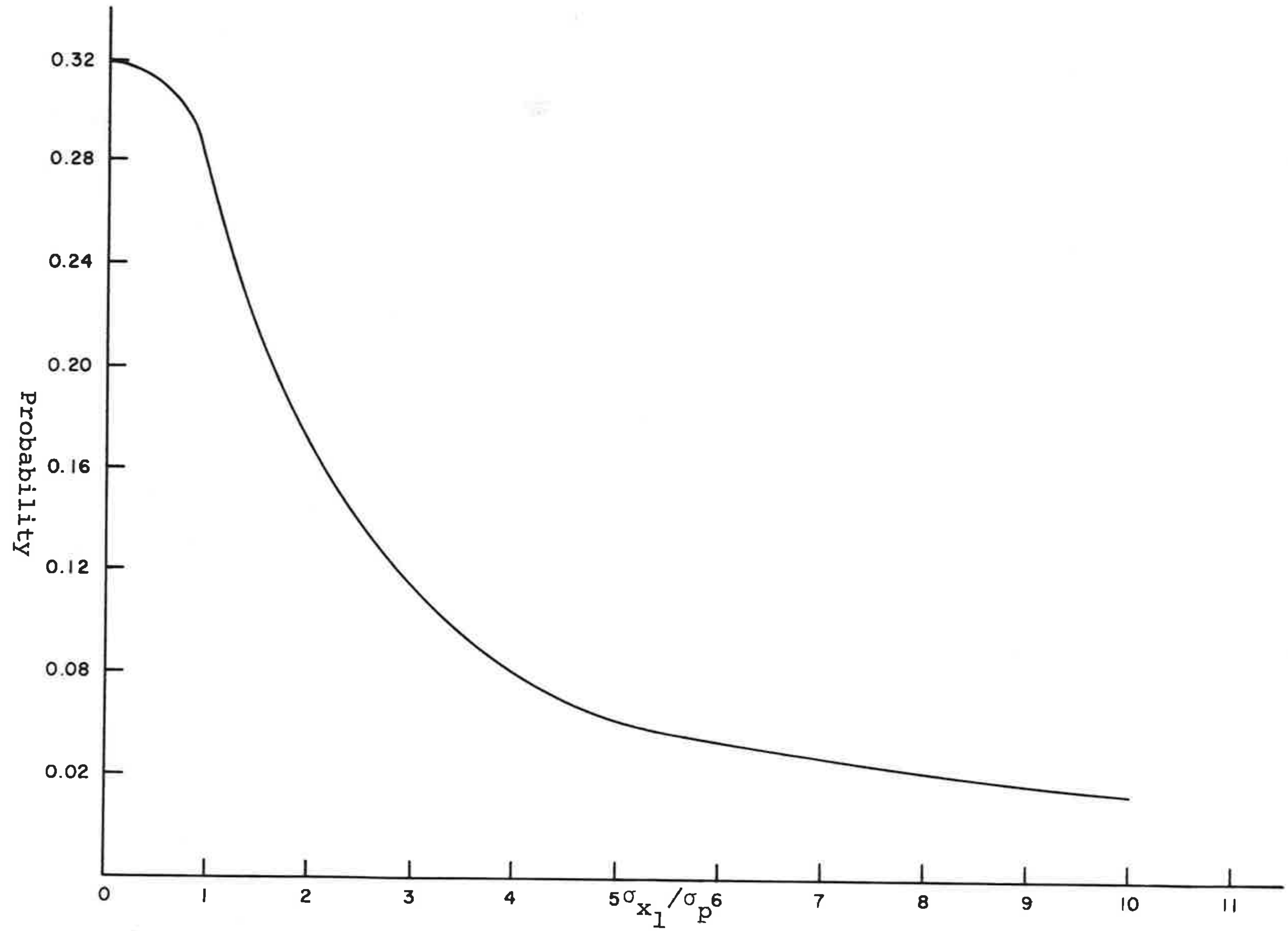
$$f_2(p) = \frac{1}{\sigma_p\sqrt{2\pi}} \exp\left(-\frac{p^2}{2\sigma_p^{\,2}}\right)$$

Substituting,

$$P = \frac{1}{\pi\sigma_{x_1}\sigma_p}\int_{-D}^{D} \exp\left(\frac{-x_1^{\,2}}{2\sigma x_1^{\,2}}\right)\int_{D-x_1}^{\infty} \exp\left(\frac{-p^2}{2\sigma_p^{\,2}}\right)dx_1 dp$$

This last expression cannot be integrated in closed form, so a series of solutions are obtained for different values of σx_1, σp, and D by means of numerical integrations carried out on a Hewlett-Packard Calculator.

Figure A-2 is a plot of the result of the integration for the case where $\frac{D}{\sigma p} = 1$, and Figure A-3. gives the results for $\frac{D}{\sigma p} = 2, 2.25, 3, 4, 6$ and 10. It can be seen that as $\sigma x/\sigma p$



A-2. Probability of False Alarms vs. $\sigma x_1/\sigma_p$ for D/σ_p = 1.0 where D is one-half the width of the NOZ

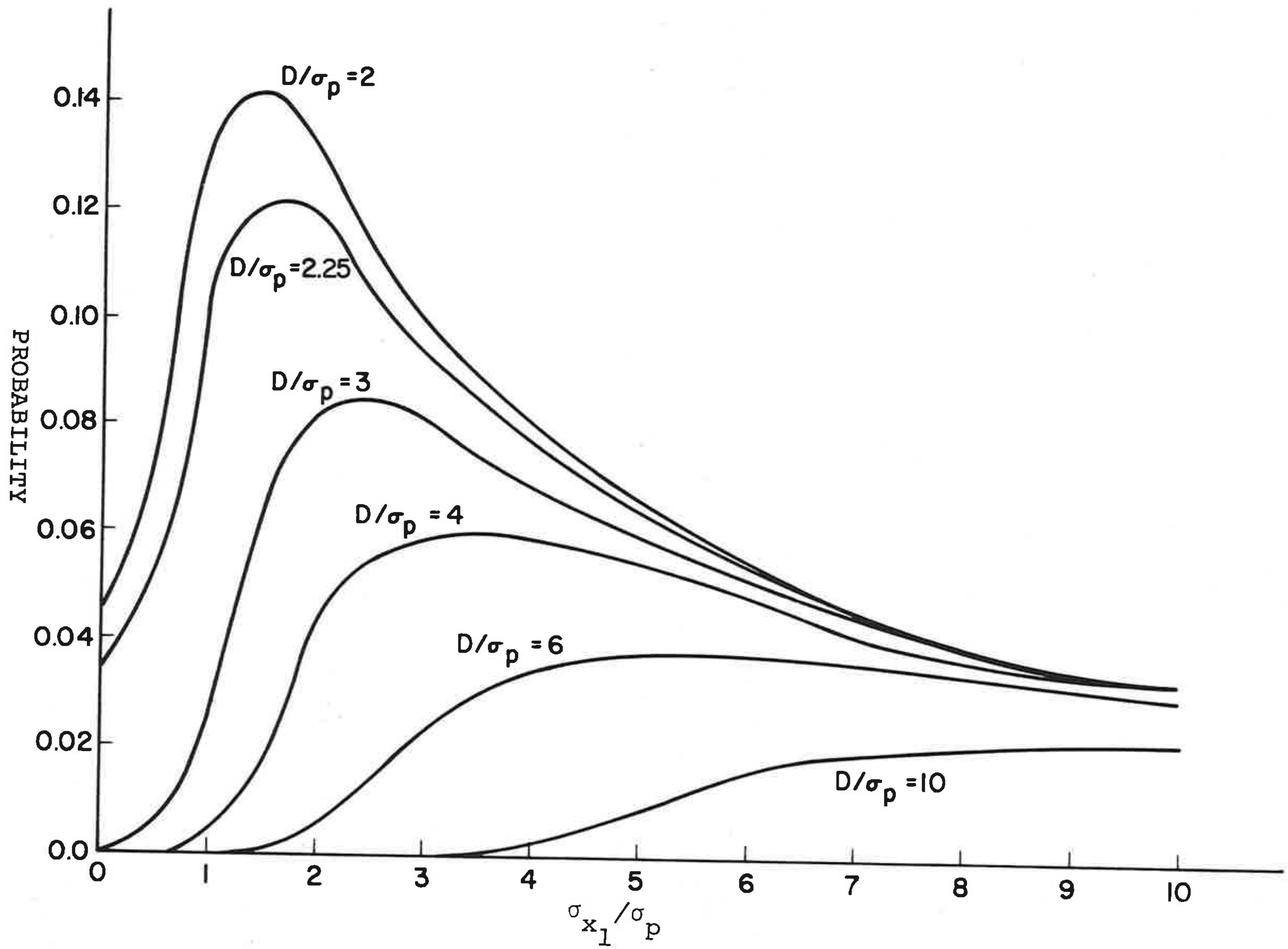


Figure A-3. Probability of False Alarm vs. $\sigma x_1/\sigma p$. The parameter is $D/\sigma p$ where D is one-half the width of the NOZ.

increases the probability of a false alarm decreases, as fewer aircraft are in the NOZ, and as $D/\sigma p$ increases (an increase in the NOZ) the probability of a false alarm decreases because a larger error is required to cause (x_1+p) to be outside the NOZ. As an example of how the curves are used, let $\sigma p = 100$ feet, $\sigma x_1 = 300$ feet and $D = 225$ feet. Then $\frac{D}{\sigma p} = 2.25$ and $\frac{\sigma x_1}{\sigma p} = 3$. From the curve in Figure A-3, for $\frac{D}{\sigma p} = 2.25$, and $\frac{\sigma x_1}{\sigma p} = 3$, $P = 0.093$. In this case then, the probability is 0.093 that on a particular update an aircraft that is actually within the NOZ will be observed outside the NOZ.

Obviously, such an aircraft is more likely to be near the edge of the NOZ than near the center of the NOZ, but for the purpose of this analysis the fact that it is observed outside the NOZ is significant. This will be discussed at greater length later on, as will the use of the curves.

A second measure of system performance is the probability that an aircraft will leave the NOZ. While the IPC data link is designed to prevent this from happening, the probability of such an occurrence is significant in determining the communications load placed on the data link by the design of the system. Again assuming a normally distributed lateral position error of standard deviation σx_1 and zero mean, this probability, P_2, is equal to one minus the probability that the aircraft is in the NOZ, or

$$P_2 = 1 - \int_{-D}^{D} f_1(x)dx.$$

From symmetry,

$$\int_{-D}^{D} f_1(x)dx = 2\int_{0}^{D} f_1(x)dx,$$

so that

$$P_2 = 1 - 2\int_{0}^{D} \frac{1}{\sigma x_1\sqrt{2\pi}} \exp\left(\frac{-x_1^{\ 2}}{2\sigma x_1^{\ 2}}\right) dx_1$$

The integral here can be found from a table of the cumulative normal distribution function with D in units of σx_1.

Figure A-4. is a plot of P_2 vs σx, with σx_1 in units of D. For example, if D = 3 and σx_1 = 1.5, the value of P_2 for $\frac{\sigma x_1}{D} = \frac{1.5}{3.0} = 0.5$ is $P_2 = 0.04$.

It can be seen immediately that for the probability of an aircraft being outside the NOZ to be less than or equal to 0.1, σx_1 must be less than or equal to 0.65D. Thus, for a standard deviation in flying error of 300 feet, D must be 461.5 feet or the NOZ must be about 920 feet. This will be discussed in more detail later on.

A third measure of system performance which is readily calculated is the probability that an aircraft which is outside the NOZ will not be detected by the surveillance system on the first data update interval after it has left the NOZ. Although the aircraft probably would be detected in the next or succeeding update intervals, this quantity is still of great interest. If the update interval is one second, an aircraft flying at 150 knots at an angle of 15^{o} to the centerline would travel about 57 feet laterally in this time, so that in effect the NOZ is extended by 114 feet. It seems clear that collision risk analyses based on a particular NOZ would have to be significantly modified to take into account these undetected excursions from the NOZ.

To determine the probability P_3 of such undetected departures from the NOZ, we will make the same assumptions as were made in determining the probability of a false alarm, (i.e., normally distributed errors in observation and position, and zero mean errors). An undetected departure from the NOZ occurs when $-D>x_1>D$ and $-D>(x_1+p)>D$. The probability that $-D>x_1>D$ is

$$1 - \int_{-D}^{D} f_1(x)dx$$

or

$$\int_{-\infty}^{-D} f_1(x)dx + \int_{D}^{\infty} f_1(x)dx.$$

From symmetry, these two integrals are equal, so this probability is

$$2\int_{-\infty}^{D} f_1(x)dx.$$

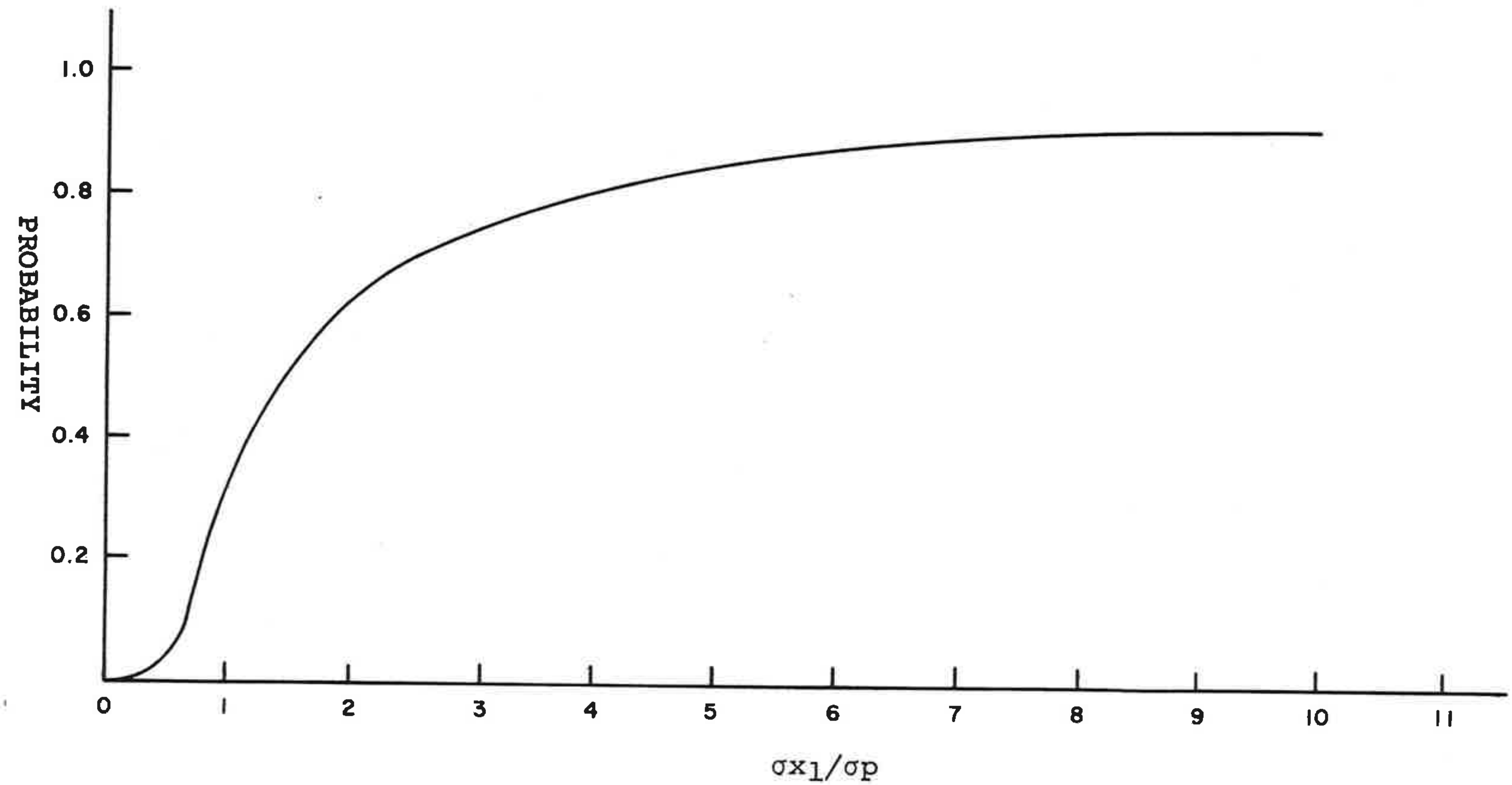


Figure A-4. Probability of an Aircraft being outside the NOZ, vs. $\sigma x_1/\sigma_p$ for D = Unit distance, where D is one-half the width of the NOZ. σx_1, σ_p, and D are all in the same units of distance.

For $-D<(x_1+p)<D$, we have $(-D-x_1)<p<(D-x_1)$. The probability of this event is given by

$$\int_{(-D-x_1)}^{(D-x_1)} f_2(p)\,dp.$$

P_3 is equal to the product of the above probabilities or

$$P_3 = 2\int_{-\infty}^{-D} f_1(x_1) \int_{-D-x_1}^{D-x_1} f_2(p)\,dp\,dx_1$$

Substituting $f_1(x)$ and $f_2(p)$,

$$P_3 = \frac{1}{\pi\sigma x_1 \sigma p} \int_{-\infty}^{D} \exp\left(-\frac{x_1^{\,2}}{2\sigma x_1^{\,2}}\right) \int_{-D-x_1}^{D-x_1} \exp\left(-\frac{p^2}{2\sigma p^2}\right) dp\,dx_1$$

Again this integral must be evaluated numerically, which was done using the Hewlett-Packard Calculator.

A series of curves giving the probability of an undetected excursion from the NOZ as a function of the standard deviation of the flying error, for various values of NOZ width, are presented in Figure A-5. The values were chosen to be in the range of interest for the purposes of this analysis, and it can be seen that values of σx_1 greater than $4\sigma p$ lead to significant probabilities of such events.

From the data on false alarms, undetected excursions and true excursions from the NOZ, the probability of the surveillance system observing an aircraft as being outside the NOZ can be obtained. Figure A-6 is a presentation of this composite data. This probability is equal to the probability of a false alarm plus the probability of an aircraft being outside the NOZ minus the probability of an undetected excursion from the NOZ. This curve will be used later in discussing the selection of runway separation parameters and analysis.

The derivation of Figure A-6 may be more clearly understood from the Table I on the next page which shows the relationship between observed position, true position and the probabilities calculated above. A false alarm occurs when the

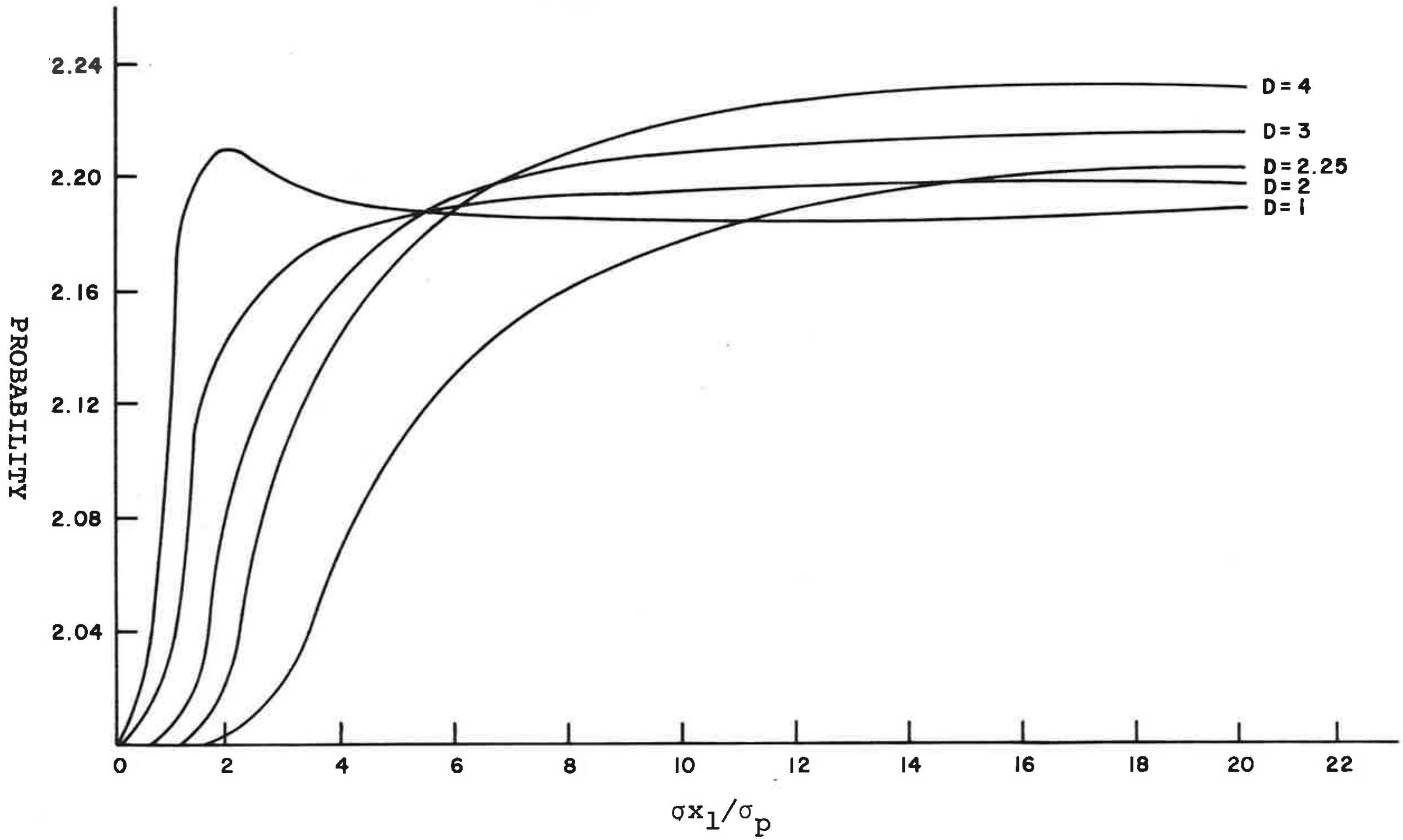


Figure A-5. Probability of an aircraft leaving the NOZ without being detected, vs. $\sigma x_1/\sigma_p$. The parameter is D, expressed in identical units of length as σx_1 and σ_p. D is one-half the width of the NOZ.

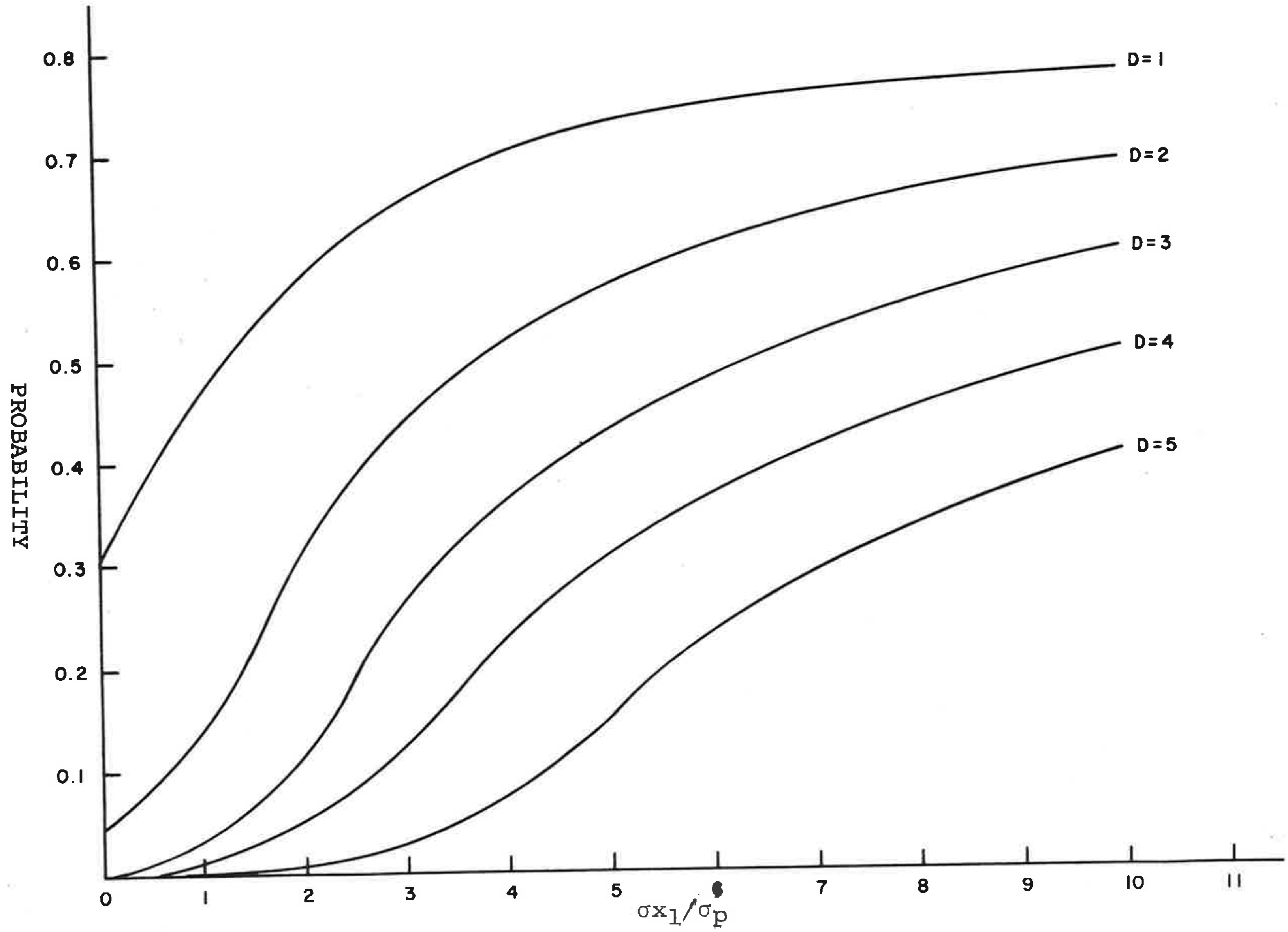


Figure A-6. Probability of an Aircraft being observed outside the NOZ vs. $\sigma x_1/\sigma p$. The parameter is D, expressed in identical units of length as σx_1 and σ_p. D is one-half the width of the NOZ.

Table A-I. Illustrating the Probabilities Connecting the True and Observed Position

True Position \ Observed Position	Inside NOZ	Outside NOZ
Inside NOZ	Normal Operation	False Alarm
Outside NOZ	P_2, P_3 Undetected Excursion	P_2 Valid Warning

true position is inside the NOZ and the observed position is outside the NOZ. P_2 is the probability that an aircraft is outside the NOZ and P_3 is the probability that an aircraft outside the NOZ is observed as being inside the NOZ.

To determine the probability of a collision due to decreased parallel runway separation, existing mathematical models were examined and one (Ref. A7) was used to determine the important parameters that enter into the collision probability for two aircraft descending abreast to parallel runways. This model assumed a Gaussian distribution of lateral aircraft separations. As this assumption did not take into account the space needed for emergency recovery maneuvers, a somewhat more realistic model which did include maneuvering space was explored in a subsequent report (Ref. A8). Figure A-7 which is taken from Ref. A8 depicts the turn off and recovery geometry used to obtain results such as those presented in Figure A.8.

In these curves, the runway spacing, D_R, required to correct pilot blunders without penetrating into the 500 foot buffer zone, is plotted vs. the cross-track surveillance error, σp, with the width of the normal operating zone, NOZ, as a parameter. Assuming D_R equal to 2500 feet, and $\sigma p = 100$ feet, then from Figure A-3. the aircraft must operate within a normal operating zone of 450 feet or less.

In general, Ref. A8 shows that in terms of this model, the runway spacing is very sensitive to the width of the normal operating zone and to the surveillance error which effectively adds to this width. Of somewhat lesser importance are the lengths of the update and response intervals; and only minor variations are produced by changes in aircraft speed and turning rate. The space needed to allow for the recovery maneuver far exceeds the width of the normal operating zone, and dominates the runway separation requirements.

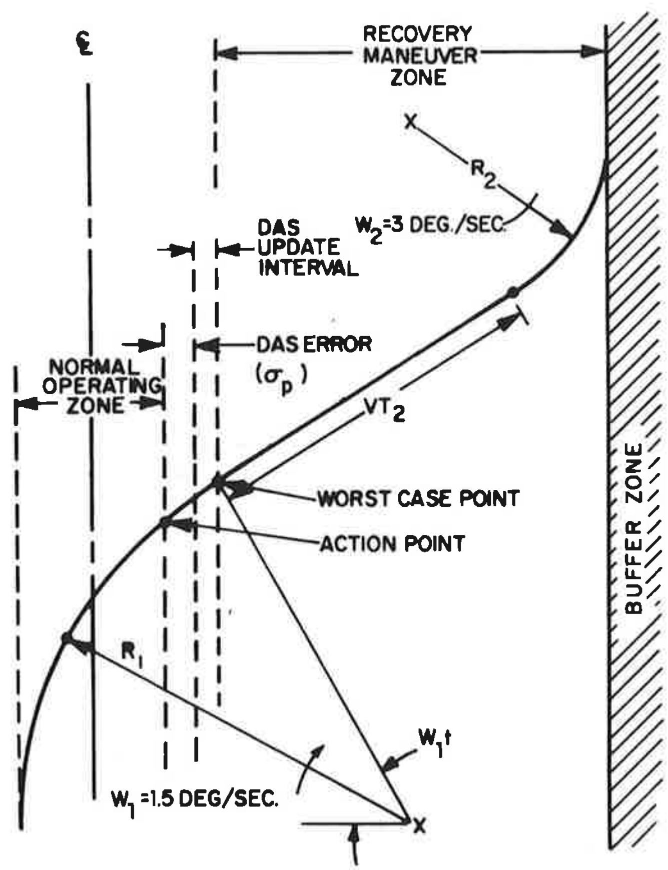


Figure A-7. Turnoff and recovery geometry (from Ref.A-8)

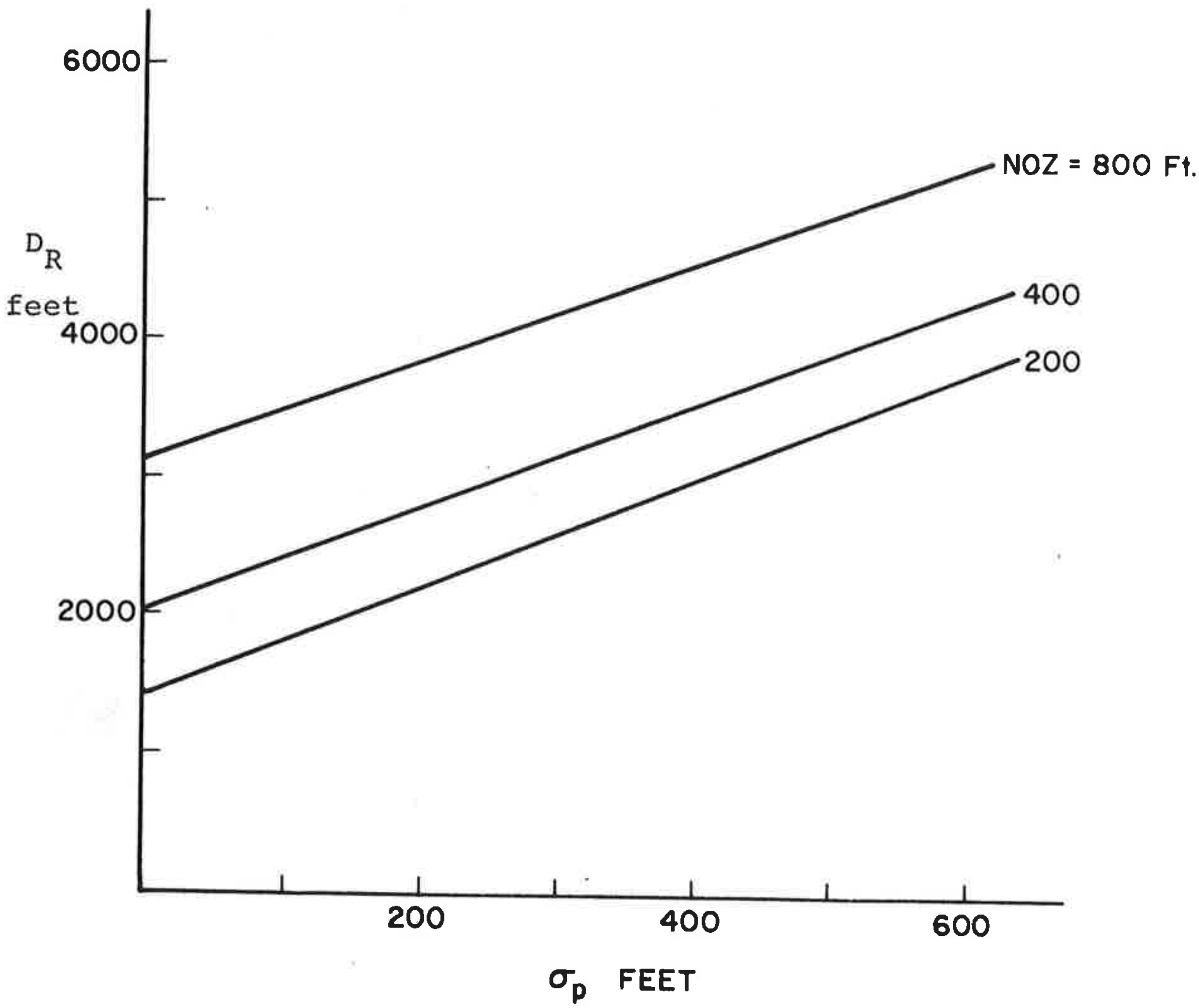


Figure A-8. Runway spacing D_R vs. surveillance error σ_p. Constants are V=150 knots, ω_1=1.5°/sec, T_u=1 sec, T_2=5 sec. The parameter is NOZ.

Having developed the previously discussed measures of system performance, it is instructive to apply them to the problem of determining an acceptable system design. For the purpose of this exercise the data presented in Ref. A9 will be used, as this is believed to be representative of the flying errors encountered in practice. It will be assumed, however, that the observed bias values can be eliminated by means of operating procedures, and only the standard deviation data will be used. The standard deviations of flying error obtained were:

Distance from Runway Threshold	Standard Deviation
3-4 miles	205.89 feet
4-5	238.90
5-6	284.33
6-7	369.32
7-8	406.70
8-9	286.64

Using 250 feet as a typical standard deviation of aircraft position error, σx_1, and 100 feet for the standard deviation of observation error, σp, one finds from Figure A-3, for a false alarm rate of 0.054, that D must be 400 feet, or the NOZ must be 800 feet.

From Figure A-5, for D = 4 and $\sigma x_1 = 2.5$, the probability is about 0.07 that an aircraft will leave the NOZ and not be observed. From Figure A-6, for D = 4 and $\sigma x_1 = 2.5$, the probability that an aircraft will be observed outside the NOZ is 0.085. Finally, from Figure A-4, for $\sigma x_1/D = 0.625$, the probability is about 0.087 that an aircraft will be outside the NOZ on a particular data update interval.

These numbers appear to be marginally acceptable. However, referring to Figure A-8, for NOZ = 800 feet, and σp = 100 feet, the required runway spacing is 3500 feet! As the desired runway spacing is 2500 feet, the maximum allowable NOZ would appear to be about 450 feet. With $\sigma p = 1$, D = 2.25, and $\sigma x_1 = 2.5$, the probability of a false alarm, from Figure A-3, is 0.104; from Figure A-5, the probability of an aircraft being outside the NOZ and not detected is 0.11; the probability of an aircraft being observed as outside the NOZ is, from Figure A-6, about 0.36. Finally, from Figure A-4, for D = 2.25 and $\sigma x_1 = 2.5$, the probability of an aircraft actually being outside the NOZ is

ACKNOWLEDGEMENT

The authors gratefully acknowledge the suggestions and corrections by Mr. Neal Blake. Robert T. Minkoff, who did the thorough work on parallel-runway spacing contained in Appendix A, has since met a sudden death. With Bob's passing, the team lost an imaginative contributor, and his colleagues lost a cheerful friend.