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REQUIREMENTS FOR INSTRUMENT APPROACHES TO CONVERGING RUNWAYS

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16. Abstract This document discusses the technical issues relevant to converging approaches and examines the feasibility of conducting instrument approaches as a means of increasing airport capacity. The main considerations in the analysis were: <ul style="list-style-type: none"> • Runway Geometry, • Missed Approach Paths, • Pilot Acceptance. A safety analysis was conducted to determine requirements and control procedures to provide protection against: <ul style="list-style-type: none"> • Random lateral variation from the missed approach path • Heading blunder • Rare and unexpected events. Requirements for final and missed approach are presented as are strategies for applying these requirements to airports with a wide variety of converging runway geometries. Preliminary recommended procedures are presented for conducting independent instrument approaches to Category I minima.			
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EXECUTIVE SUMMARY

INTRODUCTION

Independent approaches to converging runways are an accepted procedure in Visual Meteorological Conditions (VMC) at many airports, including Chicago O'Hare (ORD), Denver Stapleton (DEN), Miami (MIA), and Washington National (DCA), among others. A fundamental condition for these approaches is that the pilots or the controller be able to provide visual separation between the aircraft in the event of a missed approach.

In Instrument Meteorological Conditions (IMC), such visual separation generally cannot be applied, and therefore instrument approaches to converging runways are not currently approved. Visual separation has been deemed necessary for the safe separation of the aircraft in the unlikely event of a simultaneous missed approach, since the flight paths would intersect if the aircraft did not turn.

However, converging approaches in instrument conditions offer the potential for significant capacity increases at certain airports. For example, of the top 30 air carrier airports, 25 have at least one set of converging approaches. If the airport does not also have independent parallel approaches, independent approaches to converging runways would increase arrival capacity in IMC by 36-100 percent over the best currently available configuration.

Because of this potential for capacity improvement, a study has been performed of instrument approaches to converging runways, with particular emphasis on the missed approach problem. As a result of this analysis, it appears that missed approach procedures can be defined which provide for adequate separation between aircraft, even in the worst case of simultaneous missed approaches.

TYPES OF CONVERGING APPROACHES

Given a pair of non-parallel runways, there are three types of converging approaches possible. The point where the extended runway centerlines intersect may lie:

- On the final approach to one or both runways (the final approaches intersect) -- It would be difficult or impossible to operate such approaches safely.

- On the runways proper (the runways intersect) -- Such approaches may be feasible, depending on the distance from the threshold to the intersection.
- Beyond the runways -- Approaches to such runways would be feasible if turning missed approaches are specified which would be well separated.

This report primarily discusses the last case, where there is no physical intersection of the runways.

However, converging approaches may be feasible when the runways intersect if there is adequate distance between the runway threshold and the intersection, and adequate surveillance of the runways to detect a failure to hold short of the intersection.

It does not appear that blunders on final approach present any significant concerns for converging instrument approaches. The approach paths are far apart in the area of greatest concern, shortly after the turn on to the localizer. Closer to the runway where the approach paths are less widely separated, surveillance accuracy is greater, making early detection of a blunder more likely. Also, the pilot will have visual contact with the runway, making the blunder itself less likely.

MISSED APPROACH ANALYSIS

The analysis of converging instrument approaches has, therefore, emphasized the question of missed approaches, which have been perceived to be the principal obstacle to such operations. Converging approaches would require missed approaches that turn and diverge, in order to avoid any possible conflict. This is unlike the case of parallel approaches; although turning missed approaches are also specified, a straight missed approach would not lead directly to a conflict.

Missed approach procedures for converging approaches need to consider normal deviation about the flight path, poor adherence to the specified flight track, and human error. Even if simultaneous missed approaches should occur, and both aircraft exhibited the maximum expected deviation from their nominal flight paths, the specified procedures should provide adequate separation between the aircraft.

Several methodologies were considered for assuring that adequate separation would be provided. One methodology involved a direct calculation of the probability that a conflict would occur. This was ruled out because the available data on missed approaches was inadequate to support such a calculation, and obtaining sufficient additional data was beyond the scope of this project. Very few observations have been recorded more than three standard deviations (3 sigma) from the centerline of the missed approach path, making it impossible to completely describe the underlying statistical distribution of the deviations. In other words, the data does not allow us to describe the behavior of aircraft which deviate widely from the expected path.

Additionally, this data, which came from simulations, flight tests, and actual missed approaches, dealt only with straight missed approaches from single runways, not the turning simultaneous missed approaches required for independent converging paths.

Another methodology which was considered involved using the Obstacle Clearance Surfaces defined in the U.S. Standard for Terminal Instrument Procedures (TERPS) to describe airspace reserved for missed approaches from each runway that would not be allowed to overlap. However, such an overlap is not significant because the "TERPS Surfaces" were not designed to separate aircraft from other aircraft, but rather to protect aircraft from stationary obstacles. As such, factors are included which are not relevant to air-to-air separations; application of the TERPS Surfaces would be unnecessarily conservative. Furthermore, such an interpretation of the TERPS Obstacle Clearance Surfaces would be contradicted by other authorized procedures. For example, the TERPS Surfaces for parallel approaches to runways 4300 ft apart overlap by 1776 ft, but this has never been considered an impediment to such approaches.

Although the derivation of the TERPS Surfaces may make their use inappropriate for our purposes, the original philosophy behind the Surfaces is still valid. This philosophy is understood to be that aircraft would be protected if they deviated by no more than 3 sigma from their assigned path. Such a criterion protects more than 99 percent of all operations.

THE "WORST CASE" MISSED APPROACH PATH

This 3-sigma philosophy is the foundation for the methodology which was finally chosen for assuring adequate separation between

missed approaches. Such 3-sigma deviations have in the past been taken as the maximum deviations which were reasonable to protect against. "Worst-case" paths have been constructed using 3-sigma values from the data, when available, or else values from the TERPS procedures; a minimum separation was then provided between these worst-case paths.

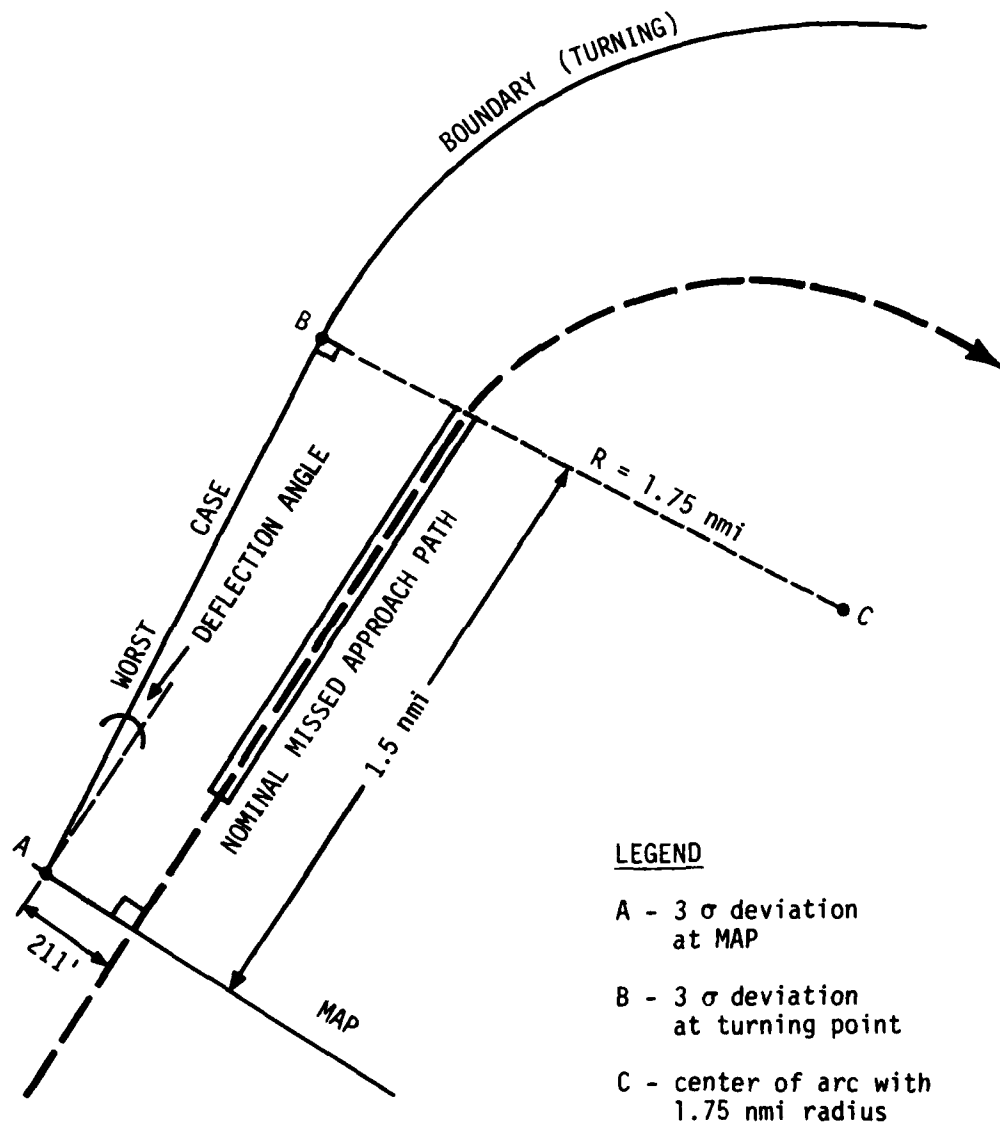
The parameters of the worst-case path have been defined as follows (Figure A):

- The lateral displacement at the Missed Approach Point (MAP) - is taken to be 211 ft towards the other approach, according to available data. This is the 3-sigma value at a 200 ft Decision Height (DH); it increases 50 ft for each 100 ft increase in Decision Height.
- The angular deviation from centerline - is 3.5° , again toward the other runway. This is derived from the increase in the 3-sigma displacement beyond the MAP; available data does not include the angular deviation for individual aircraft.
- The straight-line distance flown before the turn begins - is assumed to be 1.5 nmi, regardless of aircraft type or DH. Since no data exists on this parameter, the TERPS value was used. The pilot must establish a positive rate of climb, and be at least 400 ft above ground level (AGL), before the turn can begin. When the missed approach starts above 400 ft AGL, considerably less than 1.5 nmi would probably be needed.
- The radius of the turn - is assumed to be 1.75 nmi. Again, this value is taken from TERPS because no other data exists. This is the nominal turn radius in TERPS for heavy aircraft; other aircraft have smaller radii specified. A turn of this radius is equivalent to a half-standard rate turn ($1.5^{\circ}/s$) at 165 kn, or $2.25^{\circ}/s$ at 250 kn.

These values were chosen to be individually conservative; the combination is even more conservative, since it is quite unlikely that a single aircraft would perform poorly in all the ways assumed.

SEPARATION OF WORST CASE BOUNDARIES

This worst case path has, therefore, been used as a boundary which aircraft executing a missed approach are not expected to



LEGEND

- A - 3σ deviation at MAP
- B - 3σ deviation at turning point
- C - center of arc with 1.75 nmi radius

**FIGURE A
CONSTRUCTION OF WORST CASE BOUNDARY
FOR TURNING MISSED APPROACHES**

penetrate. Providing a minimum separation between these Worst Case Boundaries will then ensure an adequate separation between actual missed approach paths. The following procedure is used to determine whether the minimum separation between Worst Case Boundaries exists.

- First, turning Worst Case Boundaries are constructed for both runways. These paths, as described above, protect against random lateral deviation about the expected missed approach course, as well as any extended turn.
- Second, straight Worst Case Boundaries are constructed for both runways. These boundaries protect against possible pilot error, such as continuing straight ahead instead of turning as required on the missed approach. They also protect against a balked landing (i.e., when the missed approach starts at the runway threshold or beyond rather than at the MAP). The straight Worst Case Boundary is similar to the turning boundary, except that the length of the straight segment is 15 nmi rather than 1.5 nmi.

It was assumed that missed approaches would then be safely separated if the minimum distance between the turning boundary for either runway and the straight boundary for the other runway was 500 ft or more (Figure B). This 500 ft provides additional protection against rare and unexpected events.

Although the separation requirement is described with reference to the straight and turning Worst Case Boundaries, the published missed approach procedures would call for both aircraft to turn. When the above separation requirement of 500 ft is satisfied, the separation between the two turning Worst Case Boundaries, at the airports studied, has been greater than 1000 ft. Separation between actual missed approach paths would be greater still.

APPLICATION STRATEGIES

In the most desirable case, simultaneous approaches to converging runways would be authorized to Category I minima; the above worst-case separation requirement would then be satisfied at a 200 ft DH on both runways. Unfortunately, this ideal case exists at few airports. At airports where the runway layout does not allow the most desirable situation to occur, converging approaches can still be operated through the application of one or more of the following techniques:

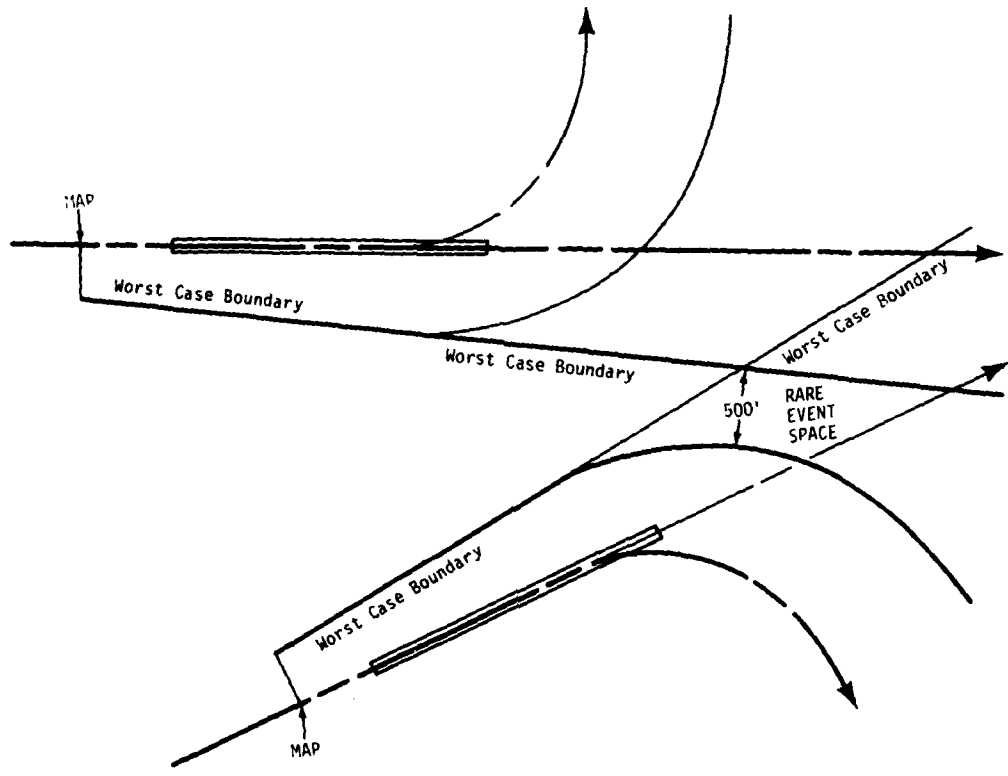


FIGURE B
APPLICATION OF MISSED APPROACH REQUIREMENTS
TO CONVERGING RUNWAYS

- Raising the Decision Height - This moves the Missed Approach Point away from the runway threshold, increasing the separation between aircraft at the start of the missed approach and consequently between the Worst Case Boundaries. Of course, since the procedure is unavailable when the ceiling is less than the Decision Height, raising the DH for the procedure reduces the percentage of the year during which the procedure could be used.
- Segregating Traffic - Aircraft with slower approach speeds could also be expected to go-around at a slower speed. Their turn radius would also be less. If one approach is reserved solely for such aircraft, the radius of the turning Worst Case Boundary for this approach would be reduced, in some cases increasing the minimum separation between the Worst Case Boundaries. Table A shows the expected turn radii for different aircraft classes as found in TERPS.
- Applying MLS Guidance - MLS offers the potential to reduce the lateral course deviation during missed approach for suitably equipped aircraft. There might also be positive guidance during the initial section of the turn.
- Operating Dependent Approaches - If none of the above techniques is adequate to allow independent converging approaches, the approaches could be operated dependently. One form of dependence which might be applied would require that the arrival be a minimum distance from the runway threshold when the previous arrival is at the threshold to the other runway. These minimum distances would be calculated to provide some minimum time separation at the intersection of two straight missed approach paths, should both aircraft go around.

Of these techniques, raising the Decision Height seems to offer the greatest potential. Twenty-five out of the top 30 U.S. Air Carrier airports have converging runway configurations; independent converging approaches are possible at sixteen of these by raising the DH appropriately. Dependent converging approaches are possible at all twenty-five airports, but capacity would not be as high.

TABLE A
 TURNING MISSED APPROACH RADII (MILES)
 (TERPS PARA. 212)
 (TERPS PARA. 275)

APPROACH CATEGORY*	OBSTACLE CLEARANCE RADIUS (R)	FLIGHT PATH RADIUS
A	2.6	1.30
B	2.8	1.40
C	3.0	1.50
D	3.5	1.75
E	5.0	2.50

***APPROACH CATEGORIES**

- A - SPEED LESS THAN 91 kn; WEIGHT LESS THAN 30,000 lbs
- B - SPEED 91 kn OR MORE, BUT LESS THAN 121 kn; WEIGHT 30,001 lbs OR MORE, BUT LESS THAN 150,000 lbs
- C - SPEED 121 kn OR MORE, BUT LESS THAN 141 kn; WEIGHT 60,000 lbs OR MORE, BUT LESS THAN 150,000 lbs
- D - SPEED 141 kn OR MORE, BUT LESS THAN 166 kn, WEIGHT 150,000 lbs OR MORE
- E - SPEED 166 kn OR MORE; ANY WEIGHT

NOTE: SPEEDS ARE BASED ON 1.3 TIMES THE STALL SPEED IN THE LANDING CONFIGURATION AT MAXIMUM GROSS LANDING WEIGHT. WEIGHTS ARE MAXIMUM AUTHORIZED GROSS LANDING WEIGHTS. AN AIRCRAFT SHALL FIT IN ONLY ONE CATEGORY, AND THAT CATEGORY SHALL BE THE HIGHEST CATEGORY IN WHICH IT MEETS EITHER OF THE SPECIFICATIONS.

PILOT ACCEPTANCE

As with any new procedure, the opinions and analysis of the people involved - the pilots - are essential to proper design and general acceptance. The testing and demonstration of converging approaches should be carried out with extensive opportunities for pilot involvement from the early stages.

Although no discussions have yet been held with the general pilot community, it is felt that the proposed requirements for converging approaches address the most likely pilot concerns. These concerns reflect the possibility that "the other pilot" may not turn (as required) during simultaneous missed approach. The safety analysis supporting the requirements allow for such outright error by either one of the two pilots.

Pilot acceptance can also be aided by a gradual implementation of converging approaches. Approaches could initially be conducted with a high Decision Height; the DH could be lowered over several years in accordance with a fixed schedule, as experience with the procedure was accumulated.

CONCLUSIONS

Based on the analysis performed to date, it appears that independent converging approaches with a Decision Height as low as 200 ft (Category I minima) are feasible at certain airports with the proper runway geometry. This feasibility is dependent primarily upon the safe separation of the aircraft if simultaneous missed approaches should occur.

The recommended procedure for determining whether this safe separation exists involves providing a minimum separation between two Worst Case Boundaries, one turning and one straight, which represent the maximum expected deviation from the nominal missed approach path. A conflict would then be extremely unlikely, since all the following conditions would need to occur:

- Two missed approaches must occur simultaneously.
- One aircraft must go straight rather than turn as required, and one or both aircraft must deviate beyond the Worst Case Boundary by more than 500 ft.

Application of this concept to particular airports may involve some modification of the basic procedures as described herein. The most effective modification involves raising the Decision Height for the converging approaches. This acts to increase the separation between the missed approach paths. Other options involve segregating traffic by speed category, utilizing MLS guidance, or operating the converging approaches dependently.

The implementation of converging instrument approaches would be beneficial to twenty-five of the top thirty U.S. air carrier airports. All twenty-five converging runway layouts could be operated dependently down to a 200 ft Decision Height; sixteen would be suitable for independent converging approaches, with Decision Heights from 325 ft to 900 ft.

RECOMMENDED PROCEDURES

Based on this analysis, independent instrument approaches to Category I minima can be conducted safely and efficiently if these procedures are employed:

- The following present requirements are satisfied:
 - 3 nmi/1000 ft. separation between aircraft at localizer intercept, and
 - functioning ILS or MLS, airport surveillance radar and air/ground communications.
- Final approach paths do not intersect.
- Missed approach procedures for both runways consist of a climb to 400 ft AGL and a diverging turn at the standard rate of $3^\circ/s$. The turns should diverge by at least 45° .
- With these procedures in effect, independent converging approaches can be authorized if for each runway, the turning Worst Case Boundary is separated by at least 500 ft from the straight Worst Case Boundary for the other runway. This accounts for the possibility that either missed approach may blunder and proceed straight ahead.

- If runway geometry does not permit Category I minima (DH = 200 feet), one of the following techniques is used to ensure safe separation between missed approaches:

- raising the DH until lateral separation between Worst Case Boundaries is greater than 500 feet.

- operating dependent approaches by insuring a minimum time separation between missed approaches at the point where extended approach center lines intersect.

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1. INTRODUCTION

1.1 Background

Current congestion levels at major airports require an increasingly efficient utilization of existing airspace and airport real estate. Several innovative techniques and Air Traffic Control (ATC) procedures can be considered to increase capacity, particularly in Instrument Meteorological Conditions (IMC).

Recent studies have identified those techniques and procedures necessary to use multiple instrument approach streams in particular applications. Specifically, requirements for their use in dual and triple parallel runways (References 3 and 5) have been specified.

This report addresses the potential for increasing capacity through the use of independent or dependent approaches to converging runways during Instrument Flight Rule (IFR) conditions. At the present time, IFR arrival operations may be conducted to single runways, to independent parallel runways spaced at least 4300 ft apart, and to dependent parallel runways at least 3000 ft apart (with 2.0 nmi diagonal aircraft separation). For runways spaced from 2500 ft to 2999 ft, a 3 nmi diagonal separation is required. IFR approaches to converging runways are not presently allowed.

The expected benefits of multiple approaches on airport arrival capacity are significant (Table 1-1 from Reference 1). Many airports have converging runways which cannot be used in IFR conditions under current ATC rules. Their arrival capacity is that of a single runway. Arrival capacity for independent converging runways is potentially twice that of a single runway. The capacity increase to be expected for a dependent converging configuration would vary from 40 to 75 percent depending on the specific geometry.

1.2 Objective

The gain in arrival capacity shown in Table 1-1 will only be a potential increase unless the concept is accepted and used. As the first step in demonstrating that converging approaches used under IFR conditions could increase airport capacity, this report presents a preliminary analysis of such operations and an initial set of requirements.

TABLE 1-1
IFR ARRIVAL RUNWAY CAPACITY

<u>RUNWAY(S)</u>	<u>NUMBER OF ARRIVALS PER HOUR</u>	
	<u>10 PERCENT HEAVY TRAFFIC</u>	<u>40 PERCENT HEAVY TRAFFIC</u>
Single	28	25
Dependent Parallels	39	38
Independent Parallels	55	51
Independent Converging	55	51
Triple Parallel (Independent/Dependent)	67	64

1.3 Organization

All runway layouts can be described as composed of single, parallel, or converging runways. Section 2 of this report discusses the various types of converging runways and compares converging approaches with parallel operations.

The requirements analysis (Section 3) identifies the major issues in operating converging runways independently. These issues are evaluated with particular attention to *simultaneous missed approaches*. Procedures are proposed which would allow safe operation of a limited set of converging runways down to Category I minima (200 ft Decision Height).

Many other configurations of converging runway geometries cannot be operated independently under the proposed procedures. Four strategies are proposed in Section 4 to allow operations under certain specific conditions. The runway geometries to which these strategies may be applied are identified.

One of the most important issues of converging approaches is the *assessment from the pilots* who will be required to operate them. The issues which are likely to affect pilot acceptance are discussed in Section 5. A summary and complete statement of requirements is enumerated in the final section.

2. DESCRIPTION AND PERSPECTIVE

The potential for increases in arrival capacity due to application of multiple approach concepts was illustrated in Table 1-1. Parallel runways are easily categorized into independent and dependent arrivals primarily on the basis of distance between runways. Under current rules, for example, if runway spacing is less than 4300 ft, arrival operation must be dependent. Converging runways, however, cannot be categorized so easily and the specification of independent and dependent is more complex. Therefore, a methodology to define and characterize converging approaches is presented in this chapter.

2.1 Definition

If two runways are not parallel, they will converge and approaches to the runways from one direction will also converge. To avoid dealing with runways that converge by so little that, for practical purposes, they are parallel, runways that converge by no more than 15° are considered to be parallel as specified in the Air Traffic Control Handbook (Reference 8). A further limitation of 100° has been applied to the maximum angle of convergence (Figure 2-1). This was done for two reasons:

1. For those runways with angles of convergence $>100^{\circ}$, it is more likely that converging approaches would be made to the runway ends defined by the complementary angle $<80^{\circ}$.
2. It is unlikely that wind conditions would allow the use of approach combinations that converge at an angle between 100° and 180° .

2.2 Types of Converging Runways

To identify the converging geometries that will provide the most capacity gain during IFR conditions, three types of converging runways were examined.

- The final approach to one converging runway may intersect the final approach or the extended centerline of the other runway.
- The two runways may physically intersect.
- The extended centerline may intersect.

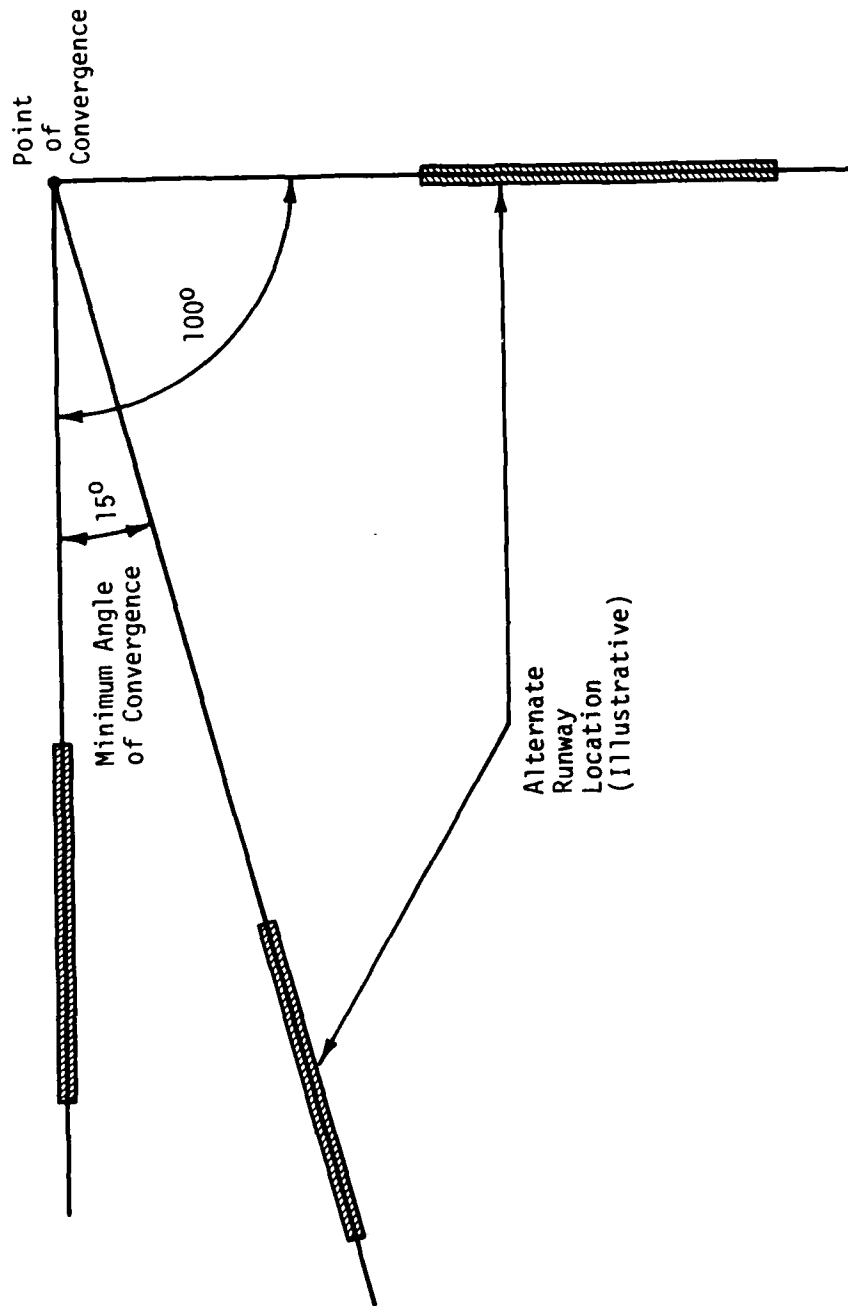


FIGURE 2-1
LIMITS OF RUNWAY LOCATION FOR CONVERGING APPROACHES

2.2.1 Intersecting Approach Streams

Converging runways in which the approach streams must intersect (Figure 2-2a) will be most difficult to operate safely during any condition. There is no precedent for this operation during VFR conditions and no effort was expended to design requirements for this type.

2.2.2 Intersecting Runways

Independent operation of converging runways that intersect will pose two kinds of problems (Figure 2-2b):

- The possibility of collision between two aircraft on that portion of each runway in which the pavement is shared
- The possibility of collision during simultaneous missed approach

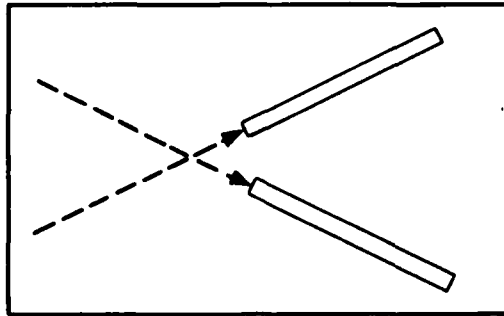
A combination of these two problems will make some intersecting runway geometries virtually impossible to operate simultaneously. If the distance between touchdown and intersection is long enough for aircraft to land and hold short, however, there are ATC procedures (designed for VFR conditions) that may be applied. For geometries in which hold-short procedures can be used, there remains the problem of simultaneous missed approach.

2.2.3 Converging Runway (Extended) Centerlines

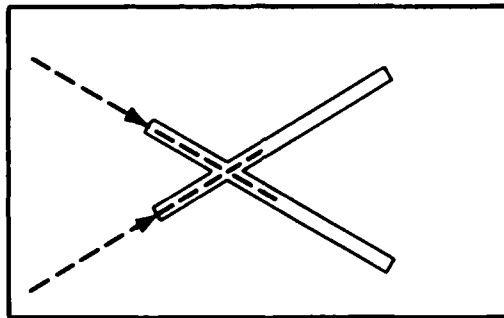
Those runways in which the extended centerlines intersect, or a variation in which the extended centerline of one runway intersects the other, present only simultaneous missed approach problems (Figure 2-2c). Because this type is the least complex and there is extensive precedence in VMC, the likelihood of creating relatively non-restrictive requirements is good. Consequently, the majority of the analysis focuses on this converging approach type and the resolution of the simultaneous missed approach issue.

2.3 Characterization

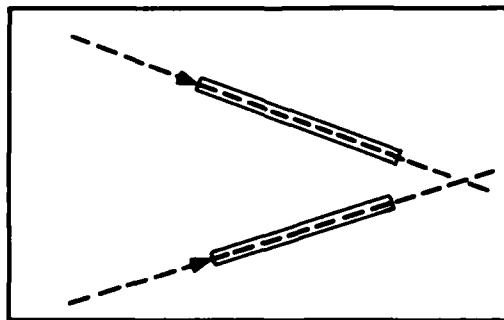
Because of the wide variety of runway geometries described as converging, some additional characterization is necessary to aid in understanding the implications of this variation. There are two major parameters that vary within the converging geometries:



a. Intersecting Approaches



b. Intersecting Runways



c. Converging Runway (Extended) Centerlines

FIGURE 2-2
TYPES OF CONVERGING APPROACHES INTERSECTING APPROACHES

1. Angle of convergence - This can vary from 15° to 100° and acts to increase or decrease separation between expected missed approach paths depending on the value of the other parameter (See Figure 2-3).
2. Distance from point-of-intersection to threshold - This distance can vary greatly depending on the position of runways and runway length. As the distance increases, the lateral separation between expected missed approach paths also increases (Figure 2-3).

Throughout this report, the nominal missed approach path is used as defined by TERPS (Reference 2) for an ILS approach (Category I*) to a single runway by an air carrier aircraft. It specifies that an aircraft will descend to a decision height (DH) of 200 ft at the missed approach point (MAP). This is approximately at the middle marker. A 1.5 nmi straight section of the missed approach area begins at the MAP and ends at a point where the missed approach flight path begins a constant radius turn. An example of a turning missed approach flight path has been superimposed over both converging approaches in Figure 2-4. The assumption that both aircraft will need to turn to avoid collision was made to insure the greatest degree of safety. The missed approach paths are shown diverging by 45° as required for parallel simultaneous ILS approaches by TERPS (para 997).

Other aspects of converging approaches will, of course, differ from parallel independent approaches. For example:

1. Many converging runways actually intersect, thus, presenting a ground collision hazard not found in parallel approaches.
2. For converging runways, the most likely missed approach maneuver would require both aircraft to turn, unlike the parallel missed approach in which one of the aircraft may not be required to turn.

*Category I approaches are the standard for the evaluation of this concept. This category requires the DH to be no less than 200 ft above ground level (AGL).

DISTANCE FROM POINT-OF-INTERSECTION TO THRESHOLD

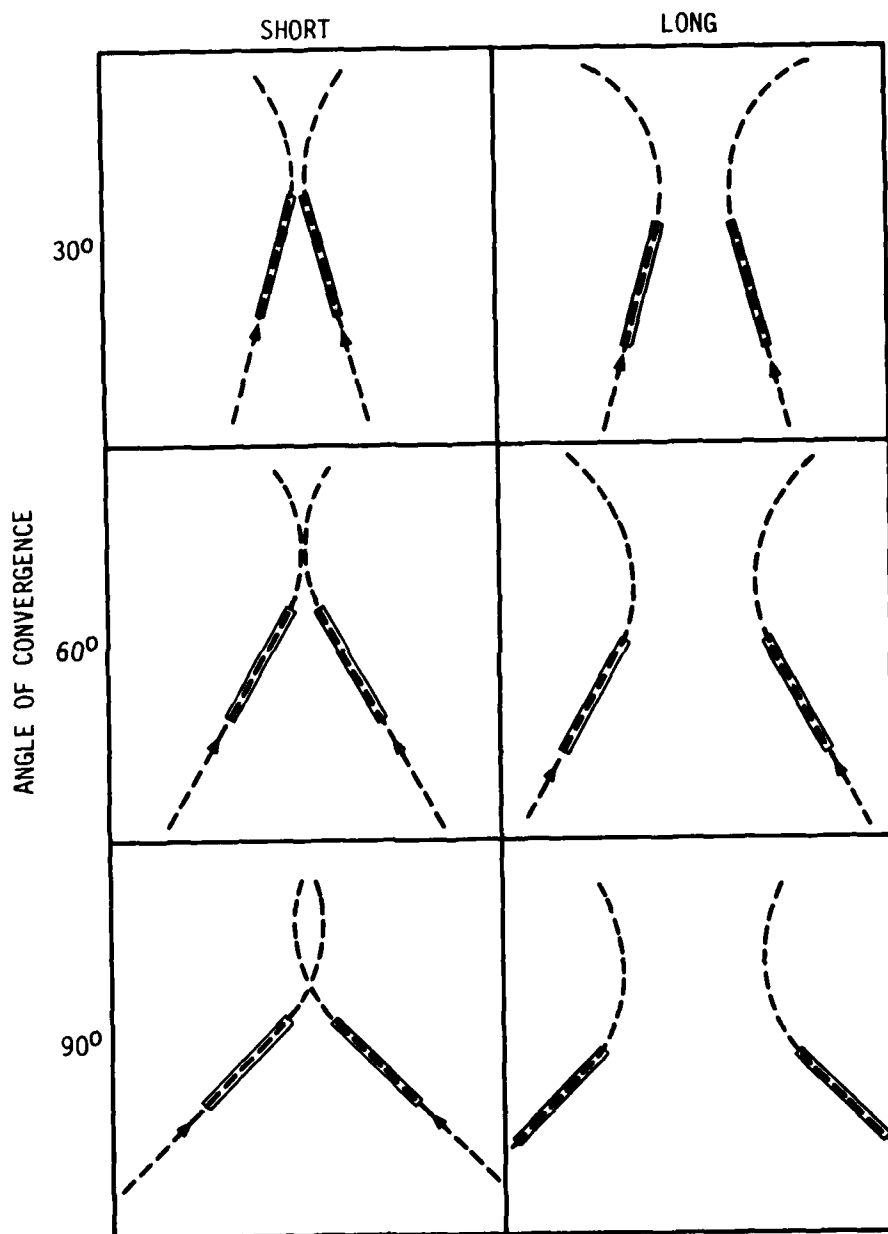


FIGURE 2-3
ILLUSTRATION OF PARAMETERS AFFECTING MISSED APPROACH
PATHS FOR CONVERGING RUNWAYS

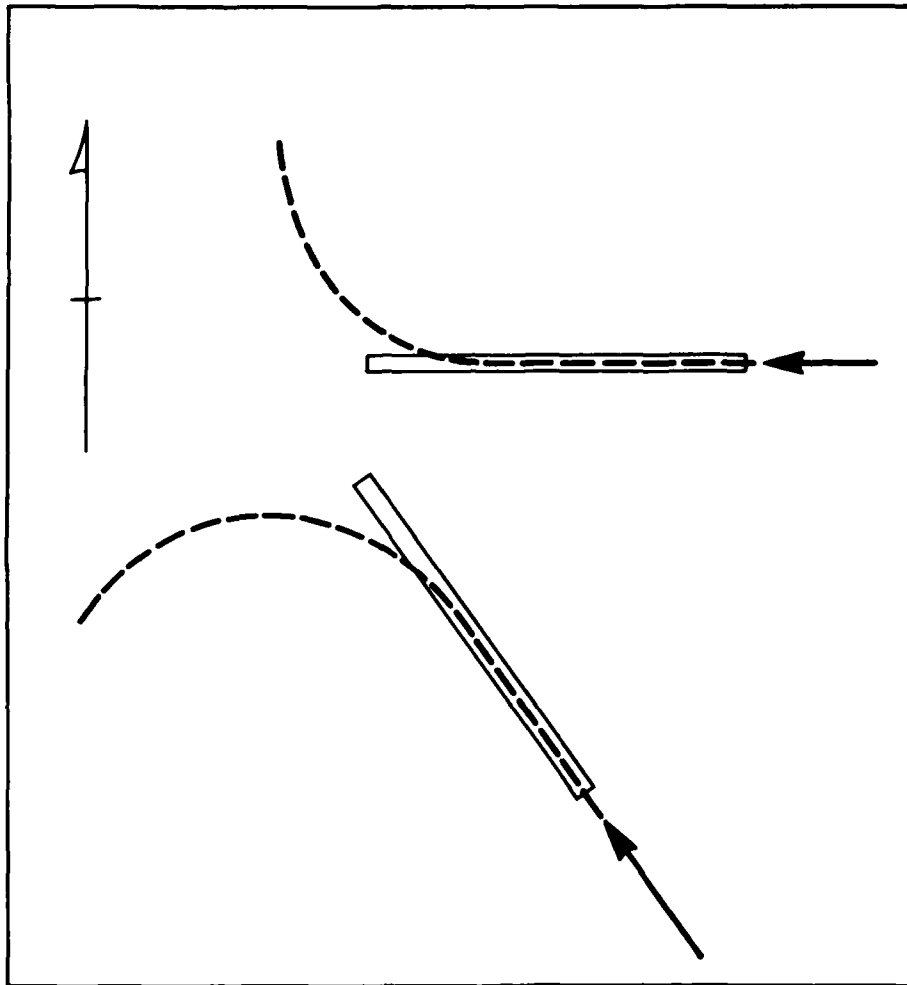


FIGURE 2-4
RUNWAYS PLAN FOR HOUSTON (IAH) ILLUSTRATING TYPICAL
(NOT OFFICIAL) TURNING MISSED APPROACH PATHS

2.4 Conclusion

Operating converging runways during IFR conditions presents several airborne and safety concerns, some of which relate to runway geometry category. Since the intersecting final approach geometry will not be considered, this concern will not arise. The consideration of intersecting runways, however, raises the problem of ground collision on the runway. This should be analyzed on a case-by-case basis to determine the feasibility of hold-short measures.

The principal problem identified for the two remaining converging geometry types (intersecting runways and converging runway (extended) centerlines) is the hazard of simultaneous missed approaches. Regardless of geometry variation within each of these types, the distinguishing characteristic of converging approaches is that simultaneous straight missed approaches intersect. Requirements to ensure separation of missed approaches will be addressed in the next section.

3. REQUIREMENTS ANALYSIS

As noted earlier, the largest gain in capacity for converging runways will result from implementation of independent arrival streams. This section examines the categories of converging runways appropriate to the application of independent approach streams and the conditions under which independent operations can safely be applied. The result is a set of requirements for independent arrival streams to converging runways.

3.1 General Considerations

During the independent operation of closely spaced parallel runways, the major issue has always been, "What will provide adequate separation during simultaneous approaches?" This issue is also relevant to the operation of converging runways.

Simultaneity implies that longitudinal spacing between parallel arrivals is zero. Also, vertical spacing between aircraft approaching adjacent runways will be very close to zero. Therefore, if simultaneous approaches are authorized, one must specify approach courses that depend primarily on lateral separation to insure safety.

Adequate lateral separation can be achieved if all aircraft follow the specified course; but errors in navigation, avionics and judgment can effectively decrease lateral separation. There are two general categories of errors that have been examined during past analysis of deviation from independent parallel courses -- blunders and random lateral deviation. The Normal Operating Zone (NOZ) provides space for random lateral deviation; only blunders deviate outside the NOZ and penetrate the No Transgression Zone (NTZ) (Figure 3-1).

For converging approaches, the potential errors are the same and the following conditions were examined:

1. Blunders during final approach and missed approach
2. Random lateral dispersion about the flight path during missed approach (the distance between courses during final approach to converging runways is generally large enough to insure adequate safety from random lateral deviation)
3. Variation in the turn that could result from the pilot executing a late turn, wide turn, or even no turn.

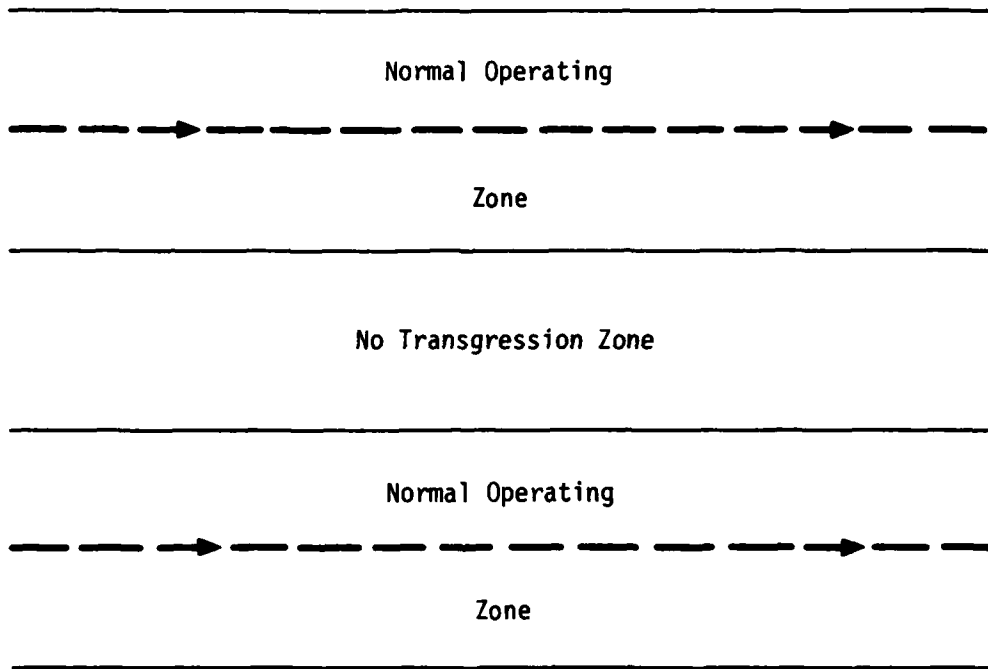


FIGURE 3-1
PLAN VIEW OF INDEPENDENT PARALLEL APPROACHES

4. Potential for collision while landing or taxiing on the pavement shared by intersecting runways

It is assumed that these procedures could be applied by responsible controllers in IFR conditions. Essential to that assumption is the understanding that the controller must judge whether the conditions (e.g., weather, surveillance of the intersection) allow the application of these procedures.

3.1.1 Final Approach Blunders

In previous analyses of parallel approaches (Reference 3), a blunder has been defined as a sudden deviation of an aircraft towards the other approach course, requiring other aircraft to turn away to avoid a conflict. Such blunders are not expected to influence the analysis of converging approaches.

In the analysis of parallel approach blunders, the region shortly after the aircraft turns onto the localizer is of greatest interest. Here, furthest away from the radar antenna, the surveillance error is greatest. Navigation error is also the greatest, because of the distance from the localizer antenna. For converging arrivals, however, the distance between approaches is also the greatest at this point. If a blunder should occur, immediate recognition and resolution is not as critical because of this extra separation. Dedicated purpose monitor controllers, as required for simultaneous parallel approaches, would probably not be needed.

Closer to the runway threshold, the distance between the approaches decreases, more closely approximating the spacing between parallel runways. For several reasons, blunders are not likely to be a significant problem in this region either. Improved surveillance accuracy closer to the airport reduces the time required to detect a blunder; also, the other aircraft is likely to be on the ground before a conflict could occur. The chance of a blunder becomes even more remote as the aircraft acquires visual contact with the runway. In addition, the requirements that will be proposed for independent converging approaches, dealing with minimum separation between missed approach paths, makes it unlikely that such operations would be conducted to runways with thresholds as close as 4300 ft.

3.1.2 Missed Approach Blunders

Review of Procedures

For the purpose of discussion in this report, only Category I approaches are assumed. Accordingly, the Decision Height (DH) at the Missed Approach Point (MAP) is assumed to be at least 200 ft above ground level (AGL) and the visibility at least one half mile.

ILS approaches to converging runways are not addressed by TERPS procedures and there is no approved missed approach course or procedure. However, for Category I approaches, TERPS has established procedures that define the obstacle clearance area and the flight path for both straight and turning missed approaches for 15 nmi beyond the MAP. Turning missed approaches are defined to begin turning at 1.5 nmi from the MAP (at which point the aircraft is expected to be at least 400 ft AGL), and the radius of the turn is determined by the aircraft category (Figure 3-2). See Table B-1, Appendix B, for aircraft categories and appropriate turn radii.

Since aircraft flying simultaneous approaches to converging runways risk collision during straight missed approach, it was assumed that any missed approach procedure would require turning missed approaches for both runways. It was further assumed that any procedures would call for both aircraft to turn as soon as possible so as to diverge by at least 45° (as required by TERPS, paragraph 997 for simultaneous parallel ILS approaches).

Type of Blunder

The type of blunder assumed by past blunder analysis (for parallel approaches) was a hypothetical change of heading by an aircraft for no apparent reason. The blunder that must be considered during missed approach is the execution of a straight missed approach instead of the turning missed approach. This is called a "heading blunder". The execution of this blunder during a simultaneous missed approach could result in a midair collision.

It is tempting to compare the simultaneous converging ILS approach with the simultaneous parallel ILS approach for which TERPS has written procedures. The singular difference between the two situations is that, if a pilot does nothing during a missed approach to alter the aircraft heading, the parallel nature of the approach will insure lateral separation of the two aircraft.

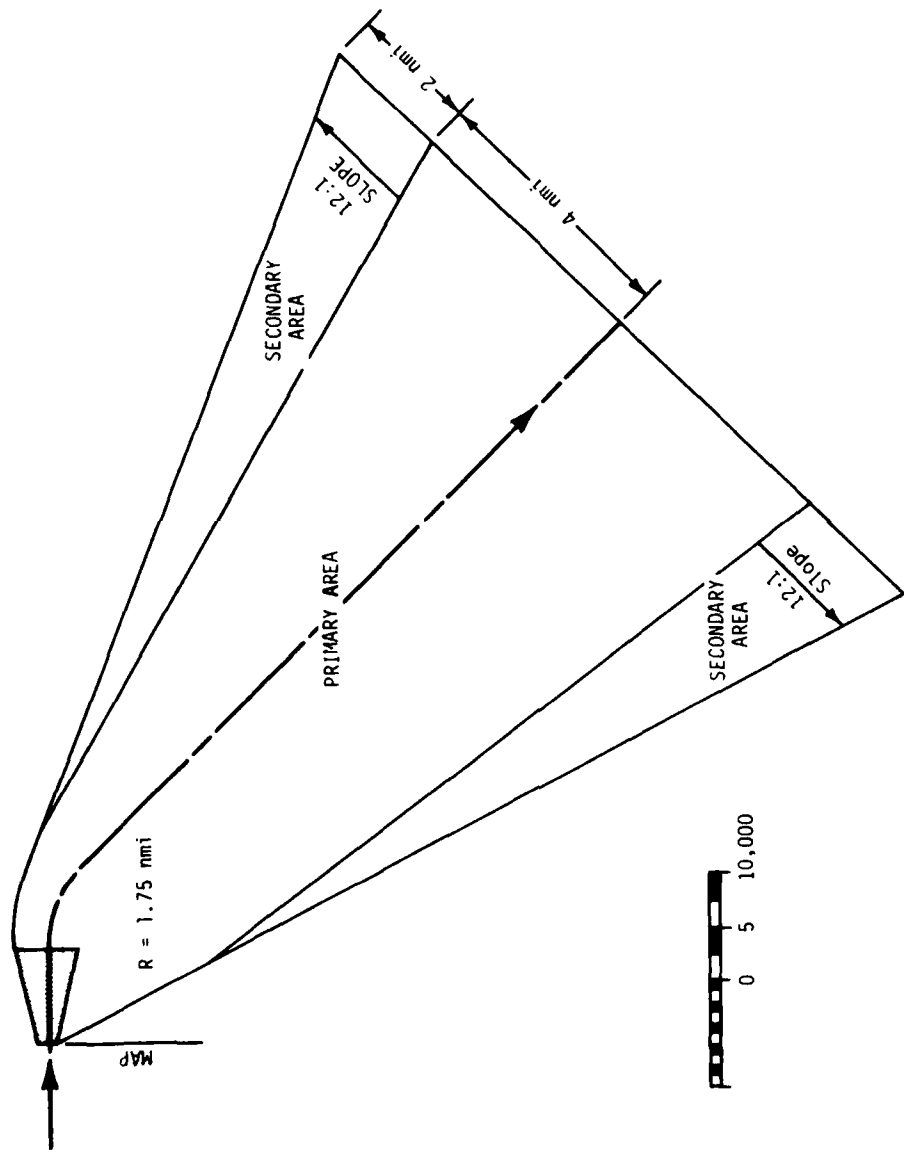


FIGURE 3-2
TERPS CATEGORY I TURNING MISSED APPROACH

If both pilots default to a straight missed approach course during the approach to converging runways, however, lateral intersection would be the likely result.

3.1.3 Random Lateral Deviation During Missed Approach

When a pilot is making a missed approach, the priority of activities during the first moments is:

- Increase thrust
- Establish positive climb rate
- Maintain correct heading

The activity of interest in this study is the maintenance of the missed approach course; and since that activity ranks third in priority during at least the early stages of missed approach, there is likely to be some random lateral dispersion about the nominal flight path.

It has been shown that this dispersion about the nominal flight path is relatively small at the MAP when the aircraft is receiving positive guidance but, when that guidance can no longer be followed (at or near the MAP) lateral dispersion increases monotonically. See Figure A-1, Appendix A for a graph of the standard deviation of lateral dispersion about the nominal flight path from 300 meters before threshold to 2700 meters beyond.

The implication of this deviation about the flight path is that one can expect aircraft to err in following their prescribed missed approach course exactly. This degree of error can be expressed as the probability of aircraft A to be at or past lateral location X at any given time. If this kind of information were accurate and available, one could calculate the probability of a collision as a result of lateral course variation of two aircraft simultaneously pursuing missed approach courses for converging runways. Section 3.2.4.2 will discuss the availability of this kind of data.

3.1.4 Crossing Runway Intersection While Landing

An obvious hazard to landing on intersecting runways is the failure of one aircraft to hold short of the runway intersection, then colliding with the aircraft landing on the other runway. If intersecting runways were operated independently, the controller would have to advise every aircraft to hold short after touchdown.

There are problems with this situation. Landing the aircraft is probably the most technically demanding part of a pilot's job and the pilot values the condition where the whole runway is dedicated to that one landing -- at least for a minute or so. It may be technically difficult for the pilot to plan on holding short. It also means that the pilot has no safety margin if the aircraft overshoots the runway slightly. Every landing will need to be executed more precisely.

Weather and visibility present larger problems. If IFR conditions are minimum but legal (200 ft ceiling, 0.5 mile visibility), it is quite possible that the intersection cannot even be seen. The conditions under which this concept is to be applied exist during weather conditions that are marginal for operating aircraft. If the ceiling is low, the runway surface may be wet and/or slippery. The two conditions co-exist naturally. The result of these conditions is poor visibility and poor braking -- two strong factors mitigating against the possibility of holding short of the runway intersection.

However, there are procedures for holding short on intersecting runways (Reference 8, Section 12, #1121b) during VFR conditions:

- Runways must be dry
- Controller must instruct aircraft to hold short of intersection. Instruction must be acknowledged.
- The distance from landing threshold for the aircraft being instructed to hold short must be in accordance with facility directives and diagrams.

Providing that the controller has adequate surveillance of the runways and intersection, there appears to be no reason why the above provisions could not be applied to instrument approaches. During conditions of low visibility or wet runways, instrument approaches would be no more appropriate than would VFR approaches.

3.1.5 Summary of Safety Issues

In summary, there are four safety issues that must be explored to determine the requirements for converging instrument approaches:

1. Blunders during final approach
2. Blunders during missed approach

3. Random lateral deviation from the nominal flight path
4. Violating a runway intersection while landing

3.2 Requirements

The requirements for instrument approaches to converging runways derive from analysis of the four safety issues identified above. The object of the following discussion is to determine requirements that resolve these issues.

3.2.1 Final Approach

Blunders during final approach are not expected to present a problem for most converging approaches. Due to the geometry of the configuration, the aircraft will, in most cases, be further than one mile away from each other at the missed approach points. Closer than the MAPs, the pilots will have the runways in sight visually, and blunders will be much less likely.

There does not appear at this time a need for any special requirements to protect against final approach blunders.

3.2.2 Intersecting Runways

The danger potential for crossing an intersecting runway was outlined earlier and derives from three basic causes:

- Weather at time of landing
- Pilot's ability to plan and execute a correct landing under demanding conditions
- Incidence of mechanical failure (or any other kind of aircraft failure) that would require more than the nominal runway length

The weather cannot be altered and will often be marginal during IFR conditions. The runway length needed for safety margin is an arguable point although 8,000 ft would seem to be an adequate length for a heavy aircraft to land under dry runway conditions. The conclusion of this study is to judge intersecting runways on a case-by-case basis, applying existing procedures (Section 3.1.4) where feasible. Since there is no evidence that intersecting runways are so hazardous that no procedure could compensate, there should be no blanket restriction against independent approaches to intersecting runways.

3.2.3 Blunders During Missed Approach

The blunder that is most likely to occur during missed approach was earlier identified as the "heading" blunder. Instead of making a turning missed approach, the pilot simply continues straight ahead while climbing to a relatively high altitude.

This blunder could possibly be identified by the controller who could advise the blundering aircraft to turn. However, airport radar is not very reliable at low altitudes because of clutter and the difficulty in detecting moving targets at slow speed. The controller must be able to immediately assess the situation at just the time when another approach requires attention.

Another way to solve this problem is to insure that standard missed approach procedures accommodate this possibility, i.e., a default option for each missed approach would allow one straight missed approach while ensuring the safety of both aircraft. This concept is illustrated in Figure 3-3 and has been specified as a requirement and described further in Section 3.3.2. The concept is rather conservative, however.

Constructing two different missed approach avenues for each runway and requiring that either missed approach could be straight ahead will utilize more lateral space than a requirement for two turning missed approaches. The result of this option is to raise the weather/visibility minima for ILS operations at all airports.

3.2.4 Random Lateral Deviation During Missed Approach

There are two indicators of expected lateral dispersion which were thoroughly reviewed during the course of this study. They are:

- Missed approach obstacle clearance surfaces described by TERPS and ICAO
- Data used in:
 1. The Collision Risk Model (CRM) (Reference 7) to model lateral variation in final approach and missed approach and
 2. The RESALAB study (Reference 4) on lateral variation about the final approach path

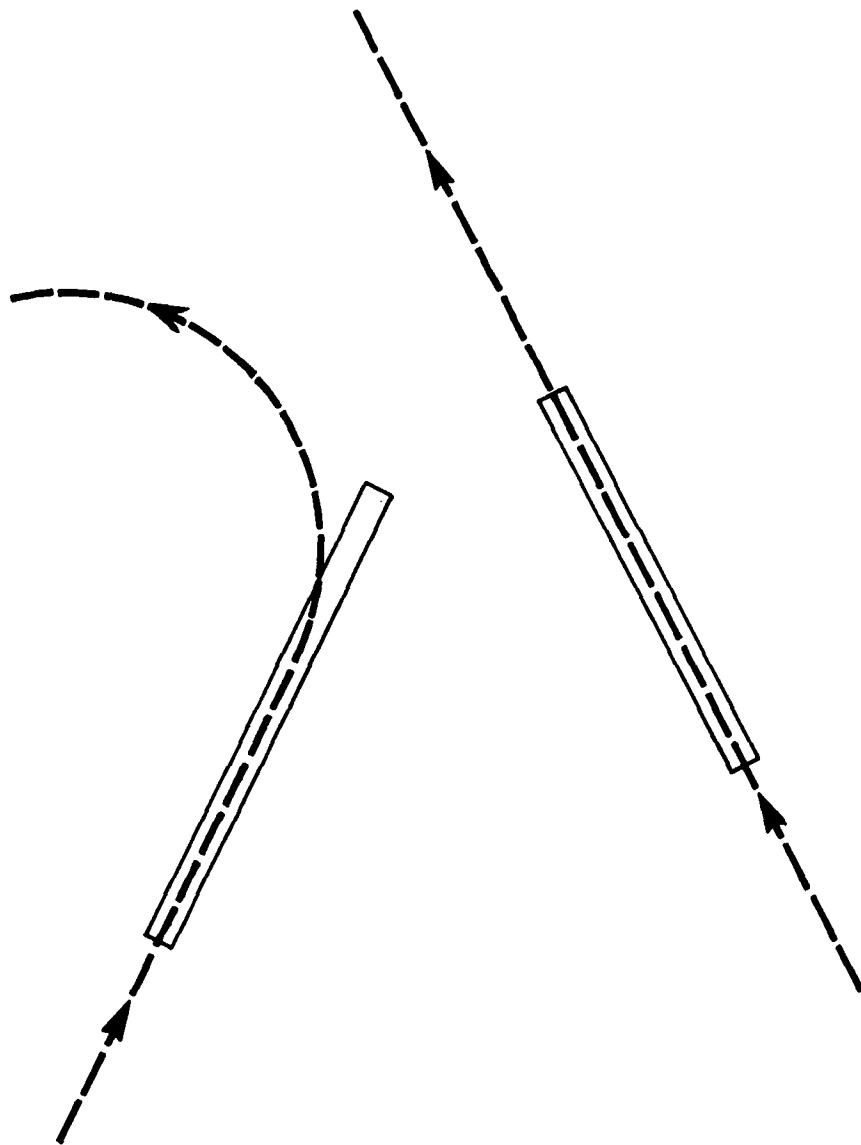


FIGURE 3-3
STRAIGHT MISSED APPROACH ON CONVERGING RUNWAYS

3.2.4.1 Obstacle Clearance Surfaces

The TERPS procedures for missed approaches call for the construction of obstacle clearance surfaces to coincide with the prescribed missed approach area (described in Appendix B). Figure B-2 illustrates the turning missed approach area. The primary motivation for constructing the area and the obstacle clearance surfaces was to protect the aircraft during missed approach from colliding with stationary objects (buildings, trees, towers, etc.). For that purpose, the obstacle clearance surfaces were constructed such that an aircraft located as much as 3σ from an assigned path would be protected.

The width of the surface at the MAP is determined by the width of the final approach area at that point (the width at the MAP is 1800 ft in Figure B-2). This width increases to 1 nmi at 1.5 nmi from the MAP. At 1.5 nmi from the MAP, the primary surfaces increase to 8 nmi in width and the secondary surfaces add another 4 nmi to the final width.

Examination of the data (next section) reveals these widths to be extraordinarily large in respect to expected lateral deviation. Clearly, the current lateral deviation is much less than that on which the obstacle clearance surfaces were originally designed. If these surfaces were used as boundaries, the resulting lateral separation would vary from 1 nmi to 12 nmi.

If concern for consistency is of value, these surfaces should not be used rigidly as boundaries. The TERPS procedures for simultaneous ILS (parallel) approaches call for course separation of 4300 ft, resulting in an overlap of the primary obstacle clearance surfaces of 1776 ft at distance of 1.5 nmi from the MAP. This is a 30% overlap of surfaces.

There is no strong theoretical argument for using the obstacle clearance surfaces as collision avoidance boundaries. The surfaces were created to guard against aircraft colliding with a stationary object, not another aircraft--a moving object.

The probability of a stationary object being in a given location is either 1 or 0. If it is 1, the probability of the aircraft colliding with it is equal to the probability of the aircraft being in that location (P_1) multiplied by 1 = P_1 . If the object were another aircraft and the probability of that aircraft being in a given location = P_2 , the probability of both aircraft being in the same location is $P_1 \times P_2 < P_1$.

Essentially, this argument maintains that a boundary designed to protect against stationary objects would have to be wider than one designed to protect against moving objects, because these objects would be present only a small proportion of the time. This fact compounds the problems of using a procedure for purposes that were not originally intended.

The obstacle clearance surfaces are obviously a conservative estimator of lateral deviation. A long term consequence of using these surfaces as boundaries is the inability to discontinue using them if they are proven to be overly conservative. Incorporating what might be a disproportionately large safety factor initially may make further application of capacity-increasing concepts difficult.

3.2.4.2 Missed Approach Data

Missed approaches on a single runway are an unusual event. The chance of one occurring during instrument conditions is about once every 53 approaches.* If operations were truly independent, the chance of two missed approaches occurring simultaneously is once every 2800 events. Because of the relative rarity of this event, there is no data on simultaneous missed approaches to parallel runways--the only situation for which procedures presently exist that resembles independent converging instrument approaches.

Data Identification

Aside from the RESALAB data (Reference 4) on final approach (which contains over 500 observations of Category I lateral flight location at the MAP), the bulk of the data on missed approaches exists at ICAO. During the mid-1970's, a major effort was made by ICAO to gather all available, relevant material on lateral and vertical dispersion from the nominal flight path during approach and missed approach. The Obstacle Clearance Data Collection Program was created to aid in the construction of a

*Unpublished FAA Memo (dated 12 July 1974) to E. E. Calloway from D. E. Vernelson, Subject: Missed Approach Information (contains results of a three-month survey of IFR operations to determine percent missed approaches. There were 376,187 IFR operations reported. Data included both precision (ILS) and non-precision (VOR, NDB, etc.) approaches.

Collision Risk Model (Reference 6). The manual for this model provides evaluation of the missed approach data that was collected from two countries and ten runways.

In spite of the intensive data gathering effort, only 483 missed approaches were observed. The resulting data is plotted in Figure A-1, showing lateral dispersion about the nominal flight path. The trend of this dispersion is unmistakable -- monotonically increasing from 300 m before the threshold to 2700 m beyond the threshold.

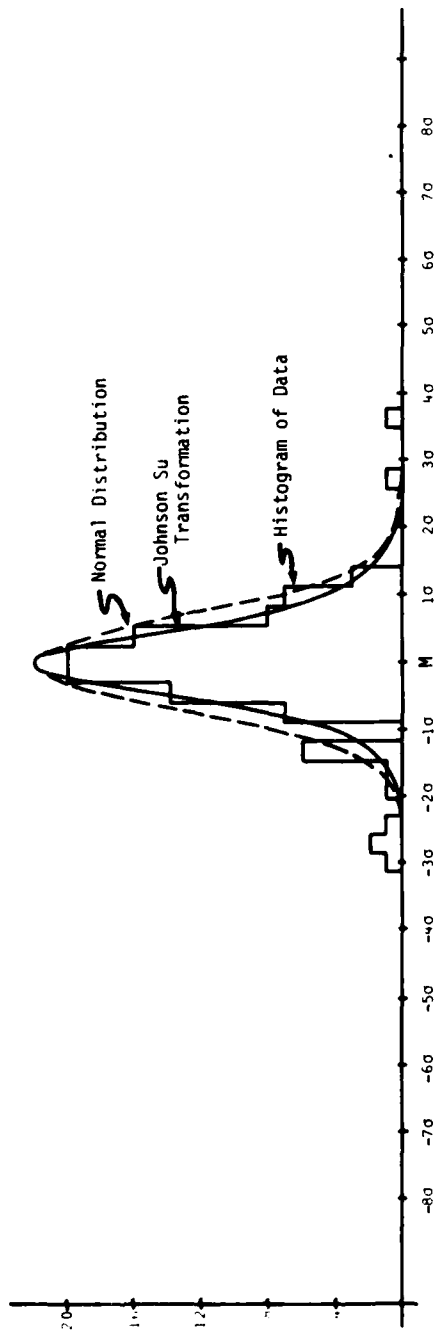
Analysis

An analysis of the data was done to determine the usefulness to the project and the limits of that usefulness. All of the data comprised samples of 120 or fewer observations (Reference 7) at each point along the missed approach course. A sample of this data was examined to determine the lateral range of its validity. One would expect that the sample of 100+ observations would adequately represent no more than 3 standard deviations (the probability of encountering observations beyond 3 standard deviations is less than 1/200). Figure 3-4 illustrates the range of observations.

Note that both distributions (normal and Johnson S_u) fit the data reasonably well, but the Johnson S_u has the best fit. This was borne out by applying a Chi Square test for Goodness of Fit by Pate (Reference 7).

However, the data consistently contains few observations beyond 3 standard deviations. The implications of this are twofold:

1. The distributions that model the data on lateral dispersion could be used to make inferences about events that are likely to happen at least once in every 200 times. That probability of occurrence is inadequate to make inferences about the probability of collision. If one were to assume that the event were the collision of two aircraft, a contingent probability (P) would apply requiring the multiplication of two individual probabilities -- $P = (1/200 \times 1/200) = 1/40,000$ -- still inadequate for our purposes for which much smaller probabilities would apply.
2. If we were to determine the distance between each nominal flight path required to assure that no collision would occur with a suitably small probability,



**FIGURE 3-4
LATERAL DISPERSION ABOUT THE MISSED APPROACH FLIGHT PATH
AT 1200 M BEYOND THE THRESHOLD**

it would require making inferences at the 7σ to 10σ level, depending upon which distribution was used (Appendix A, Table A-2). There is no way of knowing which distribution, if any, represent the true population at 7σ from the mean (at least 3σ from the most widely dispersed observations in the sample).

There are reasons to use this data for other purposes, however. Basically, they derive from the recognition that there is a job to be done (collision risk assessment for location of obstacle clearance surfaces) and this is the only data that exists. This data can be represented by an unusually thick-tailed distribution thus giving a conservative bias to inferences made far out in the tails.

This last rationale does not equally balance the inherent problems due to the small sample size. Aside from the problem with sample size there are three others, the sum of which present a strong argument for not using the data in this study.

- The data is only applicable directly to Category II conditions. Because of the broad mix of pilot skills and less sensitive avionics, the lateral deviation of aircraft flying Category I approaches (and related missed approaches) can be expected to be generally greater. (Where microwave landing systems are used, however, the improved back course guidance may act to compensate for this lateral deviation.)
- At some point during the missed approach, one would expect aircraft pilots to stop concentrating on the immediate problems of the missed approach -- stabilizing the aircraft, gaining altitude -- and start to navigate a tighter course. The data does not appear to have been recorded far enough into the missed approach to capture the expected converging tendency of the lateral dispersion.
- All data is for straight missed approaches. No turning missed approach data exists.

3.3 Worst Case Method For Defining The Major Requirement

As first discussed, both TERPS Obstacle Clearance Surfaces and ICAO missed approach data were reviewed as potential indicators of lateral dispersion during missed approach. Neither candidate was deemed suitable because of various technical, operational or

policy flaws. The review of these methods, however, gave insight as to what the requirements cannot be and led to the development of the concept described below.

The concept assumes that one must guard against some worst case scenario so that the requirements for independent converging approaches will accommodate the asking of various "what if...?" questions. (e.g., What if a heavy air carrier and a general aviation aircraft happen to simultaneously go around?) Therefore, the following concept of a collision avoidance boundary was developed, such that no aircraft could reasonably be expected to cross it through random lateral variation from the nominal missed approach course.

Because the concept requires the construction of a collision avoidance boundary, the concept description is presented in a series of statements detailing the steps required for construction. Following each step are supporting arguments, logic or precedence.

3.3.1 Construction of Boundary for Turning Missed Approach

Step One--Construct an expected missed approach path that requires the aircraft to execute a straight climbing missed approach to 400 ft AGL. At this time each aircraft shall follow a climbing, turning course (away from convergence) at the standard rate of turn ($3^{\circ}/\text{sec}$)* until the paths of simultaneously converging aircraft diverge by at least 45° .

- TERPS requires aircraft to:
 1. Reach an altitude of 400' AGL before turning;
 2. Diverge by 45° under simultaneous ILS operation.
- The turn rate of $3^{\circ}/\text{sec}$ is standard for both GA (Reference 11) and air carrier aircraft (References 10 and 12).
- The radius of the expected flight path is determined by the likely speed of the fastest air carrier aircraft

* At 160 kn, turn radius = 1 nmi

executing the maneuver. This proposed radius is 1 nmi, tracing the route of an aircraft making a standard turn at 190 knots.

Step Two--Assume that an aircraft, at worst, will deviate laterally from the nominal flight by three standard deviations in a direction toward the other converging approach. A plot of the route followed by this hypothetical aircraft is called the Worst Case Boundary (WCB).

- Three standard deviations are applied during blunder analysis as the position keeping accuracy of non-blundering aircraft (Reference 3). The analysis assumes a normal distribution which implies that there is only one chance in 740 that an aircraft would be found outside the 3σ range.
- Three standard deviations are also the standard understood to be used in constructing the obstacle clearance surfaces described in TERPS.
- The CRM data for random lateral dispersion in the first 1200 m beyond the threshold uses data to which a data-matched distribution, hereinafter called the CRM distribution, is applied. This data was discussed earlier and the sample size was identified as large enough to inspire confidence in inferences made to 3σ . This data, however, is represented by the CRM distribution which, at 3σ , infers that there is one chance in 222 of an aircraft deviating beyond the 3σ boundary.
- For the identification of the 3σ point at the MAP, RESALAB also contributes data although no distribution is fitted. The value of the standard deviation, however, is almost exactly the same as the CRM data derived value (Figure A-3).

Step Three--The boundary of the straight section of the missed approach will be identified by an angular measurement. This angle is a deflection from the straight flight path obtained by locating two points, each a distance 3σ from the expected straight flight path. The first 3σ point is located at the MAP (211 ft from the expected flight path) and the second is located at the last data point, 11,924 ft from the MAP (943 ft from the expected flight path). These points and the straight flight path

define the deflection angle calculated below and pictured in Figure A-3.

$$\tan^{-1} [(943-211) / (11,924)] = 3.50^\circ$$

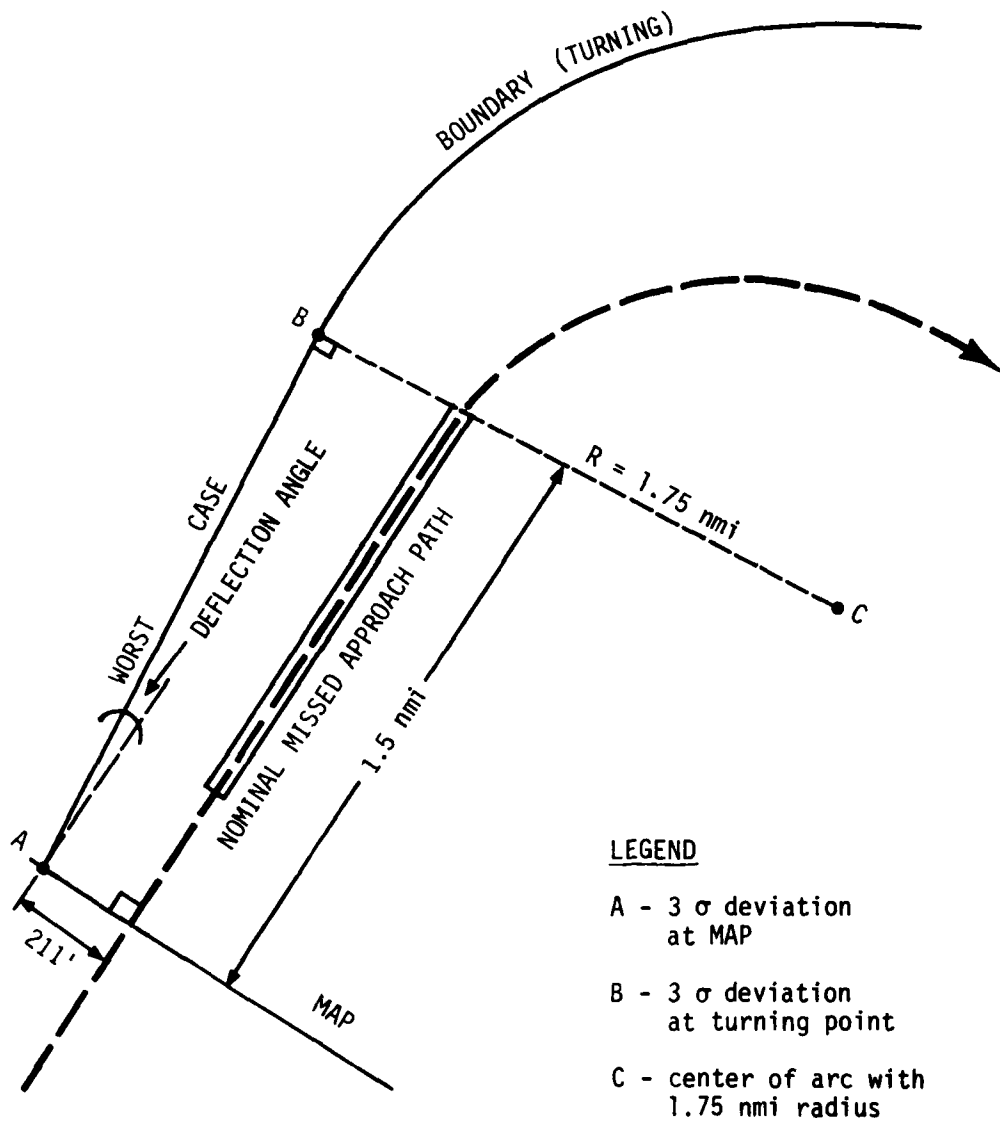
With this angular value, all straight section WCB's can be calculated by identifying point A and applying the sine of the deflection angle to the length of the straight nominal missed approach section to locate point B.

Step Four--The length of the straight missed approach section will be 1.5 nmi. From the point on the WCB at the end of the straight section B, (Figure 3-5), construct a 90° angle with the WCB such that a point on that line could represent the center of a circle 1.75 nmi in radius. Draw an arc with radius equal to 1.75 nmi beginning at B.

- The present missed approach obstacle clearance surfaces for a CAT I approach specify a 1.5 nmi straight missed approach section. The derivation is approximated by assuming a 40:1 slope from the final approach obstacle clearance surface at the MAP (DH=200') to the turning point at 400' AGL, as above.
- The straight section must be long enough to allow sufficient time to stabilize the aircraft and arrest the descent. The calculation of this distance is aircraft and situation dependent. Calculations using 160 kt horizontal air speed and 14 ft/s rate of descent show that a distance of 0.5 miles is needed to stabilize the aircraft. This implies that, for a DH of 450 ft, the aircraft could conceivably turn after 0.5 miles of straight flight.

However, because of uncertainties about several assumptions which deal with omni-directional winds, engine weight and type of aircraft, it was decided to require the conservative 1.5 nmi length of straight section for missed approaches at all decision heights.

- The radius of the arc reflects the maximum turning radius expected for heavy aircraft (class D aircraft, TERPS, Reference 2).
- As a point of reference, a turn radius of 1.75 nmi is equivalent to an aircraft executing a half-rate, 1.5° per second turn at 165 knots.



LEGEND

- A - 3σ deviation at MAP
- B - 3σ deviation at turning point
- C - center of arc with 1.75 nmi radius

**FIGURE 3-5
CONSTRUCTION OF WORST CASE BOUNDARY
FOR TURNING MISSED APPROACHES**

3.3.2 Construction of Boundary for Straight Missed Approach

The concept of using a Worst Case Boundary to avoid collision due to random variation about the nominal flight path has been applied to the expected turning missed approach. As discussed in 3.2.3, the prospect of a wrong heading blunder during missed approach needs to be addressed as well. The conclusion of that analysis was to provide for the eventuality of both a turning and a straight missed approach at each runway so that a straight missed approach could accidentally be executed on either runway without causing an unacceptable decrease in the safety of a simultaneous missed approach.

This provision requires the construction of a WCB around a straight missed approach expected path at each runway. Step Five describes this construction and Figure 3-6 illustrates it.

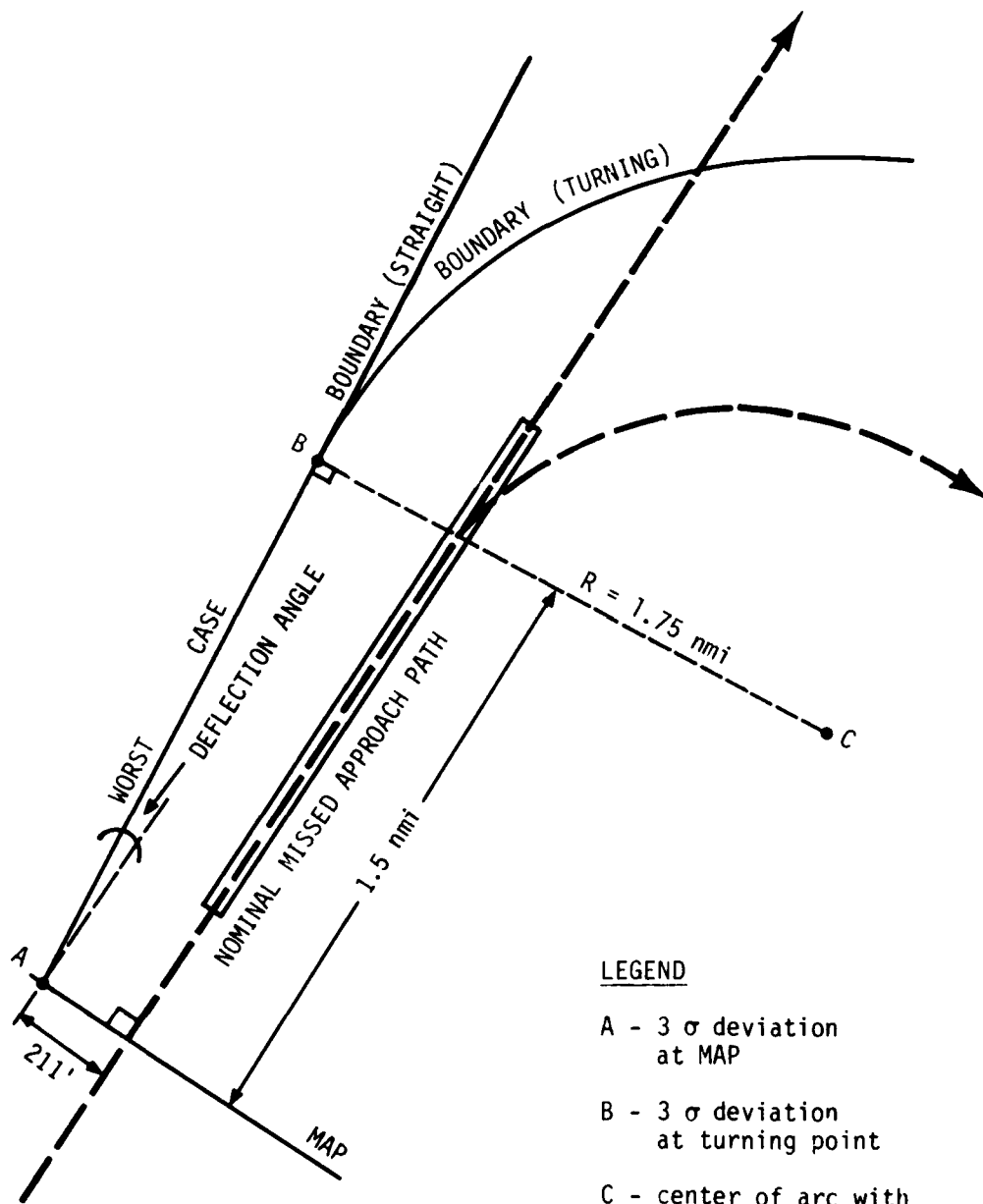
Step Five--Establish a straight missed approach Worst Case Boundary by plotting a 3σ line starting at point A and extending for 15 nmi. Use the deflection angle (3.50°) calculated in Step Three to locate the WCB (Figure 3-7).

- The logic and data used to support Step Two is equally valid for this step.
- The length of the straight WCB (15 nmi) corresponds with Obstacle Clearance Surface length.

3.3.3 Application of Worst Case Boundary Requirements

The Worst Case Boundary concept provides a protected airspace between missed approaches to converging runways. The 3σ boundary is intended to protect that space occupied by the overwhelming majority of aircraft during missed approach. Because of concern over the "heading blunder", a requirement that extra space be reserved for accidental execution of straight (instead of turning) missed approaches is also provided.

The application of these requirements may still not protect against other uncertainties that are nearly impossible to predict --unreliable equipage or extraordinarily poor pilotage. Therefore, a separation between WCB's of 500 ft is proposed to reserve space for these unpredictable events. The application of the total concept is described in Step Six and illustrated in Figure 3-7.



LEGEND

- A - 3σ deviation at MAP
- B - 3σ deviation at turning point
- C - center of arc with 1.75 nmi radius

**FIGURE 3-6
CONSTRUCTION OF WORST CASE BOUNDARY FOR
TURNING AND STRAIGHT MISSED APPROACHES**

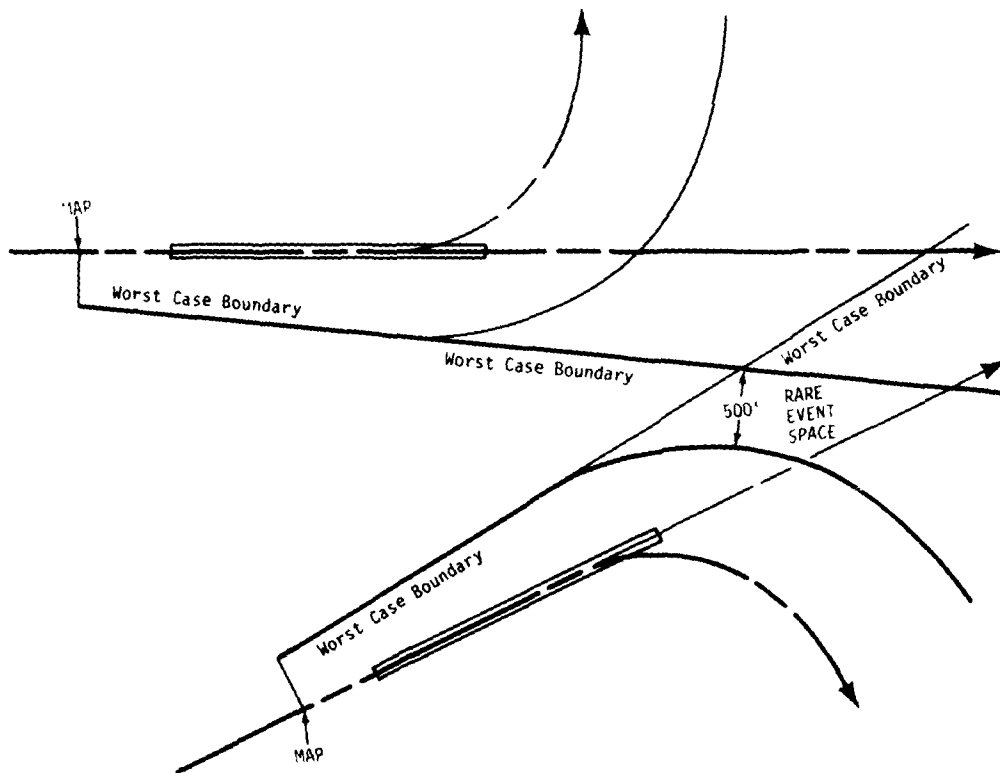


FIGURE 3-7
APPLICATION OF MISSED APPROACH REQUIREMENTS
TO CONVERGING RUNWAYS

Step Six—Construct a WCB for turning and straight nominal missed approaches at each runway. Select that combination of one straight and one turning WCB that provides a minimum of 500' between boundaries. Insuring this requirement provides the necessary airspace protection for random lateral variation, heading blunders and rare events during simultaneous missed approaches to converging runways (Figure 3-7).

4. RESOLUTION STRATEGIES

In Section 3, three general considerations for the application of simultaneous ILS approaches to converging runways were identified:

1. Blunders during final approach
2. Blunders during missed approach
3. Random lateral deviation from the nominal flight path

In hopes of quantifying these potential problems, the approach data collected by ICAO's Obstacle Clearance Data Collection Program was reviewed. The conclusions were:

- There is no data describing blunders during the final approach or missed approach.
- The data describing lateral deviation from the nominal missed approach flight path was inadequate to model the situation so that sufficiently small probabilities of collision could be examined.

During the review of potential requirements, it became clear that TERPS contains no precedent for converging ILS approach procedures although some ideas for lateral separation are contained in procedures for simultaneous ILS approaches to parallel runways. Subsequently, a new concept for procedures and requirements is being proposed (Section 3.3) that would allow independent approaches to some converging runways. This concept requires non-overlapping Worst Case Boundaries (WCB) to be constructed between converging, non-intersecting runways in order for Category I, ILS approaches to be allowed. The WCB would be applied to comply with a Category I, Decision Height (DH) at 200 ft.

In conjunction with another study of airport capacity (Reference 15) the application of these requirements to 19 out of the thirty largest airports revealed that none of the airports qualified for independent operation. If it were unnecessary to apply the straight missed approach to one of the runways, three airports could operate independent converging approaches:

- Denver, 17L and 8R
- Dallas/Ft. Worth, 31R and 35R
- Houston Intercontinental, 26 and 32

Because there are so many potential applications of converging approaches, an attempt was made to identify strategies for application. The strategies described in this section are intended to be used as alternates or modifications to the fundamental requirements. No reduction in safety is anticipated to result from the use of any of the strategies.

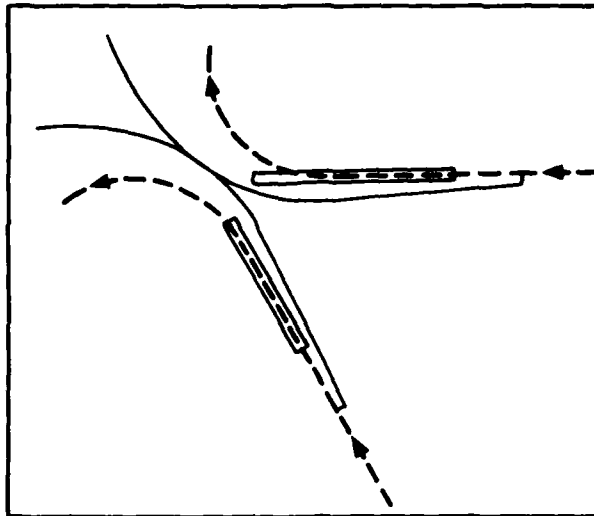
4.1 Strategy #1: Increase Minima

For those airports at which the WCB's cannot be separated by 500 ft (at a DH of 200 ft), an obvious strategy is to increase the DH and move the boundaries (which are firmly connected to the Missed Approach Point (MAP)) in a diverging direction. Of course, if the minima is raised, the weather restrictions for landing are more demanding and converging arrivals will occur a smaller percentage of the time. Presently, the ceiling limitation is 1000 ft for independent converging approaches in VFR. With visibility lower than 1000 ft, converging runways must be operated similarly to a single runway. There is still much to be gained, however, if minima were increased somewhat from the Category I standard of 200 ft.

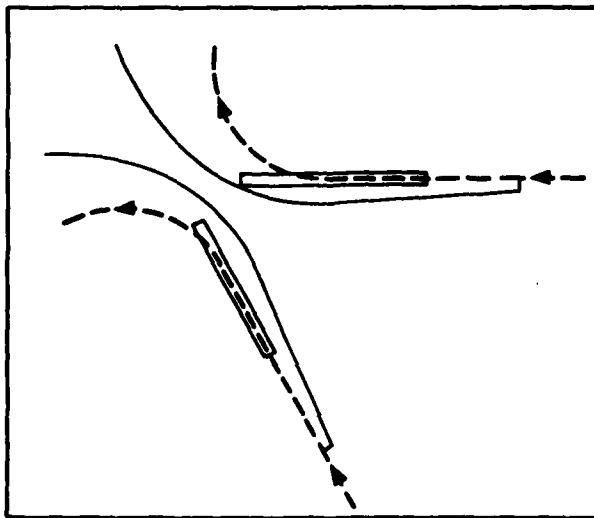
Assuming a glide slope angle of 3° , for every 100 ft increase in DH, the MAP would be displaced 1908 ft. This displacement has two effects on lateral separation.

1. Because the WCB is predicated on a 3σ distance from the approach path, the WCB moves further from the approach path as the distance from the threshold increases. This movement is approximated by a 1.5° angular measurement. (For every vertical DH movement of 100 ft, the WCB moves away from the expected approach path about 50 ft.)
2. Because of the converging nature of the approaches, any increase in vertical movement of the DH also increases lateral separation by a function of the angle of convergence and the horizontal displacement along the approach path. For a 1908 ft displacement of one MAP on a converging approach of 45° , the lateral separation increases by 730 ft.

The combined effect of the changes due to WCB relocation and angle of convergence is the algebraic sum. For the 45° example, the sum of $(2 \times 730') - (2 \times 50') = 1360'$ (Figure 4-1). Calculations have been made for converging runway geometries with several included angles and are presented in Table 4-1.



Decision Height = 200'



Decision Height = 300'

FIGURE 4-1
MISSED APPROACHES TO CONVERGING RUNWAYS ILLUSTRATING
INCREASE IN SEPARATION DUE TO INCREASE
IN DECISION HEIGHT FROM 200' TO 300'

TABLE 4-1

ILLUSTRATION OF THE
 INCREASE IN MISSED APPROACH FLIGHT PATH
 SEPARATION DUE TO RAISING DECISION HEIGHT*
 (NOMINAL DH = 200' AGL)

RUNWAY INCLUDED ANGLE	DECISION HEIGHT		
	300'	400'	500'
30°	888	1776	2664
45°	1360	2720	4080
60°	1808	3616	5424
75°	2223	4446	6669
90°	2598	5197	7795

*Data calculated for the runway geometry in Figure 4-1

The implication of this strategy is that nearly any lateral separation between WCB's can be accommodated by increasing the decision height. An application of this strategy to the aforementioned 19 of 30 largest airports leads to the inclusion of 16 more airports able to operate independent converging arrivals at a DH less than 1000 ft (See Appendix D, Table D-3).

4.2 Strategy #2 -- Backcourse Guidance

At the present time, effective positive instrument guidance ends at (about) the MAP. If the runway is visible at that point, there is no need for further guidance; and if it is not, a missed approach is required.

During the first stage of missed approach execution, no ILS guidance is observed as the majority of time and attention is spent "cleaning up" the aircraft and preparing for a go-around. After the aircraft is level and ascent is assured, positive course guidance would be desirable for the execution of the straight portion of the missed approach.

The VHF localizer has a very narrow beam width at this point, however, and the use of the ILS at this close proximity (the transmitter is typically about 1000 ft beyond the end of the runway or about 11,000 ft beyond the MAP) would require the pilot to react to rather erratic course direction from a widely swinging needle (Reference 10).

If the missed approach is a standard Category I approach, the beginning of the turn occurs when the aircraft reaches 400 ft, which is expected to be within 1.5 nmi (9114 ft) from the MAP (TERPS). At this point, the pilot is required to turn at the standard rate of 3° /second until a given heading or a fix is reached. As can be seen, there is great latitude for lateral deviation.

If a Microwave Landing System (MLS) were used, not only would the aircraft be able to utilize the MLS beam for navigation with greater ease than the VHF localizer beam, but the MLS could provide guidance through the turn to a diverging heading or to a fix. MSL is a future solution, not a present one. The least expensive receiver will have only forward aligned antennae, that is, antennae that are directed to pick up signals only from the front 180° of the aircraft.

Obviously, as soon as the least expensively equipped aircraft crosses the transmitter, no signals will henceforth be received. However, the air carrier traffic have in the past been well equipped with navigational equipment, and it is assumed that this trend will continue. Therefore, if one could direct all suitably equipped aircraft (mainly air carrier) to one runway with MLS and all aircraft not suitably equipped (mainly general aviation) to the other runway, the advantage of MLS could be utilized.

The particular advantage of MLS is the ability to provide backcourse guidance at least part way through a turning missed approach. The propagation angle of MLS can be $+40^{\circ}$, which could include most of the area taken by a 90° turn. Since the course guidance would reduce the lateral deviation of the missed approach, the 3σ Worst Case Boundary of the air carrier aircraft may be able to be reduced. The performance characteristics (rate of turn, speed) of class D aircraft were taken as the limiting parameters when the WCB was constructed; so if they can be seen to be reduced, the 3σ boundary for both runways of segregated approaches can also be reduced.

4.3 Strategy #3 -- Segregated Traffic

A concept for increasing airport capacity is the division of air traffic into two like streams: air carrier traffic and general aviation traffic (to include air taxi). The advantage of the concept is that the long longitudinal separations between the heavy category of air carrier aircraft and small, general aviation aircraft (the present solution to wake vortex effect) are unnecessary if traffic streams are segregated.

The reason that this concept is considered a strategy to ease implementability of converging approaches is due to the difference in operating characteristics between general aviation aircraft and air carrier aircraft. If all of the aircraft in one traffic stream can be relied upon to turn in a shorter radius, that increases the lateral separation between nominal converging flight paths. This is of greater advantage as the runway included angle increases to 90° (Figure 4-2).

Further, there is a vertical separation that is more likely to exist between aircraft of different size class performing missed approaches together. It is easy to visualize two air carriers flying the missed approach at almost the same altitude because their performance characteristics are so similar -- likewise for two Cessna 140s. By segregating by aircraft size, however, it is much less likely that there will be true vertical simultaneity

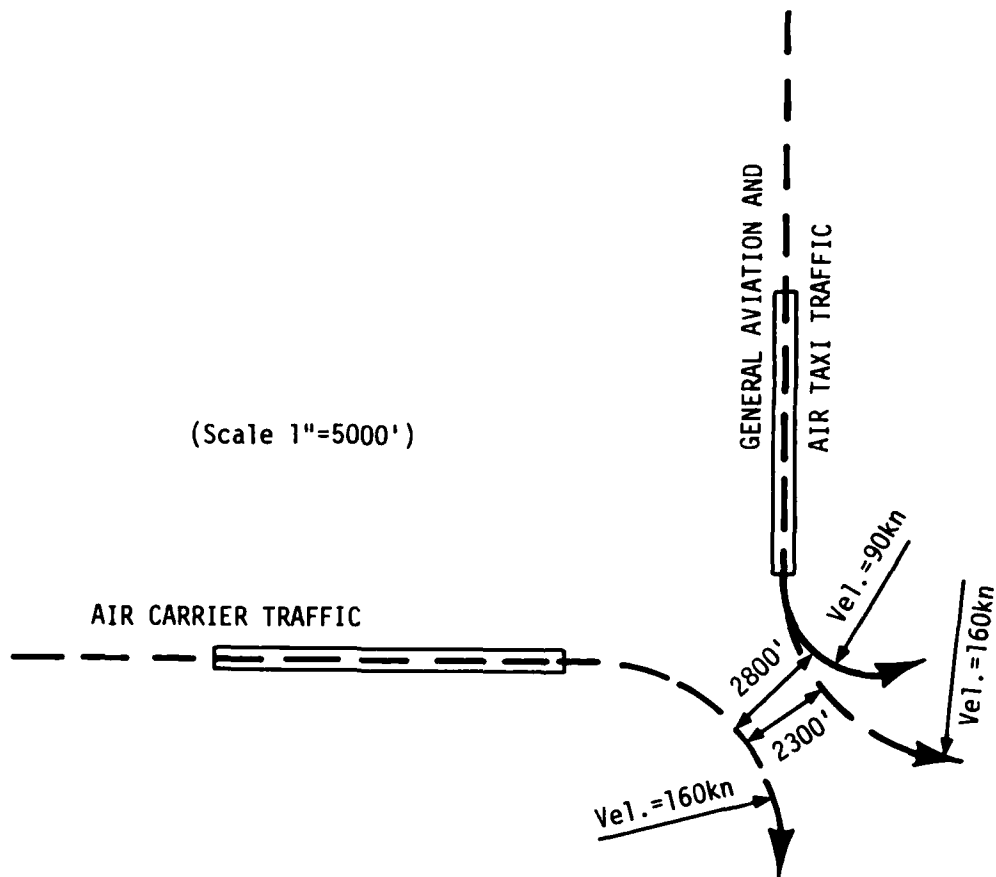


FIGURE 4-2
ILLUSTRATION OF MISSED APPROACH
FOR SEGREGATED TRAFFIC STREAMS

between the two different aircraft categories. This strategy would add to both the lateral and vertical separation of aircraft by exploiting the different performance characteristics of air carriers and general aviation aircraft.

4.4 Strategy #4 -- Dependent Approaches

The ultimate solution to the safe separation of simultaneous missed approaches would be to avoid simultaneous approaches in the first place. To that end, some form of dependency could be applied between arrivals to ensure that missed approaches are adequately separated.

In general terms, this dependency could be expressed as a minimum distance from the runway threshold when the previous arrival to the other runway is at the threshold of that runway. The exact distance of this "gate" from the threshold would depend upon the runway geometry, particularly the distance from the MAP to the point where the extended runway centerlines intersect.

Appendix E explains how this distance may be calculated, so as to provide a minimum time separation at the intersection point even if both aircraft proceed straight on their missed approach courses. The same appendix also describes the method by which the arrival capacity of such dependent approaches has been calculated.

There does not appear to be any technical reason why dependent converging approaches cannot be applied to any converging geometry. The special distance requirements are not extreme. The values calculated for converging configurations at the top thirty airports are shown in Table 4-2. Capacities have been calculated to be from 40-45 arrivals per hour, compared to 24-28 arrivals per hour for a single runway.

It is not known whether such a procedure will be difficult for the controller to apply in practice. The required distances can be added to the controller's video map, to assist his estimation of the required separations. Additional automation aids are also possible, if necessary, such as a moving "target box" on one approach which is tied to the movement of the aircraft on the other approach.

TABLE 4-2

DEPENDENT RUNWAY CHARACTERISTICS
OF CONVERGING RUNWAYS OF TOP 30 AIRPORTS

AIRPORT	R/W1	R/W2	"GATE" TO THRESHOLD DISTANCE (nm1)		CAPACITY
			R/W1	R/W2	
ORD	04R	09R	2.3	1.1	44.0
	27R	32L	1.5	1.8	44.2
	22R	27L	1.6	2.1	42.2
STL	24	30L	2.0	1.0	44.8
PHL	9R	17	.4	3.1	41.9
EWR	4R	11	1.4	1.8	43.8
DFW	31R	35R	2.3	1.6	41.6
DEN	8R	17L	5.0	-1.1*	34.4
MIA	30	27R	1.6	1.9	41.9
BOS	22R	27	1.6	1.6	44.0
IAH	26	32	2.4	1.4	40.5
MCI	19	27	1.6	2.1	42.5
MEM	35R	3	0.3	3.0	42.2
JFK	13R	22L	1.2	2.7	40.9
	4R	13L	1.8	1.4	43.4
LGA	31	4	1.3	1.6	45.8
DCA	33	36	1.8	1.0	46.1
PIT	10R	14	1.2	1.9	44.9
DTW	21R	27	1.8	1.4	43.5
MSP	22	29L	1.9	1.1	44.0
LAS	19R	25	2.5	1.1	40.0
	19L	25	2.4	1.1	40.5
CLE	5R	10L	0.8	2.3	43.4
FLL	27R	31	1.7	1.2	42.9
MSY	10	19	0.8	2.3	43.3
MKE	7R	13	1.1	2.1	42.4
HNL	22L	26L	1.1	2.5	39.7
SFO	28R	01R	1.5	1.4	45.1
TPA	18R	027	1.8	1.6	42.6

* Negative value is due to unusual runway configuration at Denver

5. PILOT ACCEPTANCE

Acceptance of any new ATC procedure by the user community is as much a political issue as a technical one. Pilots base their opinion on their personal experiences and on their impression of possible consequences as well as on the technical data. Acceptance may, therefore, be enhanced by anticipating possible objections and dealing with them at an early stage.

A pilot's first impression of converging IFR approaches is likely to be negative. We would expect pilots to react negatively to the idea of being on a collision course with another aircraft, even though they will both land before the intercept point is reached. Yet such approaches are routinely conducted today in VFR conditions. The relevant differences between Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) operations are identified, and various aspects of the recommended procedures that are anticipated to concern the pilot are discussed.

5.1 VMC Converging Approaches

Converging approaches in VFR conditions are standard procedures at O'Hare International Airport (ORD), Denver Stapleton (DEN), and possibly other airports. The procedure is apparently accepted by pilots at these fields.

The most important, and most obvious difference, between converging approaches in VMC and in IMC is the different visibility. This has many effects. The chance of a go-around is greatly decreased. Missed approaches due to mechanical problems, conflicting traffic, etc., will still occur, but the chances of a missed approach due to weather are virtually zero. If a missed approach should occur, the aircraft can hold runway heading and turn to the new heading more easily when there is visual contact with the ground.

Perhaps most importantly, in good visibility the pilot can maintain visual contact with any other missed approaches, thus providing adequate separation. Visual contact provides reassurance that separation actually exists and early detection of any turn by the other aircraft which would affect that separation. The other aircraft can be seen to bank well before the controller would detect the turn on radar.

In a few cases, such as runways 09R and 14L at O'Hare, converging approaches can be run even below the VFR minima of 1000 ft ceiling and three mile visibility. For 09R and 14L, the minima

are 800 ft and 2 miles. This is possible because visual separation between the aircraft can still be applied by the local controller. Due to the runway geometry and the location of the control tower, the controller can see both aircraft on the two approaches when they are 3.0 nmi apart--the minimum radar separation--even though they cannot see each other.

5.2 IMC Converging Approaches

The procedures proposed in this report for converging approaches in IFR weather do not consider any application of visual separation. Instead, the pilot must follow the proper missed approach procedure in order to avoid a conflict. The pilot may not even know if there is a missed approach on the other runway if there are two local controllers and different radio frequencies in use.

It is this uncertainty about the location and intention of other aircraft which underlies the anticipated objections to converging IMC approaches. These objections are likely to fall into three categories:

- A straight missed approach means conflict, since the extended runway centerlines intersect.
- There is no latitude for error in the missed approach procedure. Both aircraft in a simultaneous missed approach must follow their turning missed approach paths accurately.
- The other pilot will make a mistake.

The impression in the pilot's mind might, therefore, be that he was a blind and helpless target during a missed approach; avoiding a conflict would be purely a matter of luck.

The proposed procedures accommodate these problems. The missed approach paths need not be followed accurately; provision is made for the maximum deviation from the nominal missed approach path which could reasonably be expected. The vast majority of actual missed approach paths are expected to fall inside the "worst case" path. In addition, given the possibility of a missed approach on the other runway, pilots are expected to be quite conscientious about flying the prescribed missed approach path, thereby further reducing the likelihood of the "worst case".

Even if the other pilot should make a mistake and initiate his turn late or not at all, separation would still be provided. The proposed procedures require that the specified minimum separation exist even if one aircraft proceeds straight ahead. The chance of one aircraft turning towards the other missed approach path is too small to guard against, especially when the pilots are aware that converging approaches are in progress.

5.3 Strategies to Improve Pilot Acceptance

The implementation of converging IMC approaches could be delayed or even prevented if the procedures are not accepted by the users. Steps can be taken during the implementation process, however, to promote pilot acceptance.

Before operational implementation, there will necessarily be a stage of testing and demonstrating the procedures. During this stage, at the latest, extensive discussions should be conducted with the pilot community. These discussions will explain the proposed procedures and how they address the anticipated pilot concerns. Just as importantly, such discussions would help to raise unanticipated pilot concerns and provide feedback on the validity of the assumptions in this analysis.

A well-designed test and demonstration of converging IMC approaches should assist in gaining pilot acceptance. A gradual implementation of the procedure for daily operation should also help. Initial implementation should be at higher minima than called for by the proposed requirements. Decision height should then be reduced according to a fixed schedule, such as 100 ft per year, until the final minima were reached. At each intermediate stage, data on actual missed approach performance could be collected and analyzed to assist in the decision to reduce DH. Pilot confidence would be enhanced by actual experience at higher decision heights.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Major Issues

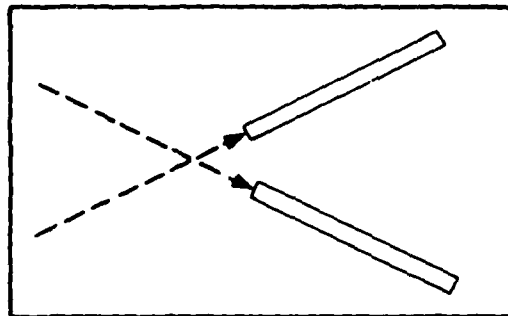
The concept of operating converging approaches simultaneously in instrument conditions has been analysed in this study, particular attention being paid to the following aspects of converging approaches:

- Runway geometry
- Final approach
- Missed approach
- Pilot acceptance

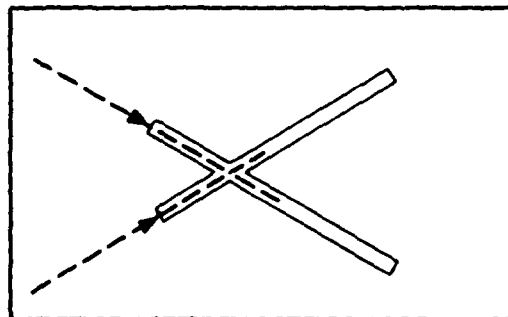
6.1.1 Runway Geometry

There are three types of runway geometry to which the converging approach concept could apply:

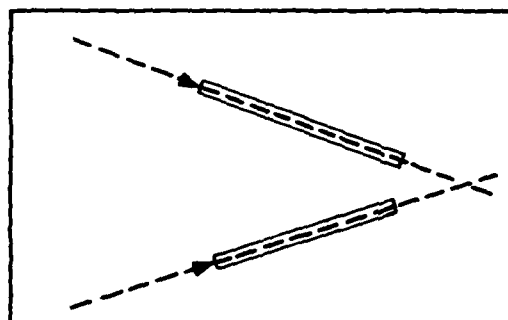
1. Intersecting Approaches - the runway extended centerlines meet during final approach. This presents obvious safety problems that could not be resolved at this time. (Figure 6-1a)
2. Intersecting Runways - when runway pavement physically converges - intersects - two issues result.
 - The possibility of collisions during missed approach
 - The possibility of collisions on the shared runwayNeither issue is as serious as intersecting final approaches and some geometries with long runways intersecting only at one end of each are amenable to the operation of simultaneous approaches (Figure 6-1b).
3. Converging Runway (Extended) Centerlines - the runway extended centerlines meet during missed approach. This geometry is the most favorable to the operation of simultaneous approaches. The only serious issue arises from the possibility of collision during simultaneous missed approach (Figure 6-1c).



a. Intersecting Approaches



b. Intersecting Runways



c. Converging Runway (Extended) Centerlines

**FIGURE 6-1
TYPES OF CONVERGING APPROACHES**

Types two and three were the only geometries analyzed in this study and the conclusions apply to both. The eligibility of converging runway geometries for the application of instrument approaches was limited to configurations with angles of convergence greater than 15° (any angle less than 15° is considered by TERPS to describe parallel runways) and less than 100° .

6.1.2 Final Approach

Since only type two and three converging geometries are considered eligible for instrument operations, the converging feature of those geometries provides adequate lateral separation during final approach. By the time the aircraft are close enough (laterally) there will not be time to blunder enough to endanger another aircraft.

6.1.3 Missed Approach

The issue of collisions during simultaneous missed approach is by far the most significant. All converging geometries require both aircraft to turn during missed approach to avoid a collision. Missed approaches to parallel runways are required to turn as well but if each aircraft flew a straight missed approach at the proper heading, they would be safe. This is not so for converging approaches. A straight flight during simultaneous missed approach invites a collision.

Because of the importance of this issue, the requirements have been designed to deal specifically with simultaneous missed approaches.

6.1.4 Pilot Acceptance

A major consideration in the creation of requirements is whether the pilot feels comfortable with the procedures for operating instrument approaches to converging runways. The major concern is that there is no latitude for error in the missed approach area. Pilots know that a straight missed approach means conflict, not safety and the other pilot could make a mistake.

6.2 Conclusions

After examining the issues raised in the analysis it was concluded that instrument approaches to type three and some type two geometries were feasible for Category I minima. For both geometries, protection during simultaneous missed approach was

the most critical issue. If requirements for operating converging approaches accommodated this issue adequately, acceptance by pilots to try the procedure is expected. A gradual approach to operating near CAT I minima would help overcome a natural caution by pilots toward trying the procedure.

Final approach requirements are not at issue. Because of large lateral separation, blunder monitoring for a short portion of the final approach (that will vary from case to case) can be adequately handled by the final approach controller. All the other requirements for final approach remain the same.

To resolve the issue of simultaneous missed approach, procedures have been defined so that the aircraft will be safely separated if:

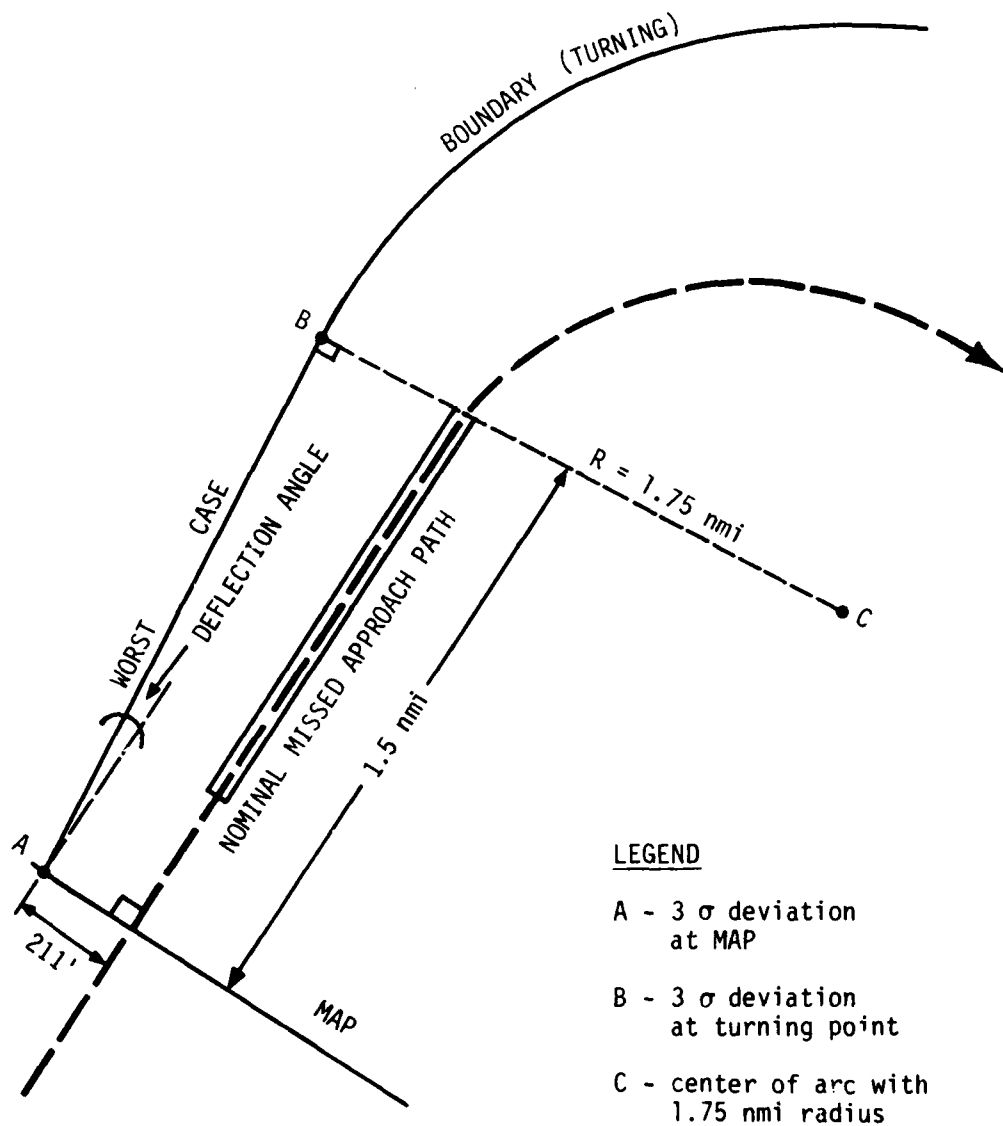
- Simultaneous missed approach occurs, and
- Both aircraft fly a "Worst Case" path

6.2.1 Worst Case Path

The worst case path is defined according to the expected maximum lateral deviation from the approach path at the Missed Approach Point (MAP) to the end of the missed approach maneuver. The beginning of this path is defined at the MAP by a point 3σ from the expected final approach path toward the other runway. The path continues straight, retaining its 3σ offset for 1.5 nmi. At that point the worst case path turns at a radius of 1.75 nmi, the TERPS value for nominal turn of a heavy aircraft. This is equivalent to a half rate turn (1.5°) at 165 kn (Figure 6-2).

The application of this path as a boundary (the Worst Case Boundary, WCB) would account for random lateral deviation of at least 99.5% of the aircraft during missed approach. Because of concern that one aircraft may make a straight missed approach or a balked landing, it was concluded that a straight WCB must be constructed at each runway.

The WCB accounts for random lateral deviation and the potential for a heading blunder. The only other consideration is the unlikely possibility of a rare event occurring that would force an aircraft into an exaggerated lateral deviation. To account for this, a requirement that 500 feet must separate the WCB's such that either worst case missed approach could be straight ahead (Figure 6-3).



**FIGURE 6-2
CONSTRUCTION OF WORST CASE BOUNDARY
FOR TURNING MISSED APPROACHES**

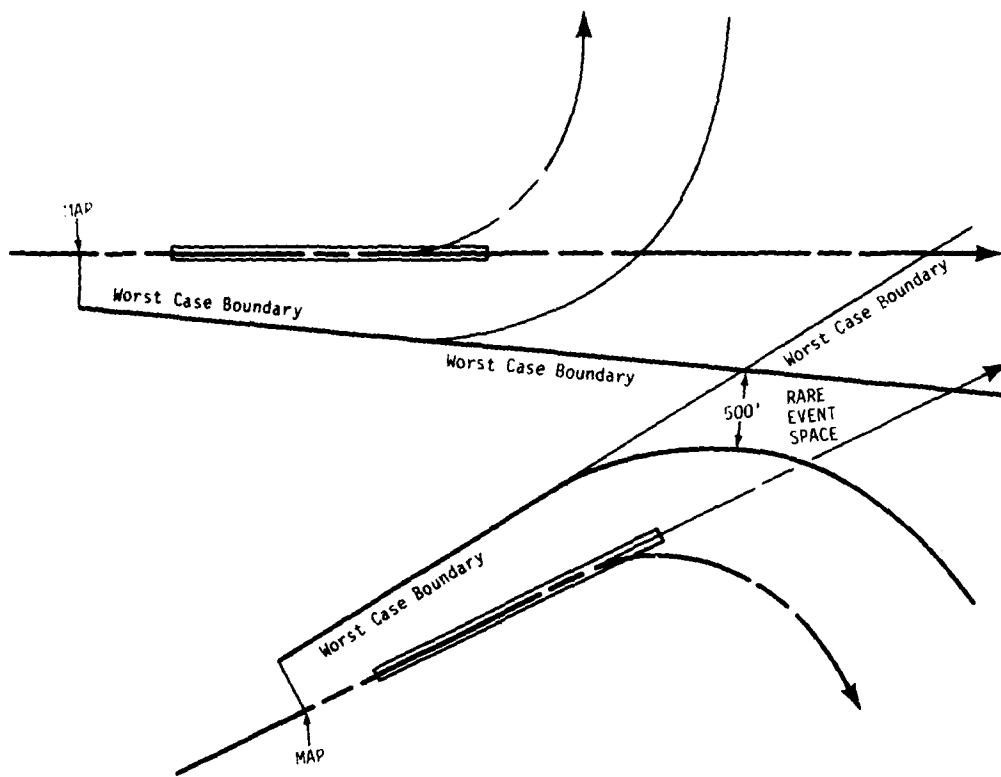


FIGURE 6-3
APPLICATION OF MISSED APPROACH REQUIREMENTS
TO CONVERGING RUNWAYS

6.2.2 Strategies

Because of the expected difficulty in meeting the requirements at the Category I minima (Decision Height = 200 feet), four strategies for altering the requirements so that converging instrument approaches can be executed are identified.

1. Raise the Decision Height (DH) until the required WCB separation occurs. Eighteen of the thirty largest hubs qualify to operate converging approaches if this strategy is used.
2. Install an MLS instrument guidance system to provide more accurate guidance through the missed approach. This added accuracy should decrease the value of the 3σ lateral deviation and thus, narrow the distance between the runway centerline and the WCB.
3. Segregate traffic so that air carriers land on one runway, general aviation (GA) and commuters land on the other. This would decrease the expected turn radius of the GA/commuter worst case missed approach thus gaining more lateral separation. Even if there were no appreciable capacity gain due to a decrease in expected turn radius, using this concept will reduce longitudinal spacing requirements (thus, increasing capacity) for both traffic streams.
4. Operate dependent approaches by providing a minimum time separation between missed approaches at the point where extended approach centerlines intersect. The form of this requirement is:

-- Aircraft #2 required to be a minimum distance from threshold #2 when aircraft #1 is over threshold #1

The actual distance would be a function of runway geometry.

6.3 Recommendations

6.3.1 Criteria

Based on this analysis, independent instrument approaches to Category I minima can be conducted safely and efficiently if the following criteria are met:

- The following present requirements should be satisfied:
 - 3 nmi/1000 ft. separation between aircraft at localizer intercept, and
 - functioning ILS or MLS, airport surveillance radar and air/ground communications.
- Final approach paths do not intersect.
- Both turning and straight Worst Case Boundaries must be constructed at each runway. It is not necessary that both boundaries be used but at least 500 feet must separate the WCB's so that either worst case missed approach could be straight ahead.
- Missed approach courses for both runways should consist of a 1.5 nmi straight section and a diverging turn at the standard rate of 3°/s. The turns should diverge by at least 45°.
- In order to initiate operations of converging instrument approaches when runway geometry doesn't permit Category I minima (DH = 200 feet), the following alternatives may be used:
 - raise the DH until lateral separation between WCB's is greater than 500 feet.
 - operate dependent approaches by insuring a minimum time separation between missed approaches at the point where extended approach center lines intersect.

If demonstration of this concept proceeds in a gradual manner, i.e., by initiating converging instrument approaches at relatively high minima and gradually reducing DH until the requirements are met, two strategies can be tested.

1. The use of MLS, particularly in conjunction with segregated traffic streams, is expected to lower lateral deviation and thus, the 3σ boundary would be less demanding.
2. The value of segregated traffic streams is in the expected reduction in worst case turning radius. This

parameter can be tested during demonstration of converging instrument approaches and alternate requirements can be specified once the parameter value is known.

APPENDIX A

REVIEW OF RELEVANT DATA

A.1 Data Needs

In determining requirements for instrument approaches to converging runways, it was necessary to deal with two issues, both concerning missed approaches.

1. What is the likelihood and character of missed approach blunders, i.e., aircraft that do not follow the prescribed missed approach path by a large degree? Executing a straight instead of turning missed approach is an example of a heading blunder.
2. What is the character of random lateral dispersion about the nominal missed approach flight path? Converging approaches always lead to turning missed approaches and there is a chance that simultaneous missed approaches will occur. An understanding of lateral dispersion at those points on the nominal missed approach flight paths where separation is at the minimum would greatly help in specifying the nominal flight path location of converging missed approach paths.

A.1.1 Blunders

Instrument approaches to converging runways do not have a precedent in the United States. There is no experience with the procedure and, therefore, no data. The operation has never been simulated so there is no recourse to simulation data either. Approaches to converging runways with minima of 1000' ceiling and three mile visibility are allowed but the authors are not aware of any effort to gather data on missed approaches nor of the likelihood of blunders.

A.1.2 Lateral Deviation

Because of the aforementioned concern about lateral separation during a simultaneous missed approach, data describing lateral dispersion during missed approach would be very useful. Obviously, there is no data for converging missed approach because of lack of experience but there are two sources of data on lateral dispersion:

- Resalab (Reference 4) has compiled data characterizing lateral dispersion on the final approach. Those observations on the final approach that also correspond to the Missed Approach Point (MAP) help define the lateral variation at the beginning of the missed approach.
- ICAO (International Civil Aviation Organization) formed the Obstacle Clearance Data Collection Program which identified four data sets comprising a total of 483 missed approach observations. This data was used to construct a collision risk model. However, none of the data was collected from flights under actual instrument conditions, but are based on training/certification flights, experiments and simulator studies.

A.1.3 Summary and Direction

The analysis of instrument approaches to converging runways reveals that blunders and lateral deviation, both in the missed approach area, are the main concerns of this project. There is no data on converging missed approaches and no data on missed approach blunders but two sources of data for lateral deviation were identified. The remainder of this appendix describes the data and identifies those portions useful to the analysis of missed approach lateral deviation.

A.2 Data Description

There are two sources of data on lateral dispersion about the missed approach flight path. Both sources are identified and the relevant data is described.

A.2.1 Resalab Data

In an effort to define the distribution of lateral, vertical and longitudinal errors for various approach systems, Resalab collected data in the form of trajectory information from several airports. The data on lateral deviation from the final approach path was collected from Chicago (ORD), Portland (PDX) and Charleston (CHS) prior to 1972.

Both FAA and Resalab collected data but different collection techniques were used by both. Resalab (e.g., at Charleston)

photographed aircraft position on Precision-Approach Radar (PAR) and used a micro-densitometer to reduce photo data to digital data for computer storage.

The data collected by Resalab for Category I approaches to the front course ILS by Conventional Takeoff and Landing (CTOL) aircraft is presented in histogram form and the mean and standard deviation have been calculated (Table A-1). However, the distribution of the data has not been characterized, although there are observations at the 10 σ point. Resalab has stated that the different sources of data have been processed to remove all known errors.

A.2.2 ICAO Data

The following description of the original sources for data used by ICAO in the construction of a collision risk model is taken directly from reference six.

Project Lookout -- a series of flight tests conducted in 1965 by the United States Federal Aviation Administration (FAA). There were a total of 224 approaches made of which 179 resulted in missed approaches -- 84 missed approaches by jet propelled aircraft and 95 missed approaches by propeller driven aircraft. All engines were operative on 59 of the 84 jet missed approaches and on 60 of the 95 propeller missed approaches; one engine was inoperative on each of the remaining missed approaches. Approach guidance for the flights resulting in missed approaches was provided by the auto-coupler on 33 jet flights, by the flight director on 40 jet flights and 23 propeller flights, and by raw ILS data on 11 jet flights and 72 propeller flights. These approaches were made to a nominal decision height of 100 ft on a 2.59 degree glide slope using an ILS facility meeting Category II standards; however, neither the ILS facility nor the aircraft were certificated for Category II.

United Kingdom Certification Data -- a total of 168 missed approaches from ILS approaches to a nominal decision height of 100 feet were monitored.

Missed Approach Flight Simulation Study -- the study comprised a total of 121 missed approach flights from Category II ILS approaches to a 100 foot decision height. This study was set up specifically to obtain data of aircraft dispersion in the missed approach maneuver and is discussed in greater detail later in this appendix.

TABLE A-1
 MEAN AND STANDARD DEVIATION VERSUS RANGE FOR
 FC-ILS-I-CTOL¹ - LATERAL²

<u>RANGE, METERS</u>	<u>NUMBER OF SAMPLES</u>	<u>MEAN, METERS</u>	<u>STANDARD DEVIATION, METERS</u>
600 (1163) ³	513	-0.02	11.89 (21.44)
1200	618	-3.04	22.07
1800	633	-5.29	26.49
2400	642	-6.76	31.92
3000	644	-2.87	35.88
3600	638	1.65	37.71
4200	622	8.98	43.60
4800	631	8.31	46.95
5400	630	8.41	53.41
6000	631	6.92	61.90
6600	629	2.97	68.51
7500	513	14.46	75.30
8100	500	11.83	83.99
8700	490	7.67	90.20
9300	468	6.37	93.00
9900	447	4.83	97.60
10500	423	12.93	92.45
11100	387	16.36	91.98
11700	342	17.42	94.11
12300	324	21.30	100.43
12900	307	26.29	96.41
13500	283	28.54	102.12
14100	245	28.99	103.63
14700	224	33.03	103.14
15300	181	27.42	97.75
15900	134	25.53	113.84

¹ FC = Front Course
 ILS = Instrument Landing System
 I = Category I
 CTOL = Conventional Take off and Landing

² Range is calculated from threshold

³ The point on the range equal to the MAP has been interpolated to 1163 m from the threshold under the conditions of:

1. 3° glide slope
2. 200' decision height

FAA Test Data -- a small sample of Boeing 727 flights. This test was set up to validate the simulation data.

The standard deviations of lateral displacement for the various data sources are plotted with respect to range in Figure A-1.

A.2.3 Data Interpretation

There are two very important characteristics of this data.

1. It does not directly apply to simultaneous approaches, multiple approaches, turning approaches, or converging approaches.
2. It is the only information on lateral dispersion during missed approach that is available.

Since there is no other data, the thrust of this analysis was to identify that part of the data that could be useful to the analysis and also, to record clearly the reasons why the remaining data was not useful.

A.2.3.1 Discussion

The ICAO data sets can be divided into those observations that were examined independent of the representations made in reference six and those to which the authors could (or needed to) find no better access. The raw data for Project Lookout is no longer available from the Flight Inspection National Field Office; the United Kingdom Data covered too short a range (see Figure A-1) to encourage further efforts to locate the raw data and FAA test flights represented too few observations to warrant further study. Only the data from the simulation was studied in depth.

Simulation Data

In order to supplement the data collected by ICAO (and referred to above) the FAA created a study of missed approaches by flight simulator. The following description is taken directly from Reference 7.

"The primary purpose of this study was to obtain sufficient data to quantify vertical and lateral dispersion of aircraft about a nominal flight path in the missed approach area. The interest was twofold: (1) to determine airspace requirements for the majority of aircraft making a normal

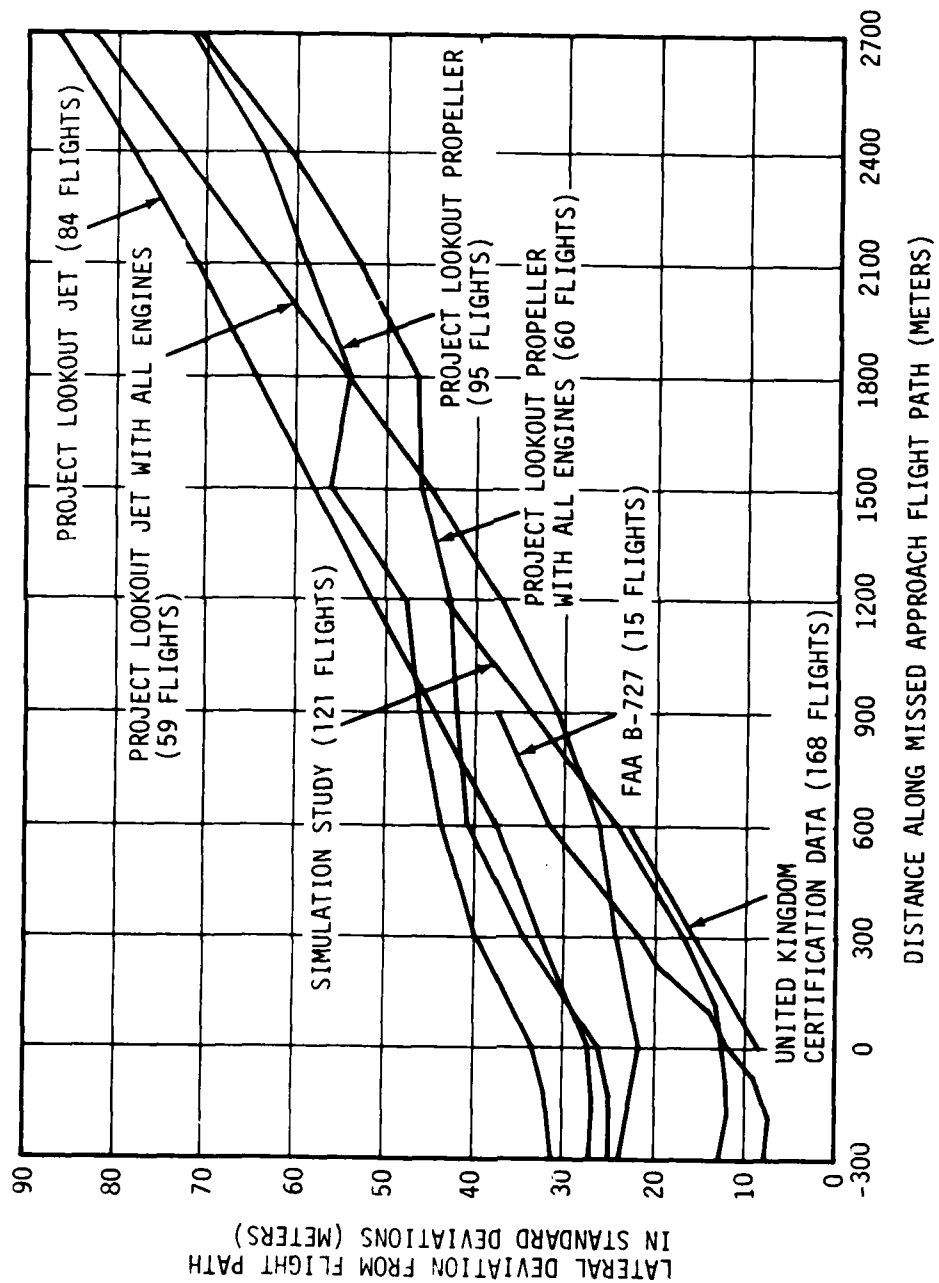


FIGURE A-1
MISSED APPROACH LATERAL STANDARD DEVIATIONS BY RANGE

missed approach encountering no events that could cause extreme vertical or lateral excursions, and (2) to determine requirements for those aircraft that might encounter "unusual" event(s) producing excursions that could result in ground contact or collision with obstacles distributed along the missed approach path."

"The flight simulation method was chosen because it offered a means of calibration of the ground facility, calibration of airborne equipment, control of accuracy of recording systems, and close monitoring and scheduling of landings vs. missed approaches so the crew would not be "keyed" to a miss. Also, subject pilots were chosen who were fully qualified, current, and ILS Category II certificated. Further, variables which cause dispersions could be put into the experiment under close control whereas in "live" testing these variables could not be introduced."

"...Since the sample size could not be large enough to obtain data in the extreme tails of a statistical distribution, it was decided that a design would be used which would permit the application of factors that were suspected of contributing to lateral and vertical dispersion, and which would allow their measurement. The experimental design included the following:

1. Six aircraft types: B-747, DC-10, B-707, B-727, DC-9, and Cessna Citation.
2. Three wind conditions: nominal (no shear), moderate shear (quartering tail of 15 knots shearing to quartering head at 4 knots per 100 feet beginning 300 feet AGL), and maximum shear, same as moderate but initially at 25 knots and shearing at 8 knots per 100 feet.
3. Two approach guidance methods: autopilot coupled and flight director.

Eighteen line pilots from U.S. air carriers were selected to fly approaches to ILS Category II minimums. Sequencing of missed approaches was randomized.

A three degree glide slope angle was used with course structure near Category II limits. The localizer course width was tailored to a 700 foot threshold width, course structure near Category II tolerances.

Temperatures used were 10 - 20° C. Pressure altitudes were sea level to 1000 ft MSL. Simulated daylight visibility was 1200 RVR. All procedures used were those established by the air carriers involved..."

The data resulting from the simulation exercise of the missed approach is illustrated in Table A-2. As can be seen, the sample size is low, 121 observations or less. Histograms of the data have been included in the appendix of Reference 7 and a representative one is reproduced in this text as Figure A-2.

Note the lack of data past 3σ and the difference between the fit of the normal distribution and the Johnson S_U Distribution. Pate (Reference 7) applied a Goodness of Fit test on the data and selected the Johnson S_U as most representative. Obviously, it is only representative to 3σ . Table A-3 compares the probability of a random variable occurring beyond certain distances from the mean among three distributions using standard deviations as distance measuring units. (The CRM Synthetic Distribution is used to represent lateral dispersion by the authors of the Collision Risk Model. It is a synthetic distribution described in Reference 6).

A.4 Data Use

The data generated by the Simulation Study, (and associated ICAO data) Resalab and Project Lookout was used as a basis for constructing the 3σ Worst Case Boundary described in Section Three. No one set of data contains observations throughout the full range (15 nmi) of the missed approach (even with the use of the three sets of data, only 11,924 ft of range beyond the map is covered).

Resalab contains observations on the final approach to the Category I MAP, the ICAO data covers the final approach and missed approach to 7000' beyond the MAP and Project Lookout data (Jet Engines) is used to describe dispersion from 7000 ft to 11,924 ft.

TABLE A-2
 MISSED APPROACH LATERAL DISTRIBUTION STATISTICS
 FROM SIMULATION STUDY²

<u>RANGE (METRES)</u>	<u>SAMPLE SIZE</u>	<u>MEAN (METRES)</u>	<u>STANDARD DEVIATION (METRES)</u>	<u>SKEWNESS</u>	<u>KURTOSIS</u>
-300	120	-2.85	12.57	-0.36	4.33
-200	120	-2.95 ¹	12.07	-0.74 ¹	5.79 ¹
-100	121	-2.61	12.06	-1.13 ¹	7.65 ¹
0	121	-2.10	12.67	-1.08 ¹	7.59 ¹
+100	121	-1.64	13.30	-0.78 ¹	6.74 ¹
+200	120	-1.16	15.03	-0.18	6.36 ¹
+300	121	-0.73	17.11	0.08	6.33 ¹
+600	120	0.40	24.65	0.15	6.54 ¹
+900	113	-0.52	34.23	0.19	7.04 ¹
+1200	110	-0.51	43.93	0.28	7.00 ¹

¹ Significant at the one per cent significance level.

² Data found in Table II-5-1, p. II-5-3, Reference 6.

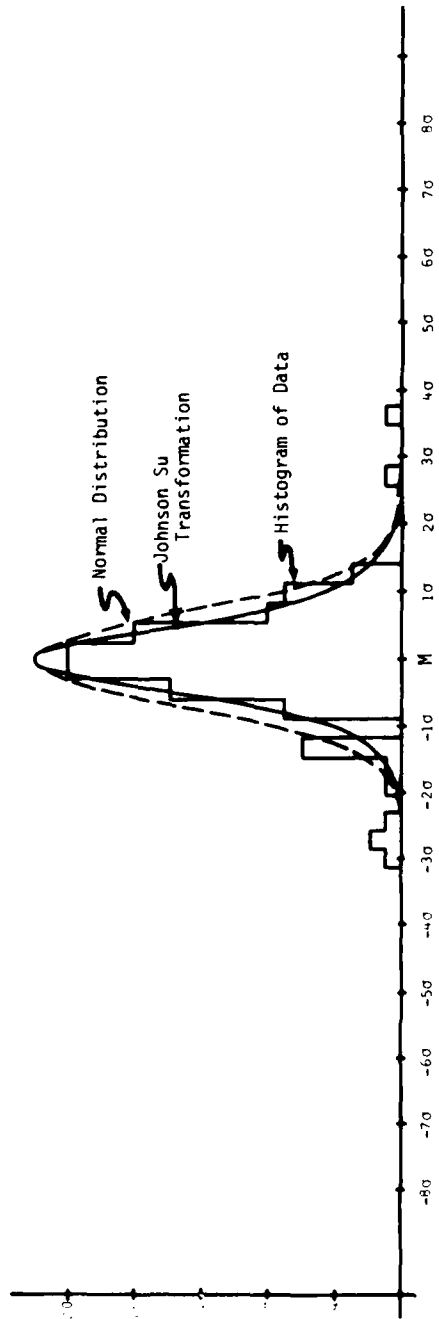


FIGURE A-2
LATERAL DISPERSION ABOUT THE MISSED APPROACH FLIGHT PATH
AT 1200 M BEYOND THE THRESHOLD

TABLE A-3

CHARACTERISTICS OF THREE DISTRIBUTIONS USED TO REPRESENT LATERAL
DISPLACEMENT OF AIRCRAFT FROM APPROACH (AND MISSED APPROACH) FLIGHT PATH

STANDARD DEVIATIONS	PROBABILITY THAT A RANDOM VARIABLE WILL EXCEED CERTAIN DISTANCES FROM THE MEAN		
	NORMAL DISTRIBUTION	CRM SYNTHETIC DISTRIBUTION ¹	JOHNSON S _u TRANSFORMATION ²
1	1 in 6	1 in 7	1 in 10
2	1 in 43	1 in 39	1 in 50
3	1 in 740	1 in 222	1 in 200
4	1 in 3.2 X 10 ⁴	1 in 1.3 X 10 ³	1 in 7.5 X 10 ²
5	1 in 3.5 X 10 ⁶	1 in 7.3 X 10 ³	1 in 2.4 X 10 ³
6	1 in 1.0 X 10 ⁹	1 in 4.6 X 10 ⁴	1 in 6.3 X 10 ³
7	1 in 7.8 X 10 ¹¹	1 in 3.5 X 10 ⁵	1 in 1.5 X 10 ⁴
8	1 in 1.6 X 10 ¹⁵	1 in 3.3 X 10 ⁶	
9	1 in 8.7 X 10 ¹⁸	1 in 3.8 X 10 ⁷	
10	1 in 1.3 X 10 ²³	1 in 4.4 X 10 ⁸	1 in 1.5 X 10 ⁵
18			1 in 1.0 X 10 ⁷

¹ Data Found in Table II-3-7, Page II-3-15, Approach Lateral
Distribution @ 1200 m Before Threshold, Reference 6

² Data Found in Table 4, Page A-7 and Page A-4, Missed Approach Data
Simulated @ 1200 m After Threshold, Reference 7

A.4.1 Resalab

The Resalab Data used to estimate the standard deviation at the MAP (Category I) was taken from Table A-3 (Reference 4, Table 3.1.1-1). Although this has not been fitted to a distribution (unlike the bulk of the data used in this analysis), it is based on substantially more samples than the ICAO (Simulation) data. The σ at 1163 m (21.44 m) represents the interpolated value at the MAP.

A.4.2 ICAO

ICAO (Reference 6) presents data from various sources for lateral dispersion from the nominal final approach course and from the simulation study of lateral dispersion about the nominal missed approach course.

Observations on the final approach were made at 1200 m, 4200 m and 7800 m from the threshold. Since the Category I MAP is located 935 m from the threshold, extrapolation of this data was done to obtain an estimate of standard deviation at the MAP.

The nominal data for lateral dispersion is taken from Reference 6, p. II-6-1. Adjustments were made to this data for differences in assumptions about the localizer beam width at the threshold and distance between localizer and threshold. These adjustments are shown in Tables A-4 and A-5. The final adjusted estimate of standard deviation at the MAP is 17.18 m, 4.26 m less than that obtained using Resalab data.

A.4.3 Choice of Standard Deviation at the MAP

The two estimates of standard deviations of the MAP may not be significantly different. The choice was made to use the Resalab derived figure, 21.44 m, primarily because it is the more conservative estimate. The importance of this figure is that it is used to adjust the standard deviations of all missed approach observations.

The rationale for this adjustment is the following: when the aircraft is attempting a Category I or a Category II approach, as soon as the MAP is crossed and a decision is made not to land, the pilot is pre-occupied with efforts to regain altitude and has neither time nor incentive to closely follow a given course. At about the MAP, localizer beam width is relatively

TABLE A-4
ADJUSTMENTS¹ TO NOMINAL STANDARD DEVIATIONS

	<u>ICAO ASSUMPTIONS</u>	<u>MITRE ASSUMPTIONS</u>	<u>ADJUSTMENT</u>
Beam Width @ Threshold	213.36 m	228.6 m (750')	$\frac{228.6}{213.36} = 1.071$
Distance, Localizer to Threshold	3800 m	2743 m (9000') ²	$\frac{3800}{2743} \cdot \frac{1200+2743}{1200+3800} = 1.092$

TABLE A-5
STANDARD DEVIATIONS OF AIRCRAFT LATERAL
DISPLACEMENT DURING CATEGORY I ILS APPROACH

<u>FINAL APPROACH RANGE (METERS)³</u>	<u>NOMINAL STANDARD DEVIATION</u>	<u>ADJUSTED STANDARD DEVIATION⁴</u>
(935)		(17.18 m)
1200	16.4 m	19.19 m
4200	35.9 m	42.00 m
7800	67.5 m	78.98 m

- 1 Explanation of adjustments are found in Reference 6, p. II-6-1
- 2 8000 foot runway, 1000' from end of runway to localizer
- 3 Taken From Reference 6, p. II-3-14
- 4 Adjustment Factor = 1.071 X 1.092 = 1.17 (See Table A-4)

narrow anyway and subsequent maneuvering to keep within the beam width during instrument meteorological conditions requires great skill to avoid constant overcorrections.

The assumption is made that the observation of missed approach flight path at the MAP obtained by the Category II missed approach simulation should be adjusted by other (Resalab and ICAO) sources of Category I data. The difference between the standard deviations of these two sources at the MAP (8.87 m) has been added to all missed approach standard deviations for the entire range. (This method follows the instructions of the Collision Risk Model and is used to account for the increased lateral spread at the initiation of an earlier missed approach; CRM 6.6.4.) Table A-6 lists the standard deviations at (approximately) 300 meter intervals from the MAP to 1200 m past the threshold.

A.4.4 Project Lookout

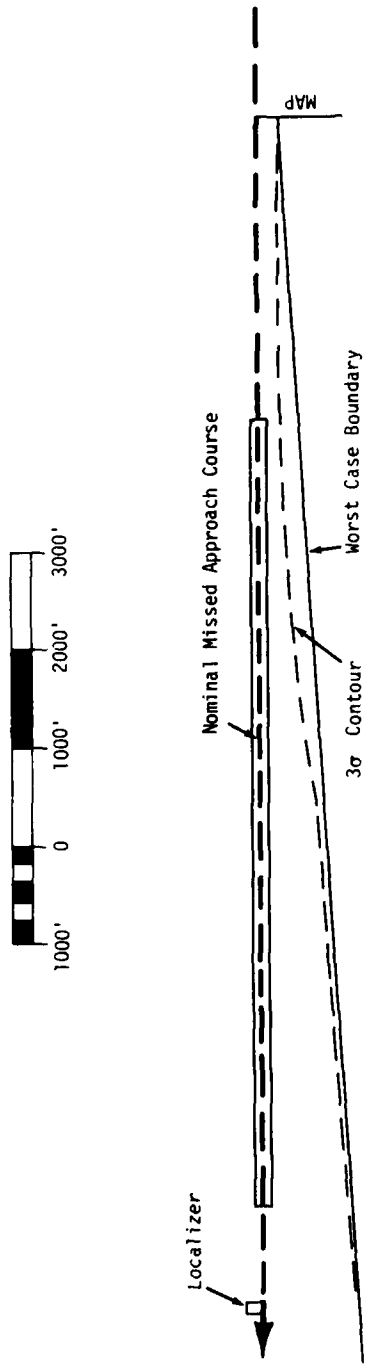
The simulation data ends at 1200 meters but Project Lookout data includes observations on Category II approaches by jet aircraft to 2700 m. Although the raw data could not be obtained from the Flight Inspection National Field Office, the plot of standard deviations (Figure A-1) showed good compatibility with the simulation data. Lacking any other quantification, standard deviations were estimated from the figure and adjusted at 1200 m to correct for the differences due to Category I vs. Category II dispersion. This adjustment required adding the 8.87 m adjustment to all Project Lookout values (Table A-6).

A.4.5 Worst Case Boundary Calculation

The final column in Table A-6 presents the adjusted lateral deviation for Category I missed approach. This 3σ boundary is plotted in Figure A-3 showing the actual 3σ contour and the simplification of that contour used in calculations and referred to as the 3σ Worst Case Boundary (WCB). It is very close to a 3.5° deflection angle from the nominal missed approach path.

TABLE A-6
ADJUSTED LATERAL MISSED APPROACH DEVIATION

Meters	RANGE	ORIGINAL STANDARD DEVIATION(m)		ADJUSTED STANDARD DEVIATION(m)		LATERAL DEVIATION AT 3 σ	
		Simulation	Project	Simulation	Project	Meters	Feet
MAP -935	-3066			21.44		64.32	211
-600	-1968			21.44		64.32	211
-300	-984			21.44		64.32	211
0	0	12.57		21.54		64.62	212
300	984	12.67		25.98		77.94	256
600	1968	17.11		33.52		100.56	330
900	2953	24.65		43.10		129.30	424
1200	3937	34.23		52.80	60.4	181.20	594
1500	4921	43.93	51.5		66.6	199.80	656
1800	5906		57.7		73.9	221.70	727
2100	6890		65.0		80.1	240.30	788
2400	7874		71.2		87.7	263.10	863
2700	8858		78.8		95.8	287.40	943
			86.9				



A-16

**FIGURE A-3
 PLAN VIEW OF 3σ LATERAL DEVIATION ABOUT THE NOMINAL MISSED
 APPROACH COURSE AND LOCATION OF WORST CASE BOUNDARY**

APPENDIX B

MISSED APPROACH SPECIFICATIONS

B.1 Procedures for Construction of Missed Approach Areas and Obstacle Clearance Areas

The object of constructing Obstacle Clearance Surfaces is to protect aircraft from colliding with objects in a fixed location -- towers, buildings, mountains. These surfaces are constructed (figuratively) in the final approach and missed approach areas and vary in height depending on the accuracy of the approach category. (Category I requires a greater clearance from obstacles than Category II.)

The procedures for defining that segment of Category I instrument approach called "missed approach" are found in:

- United States Standards for Terminal Instrument Procedures (TERPS) (Reference 2)
- Procedures for Air Navigation Services -- Aircraft Operations (PANS-OPS) (Reference 13)

Because TERPS is mandatory in the United States and PANS-OPS, formulated by the International Civil Aviation Organization (ICAO), is optional, the decision was made to examine missed approaches using TERPS criteria only. Accordingly, the following sections describe the TERPS missed approach procedures.

B.1.1 TERPS Category I Straight Missed Approaches

Missed Approach Area

The TERPS straight missed approach area is 15 nmi long and begins at the missed approach point (MAP), the point on the final approach course where the glide slope intersects the decision height (DH). Section 1 of the missed approach begins at the MAP, where it has an initial width equal to the width of the final approach area at the MAP. It extends from the MAP 1.5 nmi out the extended runway centerline, uniformly increasing in width from the width at the MAP to 1 nmi. The Section 2 primary area begins where the Section 2 primary area is 1 nmi and uniformly increases in width to 8 nmi, 15 nmi from the MAP (Figure B-1).

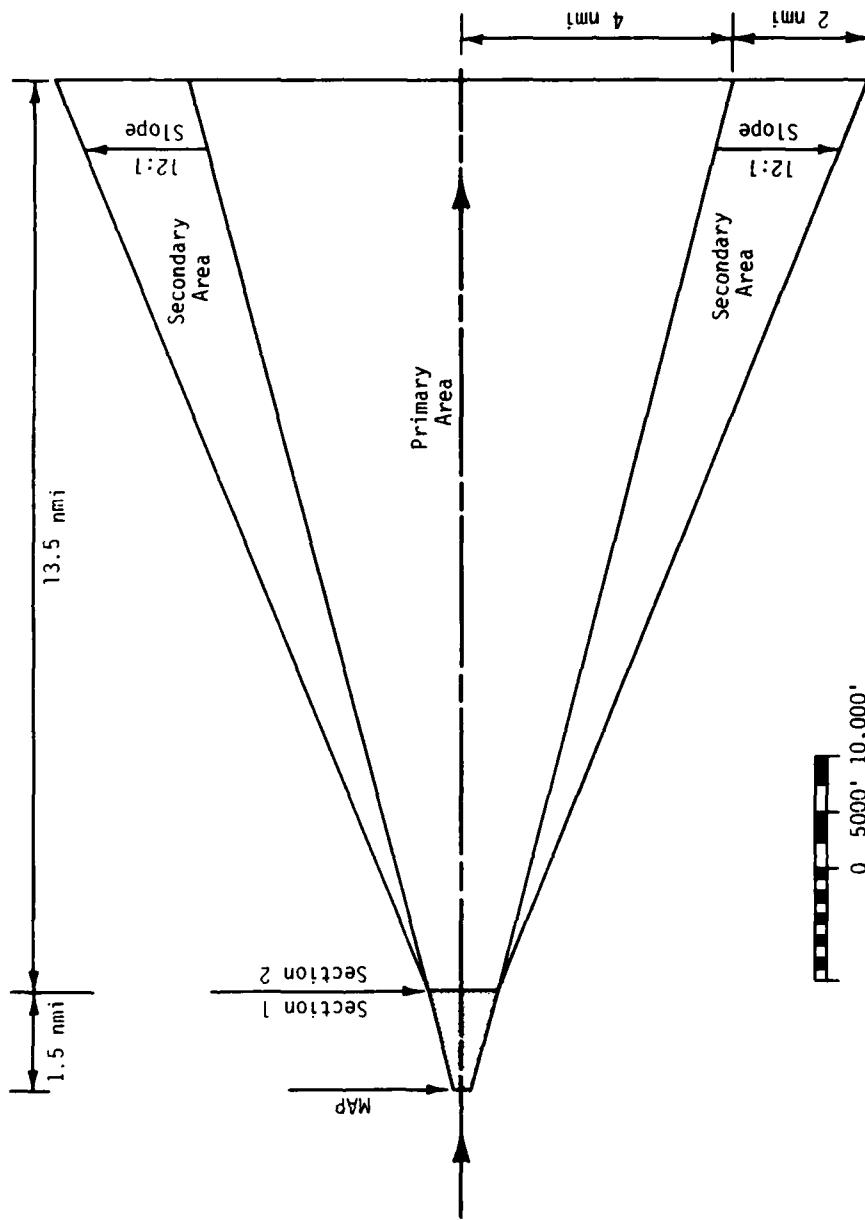


FIGURE B-1
TERPS CATEGORY I STRAIGHT MISSED APPROACH

A secondary area borders Section 2, having zero width at the beginning of Section 2 and uniformly increasing in width to 2 nmi on either side 15 nmi from the MAP.

Obstacle Clearance Surface

No obstacle in Section 1 or Section 2 primary areas may penetrate a 40:1 surface which originates at the MAP at the height of the final approach surface, but not more than 150 ft below the DH, and which overlies all of Section 1 and the primary area of Section 2. Neither may an obstacle penetrate the Section 2 secondary areas which slope up from the primary surface 12:1 laterally (TERPS para. 944). However, positive course guidance may be used to reduce obstacle clearance requirements in the secondary area (TERPS para. 940, 941 and 942).

B.1.2 TERPS Category I Turning Missed Approach

Turns of 15 degrees or less on missed approach are considered straight flight. When turns of more than 15 degrees are required, they shall begin at an altitude at least 400 ft above ground level and are assumed to commence where Section 2 begins.

The flight path radius and obstacle clearance radius are specified in Table B-1. The inner boundary line begins at the edge of Section 1 opposite the MAP, and the primary and secondary boundary lines flare to 8 nmi and 2 nmi, respectively, 15 nmi from the MAP (Figure B-2). The obstacle clearance surfaces are the same as those for the straight missed approach.

B.1.3 Application

As this is an appendix to a report on converging approaches, it is most appropriate to illustrate the construction of the missed approach area and obstacle clearance surfaces and the procedures for executing the missed approach on converging runways. Figure B-3 shows the runway geometry of Dallas Ft. Worth International Airport (DFW) which is favorable to the operation of independent approaches to converging runways. The placement of the Missed Approach Point (MAP) has been set at a decision height of 325 ft as determined by adjusting the minima until the proposed MITRE requirements for lateral separation of Worst Case Boundaries were met.

Note the overlap of the obstacle clearance surfaces in Section 2. This overlap is about the same as that for missed approaches to parallel runways spaced 4300 ft apart.

TABLE B-1
 TURNING MISSED APPROACH RADII (MILES)
 (TERPS PARA. 212)
 (TERPS PARA. 275)

APPROACH CATEGORY*	OBSTACLE CLEARANCE RADIUS (R)	FLIGHT PATH RADIUS (R1)
A	2.6	1.30
B	2.8	1.40
C	3.0	1.50
D	3.5	1.75
E	5.0	2.50

***APPROACH CATEGORIES**

- A - SPEED LESS THAN 91 kn; WEIGHT LESS THAN 30,000 lbs
- B - SPEED 91 kn OR MORE, BUT LESS THAN 121 kn; WEIGHT 30,001 lbs OR MORE, BUT LESS THAN 150,000 lbs
- C - SPEED 121 kn OR MORE, BUT LESS THAN 141 kn; WEIGHT 60,000 lbs OR MORE, BUT LESS THAN 150,000 lbs
- D - SPEED 141 kn OR MORE, BUT LESS THAN 166 kn, WEIGHT 150,000 lbs OR MORE
- E - SPEED 166 kn OR MORE; ANY WEIGHT

NOTE: SPEEDS ARE BASED ON 1.3 TIMES THE STALL SPEED IN THE LANDING CONFIGURATION AT MAXIMUM GROSS LANDING WEIGHT. WEIGHTS ARE MAXIMUM AUTHORIZED GROSS LANDING WEIGHTS. AN AIRCRAFT SHALL FIT IN ONLY ONE CATEGORY, AND THAT CATEGORY SHALL BE THE HIGHEST CATEGORY IN WHICH IT MEETS EITHER OF THE SPECIFICATIONS.

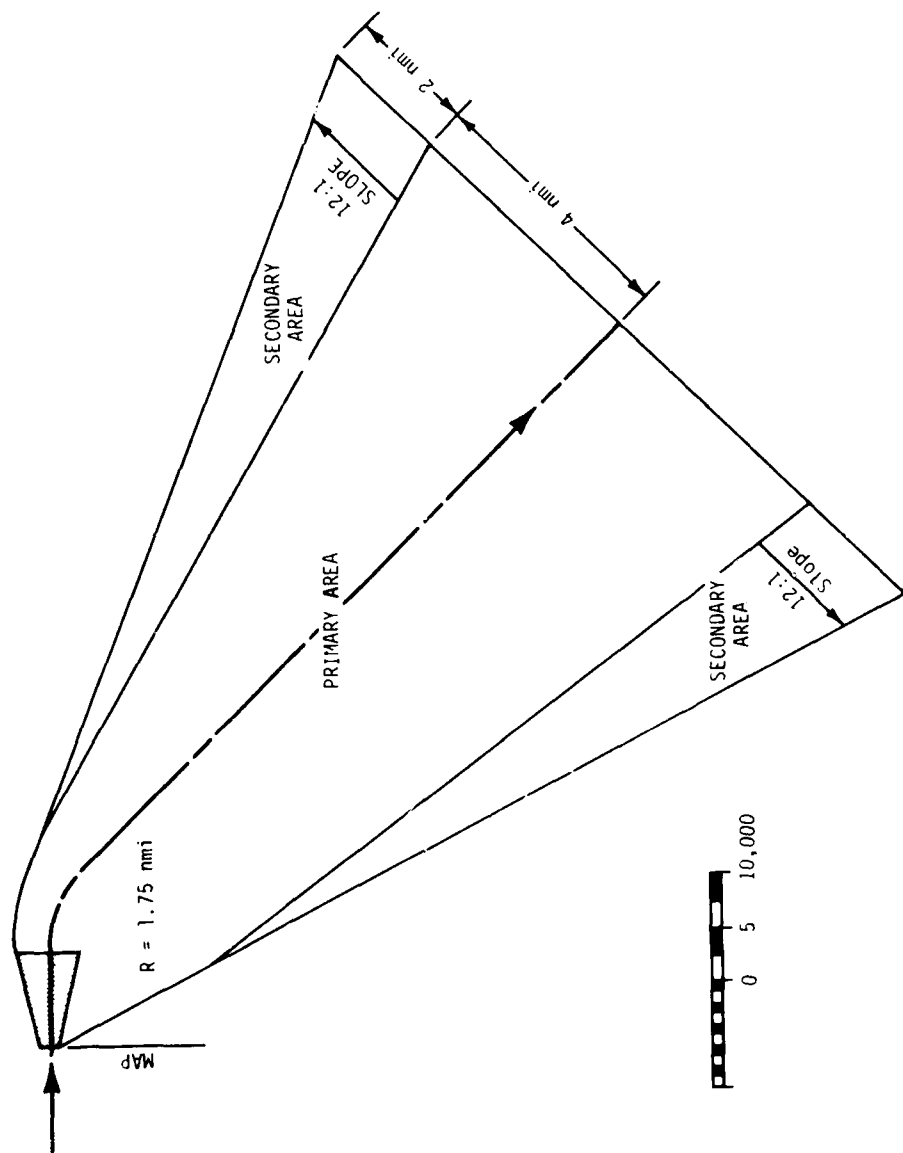


FIGURE B-2
TERPS CATEGORY I TURNING MISSED APPROACH

AD-A108 075

MITRE CORP MCLEAN VA METREX DIV

F/G 1/2

REQUIREMENTS FOR INSTRUMENT APPROACHES TO CONVERGING RUNWAYS. (U)

SEP 81 L C NEWMAN, W J SWEDISH, T N SHIMI

DTFA01-81-C-10001

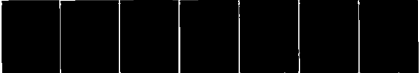
UNCLASSIFIED

MTR-81W230

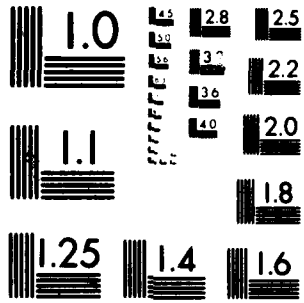
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DATE
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A.

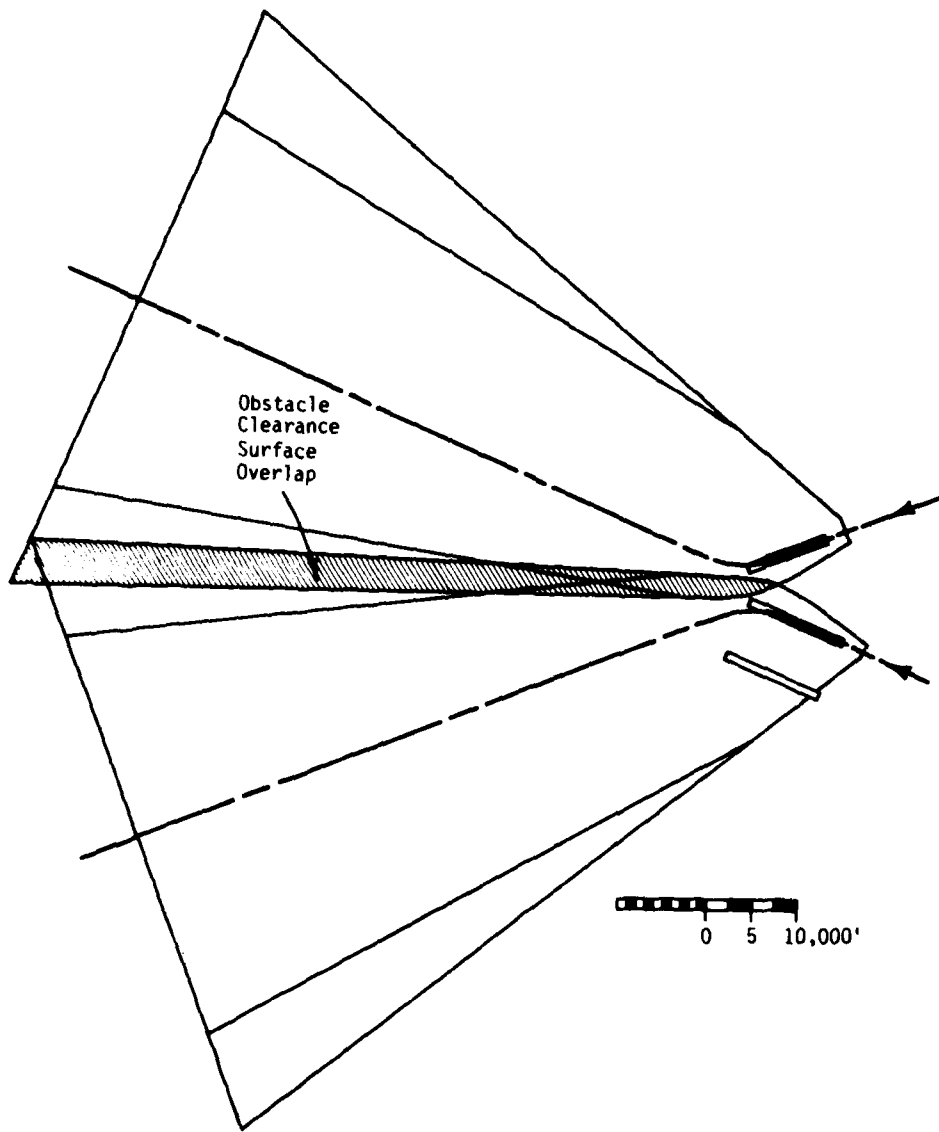


FIGURE B-3
CONVERGING RUNWAY MISSED APPROACH AREA
(DFW, DH = 200')

APPENDIX C

LOGIC AND PROGRAM FOR DISTANCE BETWEEN MISSED APPROACH PATHS

This appendix presents the mathematical modeling of the aircraft paths (expected and worst case) for converging missed approach procedures. It also derives the equations for calculating the minimum separations between these paths.

C.1 Path Modeling

The path of an aircraft executing a converging missed approach procedure is modeled as a continuous curve consisting of a straight-line segment and a circular arc. The line segment is of variable length, depending on the choice of the decision height (DH), and starts at the missed approach point (MAP) where the aircraft descends to the designated DH. At the end of the line segment, the missed approach flight-path begins a constant radius turn; the line segment is tangent to the arc at the point of intersection.

As required by TERPS for simultaneous ILS procedures, the missed approach headings must diverge by at least 45° as soon after reaching 400 ft AGL as possible. This requirement combined with the particular geometry of the airport under consideration determines the length of the circular arc (the arcs end on diverging orientation away from the opposite line segment).

C.2 Coordinate System

For the purpose of calculating the minimum separations between the paths (see Figure C-1 and Figure C-2), the two paths are designated path 1 (LINE1 and ARC1), and path 2 (LINE2 and ARC2). Let P be the intersection point of LINE1 and LINE2 (or their extensions); then

- If P lies on both LINE1 and LINE2, or on both extensions, then LINE1 is chosen such that $\text{dist}(P,1B) \leq \text{dist}(P,2B)$ (See Figure C-1, Figure C-3).
- If P lies on one line segment and on the extension of the other, then LINE1 is taken to be the one on which P lies (See Figure C-2, Figure C-4).

The origin is taken to be the center of ARC1, the positive X-direction is parallel to $\overline{1A,1B}$, and the positive Y-direction is parallel to $\overline{1C,1B}$.

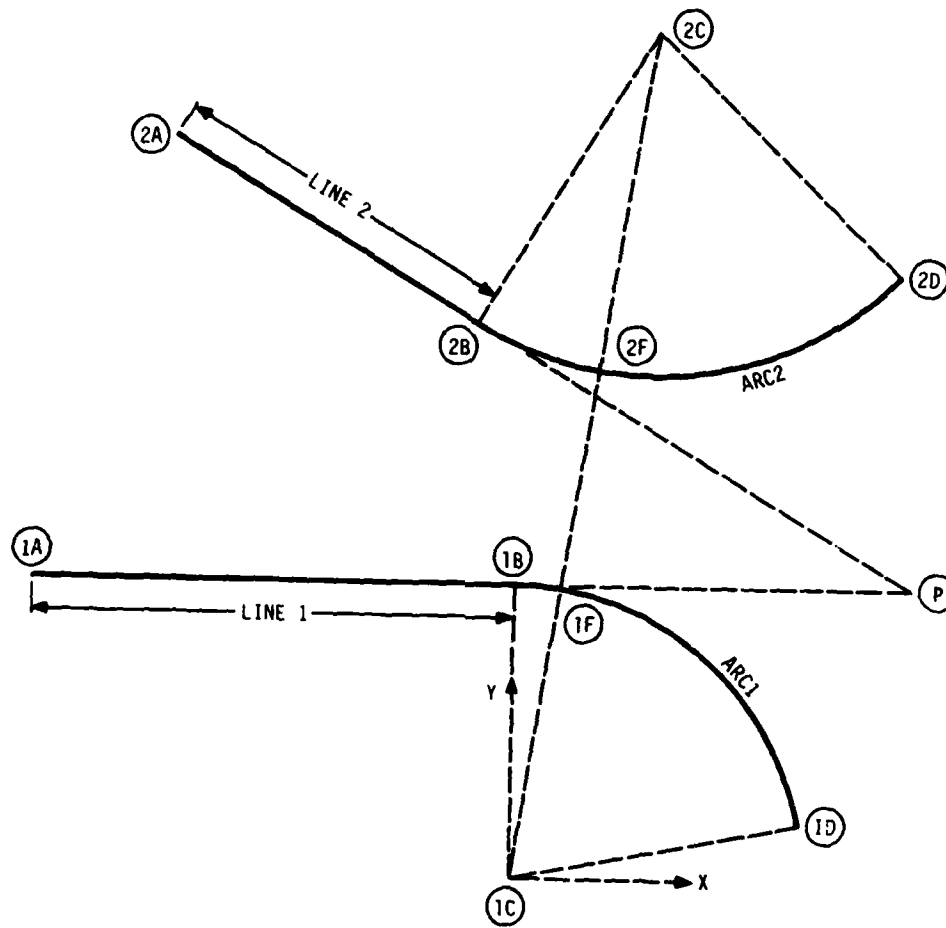


FIGURE C-1
COORDINATE SYSTEM FOR CASE 1
P LIES ON BOTH LINE EXTENSIONS

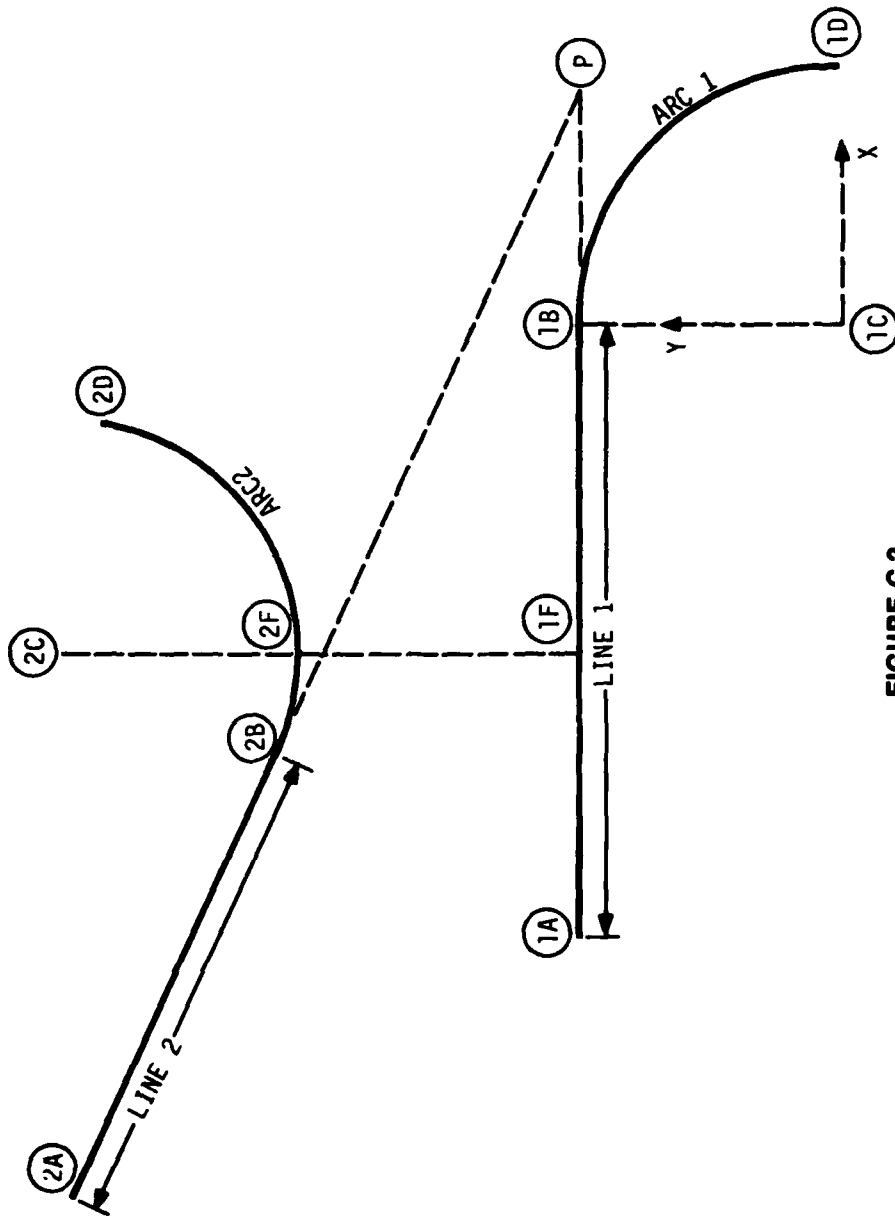


FIGURE C-2
COORDINATE SYSTEM FOR CASE 2
P LIES ON BOTH LINE EXTENSIONS

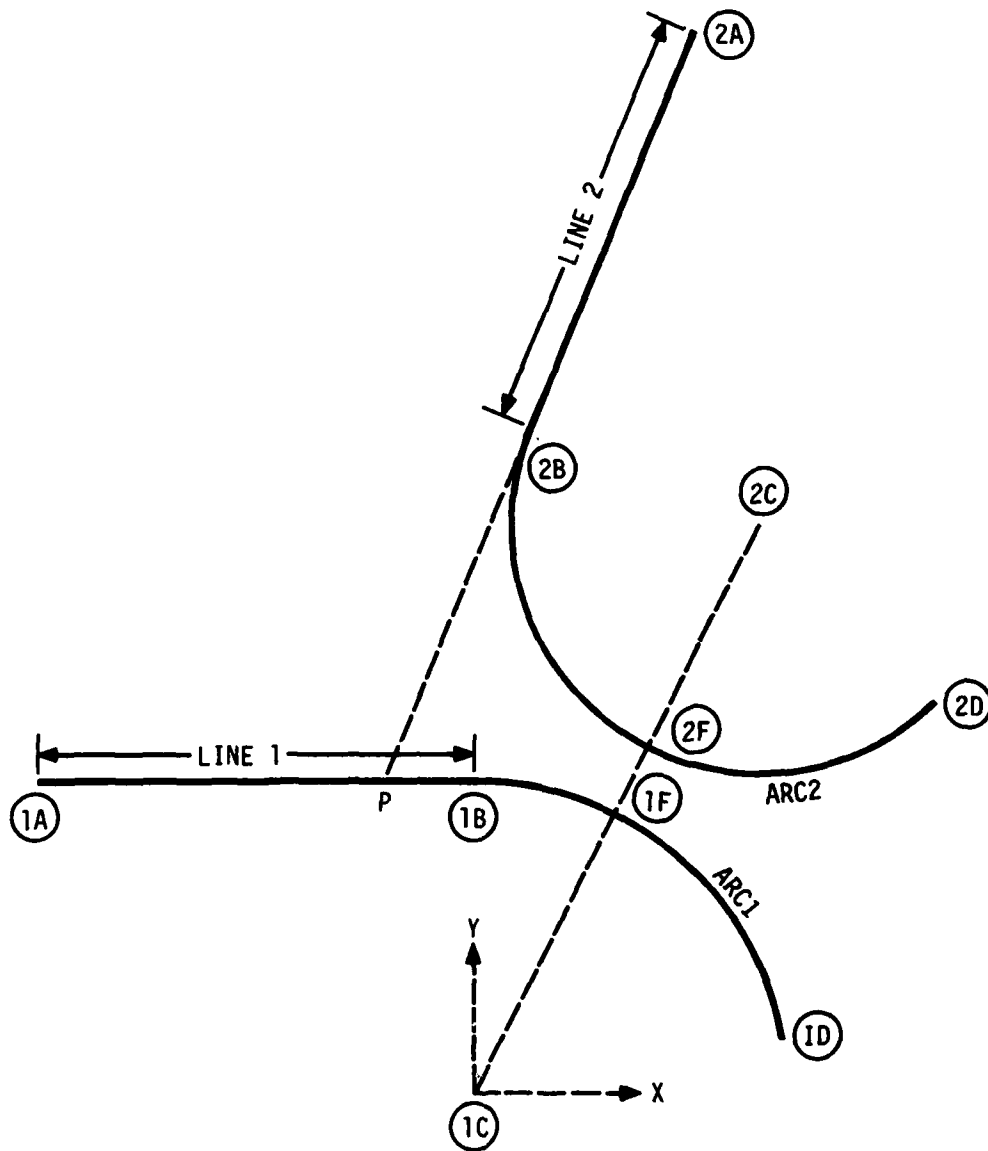


FIGURE C-3
COORDINATE SYSTEM FOR CASE 1
P LIES ON ONE LINE EXTENSION

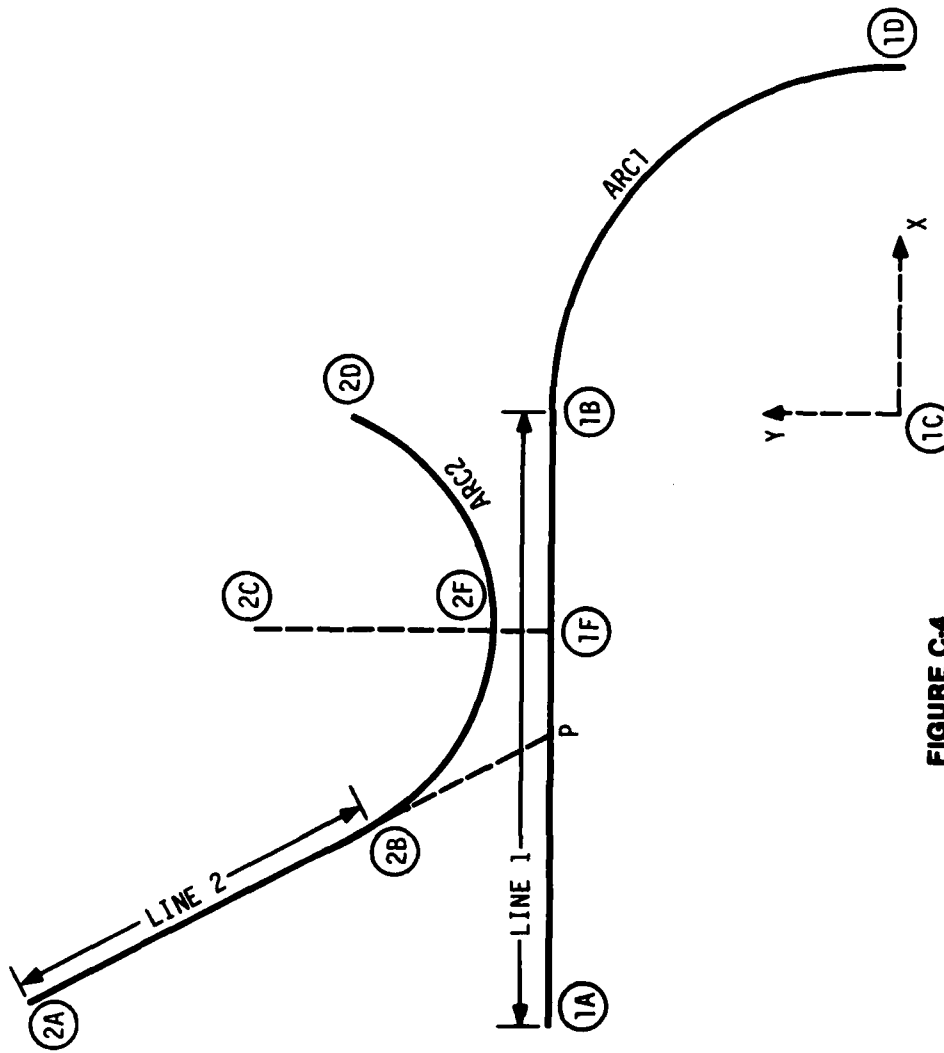


FIGURE C-4
COORDINATE SYSTEM FOR CASE 2
P LIES ON ONE LINE EXTENSION

Let 1C and 2C be the centers of the two arcs and let R1 and R2 be their radii. Let 1F and 2F be the intersection points of the line segment 1C,2C with ARC1 and ARC2 respectively (if these points actually exist); also let 2E be the point of intersection of ARC2 with the perpendicular to LINE1 through 2C (if this point exists).

C.3 Minimum Separation Logic

The choice of the coordinate system discussed above greatly simplifies the calculations of the minimum separations between the paths. Using a relatively simple geometric argument, it can be shown that for any converging runway configuration, only one of two scenarios need be considered in the calculation of the minimum separation (See Figures C-1, C-2, C-3 and C-4):

Case 1 (Figures C-1 and C-3) $X2C > X1C$

In this case the line segment 1C,2C intersects both arcs at 1F, and 2F; this is because each arc ends on a diverging orientation away from the line segment of the other path. It can also be shown that in this case the line segment 1C,2C cannot intersect LINE1 or LINE2.

The minimum separation between the paths is the distance between 1F and 2F.

Minimum Separation = $d(1F,2F) = d(1C,2C) - R1 - R2$

$$SEPMIN = \sqrt{X2C^2 + Y2C^2} - R1 - R2, \text{ and}$$

The distances travelled by the two aircraft to reach the points 1F and 2F are given below

$$DSTNCi = \sqrt{(XiA - XiB)^2 + (YiA - YiB)^2} + \cos^{-1} (1 - (Di/2*ri^2)*ri)$$

for $i = 1,2$

where

$$Di = \sqrt{(XiF - XiB)^2 + (YiF - YiB)^2} \quad \text{for } i = 1,2$$

Case 2 (Figures C-2, C-4) $X2C \leq X1C$

In this case the perpendicular to LINE1 through 2C intersects ARC2 at the point 2E = (X2C, Y2C - R2)

The minimum separation between the paths is
 $SEPMIN = Y2C - R2 - Y1B$

The points 1F and 2F, where the minimum separation occur at, is given below.

$$1F = (X2C, Y1B), \text{ and } 2F = (X2C, Y2C - R2)$$

The distances travelled by the two aircraft to reach the points 1F and 2F are given below.

$$DSTNC1 = \sqrt{(X1A - X1F)^2 + (Y1A - Y1F)^2} \quad \text{provided } X1F \geq X1A$$

$$DSTNC2 = \sqrt{(X2A - X2B)^2 + (Y2A - Y2B)^2} + \cos^{-1} (1 - (D2/2*R2^2)*R2)$$

where

$$D2 = \sqrt{(X2F - X2B)^2 + (Y2F - Y2B)^2}.$$

APPENDIX D

POTENTIAL CONVERGING APPROACHES AT MAJOR AIRPORTS-
APPLICATION OF REQUIREMENTS AND CAPACITY GAIN

D.1 Applicable Airports

MITRE's proposed requirements for Converging Approaches were applied to 30 airports cited as having the most air carrier operations in 1980 (Reference 14). Of the 30 airports:

- 5 had no converging runways,
- 20 airports had potential for converging approaches to intersecting runways (Table D-1),
- 13 airports had potential for converging approaches to non-intersecting runways (Table D-2).

D.2 Independent Approaches To Converging Runways

There were no airports at which independent operations could technically be employed (as defined by MITRE's proposed requirements, Section 3.3.3). This is because the requirements specify minimum Category I requirements (Decision Height = 200 Ft Above Ground Level). However, by employing Strategy Number One -- Increase Minima -- 15 airports were eligible to operate independent approaches at some Decision Height below 1000 ft AGL (Table D-3).

Intersecting runway configurations were included in Table D-3, if at least 8,000 ft were available from threshold to intersection on one runway, so that "hold short" procedures were possible.

TABLE D-1

AIRPORTS* WITH CONVERGING APPROACHES TO INTERSECTING RUNWAYS

<u>AIRPORT</u>	<u>RUNWAYS</u>
Miami (MIA)	12, 9R
San Francisco (SFO)	10L, 1R
New York Kennedy (JFK)	13L, 4L
New York LaGuardia (LGA)	31, 4
Washington National (DCA)	33, 36
Boston (BOS)	22R, 27
St. Louis (STL)	24, 30L
Pittsburgh (PIT)	14, 10R
Detroit Wayne (DTW)	3R, 9
Minneapolis (MSP)	22, 29L
Memphis (MEM)	21, 27
Tampa (TPA)	27, 18L
Las Vegas (LAS)	19L, 25
Cleveland (CLE)	10L, 5R
Philadelphia (PHL)	17, 9L
Honolulu (HNL)	8, 4R
Newark (EWR)	4R, 11
New Orleans (MSY)	10, 19
Ft. Lauderdale (FLL)	27R, 31
Milwaukee (MKE)	7R, 1L

*Taken from the 30 airports with the most operations recorded in 1980.

TABLE D-2

AIRPORTS¹ WITH CONVERGING APPROACHES TO NON-INTERSECTING RUNWAYS

<u>AIRPORT</u>	<u>RUNWAYS</u>
Chicago (ORD) ²	4R, 9R
Chicago (ORD) ²	27R, 32L
Chicago (ORD)	22R, 27L
Dallas Ft. Worth (DFW)	31R, 35R
Denver (DEN) ²	8R, 17L
Miami (MIA)	30, 27R
New York Kennedy (JFK) ²	13R, 22L
New York Kennedy (JFK) ²	4R, 13L
Houston (IAH)	26, 32
Memphis (MEM)	35R, 3
Tampa (TPA)	27, 18R
Philadelphia (PHL)	9R, 17
Honolulu (HNL) ²	22L, 26L
Kansas City (MCI)	19, 27
Newark (EWR)	11, 4L
Milwaukee (MKE)	7R, 13

¹ Taken from the 30 airports with the most operations recorded in 1980.

² Runway geometries with the point of intersection of extended runway centerlines located at one runway.

TABLE D-3

AIRPORTS* AT WHICH INDEPENDENT IFR APPROACHES COULD
TECHNICALLY BE OPERATED

<u>AIRPORT</u>	<u>RUNWAYS</u>	<u>DECISION HEIGHT</u>
Dallas Ft. Worth (DFW)	31R, 35R	325
Chicago (ORD)	22R, 27L	375
Miami (MIA)	30, 27R	450
Houston (IAH)	26, 32	475
Honolulu (HNL)	22L, 26L	550
Chicago (ORD)	27R, 32L	575
Boston (BOS)	22R, 27	625
Chicago (ORD)	4R, 9R	625
Kansas City (MCI)	19, 27	650
Las Vegas (LAS)	19L, 25	675
Detroit (DTW)	3R, 9	700
New York (JFK)	13R, 22L	725
Pittsburgh (PIT)	10R, 14	750
Newark (EWR)	4R, 11	775
Cleveland (CLE)	5R, 10L	800
Milwaukee (MKE)	7R, 13	800
Memphis (MEM)	35R, 3	825
Philadelphia (PHL)	9R, 17	900
New York (JFK)	4R, 13L	900

*Taken from the 30 airports with the most operations recorded in 1980.

APPENDIX E

PROCEDURES AND CAPACITY OF DEPENDENT CONVERGING APPROACHES

The use of dependent converging approaches is one technique for alleviating the potential safety hazards of simultaneous missed approaches. Procedures can be established which eliminate any chance of simultaneity by establishing a minimum time separation between the missed approaches.

E.1 Procedures

For converging approaches, dependency between approaches can take the form of a "gate" along the final approach course which an aircraft cannot cross until the preceding arrival on the other approach has crossed the runway threshold. This is illustrated in Figure E-1, using Memphis International as an example. In the illustration, one "gate" is located 3.0 nm from the threshold of runway 03. A converging arrival to runway 03 must therefore be at least 3.0 nm from the threshold when the previous arrival crosses the threshold to 35R. Similarly, there is a "gate" 0.3 nmi from the threshold of 35R.

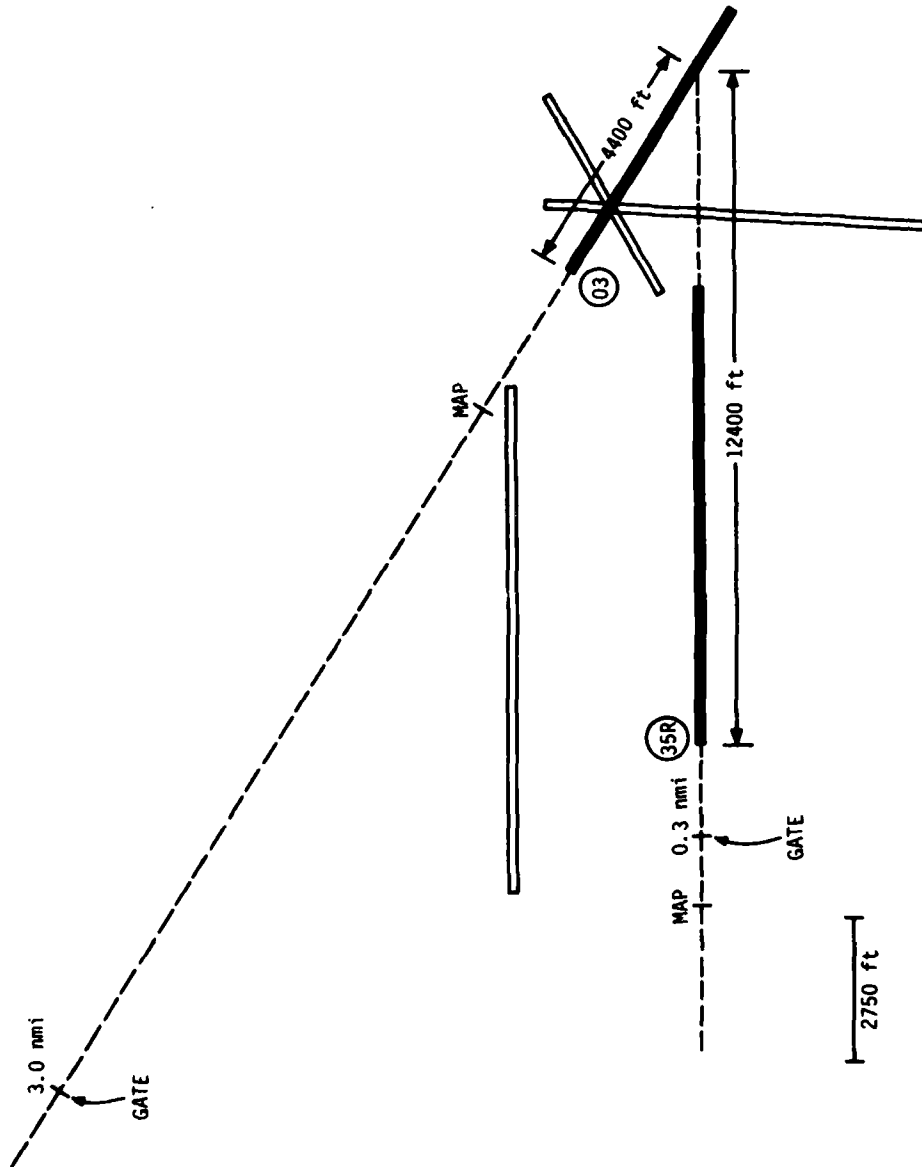
The distance of the R/W #1 "gate" from the threshold is calculated under the following assumptions:

- Aircraft #1 on R/W #1 will execute a missed approach from the MAP.
- Aircraft #2, which is at the R/W #2 threshold when aircraft #1 is at the gate, executes a missed approach from the threshold.
- Both aircraft fly straight missed approach paths.
- Aircraft #1 reaches the intersection point at a specified time Δt after aircraft #2.

These conditions can be expressed in the following equation:

$$\frac{TH2INT}{V_{MA2}} + \Delta t = \frac{(TH1INT + MAPTH1)}{V_{MA1}} + \frac{(X1 - MAPTH1)}{V_{AP1}} \quad (E.1)$$

where TH2INT = The distance from the threshold of R/W #2 to the intersection point



**FIGURE E-1
MEMPHIS DEPENDENT APPROACHES ILLUSTRATING GATE CONCEPT**

- V_{MA2} = The missed approach speed of aircraft #2
 $MAPTH1$ = The distance from the MAP to the threshold of R/W #1
 $X1$ = The distance from the "gate" to the threshold of R/W #1
 V_{AP1} = The approach speed of aircraft 1

(See Figure E-2).

This equation can be solved for $X1$:

$$X1 = MAPTH1 + V_{AP1} \left[\frac{TH2INT}{V_{MA2}} - \frac{(TH1INT + MAPTH1)}{V_{MA1}} \right] + \Delta t \quad . \quad (E.2)$$

In our calculations we assumed that $V_{AP} = 1.3 V_S$, where V_S is the aircraft stall speed, and $V_{MA} = 1.5 V_S$. Therefore,

$$V_{MA} = 1.155 V_{AP} \quad (E.3)$$

It can be seen from equation E.2 that $X1$ will be largest when V_{AP1} and V_{MA1} are large, and when V_{MA2} is small. We consequently assumed that aircraft #1 was a heavy ($V_{AP} = 140$ kn) and aircraft #2 was small ($V_{AP} = 100$ kn).

We also assumed a minimum time separation at the intersection point of 30 seconds. If aircraft #1 is slower than assumed, or aircraft #2 is faster, the actual time separation will be greater.

The possibility of a wake vortex encounter at the intersection point is not expected to be a severe restraint on dependent converging approaches. The baseline case used to calculate $X1$ involves a heavy and a small aircraft crossing the intersection point 30 seconds apart, but the small aircraft is ahead of the heavy. If the heavy aircraft had been ahead, posing a vortex hazard to the small aircraft, the time differential would have been greater--at least 52s in the case of MEM. This might be adequate, considering the lesser hazard presented by crossing a vortex obliquely, compared with an on-axis encounter. If this time is not adequate, equation E.2 can be used to calculate the gate locations necessary to produce the desired separation. (Aircraft #1 would be a small aircraft, aircraft #2 would be a heavy.)

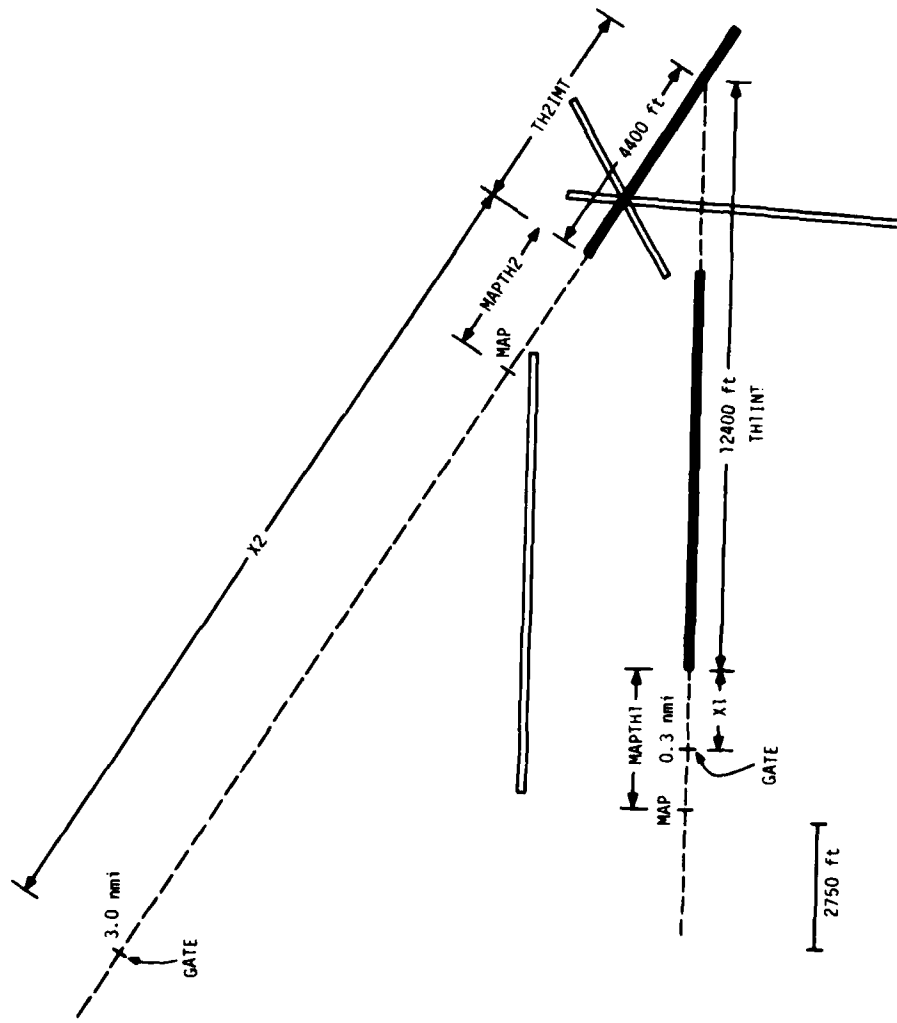


FIGURE E-2
MEMPHIS DEPENDENT APPROACHES ILLUSTRATING
GEOMETRY PARAMETERS

E.2 Capacity

The capacity of a dependent converging approach has been calculated based upon the type of dependency described above.

The time between arrivals is calculated based upon the following constraints:

- Runway occupancy time,
- Airborne separation between arrivals to the same runway, and
- Minimum time separation between alternating arrivals to different runways, based upon "gates" on the final approach.

The calculation is performed as follows. For a given quadruplet of aircraft, ijkl, with i and k arrivals to R/W #1 and j and l arrivals to R/W #2:

- The time of arrival at the R/W #1 threshold for aircraft i (TTH1) is calculated first.
- At TTH1, aircraft j is at the gate for R/W #2, X2. Its time of arrival at the threshold (TTH2) is then calculated, based upon its approach speed, with a buffer added.
- The time of arrival for k, TTH3, is the maximum of:
 - TTH1 plus runway occupancy time;
 - TTH1 plus time to fly the minimum separation between i and k;
 - TTH2 plus the time to fly from the runway 1 gate, X1;plus a buffer.
- TTH4 is calculated similarly.
- The difference between TTH4 and TTH2 is then weighted by the proportion of aircraft types i, j, k and l in the mix. Once a weighted average is obtained for all values of i, j, k, and l, the process is repeated for those cases where the first arrival is bound for runway 2.

The resulting overall average interarrival time is then inverted to give the hourly arrival capacity.

APPENDIX F

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