Development of Risk Models for Simultaneous Instrument Landing System Approaches to Closely Spaced Parallel Runways

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The potential for safely reducing the runway separation standard for simultaneous instrument landing system (ILS) approaches is demonstrated; the standard is based on the current surveillance system. A general autoregression model that generates realistic and stabilized final approach flight tracks is developed. The model is then used in a simulation of simultaneous ILS approaches during which the aircraft deviate normally about the ILS (Simulation 1), to study the probabilities of violating the no-transgression zone and causing false alarms (the probability that radar displays the aircraft in the no-transgression zone when it actually is in the normal operating zone). Simulation 2, which is similar to Simulation 1, considers a worst-case scenario of simultaneous ILS approaches during which one aircraft blunders and determines the probability of collision. Simulation 1 and 2 results indicate that the minimum runway separation that maintains the probabilities of false alarm and collision for the current runway separation and surveillance system is 3,700 ft, when used with radar having an update interval of 2.4 sec and an accuracy of 1 milliradian.

Air travel delays resulting from limited airport capacity are a significant problem for the FAA and the airline industry. Airport capacity is greatly reduced during instrument meteorological conditions (IMC), which are typically conditions with a measured or estimated ceiling less than 1,000 ft or visibility less than 3 mi; during IMC the number of arrivals that can be accepted is well below that attained during visual meteorological conditions.

To increase the capacity of existing airports, the FAA allows simultaneous, independent instrument landing system (ILS) approaches (each approach has its own ILS equipment) to closely spaced parallel runways, which will be referred to as “parallel approaches.” However, current FAA regulations stipulate that there must be at least 4,300 ft between runway centerlines for these approaches to occur under IMC with current surveillance systems, which include radar with an azimuthal accuracy of about 5 milliradians (mr), an update interval of 4.8 sec, and Automated Radar Terminal System (ARTS) displays (1). The regulation restricts arrival capacity not only at airports with parallel runways separated by less than 4,300 ft but also at airports that do not have the additional space needed to add a usable runway parallel to an existing one. The FAA is interested in decreasing the spacing regulation to help increase the capacity of airports during IMC.

Requirements for the authorized use of parallel approaches in addition to the 4,300-ft centerline spacing are as follows (2):

1. ILS, radar, and two-way radio communications;
2. Aircraft separated by a minimum of 1,000 ft vertically or 3.0 nautical-mi (nmi) longitudinally on radar until established on their respective localizer courses;
3. Two monitor controllers to ensure lateral separation between aircraft and to intercede in the event of an aircraft blunder; and
4. A 2,000-ft-wide no-transgression zone (NTZ) centered between the two extended runway centerlines.

The ILS is a combination of independent transmitters that provide navigational guidance for aircraft executing an instrument flight rules (IFR) approach. One such transmitter is the localizer, which radiates a horizontal, 3- to 6-degree fan-shaped beam that provides lateral guidance for aircraft on final approach to a distance of 18 nmi from the runway. Another transmitter is the glide slope, which provides a vertically oriented, 1.4-degree fan-shaped beam that provides altitude guidance. The composite beam resulting from these transmitters defines a precise approach course for arriving aircraft.

The approach course runs along the imaginary line (the extended runway centerline) projecting upward from the end of the aircraft’s assigned runway (the runway threshold) at approximately a 3-degree angle relative to the ground. Each runway has an approach course with an independent ILS. ILS approach procedures require that arriving aircraft be established on the localizer (flying within the localizer course) before intersecting the outer marker, which is approximately 5 nmi from the runway threshold. For parallel approaches, this distance is typically extended to 10 nmi or more (3).

During parallel approaches, two aircraft turn onto their respective approaches at different altitudes. The aircraft are required to maintain at least 1,000 ft of vertical separation until both are established on the localizer. At this point, vertical separation may be lost. Thus, after stabilization, the aircraft are proximate in the vertical direction of flight. The aircraft may also be proximate in the longitudinal direction of flight. Therefore, for stabilized parallel approaches, lateral
deviation of the aircraft from their respective ILSs must be controlled to ensure safe approaches.

Aircraft normally deviate from the ILS as a result of the angular spread of the localizer beam and the increase in the signal noise from the beam as it is radiated from the transmitter (4). The magnitude of an aircraft's lateral deviation from the ILS decreases as the distance from the runway threshold decreases. Aircraft might also blunder, or abnormally deviate from the ILS, because of pilot error or equipment failure.

Parallel approaches require two monitor controllers, who are used to ensure lateral separation between aircraft on adjacent runways. The monitor controllers are located at the same ARTS display and are responsible for keeping their aircraft within the normal operating zone (NOZ) on the proper side of the NTZ. Figure 1 illustrates the positioning of the NOZs and the NTZ between extended runway centerlines.

Most of the time, the ILS receivers and aircraft navigation systems are accurate enough to guide the aircraft directly down the path of the extended runway centerline without significant lateral deviation to either side. However, in the event that an aircraft is observed on a track that would violate the NTZ, the monitor controller in charge of that runway is required to advise the pilot to turn left (or right) and return to localizer course (5). When an aircraft is observed to be blundering and violating the NTZ in a manner that could jeopardize an aircraft on the adjacent approach, the monitor controller of the endangered aircraft orders the aircraft's pilot to execute an evasive maneuver, which is a combination turn-and-climb maneuver away from the adjacent runway. The other monitor controller should continue to attempt to have the pilot of the blundering aircraft correct the errant course.

The endangered aircraft is vectored off the ILS course instead of the blundering aircraft for two principle reasons: (a) the pilot of the blundering aircraft has demonstrated an inability to navigate or control the aircraft adequately, and (b) doing so increases the airspace between the two conflicting aircraft (5). If the monitor controller of the blundering aircraft is unable to correct its course, then it is handed off to be resequenced into the traffic pattern.

**RESEARCH OBJECTIVES**

The objective of this research is to demonstrate the potential for safely reducing the runway separation standard for parallel approaches, which is based on current surveillance system configurations. A mathematical model developed to represent the flight track of an aircraft stabilized on the ILS is used in the simulation of parallel approaches, during which both aircraft deviate normally from their respective ILSs. The simulation is run for various distances between parallel runway centerlines. This distance is referred to as "runway separation." For each runway separation considered, we determine the probability of an actual NTZ violation and of a false alarm for several combinations of radar accuracies and update intervals; a false alarm is defined as the probability that the radar displays the aircraft in the NTZ when it is actually in the NOZ. The mathematical model is used in another simulation of parallel approaches, during which a standardized aircraft blunder (abnormal lateral deviation) is introduced. The simulation is also run for different runway separations, radar accuracies, and update intervals, the probability of collision (the probability that the smallest distance between two aircraft during parallel approaches is less than or equal to 500 ft) is determined for each runway separation. The results from the 4,300-ft runway separation regulation with current system configurations are compared with those from smaller runway separations with different system configurations. Conclusions are drawn about the possible reduction of the current runway separation regulation.

**LITERATURE REVIEW**

Research on the risk analysis of parallel approaches that is related to this work can be grouped into two categories: (a) data collection and analysis studies and (b) parametric blunder resolution models (6). For both categories, we limit our discussion to the most recent and most relevant studies.

**Data Collection and Analysis Studies**

Data from direct observation of aircraft executing IFR approaches are collected and analyzed to determine the risk involved in parallel approaches. The resulting data are compiled to generate statistics for the lateral ILS deviation of the aircraft such as the mean, standard deviation, and percentage containment (the percentage of aircraft that fly within the respective NOZs).

In early 1989, under the objective of decreasing the spacing regulation, Thomas and Timoteo conducted a study at O'Hare International Airport in Chicago during which ILS flight tracks were collected, written to a data base, and analyzed (3). The analysis consisted of considering the flight tracks in three different views depending on the definition chosen for ILS localizer acquisition. Each successive view removed slightly more data from the approach's localizer acquisition phase. View 1 included some turn-on and all initial overshoot. (Turn-on is defined as the aircraft's turn onto the extended runway centerline in order to begin the final approach. The aircraft may overshoot the extended runway centerline when turning onto it and must turn back toward it, hence the oscillations during final approach.) View 2 included either a small amount of initial overshoot or, if there was no initial overshoot, a small amount of turn-on. View 3 contained only the View 2 tracks with initial localizer stability points of 10.5 mi or more from touchdown. The analysis showed that after
stabilization on the localizer (View 2), the lateral ILS deviation decreased with the range from runway threshold. The data generally suggested that the current ILS navigational performance of a typical mix of aircraft types at a large airport could support a decreased runway separation over what is currently permissible during IMC.

**Parametric Blunder Resolution Models**

Parametric blunder resolution models are for parallel approaches during which at least one aircraft abnormally deviates from the ILS. They are used to determine if a standardized worst-case blunder situation can be resolved safely. A standardized worst-case blunder is described by the maneuver in which an aircraft makes an unusually sharp 30-degree turn off its assigned ILS, toward the aircraft on the adjacent ILS. This turn is defined as the worst conceivable excursion from an assigned course that an aircraft could experience, because of pilot error or equipment failure. Although there is no documented instance of an actual blunder of this magnitude, this modeling approach for evaluating safety risk has become generally accepted by researchers and the FAA.

To resolve the blunder situation, an evasive maneuver is executed by the endangered aircraft. This conservatively assumes that the blundering aircraft has lost either communications or control and the monitor controller’s attempts to correct the errant course are unsuccessful. The situation is considered resolved when the endangered aircraft, after receiving instructions from the monitor controller, achieves a heading parallel to that of the blundering aircraft. The miss distance is defined as the smallest lateral or slant distance between the aircraft that are conducting parallel approaches.

Altschuler developed a model to determine the risk of collision for simultaneous ILS approaches (6). Altschuler used analytical models and fast-time simulation to determine the probability of collision. The model was based on the assumption that the lateral ILS deviation can be modeled using a Gaussian distribution with a mean of zero and a constant standard deviation. It also used estimates of significant parameters, such as the controller-to-pilot communication delay and the pilot/aircraft response delay.

Hollister developed the Blunder Risk Model for Lincoln Laboratory; the model is a Monte Carlo simulation of the events and aircraft positions during a worst-case blunder situation (7,8). The model was designed to assist in the evaluation of Precision Runway Monitor (PRM) radars and displays. The per-blunder failure (collision) rate was calculated on the basis of the number of approaches during which the miss distance was less than 500 ft. It is important to note that the results of this simulation were based on PRM aircraft tracking and alert generation algorithms. It could not be used in its present form to model the current surveillance system. In addition, raw data distributions were used to estimate controller response and communication delay times.

The Blunder Resolution Performance Model (BRPM) was a Monte Carlo simulation model developed by MITRE Corporation (9). It was intended to assist the FAA in the development of national standards for multiple parallel approaches. The BRPM was a Lotus 1-2-3 spreadsheet that represented a single blunder scenario and operated under the following assumptions:

1. There is no glide slope error.
2. Course deviations have a Gaussian distribution with a zero mean and a standard deviation proportional to the distance from the runway threshold.
3. The statistical distributions for controller and pilot delay times are known and statistically independent of one another.

The BRPM is similar to Hollister’s model and can be used to model both current and PRM surveillance systems. BRPM determines the minimum slant range and horizontal range for each iteration and statistically analyzes the results after all iterations have been completed.

**Summary**

Data collection and analysis studies are advantageous because there is little need for simplifying assumptions. Accordingly, results based on collected data traditionally have been more convincing to policy makers. However, to obtain a statistic such as the probability of NTZ penetration, enormous amounts of data are needed. In addition, sensitivity analyses are difficult to perform. This research develops a mathematical model based on the Chicago data (3) that is capable of generating thousands of realistic, stabilized flight tracks. The model will be used in determining the probability of NTZ penetration and the corresponding probability of a false alarm for various runway spacings.

The main advantage of parametric blunder resolution models is that they support parametric analysis of controllable design parameters and allow for sensitivity analysis of competing systems. However, it is very difficult to estimate some parameters accurately because such data are not readily available. This research develops a simulation model similar to those of Hollister and MITRE that is used to model the current surveillance system. It is different from the previous models because probability distributions that describe actual data are used to generate delay times. In addition, an evasive maneuver model is used to generate the path of the endangered plane. This gives control over parameters such as the velocity of the endangered plane and the turn rate that it uses in its evasive maneuver. The model will be discussed in the following sections.

**MATHEMATICAL MODEL DEVELOPMENT**

This research uses the Chicago View 2 data in the development of a mathematical model that represents the approach path of an airplane flying the ILS after it is stabilized on the localizer. View 2 data are used because, according to Thomas and Timoteo, View 2 gives the best estimate of how the general population of simultaneous ILS approaches at Chicago navigate the ILS (3). After extensive review of the actual stabilized flight tracks, it is determined that representing all of the tracks with a single model would be difficult. Further review of the data indicates that many flight tracks share
similar characteristics with respect to shape and can be categorized into the following families:

<table>
<thead>
<tr>
<th>Family</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Asymptotic approach to centerline</td>
</tr>
<tr>
<td>2</td>
<td>Asymptotic approach to shifted centerline</td>
</tr>
<tr>
<td>3</td>
<td>Multiple deviations around centerline</td>
</tr>
<tr>
<td>4</td>
<td>Multiple deviations around shifted centerline</td>
</tr>
<tr>
<td>5</td>
<td>Multiple deviations around radial centerline</td>
</tr>
</tbody>
</table>

Figure 2 illustrates a sample flight track for each family.

Categorizing the flight tracks into the five families facilitates the mathematical model development because of the common characteristics within each family. Flight tracks of 1,377 airplanes are visually inspected and assigned a family number and a value for the centerline shift when applicable. Shift values range between -200 and 250 ft. A positive shift value indicates that the approach is shifted to the right of the extended runway centerline, and a negative shift value indicates that the approach is shifted to the left. A positive shift value is depicted in Figure 2 for Families 2 and 4. The probability distribution of the categorization is as follows:

<table>
<thead>
<tr>
<th>Family</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0261</td>
</tr>
<tr>
<td>2</td>
<td>0.0232</td>
</tr>
<tr>
<td>3</td>
<td>0.3501</td>
</tr>
<tr>
<td>4</td>
<td>0.4989</td>
</tr>
<tr>
<td>5</td>
<td>0.1017</td>
</tr>
</tbody>
</table>

Families 1 and 2 represent a small proportion of the total flight tracks. Most flight tracks fall into Families 3 and 4. Therefore, the mathematical model is developed to represent specifically Families 3 and 4 and is modified to represent Families 1, 2, and 5.

An autoregression model is developed that is a general case of control theory's second-order damping model. It is a position-dependent model (the current position can only be determined if the previous two positions are known) that includes a parameter $\beta$ and an error term, which is normally distributed with a mean of zero and a standard deviation of $\sigma$. The model is explained as follows: let $y_t$ be the aircraft's location at time $t$; the flight track is assumed to be represented by a cosine curve.

$$y_t = \cos(t)$$  \hspace{1cm} (1)

Assume $\beta$ to be a small time increment. Then $y_{t-1}$ is the location of the plane at time $t - 1$, and $y_{t-2}$ is the location of the plane at time $t - 2$. It follows that

$$y_{t-1} = \cos(t - \beta)$$  \hspace{1cm} (2)

$$y_{t-2} = \cos(t - 2\beta)$$  \hspace{1cm} (3)

After substituting trigonometric expansions and simplification:

$$y_t = \frac{1}{1 + \beta^2} (2y_{t-1} - y_{t-2}) + \epsilon$$  \hspace{1cm} (4)

$$\epsilon \sim N(0, \sigma)$$

The $1/(1 + \beta^2)$ term is responsible for the rate of damping (the rate at which the amplitude of the deviations decreases with time). As $\beta$ becomes larger, the approach to the centerline becomes steeper, the amplitude of the deviations around the centerline becomes smaller, and the flight track stabilizes sooner.

Further examination of the autoregression model reveals that it can be used to represent flight tracks in Families 1 and 2 as well as Families 3 and 4 with a change in the range of the parameter $\beta$. However, Family 5 can be represented only when a radial term is added to the autoregression model:

$$y_t = \frac{1}{1 + \beta^2} (2y_{t-1} - y_{t-2}) + \epsilon + \Delta$$  \hspace{1cm} (5)
where \( \Delta \) is the vertical component of the radial shift that decreases with the range from the runway threshold. The radial shift can be calculated as follows:

\[
\Delta = x \tan(\phi)
\]  

(6)

where \( \phi \) is the radial shift angle and \( x \) is the airplane's range from the runway threshold.

The autoregression model is based on the following simplifying assumptions:

1. The shapes of the actual, stabilized ILS flight tracks used in generating the model are representative of all possible flight track shapes.
2. All possible combinations of visibility and ceilings, as well as crosswind and shear conditions, are represented in the actual data on which the model is based.
3. The aircraft types included in the data are representative of all aircraft.

At this point, a computer program is written to determine the extent to which the autoregression model represents the flight tracks in all five families. The program reads an actual flight track from a data file and generates many simulated flight tracks that have all possible parameter value combinations chosen from a wide range of \( \beta \) and \( \sigma \)-values. These initial ranges of \( \beta \) and \( \sigma \) are determined empirically by comparing model behavior with flight track behavior. A simulated flight track has the same length as the corresponding actual track and is composed of a series of lateral positions that are generated by the autoregression model every 0.45 nmi along the final approach. The simulated track's lateral positions are compared to those of the corresponding actual track every 0.45 nmi. The sum of squared errors between the simulated and actual lateral positions is calculated, and it is decided whether the autoregression model can be used to represent the actual flight track using the following criterion: the autoregression model adequately represents an actual flight track when, for at least one of the simulated flight tracks, 70 percent of the simulated lateral positions are within 150 ft of the actual lateral positions.

If the actual track is adequately represented by the autoregression model, the parameters of the simulated flight track with the smallest sum of squared errors are considered to represent optimally that actual track.

The program is run using 1,377 actual flight tracks. Results indicate that the autoregression model adequately represents 1,203 of 1,377 actual flight tracks, or 87.36 percent. The optimal parameters of each family's actual tracks are developed into probability distributions for use in the simulations. The range of \( \sigma \) is the same for each family, 0.004 \( \leq \sigma \leq 0.008 \). The ranges of \( \beta \) are as follows:

- Families 1 and 2: \( 2.0 \leq \beta \leq 4.0 \)
- Families 3 and 4: \( 0.5 \leq \beta \leq 1.4 \)
- Family 5: \( 0.5 \leq \beta \leq 1.0 \)

The range of \( \phi \) for the Family 5 model is \( 0.20 \leq \phi \leq 0.30 \).

Because of statistical similarities between the \( \beta \) and \( \sigma \) probability distributions of Families 1 and 2, they are combined.

The same occurs for the probability distributions of Families 3 and 4.

The family probability distribution, autoregression model, and its parameter distributions for each family, along with other distributions for the shift values and the initial two lateral locations, are used to generate stabilized flight tracks for the simulation models explained in the following.

**SIMULATION 1: RISK MODEL FOR NORMAL ILS DEVIATION**

Simulation 1 generates the probability of NTZ violation and the probability of false alarm for different combinations of runway separation, radar update intervals, and radar accuracies.

**Methodology**

Simulation 1 generates parallel approaches during which aircraft normally deviate about the ILS. An experiment is run for a given set of variables; it consists of 5,000 trials of parallel approaches. In each trial, two stabilized flight tracks are generated randomly by the autoregression model and are superimposed on final approach paths. After a random delay time to the first radar update, which is less than or equal to the radar update interval, an amount of radar error is generated randomly and added to the actual lateral location to give the radar lateral location. Next, the actual and radar lateral locations of both aircraft are checked to determine if an actual or radar NTZ violation occurs. If neither occurs, the program waits until the next radar update, again adds radar accuracy to the actual lateral location and checks the actual and radar lateral locations of both aircraft. If the actual or radar (or both) indicates NTZ violation, the trial is stopped momentarily and statistics for the number of false alarms and actual NTZ violations are updated. The trial is then continued in the same manner to collect only actual NTZ violation data. The trial ends after both aircraft have reached their respective runway thresholds and the probabilities of NTZ violation and false alarm are computed.

**Variables**

1. Runway separation: Values between 3,400 and 4,300 ft, inclusive, are considered. The 4,300-ft distance represents the U.S. national standard with current surveillance systems. Runway separations of less than 3,400 ft are not considered because a recent FAA regulation specifies that parallel approaches are allowed when runway separation is at least 3,400 ft and the PRM surveillance system is in use (7). Therefore, it is unrealistic to consider the current surveillance system with runway separations of less than 3,400 ft.

2. Radar update interval: Values of 1, 2.4, and 4.8 sec are considered on the basis of the current surveillance system and other available technologies (7).

3. Radar accuracy: Values between 1 and 5 mr, inclusive, are considered.
4. Stabilization range: The stabilization range for the aircraft on the right approach is 12.5 nmi. The range for the aircraft on the left approach is generated randomly in the following manner:

\[ \text{velocity} = 129.3 + (R \times 64.9) \]

where \( R \) is uniform \((0,1)\) and 129.3 knots/194.2 knots represents the minimum/maximum airspeed attained by aircraft on final approach, as studied by the FAA’s Aviation Standards \((8,10,11)\).

5. Velocity: The velocity (measured in knots) of each plane is generated randomly in the following manner:

\[ \text{velocity} = \frac{2,000}{2}. \]

Results from the NTZ violation analysis provide the probability of an aircraft’s entering the NTZ during its approach to either of the parallel runways. Results from the false alarm analysis give the probability of an aircraft’s, on either approach, being displayed within the NTZ when its actual location is in the NOZ. Table 1 gives the average results of the experiments.

The analysis may be considered a worst case with respect to both the probabilities of NTZ violation and of a false alarm because controller intervention is assumed to occur only after the aircraft is displayed by the radar to be violating the NTZ. If the controller intervenes when it appears that the aircraft is heading toward the NTZ, to turn the aircraft back toward its ILS, some NTZ violations and false alarms may be prevented.

From Table 1, as expected, the probability of NTZ violation increases as the runway separation decreases. In addition, the marginal increase in the probability of NTZ violation is greater for smaller runway separations. If the runway separation regulation can be decreased only when the current probability of NTZ violation is maintained \((0.0057, or 1 in 175 approaches during which NTZ violation occurs), clearly the accuracy of aircraft ILS navigation must be improved.

The false alarm probabilities are plotted in Figure 3. For each update interval/accuracy combination, the probability of a false alarm increases as runway separation decreases. And like the probability of NTZ violation, the marginal increase in the probability of a false alarm is greater for smaller runway separations. The radar update interval/accuracy combination that shows the worst performance is 4.8 sec/5 mr; that which shows the best performance is 2.4 sec/1 mr. Although the 1.0 sec/l mr combination has the same radar accuracy as the 2.4 sec/1 mr combination, it results in a greater probability of false alarm for every runway separation because there are approximately 2.5 more radar updates.

These results suggest that the current probability of a false alarm is between the two bounds of 0.0065 and 0.0357. If the lower bound \((0.0065, or 1 false alarm in 153 approaches) is the probability that must be maintained when considering the reduction of the 4,300-ft runway separation regulation, fea-

**Assumptions**

Simulation 1 operates under the following assumptions:

1. The moment that the monitor controller perceives an aircraft (its radar lateral location) to be within the NTZ, he or she instructs the plane on the adjacent approach to execute an evasive maneuver.

2. All movements by both aircraft take place in the assigned glide slope.

3. Radar error is normally distributed with a mean of zero and a standard deviation equal to the radar accuracy \((1 - 5 \text{ mr})\).

4. Radar range error is negligible.

5. The width of the NTZ is 2,000 ft.

6. The width of the NOZ is equal for each plane and is calculated as \((\text{runway spacing} - 2,000)/2\).

7. The autoregression model generates realistic, stabilized flight tracks for a typical mix of today’s aircraft.

**Simulation 1 Results**

For each runway separation considered, 18 experiments are run, each having a unique combination of random number stream seeds. An update interval of 4.8 sec is studied with radar accuracies of 3, 4, and 5 mr. These combinations reflect the parameter values of current surveillance systems \((1,6)\). In addition, more recent technologies have the following radar update interval and accuracy values: 4.8 sec/2 mr, 2.4 sec/1 mr, and 1.0 sec/1 mr \((7)\). These combinations are also considered in the analysis.

<table>
<thead>
<tr>
<th>Runway Separation (feet)</th>
<th>Probability of NTZ Violation</th>
<th>Radar Update (seconds) / Radar Accuracy (milliradians)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4.8 sec</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 mr</td>
</tr>
<tr>
<td>4300</td>
<td>0.0057</td>
<td>0.0026</td>
</tr>
<tr>
<td>4200</td>
<td>0.0076</td>
<td>0.0030</td>
</tr>
<tr>
<td>4100</td>
<td>0.0090</td>
<td>0.0034</td>
</tr>
<tr>
<td>4000</td>
<td>0.0112</td>
<td>0.0042</td>
</tr>
<tr>
<td>3900</td>
<td>0.0135</td>
<td>0.0050</td>
</tr>
<tr>
<td>3800</td>
<td>0.0166</td>
<td>0.0073</td>
</tr>
<tr>
<td>3700</td>
<td>0.0196</td>
<td>0.0077</td>
</tr>
<tr>
<td>3600</td>
<td>0.0234</td>
<td>0.0139</td>
</tr>
<tr>
<td>3500</td>
<td>0.0274</td>
<td>0.0185</td>
</tr>
<tr>
<td>3400</td>
<td>0.0333</td>
<td>0.0244</td>
</tr>
</tbody>
</table>
TABLE 2 Alternatives for Runway Separation Regulation Based on Probability of False Alarm

<table>
<thead>
<tr>
<th>Runway Separation (ft)</th>
<th>Update Interval/Accuracy</th>
<th>Probability of False Alarm</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,000</td>
<td>1.0 sec/1 mr</td>
<td>0.0062 (1 FA/161 approaches)</td>
</tr>
<tr>
<td>3,900</td>
<td>4.8 sec/2 mr</td>
<td>0.0050 (1 FA/200 approaches)</td>
</tr>
<tr>
<td>3,600</td>
<td>2.4 sec/1 mr</td>
<td>0.0046 (1 FA/217 approaches)</td>
</tr>
</tbody>
</table>

Note: FA = false alarm

FIGURE 4 Illustration of standardized worst-case blunder.
aircraft on the adjacent approach. An experiment consists of 5,000 trials of parallel approaches and is run for a given set of variables, the same as defined for Simulation 1 in addition to those defined in the following. The blundering aircraft travels at a constant speed along an approach track randomly generated by the autoregression model. When it reaches the blunder range, it begins its blunder maneuver and turns toward the adjacent approach, with its turn rate accelerating until the desired rate is obtained. The blundering aircraft continues to turn at this rate until it reaches the blunder angle. It continues to fly at this heading for the rest of the trial. At the same time, the endangered plane flies at a constant speed along its approach track, which is also determined randomly by the autoregression model. Before the endangered aircraft can begin its evasive maneuver, a series of time delays must take place: detection delay, possible blocked frequency delay and communication/start turn delay. After the delays, the endangered aircraft turns in the same manner as described for the blundering aircraft, until it achieves a heading parallel to that of the blundering aircraft. The miss distance, or the smallest distance between the aircraft, is calculated every second after the blunder maneuver is initiated. The trial is terminated after both aircraft have flown at the same blunder heading for 5 sec. The minimum miss distance for each trial is recorded. If the minimum miss distance is less than 500 ft, a collision is assumed to occur. After the desired number of simulation trials are completed, the probability of collision is calculated as the number of collisions divided by the total number of trials.

Variables

1. Blundering aircraft: It is randomly determined before the start of each parallel approach whether the blundering aircraft is on the left or on the right approach.
2. Blunder range: The blunder range is generated randomly and varies between 5 and 12 nmi.
3. Turn rate acceleration: The acceleration is 1 degree per second
4. Turn rate: The rate is 3 degrees per second.
5. Blunder angle: The angle is 30 degrees.
6. Detection delay: This delay is the time lapse from the start of the blunder to the first time the blundering aircraft is displayed by the radar to be in the NTZ. This variable is dependent on the radar update interval and accuracy.
7. Blocked frequency blocking delay: This delay occurs if the controller’s frequency is blocked by noncontroller transmissions when he/she attempts to issue an evasive command to the endangered aircraft, with a probability of 0.0675 (7). This delay is the time that the controller must wait before he/she is able to access the frequency. Raw data for this delay have been obtained from Lincoln Laboratories, and can be represented with a Weibull distribution.
8. Communication/start turn delay: This delay begins with the time the controller begins to issue the evasive command and ends with the time that the endangered aircraft begins its evasive maneuver. Statistics on this delay are obtained from the FAA’s Aviation Standards (14,15). The communication/start turn delay is estimated to follow a Weibull distribution.

Assumptions

Simulation 2 operates under the same assumptions as Simulation 1 along with the following:

1. The course of the blundering aircraft is a linear path toward the adjacent runway at a constant blunder angle with respect to the assigned approach (I,6).
2. The pilot of the blundering aircraft is either unaware of the significant course deviation or unable to effect a correction (I,6). Any attempt by the pilot or monitor controller to correct this course will prove futile.

Simulation 2 Results

As with Simulation 1, 18 experiments are run for each runway separation using a unique combination of random number stream seeds. The same radar update interval/accuracy combinations used for Simulation 1 are considered in this analysis.

The results from Simulation 2 provide the probability of collision given a standardized blunder executed by an aircraft on either of the two final approaches. The average results of the experiments are given in Table 3.

The probabilities of collision are plotted in Figure 5. As expected, the probability of collision, for all combinations of radar update/accuracy, generally increases as the runway separation decreases. The update interval/accuracy combination that shows the best performance is 1.0 sec/1 mr, and that which shows the worst performance is 4.8 sec/5 mr. These results are consistent because with a smaller radar update interval, the aircraft locations are more frequently updated. This allows the controller to detect an aircraft that is violating the NTZ sooner and to issue evasive maneuver instructions immediately to the aircraft on the adjacent approach, generally resulting in a larger miss distance and therefore fewer collisions.

From Table 3, for a 4,300-ft runway separation, the probability of collision, given a worst-case blunder, is between the bounds of 0.0025 and 0.0028. If the lower bound (0.0025), which equates to 1 collision in 400 standardized worst-case blunders, must be maintained when considering a reduction in the runway spacing regulation, feasible alternatives are shown in Table 4.

**Table 3 Simulation 2: Probability of Collision**

<table>
<thead>
<tr>
<th>Runway Separation (feet)</th>
<th>Radar Update (seconds) / Radar Accuracy (milliradians)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.8 sec</td>
</tr>
<tr>
<td>4300</td>
<td>0.0019</td>
</tr>
<tr>
<td>4200</td>
<td>0.0024</td>
</tr>
<tr>
<td>4100</td>
<td>0.0035</td>
</tr>
<tr>
<td>4000</td>
<td>0.0042</td>
</tr>
<tr>
<td>3900</td>
<td>0.0045</td>
</tr>
<tr>
<td>3800</td>
<td>0.0059</td>
</tr>
<tr>
<td>3700</td>
<td>0.0075</td>
</tr>
<tr>
<td>3600</td>
<td>0.0081</td>
</tr>
<tr>
<td>3500</td>
<td>0.0091</td>
</tr>
<tr>
<td>3400</td>
<td>0.0111</td>
</tr>
</tbody>
</table>


FIGURE 5  Plots of probability of collision versus runway separation for various combinations of radar accuracy and update.

TABLE 4  Alternatives for Runway Separation Regulation Based on Probability of Collision

<table>
<thead>
<tr>
<th>Runway Separation (ft)</th>
<th>Update Interval/Accuracy</th>
<th>Probability of Collision</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,200</td>
<td>4.8 sec/2 mr</td>
<td>0.0024 (1 COL/416 WCB)</td>
</tr>
<tr>
<td>3,700</td>
<td>2.4 sec/1 mr</td>
<td>0.0024 (1 COL/416 WCB)</td>
</tr>
<tr>
<td>3,400</td>
<td>1.0 sec/1 mr</td>
<td>0.0021 (1 COL/467 WCB)</td>
</tr>
</tbody>
</table>

Note: COL = collision, WCB = worst-case blunder

TABLE 5  Current Regulation Compared with Suggested Regulation

<table>
<thead>
<tr>
<th>Runway Separation (ft)</th>
<th>P(NTZ)</th>
<th>P(FA)</th>
<th>P(COL/WCB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current standards 4,300</td>
<td>0.0057</td>
<td>0.0065</td>
<td>0.0025</td>
</tr>
<tr>
<td>Research results 3,700</td>
<td>0.0196</td>
<td>0.0035</td>
<td>0.0024</td>
</tr>
</tbody>
</table>

CONCLUSIONS

This research is intended to aid the FAA in its decision to reduce the parallel approach runway spacing regulation for current surveillance system configurations. Simulations are developed to quantify the probabilities of NTZ violation, false alarm, and collision given a standardized worst-case blunder, for different runway separations and combinations of radar update interval and accuracy. Simulation results for current surveillance system configurations are considered to be the level that must be maintained when a reduction in the standard is being considered.

When considering the probability of NTZ violation and the results of this research, which are based on the assumption that the monitor controller intervenes only after a NTZ violation occurs, reducing the separation regulation is possible only if aircraft ILS navigational accuracy is improved. In addition, the increased navigational accuracy, when combined with a reduced runway separation, must result in a P(NTZ) of at most 0.0057 (result for 4,300-ft runway separation). If this assumption is relaxed and an accurate controller response algorithm is developed in which controllers intervene to change the course of an aircraft when it appears to be on a path that will violate the NTZ, more realistic statistics about NTZ violation can be collected. These statistics may support a decrease in the separation regulation.

The current probability of false alarm, as calculated by Simulation 1, is equal to 0.0065. The minimum runway separation that maintains this, with a P(FA) equal to 0.0046, is 3,600 ft, when combined with a radar update interval of 2.4 sec and accuracy of 1 mr. From Simulation 2, the current probability of collision given a worst-case blunder is equal to
0.0025. The minimum runway separation that maintains this, with a \( P(\text{COL/WCB}) \) equal to 0.0021, is 3,400 ft, when combined with a radar update interval of 1.0 sec and accuracy of 1 mr. However, both the \( P(\text{FA}) \) and \( P(\text{COL/WCB}) \) must be maintained to consider a decrease in the runway separation regulation. From Tables 1 and 3, the smallest runway separation that maintains both probabilities, with a \( P(\text{FA}) \) of 0.0035 and a \( P(\text{COL/WCB}) \) of 0.0024, is 3,700 ft, when using a radar with an update interval of 2.4 sec and accuracy of 1 mr. These results are summarized in Table 5.

When examining the results, it is important to remember that \( P(\text{NTZ}) \) is based on a radar update of 4.8 sec and an accuracy of 3 mr. When the update interval is reduced, the monitor controllers have better control over the locations of the aircraft because of the increase in radar updates. For this reason, it is most likely that the \( P(\text{NTZ}) \) will be smaller for the runway separation of 3,700 ft. This research suggests that, with an improved surveillance system that has a radar update interval of 2.4 sec and accuracy of 1 mr, the runway separation regulation can be reduced to 3,700 ft, if the reduced update interval results in a \( P(\text{NTZ}) \) less than or equal to 0.0057. However, the accuracy of the risk quantifications remains untested because of the lack of available empirical data. In addition, the risk quantifications are based on many conservative assumptions and are probably conservative themselves.

REFERENCES