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Evaluation of High Update Rate Surveillance System Parameters for Closely Spaced Parallel Operations

June 2017

Technical Report

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12. Abstract

This report presents the results obtained from a fast-time simulation study of parameters upon which the performance of a high update rate (HUR) surveillance system is based. Performance parameters such as position measurement accuracy, sensor update rate, and processing time were evaluated at a runway spacing of 3400 feet, the current minimum runway spacing for HUR surveillance operations with parallel runways and final approach courses. The determination of these HUR surveillance system performance capabilities will support a follow-on analysis of collision risk as a function of HUR surveillance capabilities and runway centerline spacing to parallel and offset final approach courses for simultaneous independent parallel instrument approach procedures to closely spaced parallel runways.

The results of this study indicate that collision risk increases as surveillance sensor update rate decreases and processing time increases. From a 1-second to 2-second sensor update rate, collision risk increases sharply as position measurement accuracy improves. Beyond a 2-second surveillance sensor update rate, position measurement accuracy has a negligible impact on collision risk.

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High Update Rate (HUR) Test Criterion Violation (TCV) Final Monitor Aid (FMA) No Transgression Zone (NTZ) Precision Runway Monitor (PRM) Predictor Target Line (PTL)	Uncontrolled
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Executive Summary

This report presents the results obtained from a fast-time simulation study of surveillance parameters upon which the performance of a high update rate (HUR) surveillance system is based. An HUR surveillance system is defined as one with a sensor update rate of less than 4.8 seconds. The performance parameters of position measurement accuracy, sensor update rate, and processing time were evaluated at a runway spacing of 3400 feet (ft), the current minimum runway spacing authorized for HUR surveillance operations with parallel runways and final approach courses.

The current study indicates that collision risk increases as the surveillance sensor update rate decreases, i.e., updates slow down. It also increases as processing time increases, and it increases as position measurement accuracy improves.

The dominant factor is the surveillance sensor update rate. Position measurement accuracy has minimal impact on collision risk relative to the other parameters. The impact of each 1-second change in processing time is almost identical throughout the range of surveillance sensor update rates evaluated and results in a small change to collision risk.

The results of this evaluation will support a future analysis of simultaneous independent parallel instrument approach procedures to closely spaced parallel runways with parallel and offset final approach courses, and may also provide a foundation for the development of future HUR surveillance system capabilities as a function of HUR surveillance capabilities.

1 Introduction

When visual approaches cannot be conducted, capacity at busy airports has been significantly increased by using simultaneous independent approaches to closely spaced parallel runways, which are defined as two parallel runways whose runway centerline spacing (RCLS) is less than 4300 ft.[1] Reductions in RCLS have been achieved by use of precise navigation capabilities, improved analysis techniques, offset approaches, and specific air traffic equipment and procedures. The utilization of HUR surveillance systems has been integral in this reduction. The benefits of future HUR surveillance systems warrant further study of their associated parameters to establish performance-based capabilities. The determination of these capabilities for HUR surveillance systems may facilitate the development of future HUR surveillance systems.

1.1 Background

Standards for conducting dual simultaneous independent approaches to closely spaced parallel runways in the National Airspace System (NAS) are contained in Federal Aviation Administration (FAA) Order 8260.3, *United States Standard for Terminal Instrument Procedures* and FAA Order 7110.65, *Air Traffic Control*.[2,3]

A precision runway monitor (PRM) system is a specialized air traffic control (ATC) surveillance system required to monitor closely spaced simultaneous approaches. The FAA uses three PRM systems for these operations: (1) a standalone, Electronic Scan (E-Scan) Monopulse Secondary Surveillance Radar (MSSR) with a sensor update rate of 1 second, (2) a Standard Terminal Automation Replacement System (STARS) with multilateration with an update rate of 1 second, and (3) a STARS with an airport surveillance radar (ASR-9) Mode S MSSR with a sensor update rate of 4.8 seconds.

Each PRM system requires a high resolution color Final Monitor Aid (FMA) display with automated visual and aural alerts for each monitored runway. The monitored zone, the runways, the final approach courses, and the 2000 ft wide no transgression zone (NTZ) established equidistant between the extended final approach courses are all displayed on the FMA display. Separate monitor controllers, each with transmit/receive and override capability on the local control frequency, must ensure aircraft do not penetrate the NTZ.

Of the three PRM systems above, all but system (3) meet the HUR surveillance requirement. For approach operations to dual parallel runways spaced less than 3600 ft apart, current standards require either the use of a PRM system with an HUR surveillance sensor (less than 4.8 seconds), or one of the approaches to be offset by at least 2.5°.

[1] Air Traffic Organization, *Order JO 7110.65, Air Traffic Control*.
[2] Flight Standards Service, *Order 8260.3, United States Standard for Terminal Instrument Procedures*.
[3] Air Traffic Organization, *Order 7110.65, Air Traffic Control*.

The main parameters of an HUR surveillance system are described in detail as follows:

- A surveillance sensor capable of an update rate of less than 4.8 seconds
- An automation system processor to process the sensor data and provide target information to the display in less than 4.0 seconds
- A 1-second update rate FMA display. The FMA display is a large (not less than 20”×20”), high-resolution color monitor. The display, as shown in Figure 1-1, must be capable of depicting the NTZ, a 10-second predictor target line (PTL), and must provide visual and aural alerts when an aircraft is projected to enter, or has entered the NTZ. Final approach monitor controllers are dedicated to each runway and each is provided a display.

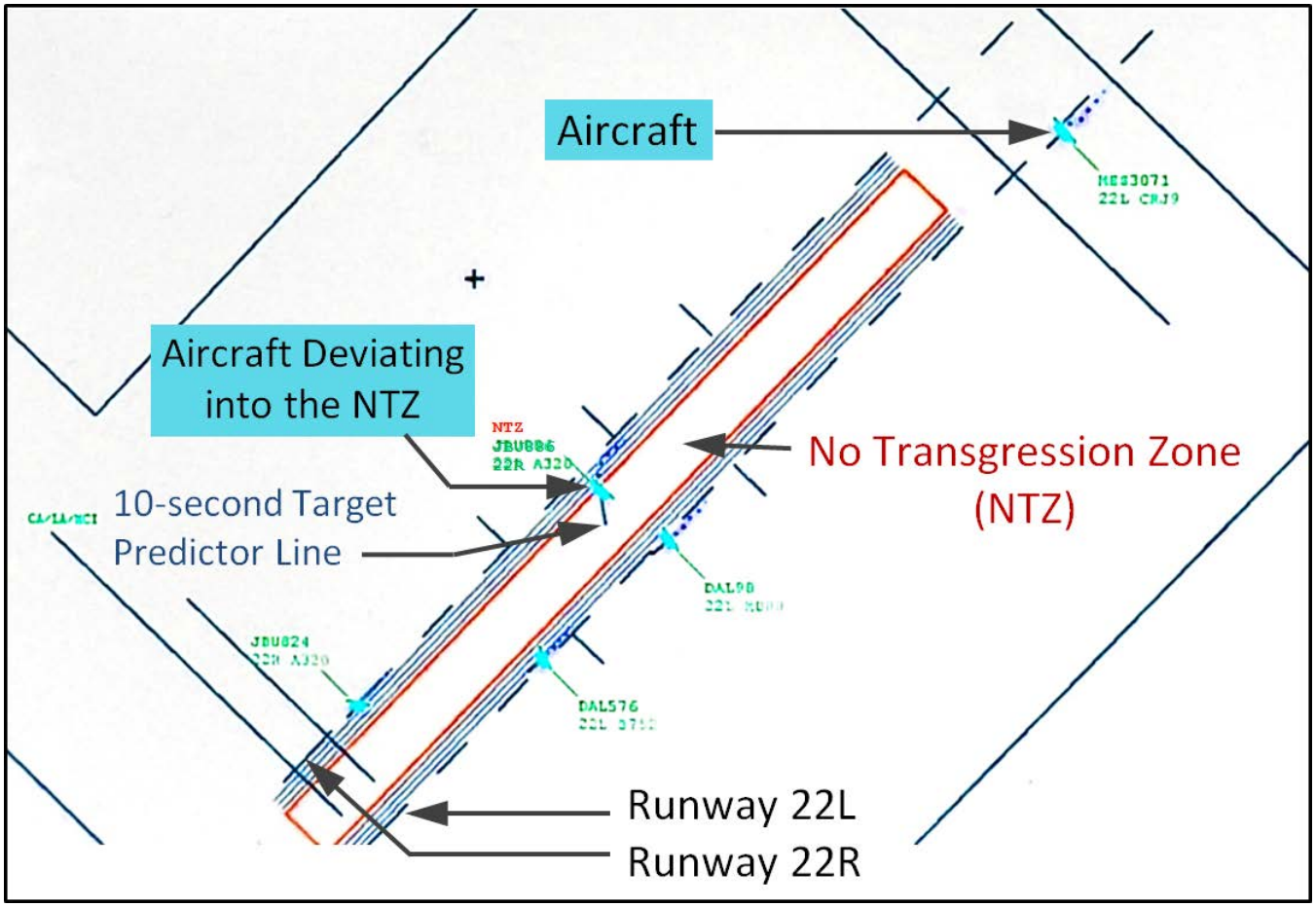

Figure 1-1: Example of FMA Display

Despite being operationally effective, the PRM system using the E-Scan radar has proven costly to procure and maintain. The PRM-Alternative (PRM-A) multilateration system is a substitute for E-Scan radar in meeting the HUR surveillance system requirement. A multilateration system determines the aircraft’s position by measuring the time of arrival of the signal from an aircraft’s beacon transponder to small, strategically placed sensors on the airport and along the final approach courses to be monitored. STARS, which is currently being deployed at various FAA facilities, includes a controller display with the features and functionality to serve as an FMA.

1.2 Purpose

The purpose of this report is to present the results of an analysis identifying the impact of various HUR surveillance system parameters on the collision risk associated with dual simultaneous independent instrument approaches to parallel runways and final approach courses. The system parameters depicted in Figure 1-2 were used in the evaluation of an HUR surveillance system with a 10-second track predictor and a 1-second FMA display update rate.

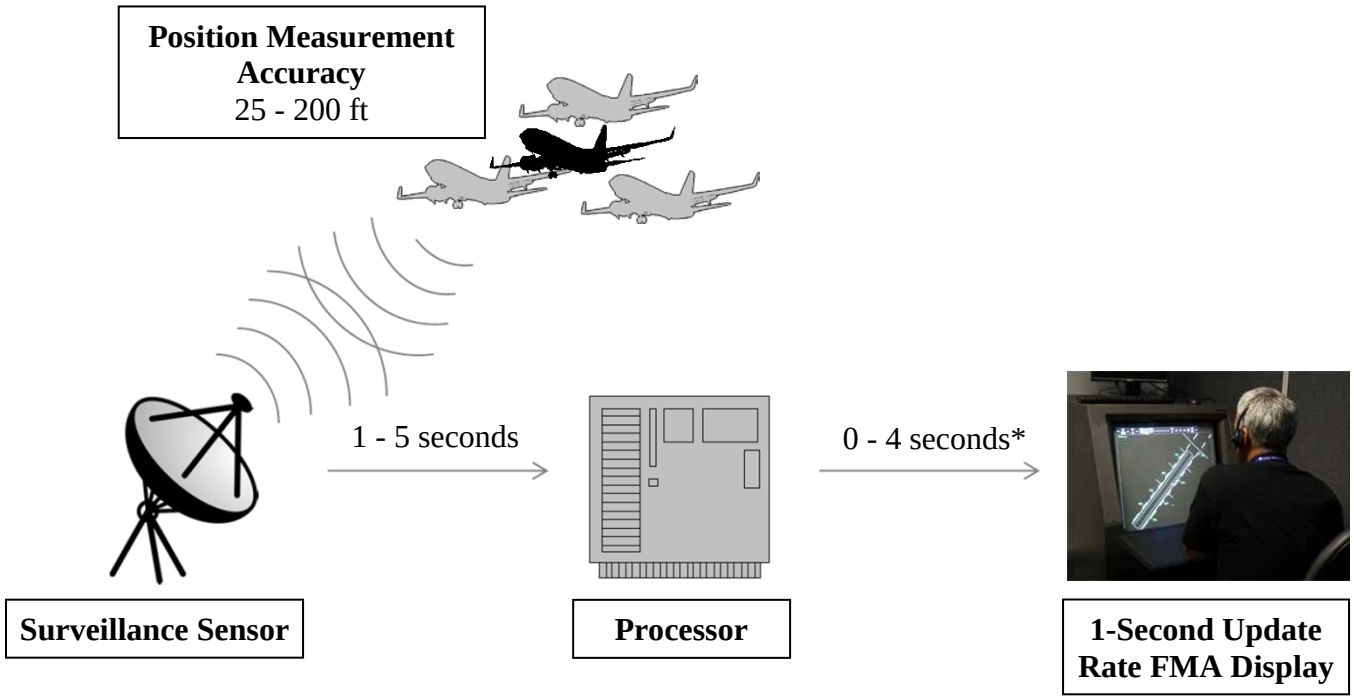

Figure 1-2: HUR Surveillance System Parameters

* A zero (0) processing time was simulated as there may be a system capability less than 1.0 second in the future. To cover that possibility, a zero value was chosen. A second possibility is the processed target information may be delivered to the display an instant before the display update, in which case, it will be displayed as though the processing time was essentially zero.

The results of this report will be used in a future analysis of the collision risk associated with approaches to parallel runways with an RCLS of less than 3600 ft including both straight-in and offset final approach courses.

2 Objective and Scope

The objective of this study was to establish values for various parameters of HUR surveillance systems that will be acceptable for use in future closely spaced parallel operations (CSPO) analysis of parallel runways with both parallel and offset final approach courses. The scope of this report is limited to collision risk and did not address wake turbulence avoidance, radar separation standards, or controlled flight into terrain.

3 Methodology

3.1 Fast-Time Simulation

The primary analysis tool for this evaluation was the Airspace Simulation and Analysis Tool – Next Generation (ASAT^{ng}). ASAT^{ng} is a multifaceted fast-time simulation tool for aviation related safety assessments. ASAT^{ng} uses high fidelity models of all components of an aviation scenario to evaluate the overall risk of an operation. A wide range of parameters covering operational aspects such as aircraft performance, atmospheric conditions, navigation system performance, ATC monitoring equipment, ATC surveillance equipment, pilot response time, and controller response time enable very efficient and realistic modeling of complex operational scenarios. ASAT^{ng} also uses official FAA databases of navigation and surveillance facilities, runways, fixes, etc. Additionally, aircraft fleet mix for the area of interest was incorporated into the simulations.

The ATC surveillance automation system accepts surveillance information from multiple sources, e.g., radar, multilateration and Automatic Dependent Surveillance-Broadcast (ADS-B). This information is input to a tracker algorithm for data smoothing and position estimation, and provides a predicted or "extrapolated" next target position to the controller display. The STARS tracker is proprietary to the manufacturer; hence, the tracker chosen for this ASAT^{ng} simulation utilized an alpha-beta-gamma filter for ease of design and modification. An alpha-beta filter is a standard filter for position estimation, data smoothing, and control applications. An alpha-beta filter presumes that a system is adequately approximated by a model having two internal states, where the first state, alpha (target position), is obtained by integrating the value of the second state, beta (target velocity), over time. When the second state variable changes significantly in a short period of time, it can be useful to extend the alpha-beta filter an additional level to an alpha-beta-gamma filter. The third state, gamma, represents the target acceleration.

Based on the previous trend of aircraft position, velocity, and acceleration, the tracker predicts the aircraft's next position and presents that to the controller. If the aircraft is decelerating or accelerating along its track, or maneuvering as in a turn, the extrapolated position will not depict the true position of the aircraft. The FMA presents a PTL to the controller. The tip of the PTL predicts where the aircraft will be in 10 seconds. The PTL exhibits some sweep to sweep oscillation from one update to the next caused by errors in the tracker's predicted position. For convergence and stability, the values of the alpha, beta, and gamma state coefficients should be positive and small. Larger alpha beta gamma tracker state coefficient values increase tracker sensitivity while smaller values decrease sensitivity. At higher sensitivity the 10-second PTL will oscillate at greater amplitudes. This results in unnecessary PTL penetrations of the NTZ, causing alerts to be triggered earlier, requiring a corrective controller response and an increased level of safety. However, the rate of nuisance alerts will be higher. Therefore, the establishment of alpha-beta-gamma tracker state coefficient values that yield adequate tracker sensitivity without generating an overabundance of nuisance alerts is desired. Tracker state coefficient values are unique for a given set of specific HUR system parameters and RCLS. The values of the coefficients utilized in this evaluation, 0.35, 0.25, and 0.05, were determined from simulations using combinations of the sensor accuracies, sensor update rates, and processing times.

3.2 Test Design and Scenarios

ASAT^{ng} was utilized to create the basic operational scenario that consisted of two aircraft initialized on their respective final approach courses with one aircraft unexpectedly deviating toward the other final approach course. In the NAS during closely spaced parallel operations, when the deviating aircraft is determined by the PRM system to be 10 seconds from NTZ penetration, visual yellow caution and aural alerts are issued to the monitor controller. In response to the alerts, the controller will attempt to return the aircraft to its assigned final approach course. If the aircraft continues toward or enters the NTZ, the monitor controller responsible for the adjacent final approach course will issue evasion commands to the pilot of the endangered aircraft. The pilot of the endangered aircraft maneuvers in response to the controller's commands. ASAT^{ng} simulates each of these actions and response times and can display individual paired flights.

From human-in-the-loop simulations, probability density functions (pdfs) have been developed and refined for controller, pilot, and aircraft response times. Deviation pdfs have also been created from data collected during actual simultaneous independent parallel instrument approaches during instrument flight conditions. As ASAT^{ng} runs a scenario, it samples deviation angles and response times from these pdfs and simulates the paired flights to termination. The closest point of approach between the deviating aircraft and the endangered aircraft is recorded for each simulation run.

For this study, the surveillance parameters of position measurement accuracy, sensor update rate, and processing time were evaluated as follows:

- Position measurement accuracy was varied at values of 25, 60, 100, 150 and 200 ft. These values meet or exceed the accuracies of surveillance sensors in the NAS. None are capable of 25 ft. The 150 ft value was specified by the Surveillance and Broadcast Services Program Office to accommodate the requirements of ADS-B. The 200 ft value was chosen to evaluate degraded sensor performance.
- Surveillance sensor update rate was varied at values of 1, 2, 3, 4 and 5 seconds. These values encompass the sensor update rates available in the NAS, which range from 1.0 to 4.8 seconds.
- Processing time was varied at values of 0 to 4 seconds. Currently no system is capable of a zero processing time, but it was incorporated to address future values that could possibly be less than 1 second, and to accommodate the timing of processed target information delivered to the display in less than 1 second from the time it occurred.
- Level and descending course deviations were varied at values ranging from 15° to 35°. These values were determined from deviation data taken by MITRE at 12 airports during fiscal years 2008 through 2012, during simultaneous independent parallel instrument approaches conducted in less than visual conditions. Probability density functions were developed from these data and, during fast time simulation, the magnitude of the deviation is sampled from the pdfs and applied to each scenario of the simulation.

Four fundamental deviation scenarios were modeled utilizing each of the above parameters and each scenario consisted of 125 permutations, as identified in Table 3-1. The operations analyzed in this study were simultaneous independent straight-in approach operations to dual parallel runways with an RCLS of 3400 ft, a 2000 ft wide NTZ equidistant between the runway centerlines, and a field elevation of 2000 ft mean sea level (MSL). Runway stagger was not evaluated because it was not a factor that would adversely impact the overall risk.

Table 3-1: Scenario Matrix

Scenario Permutation Number	Position Measurement Accuracy (ft)	Surveillance Sensor Update Rate (sec)	Processing Time (sec)
1, 26, 51, 76, 101	25, 60, 100, 150, 200	1	0
2, 27, 52, 77, 102	25, 60, 100, 150, 200	1	1
3, 28, 53, 78, 103	25, 60, 100, 150, 200	1	2
4, 29, 54, 79, 104	25, 60, 100, 150, 200	1	3
5, 30, 55, 80, 105	25, 60, 100, 150, 200	1	4
6, 31, 56, 81, 106	25, 60, 100, 150, 200	2	0
7, 32, 57, 82, 107	25, 60, 100, 150, 200	2	1
8, 33, 58, 83, 108	25, 60, 100, 150, 200	2	2
9, 34, 59, 84, 109	25, 60, 100, 150, 200	2	3
10, 35, 60, 85, 110	25, 60, 100, 150, 200	2	4
11, 36, 61, 86, 111	25, 60, 100, 150, 200	3	0
12, 37, 62, 87, 112	25, 60, 100, 150, 200	3	1
13, 38, 63, 88, 113	25, 60, 100, 150, 200	3	2
14, 39, 64, 89, 114	25, 60, 100, 150, 200	3	3
15, 40, 65, 90, 115	25, 60, 100, 150, 200	3	4
16, 41, 66, 91, 116	25, 60, 100, 150, 200	4	0
17, 42, 67, 92, 117	25, 60, 100, 150, 200	4	1
18, 43, 68, 93, 118	25, 60, 100, 150, 200	4	2
19, 44, 69, 94, 119	25, 60, 100, 150, 200	4	3
20, 45, 70, 95, 120	25, 60, 100, 150, 200	4	4
21, 46, 71, 96, 121	25, 60, 100, 150, 200	5	0
22, 47, 72, 97, 122	25, 60, 100, 150, 200	5	1
23, 48, 73, 98, 123	25, 60, 100, 150, 200	5	2
24, 49, 74, 99, 124	25, 60, 100, 150, 200	5	3
25, 50, 75, 100, 125	25, 60, 100, 150, 200	5	4

The position measurement accuracy is the difference between the aircraft's actual position and detected position. The surveillance sensor update rate is the time between updates of target position information from the sensor to the processor. The processing time is the inherent latency between the time the surveillance system target position information becomes available from the sensor and the time that this information is made available to the FMA display.

All aircraft were simulated using Category II (CAT II) Instrument Landing System (ILS) approaches with flight director at a glide slope of 3°. The aircraft release positions were distributed uniformly between 16 and 3 nautical miles (NM) from their respective thresholds. Each pair was released at risk. The ASAT^{ng} at-risk design element ensures the centers of gravity of the two aircraft will pass within 265 ft of each other laterally. This will result in a collision if the centers of gravity of the two aircraft also pass within 80 ft vertically of each other. A test criterion violation (TCV) will occur without timely action from both the controller and the pilot of the endangered aircraft if the previous two conditions are met. The TCV volume is depicted in Figure 3-1.

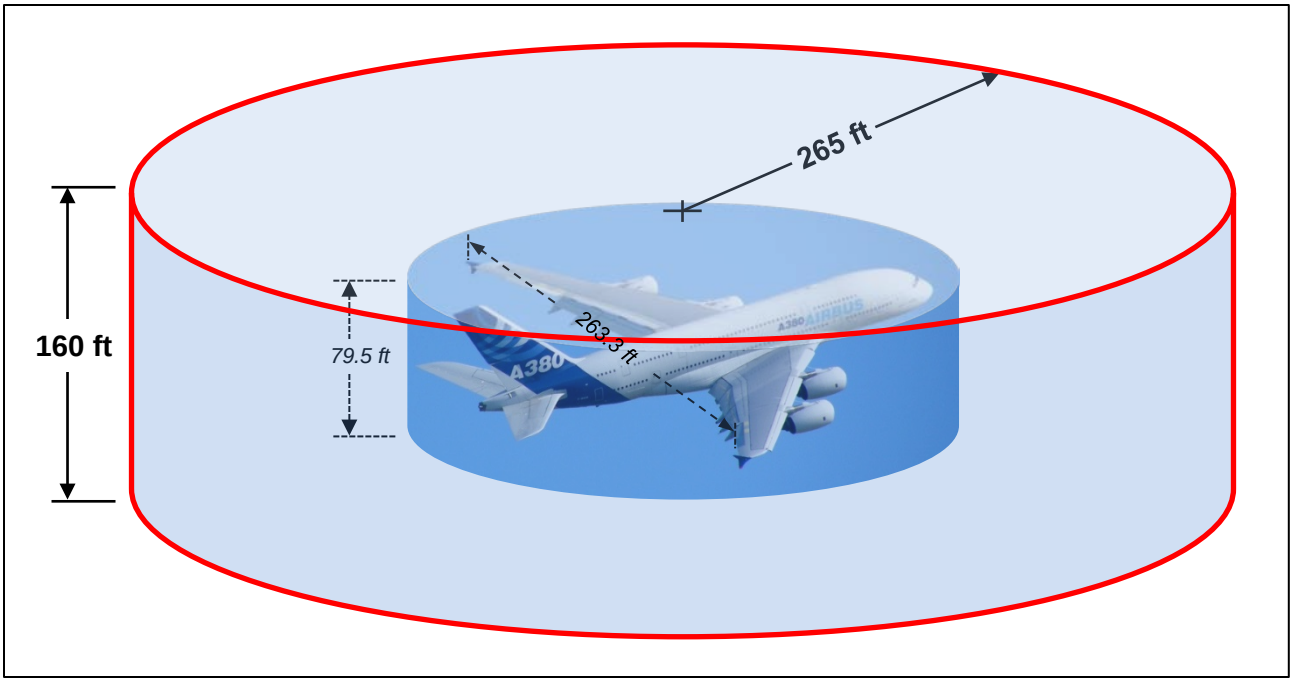

Figure 3-1: TCV Volume

The fleet mix utilized 20% heavy aircraft, 40% large aircraft, and 40% small aircraft. Half of the heavy aircraft were represented by the Airbus A330 and the other half by the Boeing 747-400 (B747). The large aircraft were all represented by the Boeing 737-800 (B737) and the small aircraft were all represented by an Embraer regional jet (ERJ). Each aircraft type in the mix had different approach speeds and dynamics.

Among the four fundamental scenarios, no determination was made of the prevalence of a descending or level aircraft deviation. The choice was made to cover the two equally. There were two controller response time distributions utilized in this study, one for 20° deviations and one for 30° deviations. The 20° deviations and 30° deviations were sampled from bounded uniform distributions with ranges from 15° to 25° and 25° to 35°, respectively. The controller response time mean for the 20° deviation utilized was 4.067 seconds with a standard deviation of 2.4435 seconds, while the controller response time mean for the 30° deviation utilized was 4.953 seconds with a standard deviation of 3.2618 seconds. Both 20° and 30° deviations were fitted to a Johnson SB distribution.

In each ASAT^{ng} simulation run, the closest point of approach was recorded along with the positions of the two aircraft. If the deviating aircraft's center of gravity penetrated the TCV volume, a cylinder with a radius of 265 ft and a height of 160 ft, then a TCV occurred and was considered to result in a collision.

3.3 Simulation Assumptions

Several assumptions were made regarding the requirements and conduct of these operations:

- Aircraft were established on the final approach course pursuant to all other criteria contained in FAA Order JO 7110.65[4]
- Aircraft followed approach control directed speeds up to the point of configuring for the final approach
- Aircraft did not slow until within 2 NM prior to the final approach fix
- The aircraft were flown using a flight director
- Aircraft deviations were distributed uniformly along the final approach course
- RCLS and final approach course spacing were 3400 ft
- Airport elevation was 2000 ft MSL
- The temperature profile was based on the International Standard Atmosphere with winds at zero knots
- FMA display update rate was 1 second
- The 10-second PTL was modeled using an alpha-beta-gamma filter to smooth parameters which minimized noise and tracking error
- There was no stagger between thresholds of the parallel runways

3.4 Independent Variables

The parameters used to realistically model these complex operational scenarios included the following:

- Aircraft fleet mix
- Pilot response time
- Controller response time
- Aircraft performance
- Atmospheric conditions
- Navigation system performance
- ATC monitoring and surveillance equipment
  - Position measurement accuracy
  - Surveillance sensor update rate
  - Processing time

3.5 Dependent Variables

- TCV rate

[4] FAA Order JO 7110.65, *Air Traffic Control*.

4 Data Analysis

4.1 Collision Risk

The analysis methodology used to determine the probability of collision risk is described in Appendix A. The results of the analysis of the 500 combinations examined in this study are included in Appendix B. They show the various combinations of surveillance sensor update rates and processing times, while using one specific value for position measurement accuracy. Two hundred thousand runs were completed for each combination, for a total of 50 million simulated aircraft pairs.

Four mutually exclusive types of deviation events were considered in this study: a 20° level deviation, a 20° descending deviation, a 30° level deviation, and a 30° descending deviation. Each of the risk plots depicted in Figure 4-1 is the summation of the four deviation event types for a given processing time, see Figures A-1 through A-5 in Appendix A. Figures 4-2 through 4-6 depict the individual results for position measurement accuracy values of 25 ft through 200 ft, respectively.

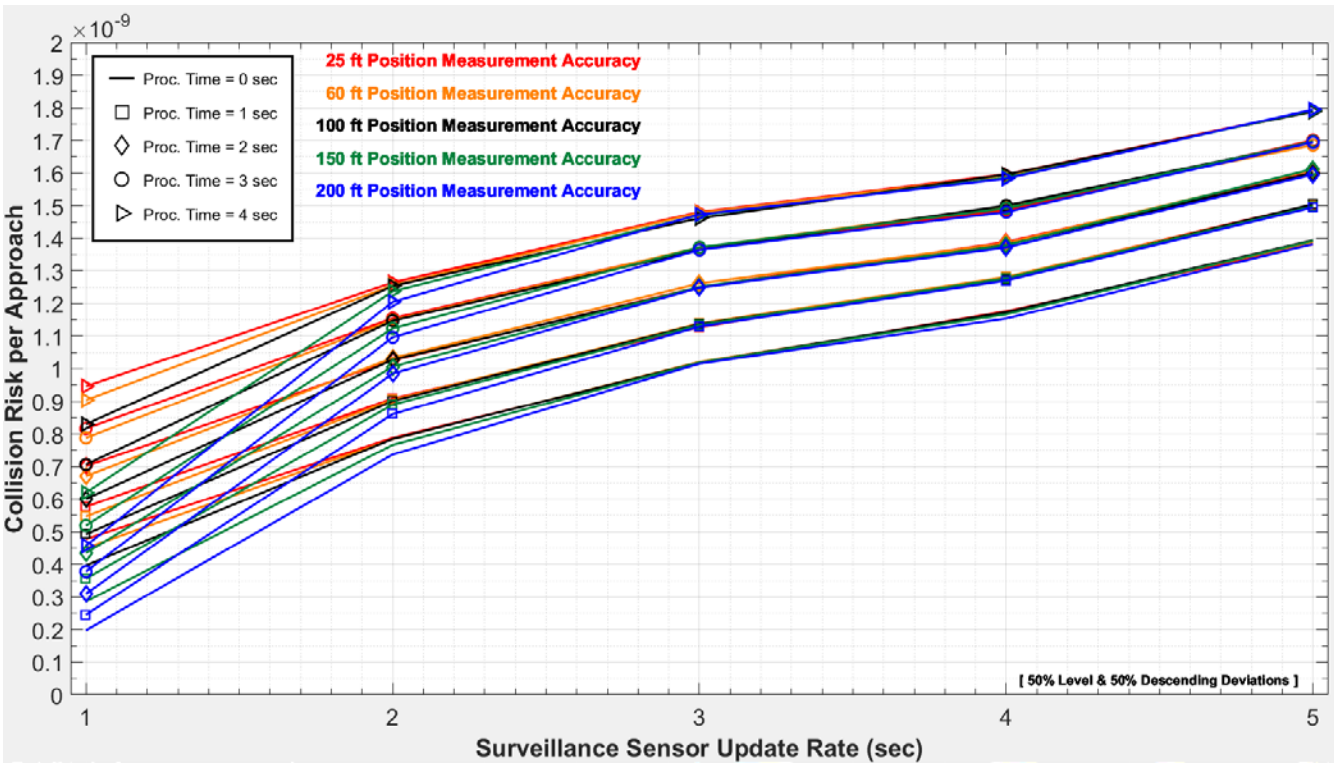

Figure 4-1: Risk as a Function of Position Accuracy, Sensor Update Rate, and Processing Time

Position measurement accuracy values had a noticeable impact on collision risk at a surveillance sensor update rate of 1 second, but had a negligible impact from 2 to 5 seconds. It was anticipated that less precise position measurement accuracy would exhibit more risk than more precise position measurement accuracy. However, because the PTL sweep-to-sweep variance increased due to the less precise position measurement accuracy, the tracker's PTL sweep amplitudes were greater, triggering earlier alerts and controller responses. Position measurement accuracy affected collision risk by as much as 141% at a surveillance sensor update rate of 1 second and a processing time of 0 seconds. The maximum difference in risk noted for surveillance sensor update rates from 2 to 5 seconds was only 7% at a surveillance sensor

update rate of 2 seconds and a processing time of 0 seconds. The average difference in risk for all position measurement accuracies and processing times was 125% at a 1-second sensor update rate, 5.5% at a 2-second sensor update rate, and only 1% for sensor update rates of 3 to 5 seconds.

The impact of surveillance sensor update rate on collision risk was relatively linear in nature. Collision risk increases as the surveillance sensor update rate decreases from 1 second to 5 seconds. A 1-second change in surveillance sensor update rate from 1 second to 2 seconds result in an 89% average increase in risk. A 1-second change in surveillance sensor update rate from 2 seconds to 5 seconds results in a 17% average increase in risk.

Variations in processing time exhibit similar properties to surveillance sensor update rate. Collison risk increases as processing time increases from zero seconds to 4 seconds. Each 1-second increase in processing time produces an approximate 1×10^{-10} increase in collision risk. This equates to a 20% average increase in collision risk per second increase in processing time at a surveillance sensor update rate of 1 second; and a 9% average increase in collision risk per second increase in processing time at surveillance sensor update rates from 2 seconds to 5 seconds. For more details, refer to Appendix A.

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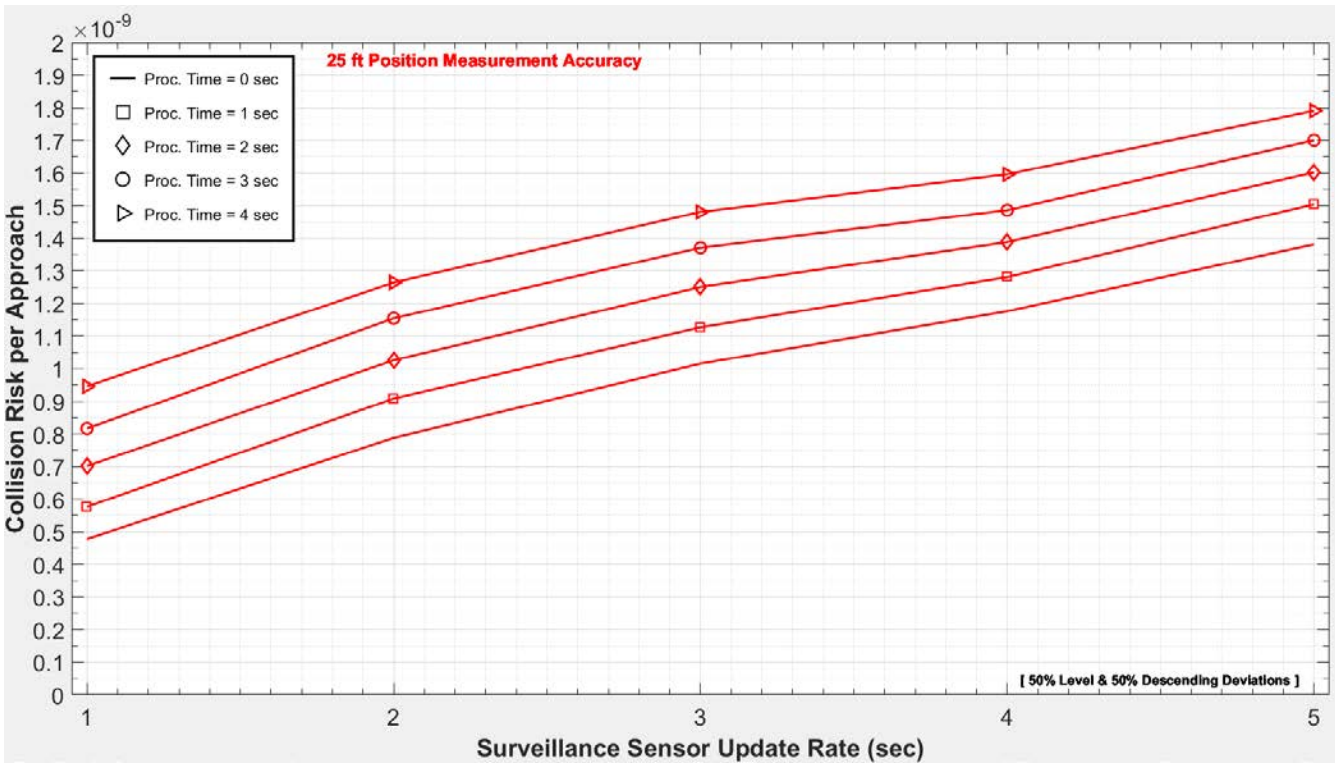

Figure 4-2: Collision Risk per Approach for 25 ft Position Measurement Accuracy

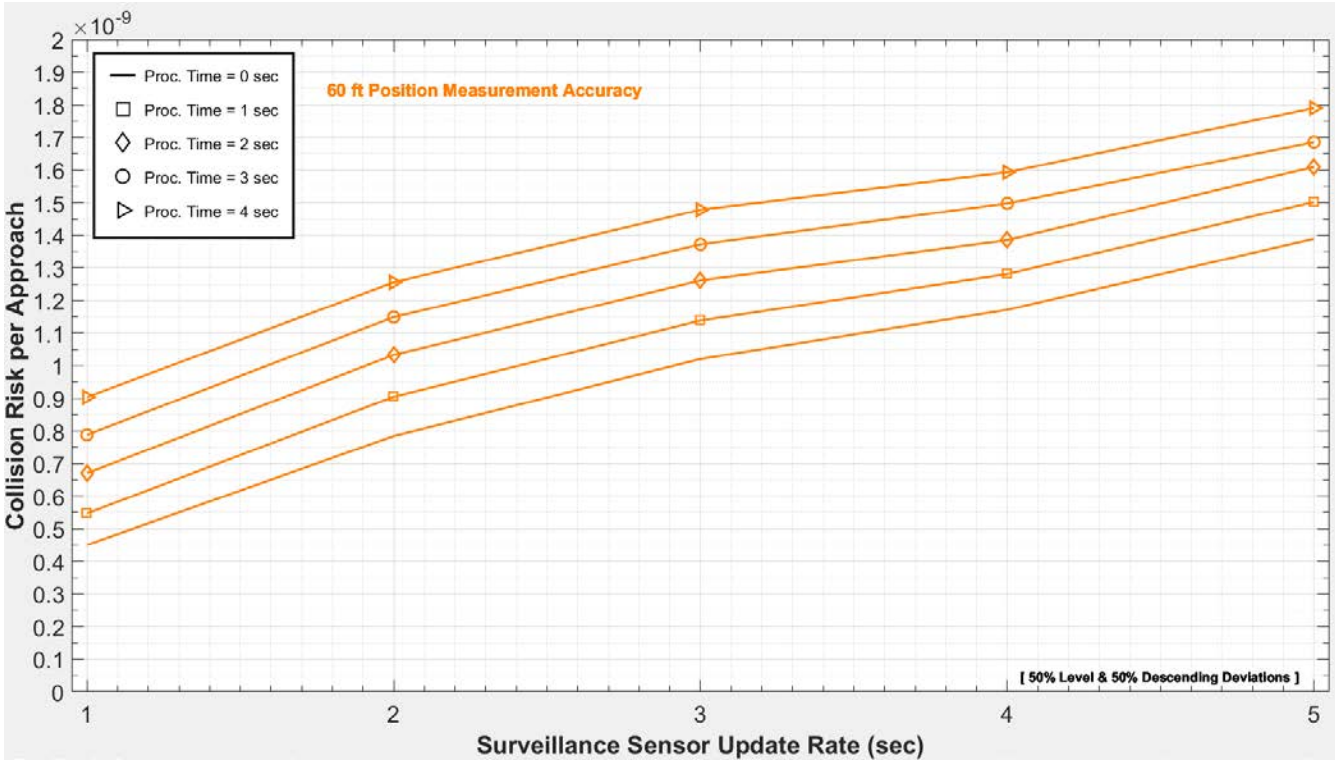

Figure 4-3: Collision Risk per Approach for 60 ft Position Measurement Accuracy

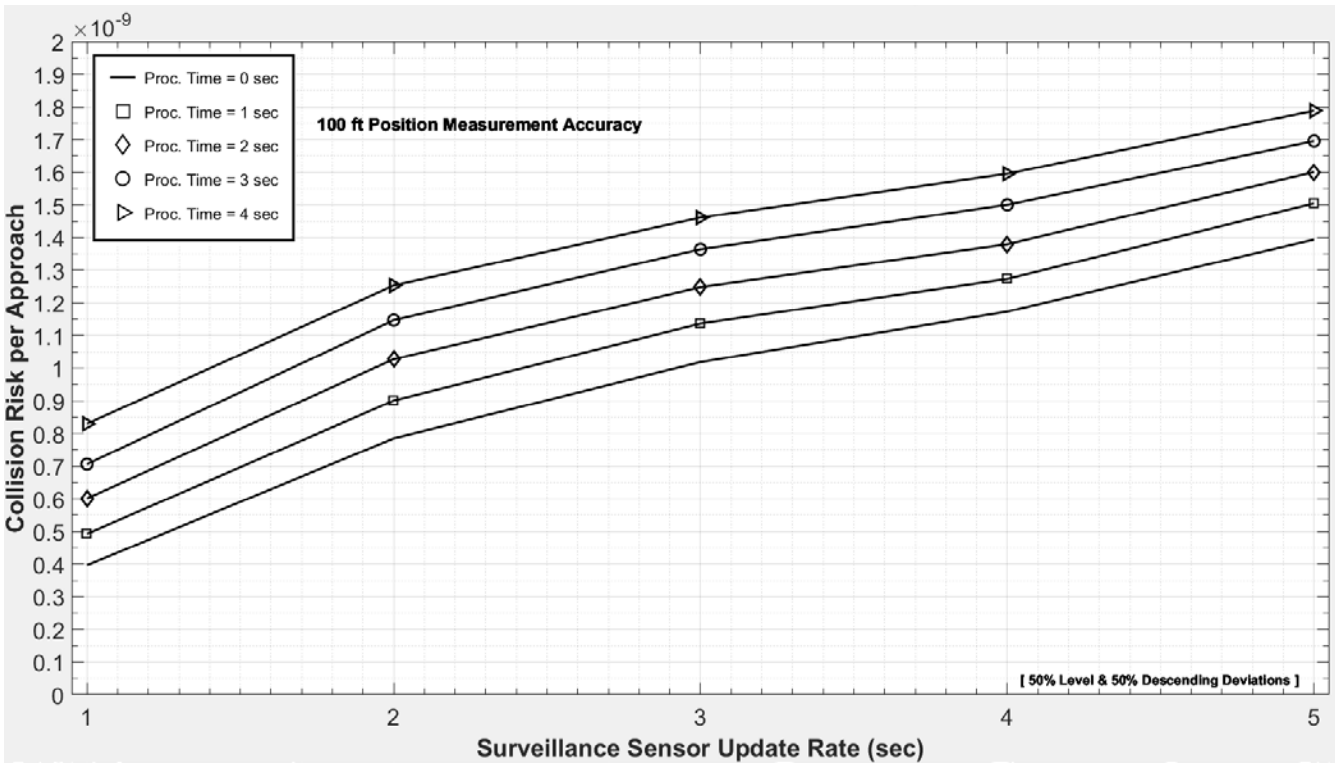

Figure 4-4: Collision Risk per Approach for 100 ft Position Measurement Accuracy

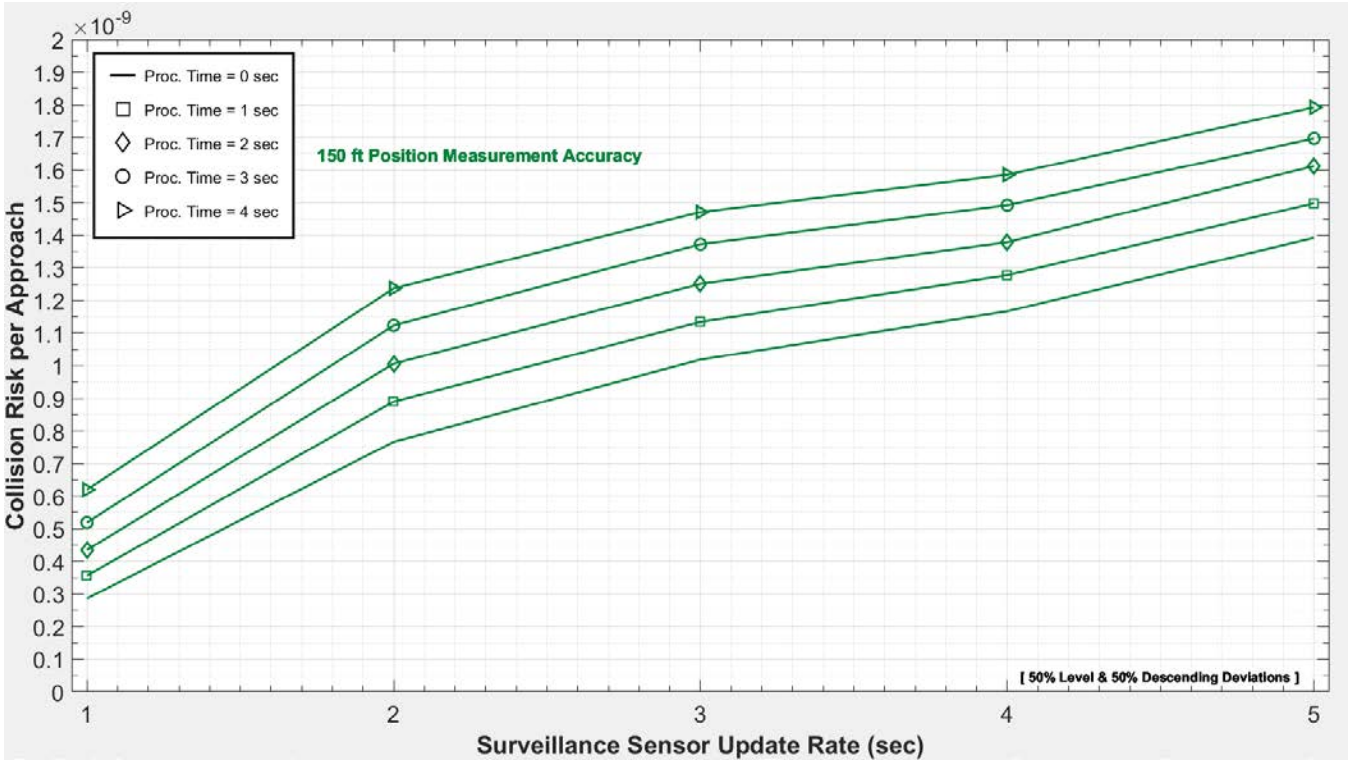

Figure 4-5: Collision Risk per Approach for 150 ft Position Measurement Accuracy

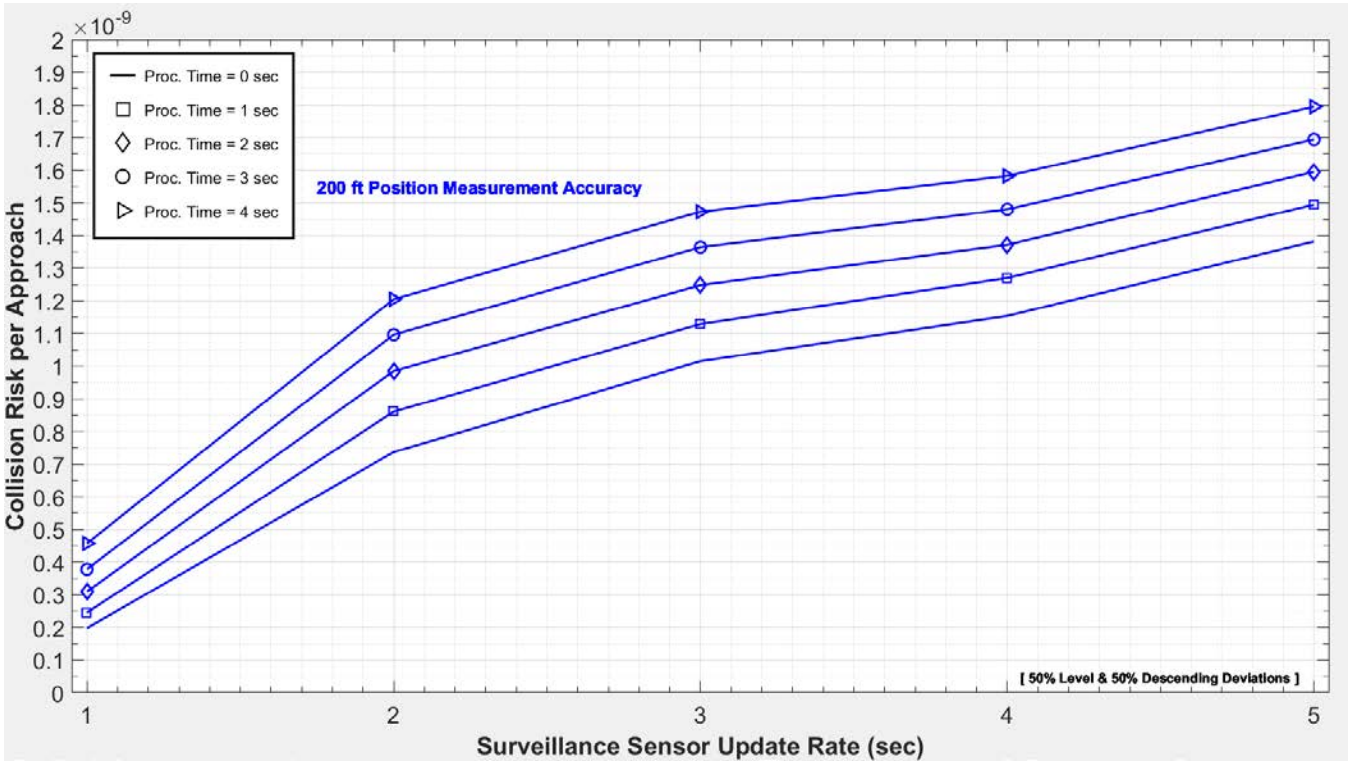

Figure 4-6: Collision Risk per Approach for 200 ft Position Measurement Accuracy

5 Conclusions

This report presents the results of an analysis of various parameters of HUR surveillance systems. The study assessed the impact to collision risk associated with dual simultaneous independent instrument approaches to parallel runways and final approach courses with an RCLS of 3400 ft and an airport elevation of 2000 ft MSL. Specific combinations of the following critical parameters were used as an HUR surveillance system with a 10-second PTL and a 1-second FMA display update rate: (1) position measurement accuracy, (2) surveillance sensor update rate, and (3) processing time. The results can be generalized to any surveillance/display system.

The results of this study indicate that collision risk increases as:

- surveillance sensor update rate decreases (gets slower)
- processing time increases (gets longer)
- position measurement accuracy improves

Sensor update rates faster than 2 seconds have a significant impact on reducing collision risk. For any given position measurement accuracy or processing time, as the sensor update rate gets closer to 1 second, the 10-second PTL oscillates at greater amplitudes, causing it to penetrate the NTZ boundary. This initiates a controller response to separate the aircraft, resulting in a reduction in collision risk for sensor update rates of less than 2 seconds. At update rates longer than 2 seconds, the 10-second PTL oscillation amplitude decreases with fewer and more accurate alerts. This results in reduced alerts and a minimal impact on collision risk relative to the other parameters. At a surveillance sensor update rate longer than 2 seconds, the impact on collision risk of position measurement accuracy becomes negligible, compared to sensor update rate and processing time.

The change in collision risk for each 1-second change in processing time is approximately 1×10^{-10} per approach, throughout the range of surveillance sensor update rates evaluated. The change in collision risk for each 1-second change in surveillance sensor update rate, beyond 2 seconds, is approximately 2×10^{-10} per approach, throughout the range of processing times. The change in collision risk as a function of position measurement accuracy is negligible at sensor update rates of 2 to 5 seconds over all processing times.

A future evaluation of simultaneous independent parallel instrument approach procedures to closely spaced parallel runways with parallel and offset final approach courses will utilize the findings of this analysis.

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Appendix A: Risk Analysis–Probability of a Collision

This appendix describes the analysis methodology used to determine the probability of collision risk. Several events must happen concurrently for a collision to occur during simultaneous instrument approaches. First, an aircraft must deviate from its approach course and continue deviating. Next, the pilots of the deviating aircraft must not respond to ATC instructions. Then, both aircraft must be aligned so that a TCV will occur if the controllers and pilots fail to react in sufficient time to separate the deviating and the endangered aircraft. This is referred to as an at-risk deviation and is denoted in the equation below. If all of the above events develop in sequence, a TCV occurs, resulting in two accidents. There are two approaches in each operation. Therefore, a TCV will result in two accidents per operation, but only one accident per approach. Hence, the results of Equation 1 yield the probability in terms of accidents per approach.

There were a total of four mutually exclusive types of deviations in this study: a 20° level deviation, a 20° descending deviation, a 30° level deviation, and a 30° descending deviation. A collision involves two aircraft on two separate approaches and results in two accidents, as defined by the National Transportation Safety Board. Assuming that a TCV will result in a collision, the probability of a collision can be expressed in mathematical terms as a joint occurrence. The probability of a joint occurrence is the product of all independent events:

$$P(TCV[DeviationType]) = P(TCV|D\cap NRD\cap ARD)\times P(NRD|D\cap ARD)\times P(ARD|D)\times P(D|\theta_{deviation})\times P(D|V_{deviation}) \quad (1)$$

D stands for deviation, *NRD* stands for non-responding deviation, *ARD* stands for at-risk deviation, the symbol ∩ is read *and*, and the symbol | is read *given that* or *given*. A deviation for a specific angle, θ, refers to either a 20° or 30° deviation. *V* refers to a deviation for either a level or descending vertical profile. All of these events are independent.

Equation 1 would then be read: *The probability of a collision [for a specific deviation event type] is equal to the probability of a TCV, given a deviation that is both non-responding and at risk, times the probability of a non-responding deviation, given a deviation that is at risk, times the probability of an at-risk deviation, given a deviation, times the probability of a deviation, given its angle, times the probability of a deviation, given its vertical profile.*

Factor 1 determines the probability that a TCV occurs given that a non-responding, at-risk deviation has occurred. This was the TCV rate determined from the simulation. The probability of a TCV occurring for a given type is equal to the number of deviations resulting in a TCV divided by the total aircraft pairs simulated for that deviation type, as expressed in Equation 2. 100,000 pairs were simulated for each of the four types of deviation events.

$$P(TCV|D \cap NRD \cap ARD) = \frac{number\ deviations\ resulting\ in\ a\ TCV}{total\ aircraft\ pairs} \quad (2)$$

Factor 2 determines the probability that the deviating aircraft does not respond to air traffic controllers' instructions to return to course, given that a deviation has occurred which is also at risk. The value of this factor is 8.32×10^{-3}.[5] Factor 2 in Equation 1 is expressed as:

$$P(NRD|D\cap ARD)$$

Factor 3 is the probability that the deviation is an at-risk deviation given that a deviation has occurred. The value of this factor was estimated from simulation data using the TCV shape described in section 3.2 of this report and was found to be 3.17×10^{-2}. This value represents the likelihood that another aircraft will be at risk with the deviating aircraft. It assumes that the deviation is occurring during peak traffic times where there are aircraft separated by 3 NM in-trail on the other runway. Factor 3 in Equation 1 is expressed as:

$$P(ARD|D)$$

Factor 4, as expressed in Equation 1, is the probability of a deviation of a specified angle. Deviation data was captured from actual simultaneous approaches conducted in less than visual conditions. The probability and frequency of the occurrence of various deviation angles has been determined from the data and binned at 10° increments up to 35° as indicated in Table A-1.[6] Only the 20° and 30° bins were used in this study.

$$P(D|\theta)$$

Table A-1: 99% Confidence Intervals for NTZ Penetration Rates

Deviation Degrees	High Confidence Limit
$5° \leq \theta < 15°$	4.58E-5
$15° \leq \theta < 25°$	2.55E-5
$25° \leq \theta < 35°$	1.18E-5

Factor 5, the probability of a deviation occurring in either a level or descending vertical profile was not determined. Equal probabilities for level deviations and descending deviations were used, as has been done in previous collision risk studies:

$$P(D|V_{level}) = 0.50$$
$$P(D|V_{descending}) = 0.50$$

[5] Flight Technologies and Procedures Division, *DOT-FAA-AFS-400-83, Reduction of Diagonal Separation from 1.5 Nautical Miles to 1.0 Nautical Mile for Parallel Dependent Approaches*.

[6] MP090245, *Frequency and Severity of Deviations during Simultaneous Independent Approaches to Parallel Runways – A 2009 Update*.

Given that there were four mutually exclusive types of deviation events possible, finding the probability of one of them occurring was accomplished by summing their probabilities. Therefore, the total probability of a collision can be expressed using Equation 1 with each of the two deviation angles considered and each of the two types of vertical profiles considered:

$$
\begin{aligned}
P(TCV) = {} & P(TCV|D \cap NRD \cap ARD) \times P(NRD|D \cap ARD) \times P(ARD|D) \times P(D|\theta_{20°}) \times P(D|V_{level}) \\
& + \\
& P(TCV|D \cap NRD \cap ARD) \times P(NRD|D \cap ARD) \times P(ARD|D) \times P(D|\theta_{20°}) \times P(D|V_{descending}) \\
& + \\
& P(TCV|D \cap NRD \cap ARD) \times P(NRD|D \cap ARD) \times P(ARD|D) \times P(D|\theta_{30°}) \times P(D|V_{level}) \\
& + \\
& P(TCV|D \cap NRD \cap ARD) \times P(NRD|D \cap ARD) \times P(ARD|D) \times P(D|\theta_{30°}) \times P(D|V_{descending})
\end{aligned}
\tag{3}
$$

Figures A-1 through A-5 illustrate the use of Equation 3 for each processing time evaluated in this study. The total risk plots in Figures A-1 through A-5 are combined in Figure 4-1 and labeled by their corresponding processing times.

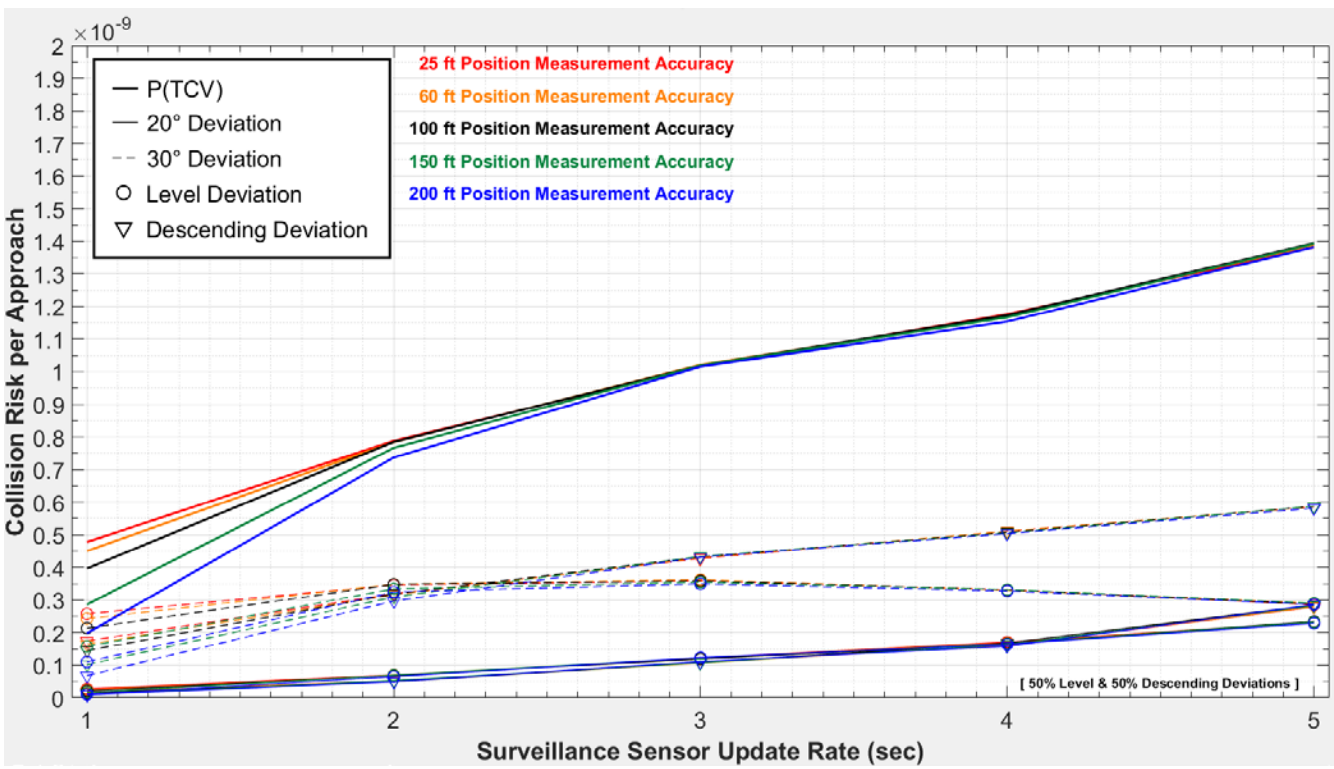

Figure A-1: Risk for a Processing Time of 0 seconds

Collision risk results are summarized in Table A-2 through Table A-6. Each table consists of appropriate combinations of surveillance sensor update rate and processing time, while using one specific value for position measurement accuracy.

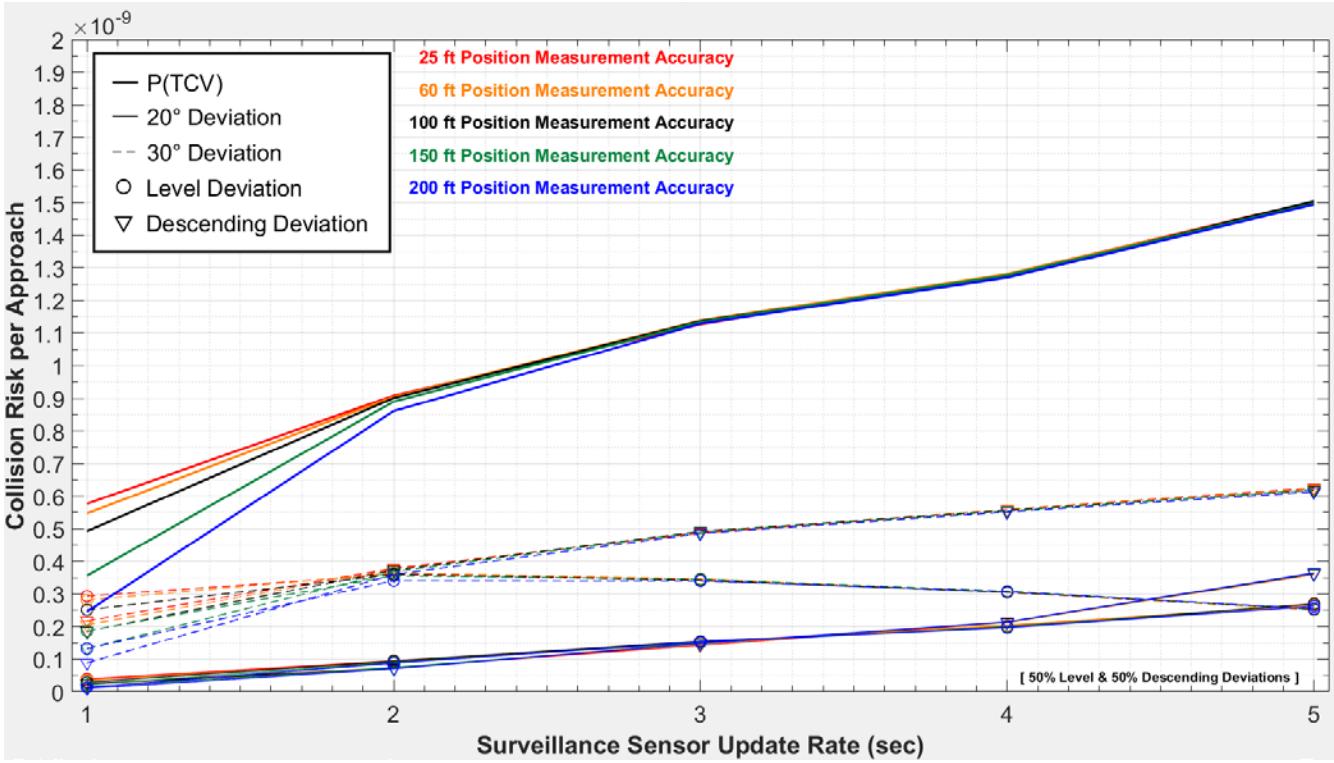

Figure A-2: Risk for a Processing Time of 1 second

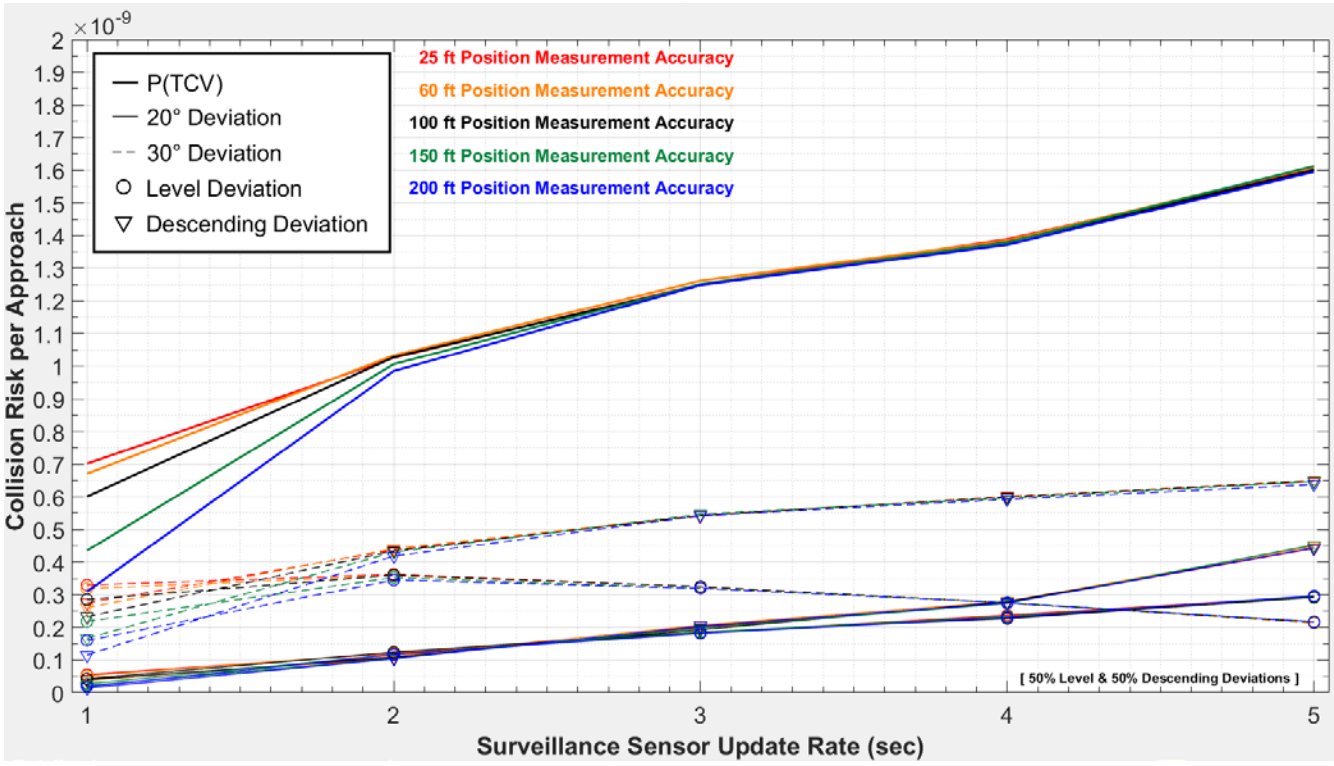

Figure A-3: Risk for a Processing Time of 2 seconds

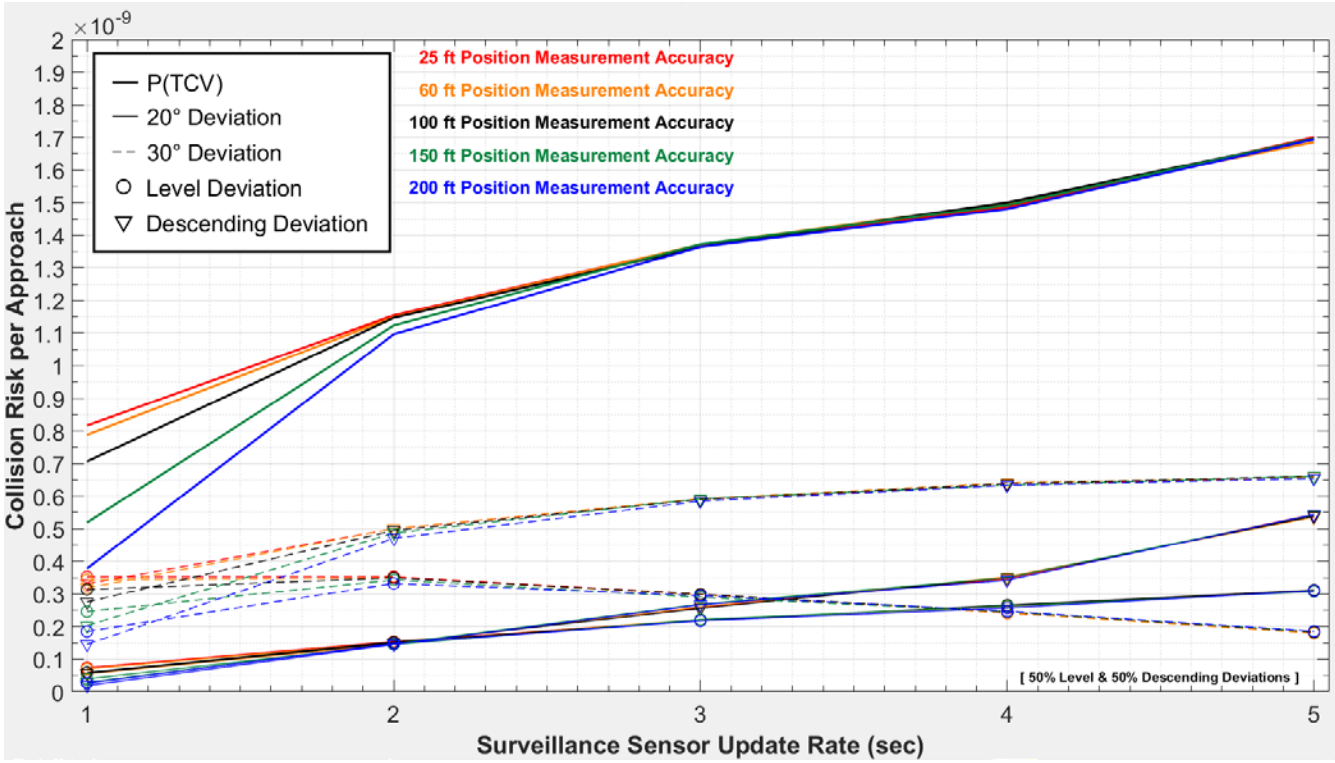

Figure A-4: Risk for a Processing Time of 3 seconds

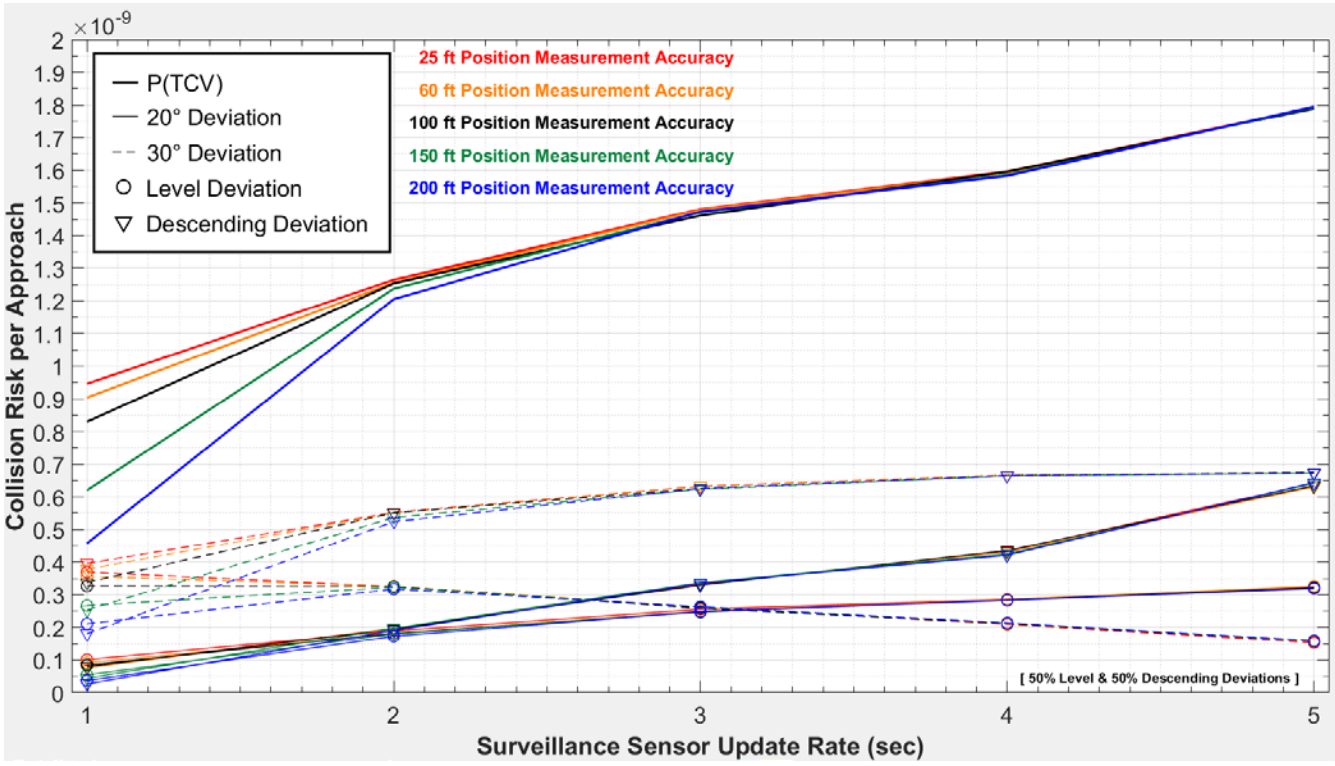

Figure A-5: Risk for a Processing Time of 4 seconds

Table A-2: Collision Risk Probabilities with 25 ft Position Accuracy

Processing Time (sec)	Surveillance Sensor Update Rate (sec)				
	1	2	3	4	5
0	4.78E-10	7.88E-10	1.02E-09	1.18E-09	1.38E-09
1	5.77E-10	9.09E-10	1.13E-09	1.28E-09	1.50E-09
2	7.01E-10	1.03E-09	1.25E-09	1.39E-09	1.60E-09
3	8.17E-10	1.15E-09	1.37E-09	1.49E-09	1.70E-09
4	9.46E-10	1.26E-09	1.48E-09	1.60E-09	1.79E-09

Table A-3: Collision Risk Probabilities with 60 ft Position Accuracy

Processing Time (sec)	Surveillance Sensor Update Rate (sec)				
	1	2	3	4	5
0	4.50E-10	7.84E-10	1.02E-09	1.17E-09	1.39E-09
1	5.47E-10	9.05E-10	1.14E-09	1.28E-09	1.50E-09
2	6.70E-10	1.03E-09	1.26E-09	1.39E-09	1.61E-09
3	7.88E-10	1.15E-09	1.37E-09	1.50E-09	1.69E-09
4	9.04E-10	1.26E-09	1.48E-09	1.59E-09	1.79E-09

Table A-4: Collision Risk Probabilities with 100 ft Position Accuracy

Processing Time (sec)	Surveillance Sensor Update Rate (sec)				
	1	2	3	4	5
0	3.97E-10	7.85E-10	1.02E-09	1.17E-09	1.39E-09
1	4.93E-10	9.01E-10	1.14E-09	1.27E-09	1.51E-09
2	6.01E-10	1.03E-09	1.25E-09	1.38E-09	1.60E-09
3	7.06E-10	1.15E-09	1.36E-09	1.50E-09	1.70E-09
4	8.30E-10	1.25E-09	1.46E-09	1.60E-09	1.79E-09

Table A-5: Collision Risk Probabilities with 150 ft Position Accuracy

Processing Time (sec)	Surveillance Sensor Update Rate (sec)				
	1	2	3	4	5
0	2.86E-10	7.67E-10	1.02E-09	1.17E-09	1.39E-09
1	3.56E-10	8.90E-10	1.13E-09	1.28E-09	1.50E-09
2	4.35E-10	1.01E-09	1.25E-09	1.38E-09	1.61E-09
3	5.19E-10	1.12E-09	1.37E-09	1.49E-09	1.70E-09
4	6.20E-10	1.24E-09	1.47E-09	1.59E-09	1.79E-09

Table A-6: Collision Risk Probabilities with 200 ft Position Accuracy

Processing Time (sec)	Surveillance Sensor Update Rate (sec)				
	1	2	3	4	5
0	1.98E-10	7.37E-10	1.02E-09	1.15E-09	1.38E-09
1	2.46E-10	8.61E-10	1.13E-09	1.27E-09	1.49E-09
2	3.10E-10	9.85E-10	1.25E-09	1.37E-09	1.60E-09
3	3.78E-10	1.10E-09	1.36E-09	1.48E-09	1.69E-09
4	4.57E-10	1.21E-09	1.47E-09	1.58E-09	1.80E-09

Appendix B: TCV Rates and Collision Risk Probabilities

This appendix includes the results of the analysis of the 500 scenarios examined in this study. TCV rates and collision risk probabilities for examined HUR surveillance system parameters are contained in Table B-1 through Table B-5. One hundred thousand aircraft pairs were completed for each scenario. Each of the 4 fundamental scenarios (i.e., 20° and 30° level and descending deviations) consisted of 50 scenario permutations utilizing various surveillance sensor accuracies, surveillance sensor update rates, and processing times. Each table consists of appropriate combinations of surveillance sensor update rate and processing time, while using one specific value for position measurement accuracy. Position measurement accuracy values utilized were 25 ft, 60 ft, 100 ft, 150 ft, and 200 ft in Table B-1 through Table B-5.

Table B-1: TCV Rates and Collision Risk Probabilities with 25 ft Position Accuracy

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
1	25 ft	0	1	20°	Level	100,000	833	0.0083	2.80E-11	**4.78E-10**
2	25 ft	0	1	20°	Descending	100,000	531	0.0053	1.78E-11	
3	25 ft	0	1	30°	Level	100,000	16,564	0.1656	2.58E-10	
4	25 ft	0	1	30°	Descending	100,000	11,213	0.1121	1.74E-10	
5	25 ft	0	2	20°	Level	100,000	2,083	0.0208	7.00E-11	**7.88E-10**
6	25 ft	0	2	20°	Descending	100,000	1,566	0.0157	5.26E-11	
7	25 ft	0	2	30°	Level	100,000	22,279	0.2228	3.47E-10	
8	25 ft	0	2	30°	Descending	100,000	20,511	0.2051	3.19E-10	
9	25 ft	0	3	20°	Level	100,000	3,635	0.0364	1.22E-10	**1.02E-09**
10	25 ft	0	3	20°	Descending	100,000	3,182	0.0318	1.07E-10	
11	25 ft	0	3	30°	Level	100,000	23,076	0.2308	3.59E-10	
12	25 ft	0	3	30°	Descending	100,000	27,490	0.2749	4.28E-10	
13	25 ft	0	4	20°	Level	100,000	5,089	0.0509	1.71E-10	**1.18E-09**
14	25 ft	0	4	20°	Descending	100,000	4,814	0.0481	1.62E-10	
15	25 ft	0	4	30°	Level	100,000	21,343	0.2134	3.32E-10	
16	25 ft	0	4	30°	Descending	100,000	32,885	0.3289	5.11E-10	
17	25 ft	0	5	20°	Level	100,000	6,914	0.0691	2.32E-10	**1.38E-09**
18	25 ft	0	5	20°	Descending	100,000	8,279	0.0828	2.78E-10	
19	25 ft	0	5	30°	Level	100,000	18,346	0.1835	2.85E-10	
20	25 ft	0	5	30°	Descending	100,000	37,663	0.3766	5.86E-10	
21	25 ft	1	1	20°	Level	100,000	1,185	0.0119	3.98E-11	**5.77E-10**
22	25 ft	1	1	20°	Descending	100,000	764	0.0076	2.57E-11	
23	25 ft	1	1	30°	Level	100,000	18,864	0.1886	2.93E-10	
24	25 ft	1	1	30°	Descending	100,000	14,004	0.1400	2.18E-10	
25	25 ft	1	2	20°	Level	100,000	2,828	0.0283	9.51E-11	**9.09E-10**
26	25 ft	1	2	20°	Descending	100,000	2,199	0.0220	7.39E-11	
27	25 ft	1	2	30°	Level	100,000	23,193	0.2319	3.61E-10	
28	25 ft	1	2	30°	Descending	100,000	24,359	0.2436	3.79E-10	
29	25 ft	1	3	20°	Level	100,000	4,527	0.0453	1.52E-10	**1.13E-09**
30	25 ft	1	3	20°	Descending	100,000	4,238	0.0424	1.42E-10	
31	25 ft	1	3	30°	Level	100,000	22,213	0.2221	3.46E-10	
32	25 ft	1	3	30°	Descending	100,000	31,302	0.3130	4.87E-10	
33	25 ft	1	4	20°	Level	100,000	6,054	0.0605	2.03E-10	**1.28E-09**

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
34	25 ft	1	4	20°	Descending	100,000	6,336	0.0634	2.13E-10	
35	25 ft	1	4	30°	Level	100,000	19,633	0.1963	3.05E-10	
36	25 ft	1	4	30°	Descending	100,000	35,951	0.3595	5.59E-10	
37	25 ft	1	5	20°	Level	100,000	7,939	0.0794	2.67E-10	**1.50E-09**
38	25 ft	1	5	20°	Descending	100,000	10,731	0.1073	3.61E-10	
39	25 ft	1	5	30°	Level	100,000	16,142	0.1614	2.51E-10	
40	25 ft	1	5	30°	Descending	100,000	40,234	0.4023	6.26E-10	
41	25 ft	2	1	20°	Level	100,000	1,662	0.0166	5.59E-11	**7.01E-10**
42	25 ft	2	1	20°	Descending	100,000	1,209	0.0121	4.06E-11	
43	25 ft	2	1	30°	Level	100,000	21,230	0.2123	3.30E-10	
44	25 ft	2	1	30°	Descending	100,000	17,658	0.1766	2.75E-10	
45	25 ft	2	2	20°	Level	100,000	3,575	0.0358	1.20E-10	**1.03E-09**
46	25 ft	2	2	20°	Descending	100,000	3,149	0.0315	1.06E-10	
47	25 ft	2	2	30°	Level	100,000	23,326	0.2333	3.63E-10	
48	25 ft	2	2	30°	Descending	100,000	28,105	0.2811	4.37E-10	
49	25 ft	2	3	20°	Level	100,000	5,474	0.0547	1.84E-10	**1.25E-09**
50	25 ft	2	3	20°	Descending	100,000	5,973	0.0597	2.01E-10	
51	25 ft	2	3	30°	Level	100,000	20,893	0.2089	3.25E-10	
52	25 ft	2	3	30°	Descending	100,000	34,784	0.3478	5.41E-10	
53	25 ft	2	4	20°	Level	100,000	7,074	0.0707	2.38E-10	**1.39E-09**
54	25 ft	2	4	20°	Descending	100,000	8,185	0.0819	2.75E-10	
55	25 ft	2	4	30°	Level	100,000	17,640	0.1764	2.74E-10	
56	25 ft	2	4	30°	Descending	100,000	38,676	0.3868	6.02E-10	
57	25 ft	2	5	20°	Level	100,000	8,756	0.0876	2.94E-10	**1.60E-09**
58	25 ft	2	5	20°	Descending	100,000	13,149	0.1315	4.42E-10	
59	25 ft	2	5	30°	Level	100,000	14,022	0.1402	2.18E-10	
60	25 ft	2	5	30°	Descending	100,000	41,617	0.4162	6.47E-10	
61	25 ft	3	1	20°	Level	100,000	2,209	0.0221	7.43E-11	**8.17E-10**
62	25 ft	3	1	20°	Descending	100,000	1,733	0.0173	5.83E-11	
63	25 ft	3	1	30°	Level	100,000	22,685	0.2269	3.53E-10	
64	25 ft	3	1	30°	Descending	100,000	21,298	0.2130	3.31E-10	
65	25 ft	3	2	20°	Level	100,000	4,589	0.0459	1.54E-10	**1.15E-09**
66	25 ft	3	2	20°	Descending	100,000	4,366	0.0437	1.47E-10	
67	25 ft	3	2	30°	Level	100,000	22,706	0.2271	3.53E-10	
68	25 ft	3	2	30°	Descending	100,000	32,176	0.3218	5.00E-10	
69	25 ft	3	3	20°	Level	100,000	6,585	0.0659	2.21E-10	**1.37E-09**
70	25 ft	3	3	20°	Descending	100,000	7,724	0.0772	2.60E-10	
71	25 ft	3	3	30°	Level	100,000	19,266	0.1927	3.00E-10	
72	25 ft	3	3	30°	Descending	100,000	37,974	0.3797	5.91E-10	
73	25 ft	3	4	20°	Level	100,000	7,845	0.0785	2.64E-10	**1.49E-09**
74	25 ft	3	4	20°	Descending	100,000	10,335	0.1034	3.47E-10	
75	25 ft	3	4	30°	Level	100,000	15,514	0.1551	2.41E-10	
76	25 ft	3	4	30°	Descending	100,000	40,755	0.4076	6.34E-10	
77	25 ft	3	5	20°	Level	100,000	9,261	0.0926	3.11E-10	**1.70E-09**

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
78	25 ft	3	5	20°	Descending	100,000	16,200	0.1620	5.45E-10	
79	25 ft	3	5	30°	Level	100,000	11,913	0.1191	1.85E-10	
80	25 ft	3	5	30°	Descending	100,000	42,409	0.4241	6.60E-10	
81	25 ft	4	1	20°	Level	100,000	3,010	0.0301	1.01E-10	**9.46E-10**
82	25 ft	4	1	20°	Descending	100,000	2,366	0.0237	7.95E-11	
83	25 ft	4	1	30°	Level	100,000	23,761	0.2376	3.70E-10	
84	25 ft	4	1	30°	Descending	100,000	25,449	0.2545	3.96E-10	
85	25 ft	4	2	20°	Level	100,000	5,636	0.0564	1.89E-10	**1.26E-09**
86	25 ft	4	2	20°	Descending	100,000	5,868	0.0587	1.97E-10	
87	25 ft	4	2	30°	Level	100,000	20,936	0.2094	3.26E-10	
88	25 ft	4	2	30°	Descending	100,000	35,496	0.3550	5.52E-10	
89	25 ft	4	3	20°	Level	100,000	7,613	0.0761	2.56E-10	**1.48E-09**
90	25 ft	4	3	20°	Descending	100,000	9,840	0.0984	3.31E-10	
91	25 ft	4	3	30°	Level	100,000	16,805	0.1681	2.61E-10	
92	25 ft	4	3	30°	Descending	100,000	40,688	0.4069	6.33E-10	
93	25 ft	4	4	20°	Level	100,000	8,505	0.0851	2.86E-10	**1.60E-09**
94	25 ft	4	4	20°	Descending	100,000	12,909	0.1291	4.34E-10	
95	25 ft	4	4	30°	Level	100,000	13,470	0.1347	2.10E-10	
96	25 ft	4	4	30°	Descending	100,000	42,873	0.4287	6.67E-10	
97	25 ft	4	5	20°	Level	100,000	9,628	0.0963	3.24E-10	**1.79E-09**
98	25 ft	4	5	20°	Descending	100,000	19,107	0.1911	6.42E-10	
99	25 ft	4	5	30°	Level	100,000	9,852	0.0985	1.53E-10	
100	25 ft	4	5	30°	Descending	100,000	43,235	0.4324	6.72E-10	

Table B-2: TCV Rates and Collision Risk Probabilities with 60 ft Position Accuracy

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
101	60 ft	0	1	20°	Level	100,000	742	0.0074	2.49E-11	**4.50E-10**
102	60 ft	0	1	20°	Descending	100,000	537	0.0054	1.81E-11	
103	60 ft	0	1	30°	Level	100,000	15,618	0.1562	2.43E-10	
104	60 ft	0	1	30°	Descending	100,000	10,561	0.1056	1.64E-10	
105	60 ft	0	2	20°	Level	100,000	2,039	0.0204	6.85E-11	**7.84E-10**
106	60 ft	0	2	20°	Descending	100,000	1,520	0.0152	5.11E-11	
107	60 ft	0	2	30°	Level	100,000	22,411	0.2241	3.49E-10	
108	60 ft	0	2	30°	Descending	100,000	20,329	0.2033	3.16E-10	
109	60 ft	0	3	20°	Level	100,000	3,622	0.0362	1.22E-10	**1.02E-09**
110	60 ft	0	3	20°	Descending	100,000	3,180	0.0318	1.07E-10	
111	60 ft	0	3	30°	Level	100,000	23,303	0.2330	3.62E-10	
112	60 ft	0	3	30°	Descending	100,000	27,621	0.2762	4.30E-10	
113	60 ft	0	4	20°	Level	100,000	4,991	0.0499	1.68E-10	**1.17E-09**
114	60 ft	0	4	20°	Descending	100,000	4,833	0.0483	1.62E-10	
115	60 ft	0	4	30°	Level	100,000	21,230	0.2123	3.30E-10	
116	60 ft	0	4	30°	Descending	100,000	32,862	0.3286	5.11E-10	
117	60 ft	0	5	20°	Level	100,000	6,961	0.0696	2.34E-10	**1.39E-09**
118	60 ft	0	5	20°	Descending	100,000	8,306	0.0831	2.79E-10	
119	60 ft	0	5	30°	Level	100,000	18,652	0.1865	2.90E-10	
120	60 ft	0	5	30°	Descending	100,000	37,689	0.3769	5.86E-10	
121	60 ft	1	1	20°	Level	100,000	1,083	0.0108	3.64E-11	**5.47E-10**
122	60 ft	1	1	20°	Descending	100,000	713	0.0071	2.40E-11	
123	60 ft	1	1	30°	Level	100,000	18,064	0.1806	2.81E-10	
124	60 ft	1	1	30°	Descending	100,000	13,238	0.1324	2.06E-10	
125	60 ft	1	2	20°	Level	100,000	2,740	0.0274	9.21E-11	**9.05E-10**
126	60 ft	1	2	20°	Descending	100,000	2,154	0.0215	7.24E-11	
127	60 ft	1	2	30°	Level	100,000	23,451	0.2345	3.65E-10	
128	60 ft	1	2	30°	Descending	100,000	24,146	0.2415	3.76E-10	
129	60 ft	1	3	20°	Level	100,000	4,508	0.0451	1.52E-10	**1.14E-09**
130	60 ft	1	3	20°	Descending	100,000	4,470	0.0447	1.50E-10	
131	60 ft	1	3	30°	Level	100,000	22,298	0.2230	3.47E-10	
132	60 ft	1	3	30°	Descending	100,000	31,505	0.3151	4.90E-10	
133	60 ft	1	4	20°	Level	100,000	6,085	0.0609	2.05E-10	**1.28E-09**
134	60 ft	1	4	20°	Descending	100,000	6,331	0.0633	2.13E-10	
135	60 ft	1	4	30°	Level	100,000	19,592	0.1959	3.05E-10	
136	60 ft	1	4	30°	Descending	100,000	35,941	0.3594	5.59E-10	
137	60 ft	1	5	20°	Level	100,000	7,920	0.0792	2.66E-10	**1.50E-09**
138	60 ft	1	5	20°	Descending	100,000	10,762	0.1076	3.62E-10	
139	60 ft	1	5	30°	Level	100,000	16,170	0.1617	2.52E-10	
140	60 ft	1	5	30°	Descending	100,000	40,056	0.4006	6.23E-10	
141	60 ft	2	1	20°	Level	100,000	1,556	0.0156	5.23E-11	**6.70E-10**
142	60 ft	2	1	20°	Descending	100,000	1,132	0.0113	3.80E-11	
143	60 ft	2	1	30°	Level	100,000	20,540	0.2054	3.19E-10	
144	60 ft	2	1	30°	Descending	100,000	16,753	0.1675	2.61E-10	

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
145	60 ft	2	2	20°	Level	100,000	3,628	0.0363	1.22E-10	**1.03E-09**
146	60 ft	2	2	20°	Descending	100,000	3,291	0.0329	1.11E-10	
147	60 ft	2	2	30°	Level	100,000	23,081	0.2308	3.59E-10	
148	60 ft	2	2	30°	Descending	100,000	28,391	0.2839	4.42E-10	
149	60 ft	2	3	20°	Level	100,000	5,501	0.0550	1.85E-10	**1.26E-09**
150	60 ft	2	3	20°	Descending	100,000	6,170	0.0617	2.07E-10	
151	60 ft	2	3	30°	Level	100,000	20,920	0.2092	3.25E-10	
152	60 ft	2	3	30°	Descending	100,000	34,966	0.3497	5.44E-10	
153	60 ft	2	4	20°	Level	100,000	6,852	0.0685	2.30E-10	**1.39E-09**
154	60 ft	2	4	20°	Descending	100,000	8,312	0.0831	2.79E-10	
155	60 ft	2	4	30°	Level	100,000	17,693	0.1769	2.75E-10	
156	60 ft	2	4	30°	Descending	100,000	38,605	0.3861	6.00E-10	
157	60 ft	2	5	20°	Level	100,000	8,812	0.0881	2.96E-10	**1.61E-09**
158	60 ft	2	5	20°	Descending	100,000	13,356	0.1336	4.49E-10	
159	60 ft	2	5	30°	Level	100,000	13,752	0.1375	2.14E-10	
160	60 ft	2	5	30°	Descending	100,000	41,829	0.4183	6.51E-10	
161	60 ft	3	1	20°	Level	100,000	2,092	0.0209	7.03E-11	**7.88E-10**
162	60 ft	3	1	20°	Descending	100,000	1,650	0.0165	5.55E-11	
163	60 ft	3	1	30°	Level	100,000	22,113	0.2211	3.44E-10	
164	60 ft	3	1	30°	Descending	100,000	20,476	0.2048	3.18E-10	
165	60 ft	3	2	20°	Level	100,000	4,523	0.0452	1.52E-10	**1.15E-09**
166	60 ft	3	2	20°	Descending	100,000	4,358	0.0436	1.46E-10	
167	60 ft	3	2	30°	Level	100,000	22,495	0.2250	3.50E-10	
168	60 ft	3	2	30°	Descending	100,000	32,193	0.3219	5.01E-10	
169	60 ft	3	3	20°	Level	100,000	6,601	0.0660	2.22E-10	**1.37E-09**
170	60 ft	3	3	20°	Descending	100,000	7,751	0.0775	2.61E-10	
171	60 ft	3	3	30°	Level	100,000	19,150	0.1915	2.98E-10	
172	60 ft	3	3	30°	Descending	100,000	38,069	0.3807	5.92E-10	
173	60 ft	3	4	20°	Level	100,000	7,783	0.0778	2.62E-10	**1.50E-09**
174	60 ft	3	4	20°	Descending	100,000	10,500	0.1050	3.53E-10	
175	60 ft	3	4	30°	Level	100,000	15,564	0.1556	2.42E-10	
176	60 ft	3	4	30°	Descending	100,000	41,230	0.4123	6.41E-10	
177	60 ft	3	5	20°	Level	100,000	9,244	0.0924	3.11E-10	**1.69E-09**
178	60 ft	3	5	20°	Descending	100,000	15,942	0.1594	5.36E-10	
179	60 ft	3	5	30°	Level	100,000	11,594	0.1159	1.80E-10	
180	60 ft	3	5	30°	Descending	100,000	42,358	0.4236	6.59E-10	
181	60 ft	4	1	20°	Level	100,000	2,731	0.0273	9.18E-11	**9.04E-10**
182	60 ft	4	1	20°	Descending	100,000	2,278	0.0228	7.66E-11	
183	60 ft	4	1	30°	Level	100,000	22,964	0.2296	3.57E-10	
184	60 ft	4	1	30°	Descending	100,000	24,313	0.2431	3.78E-10	
185	60 ft	4	2	20°	Level	100,000	5,411	0.0541	1.82E-10	**1.26E-09**
186	60 ft	4	2	20°	Descending	100,000	5,857	0.0586	1.97E-10	
187	60 ft	4	2	30°	Level	100,000	20,972	0.2097	3.26E-10	
188	60 ft	4	2	30°	Descending	100,000	35,411	0.3541	5.51E-10	

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
189	60 ft	4	3	20°	Level	100,000	7,434	0.0743	2.50E-10	**1.48E-09**
190	60 ft	4	3	20°	Descending	100,000	9,946	0.0995	3.34E-10	
191	60 ft	4	3	30°	Level	100,000	16,853	0.1685	2.62E-10	
192	60 ft	4	3	30°	Descending	100,000	40,635	0.4064	6.32E-10	
193	60 ft	4	4	20°	Level	100,000	8,480	0.0848	2.85E-10	**1.59E-09**
194	60 ft	4	4	20°	Descending	100,000	12,819	0.1282	4.31E-10	
195	60 ft	4	4	30°	Level	100,000	13,528	0.1353	2.10E-10	
196	60 ft	4	4	30°	Descending	100,000	42,868	0.4287	6.67E-10	
197	60 ft	4	5	20°	Level	100,000	9,719	0.0972	3.27E-10	**1.79E-09**
198	60 ft	4	5	20°	Descending	100,000	18,776	0.1878	6.31E-10	
199	60 ft	4	5	30°	Level	100,000	10,278	0.1028	1.60E-10	
200	60 ft	4	5	30°	Descending	100,000	43,269	0.4327	6.73E-10	

Table B-3: TCV Rates and Collision Risk Probabilities with 100 ft Position Accuracy

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
201	100 ft	0	1	20°	Level	100,000	651	0.0065	2.19E-11	**3.97E-10**
202	100 ft	0	1	20°	Descending	100,000	473	0.0047	1.59E-11	
203	100 ft	0	1	30°	Level	100,000	13,745	0.1375	2.14E-10	
204	100 ft	0	1	30°	Descending	100,000	9,321	0.0932	1.45E-10	
205	100 ft	0	2	20°	Level	100,000	2,054	0.0205	6.90E-11	**7.85E-10**
206	100 ft	0	2	20°	Descending	100,000	1,476	0.0148	4.96E-11	
207	100 ft	0	2	30°	Level	100,000	22,387	0.2239	3.48E-10	
208	100 ft	0	2	30°	Descending	100,000	20,457	0.2046	3.18E-10	
209	100 ft	0	3	20°	Level	100,000	3,535	0.0354	1.19E-10	**1.02E-09**
210	100 ft	0	3	20°	Descending	100,000	3,223	0.0322	1.08E-10	
211	100 ft	0	3	30°	Level	100,000	23,074	0.2307	3.59E-10	
212	100 ft	0	3	30°	Descending	100,000	27,827	0.2783	4.33E-10	
213	100 ft	0	4	20°	Level	100,000	4,938	0.0494	1.66E-10	**1.17E-09**
214	100 ft	0	4	20°	Descending	100,000	5,004	0.0500	1.68E-10	
215	100 ft	0	4	30°	Level	100,000	21,335	0.2134	3.32E-10	
216	100 ft	0	4	30°	Descending	100,000	32,624	0.3262	5.07E-10	
217	100 ft	0	5	20°	Level	100,000	6,979	0.0698	2.35E-10	**1.39E-09**
218	100 ft	0	5	20°	Descending	100,000	8,473	0.0847	2.85E-10	
219	100 ft	0	5	30°	Level	100,000	18,464	0.1846	2.87E-10	
220	100 ft	0	5	30°	Descending	100,000	37,781	0.3778	5.88E-10	
221	100 ft	1	1	20°	Level	100,000	894	0.0089	3.00E-11	**4.93E-10**
222	100 ft	1	1	20°	Descending	100,000	747	0.0075	2.51E-11	
223	100 ft	1	1	30°	Level	100,000	16,170	0.1617	2.52E-10	
224	100 ft	1	1	30°	Descending	100,000	11,962	0.1196	1.86E-10	
225	100 ft	1	2	20°	Level	100,000	2,812	0.0281	9.45E-11	**9.01E-10**
226	100 ft	1	2	20°	Descending	100,000	2,170	0.0217	7.29E-11	
227	100 ft	1	2	30°	Level	100,000	23,173	0.2317	3.60E-10	
228	100 ft	1	2	30°	Descending	100,000	23,985	0.2399	3.73E-10	
229	100 ft	1	3	20°	Level	100,000	4,611	0.0461	1.55E-10	**1.14E-09**
230	100 ft	1	3	20°	Descending	100,000	4,395	0.0440	1.48E-10	
231	100 ft	1	3	30°	Level	100,000	21,988	0.2199	3.42E-10	
232	100 ft	1	3	30°	Descending	100,000	31,639	0.3164	4.92E-10	
233	100 ft	1	4	20°	Level	100,000	5,868	0.0587	1.97E-10	**1.27E-09**
234	100 ft	1	4	20°	Descending	100,000	6,367	0.0637	2.14E-10	
235	100 ft	1	4	30°	Level	100,000	19,647	0.1965	3.06E-10	
236	100 ft	1	4	30°	Descending	100,000	35,779	0.3578	5.57E-10	
237	100 ft	1	5	20°	Level	100,000	8,031	0.0803	2.70E-10	**1.51E-09**
238	100 ft	1	5	20°	Descending	100,000	10,791	0.1079	3.63E-10	
239	100 ft	1	5	30°	Level	100,000	16,337	0.1634	2.54E-10	
240	100 ft	1	5	30°	Descending	100,000	39,755	0.3976	6.18E-10	
241	100 ft	2	1	20°	Level	100,000	1,284	0.0128	4.32E-11	**6.01E-10**
242	100 ft	2	1	20°	Descending	100,000	1,193	0.0119	4.01E-11	
243	100 ft	2	1	30°	Level	100,000	18,326	0.1833	2.85E-10	
244	100 ft	2	1	30°	Descending	100,000	14,952	0.1495	2.33E-10	

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
245	100 ft	2	2	20°	Level	100,000	3,688	0.0369	1.24E-10	**1.03E-09**
246	100 ft	2	2	20°	Descending	100,000	3,231	0.0323	1.09E-10	
247	100 ft	2	2	30°	Level	100,000	23,192	0.2319	3.61E-10	
248	100 ft	2	2	30°	Descending	100,000	27,922	0.2792	4.34E-10	
249	100 ft	2	3	20°	Level	100,000	5,551	0.0555	1.87E-10	**1.25E-09**
250	100 ft	2	3	20°	Descending	100,000	5,758	0.0576	1.94E-10	
251	100 ft	2	3	30°	Level	100,000	20,930	0.2093	3.26E-10	
252	100 ft	2	3	30°	Descending	100,000	34,886	0.3489	5.43E-10	
253	100 ft	2	4	20°	Level	100,000	6,765	0.0677	2.27E-10	**1.38E-09**
254	100 ft	2	4	20°	Descending	100,000	8,292	0.0829	2.79E-10	
255	100 ft	2	4	30°	Level	100,000	17,642	0.1764	2.74E-10	
256	100 ft	2	4	30°	Descending	100,000	38,539	0.3854	5.99E-10	
257	100 ft	2	5	20°	Level	100,000	8,682	0.0868	2.92E-10	**1.60E-09**
258	100 ft	2	5	20°	Descending	100,000	13,186	0.1319	4.43E-10	
259	100 ft	2	5	30°	Level	100,000	13,890	0.1389	2.16E-10	
260	100 ft	2	5	30°	Descending	100,000	41,745	0.4175	6.49E-10	
261	100 ft	3	1	20°	Level	100,000	1,774	0.0177	5.96E-11	**7.06E-10**
262	100 ft	3	1	20°	Descending	100,000	1,699	0.0170	5.71E-11	
263	100 ft	3	1	30°	Level	100,000	20,184	0.2018	3.14E-10	
264	100 ft	3	1	30°	Descending	100,000	17,713	0.1771	2.76E-10	
265	100 ft	3	2	20°	Level	100,000	4,545	0.0455	1.53E-10	**1.15E-09**
266	100 ft	3	2	20°	Descending	100,000	4,453	0.0445	1.50E-10	
267	100 ft	3	2	30°	Level	100,000	22,485	0.2249	3.50E-10	
268	100 ft	3	2	30°	Descending	100,000	31,817	0.3182	4.95E-10	
269	100 ft	3	3	20°	Level	100,000	6,527	0.0653	2.19E-10	**1.36E-09**
270	100 ft	3	3	20°	Descending	100,000	7,612	0.0761	2.56E-10	
271	100 ft	3	3	30°	Level	100,000	19,252	0.1925	2.99E-10	
272	100 ft	3	3	30°	Descending	100,000	37,919	0.3792	5.90E-10	
273	100 ft	3	4	20°	Level	100,000	7,904	0.0790	2.66E-10	**1.50E-09**
274	100 ft	3	4	20°	Descending	100,000	10,438	0.1044	3.51E-10	
275	100 ft	3	4	30°	Level	100,000	15,785	0.1579	2.46E-10	
276	100 ft	3	4	30°	Descending	100,000	41,069	0.4107	6.39E-10	
277	100 ft	3	5	20°	Level	100,000	9,285	0.0929	3.12E-10	**1.70E-09**
278	100 ft	3	5	20°	Descending	100,000	16,026	0.1603	5.39E-10	
279	100 ft	3	5	30°	Level	100,000	11,824	0.1182	1.84E-10	
280	100 ft	3	5	30°	Descending	100,000	42,504	0.4250	6.61E-10	
281	100 ft	4	1	20°	Level	100,000	2,520	0.0252	8.47E-11	**8.30E-10**
282	100 ft	4	1	20°	Descending	100,000	2,374	0.0237	7.98E-11	
283	100 ft	4	1	30°	Level	100,000	21,032	0.2103	3.27E-10	
284	100 ft	4	1	30°	Descending	100,000	21,744	0.2174	3.38E-10	
285	100 ft	4	2	20°	Level	100,000	5,407	0.0541	1.82E-10	**1.25E-09**
286	100 ft	4	2	20°	Descending	100,000	5,801	0.0580	1.95E-10	
287	100 ft	4	2	30°	Level	100,000	20,939	0.2094	3.26E-10	
288	100 ft	4	2	30°	Descending	100,000	35,432	0.3543	5.51E-10	

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
289	100 ft	4	3	20°	Level	100,000	7,352	0.0735	2.47E-10	**1.46E-09**
290	100 ft	4	3	20°	Descending	100,000	9,817	0.0982	3.30E-10	
291	100 ft	4	3	30°	Level	100,000	16,602	0.1660	2.58E-10	
292	100 ft	4	3	30°	Descending	100,000	40,250	0.4025	6.26E-10	
293	100 ft	4	4	20°	Level	100,000	8,435	0.0844	2.84E-10	**1.60E-09**
294	100 ft	4	4	20°	Descending	100,000	12,953	0.1295	4.35E-10	
295	100 ft	4	4	30°	Level	100,000	13,644	0.1364	2.12E-10	
296	100 ft	4	4	30°	Descending	100,000	42,714	0.4271	6.64E-10	
297	100 ft	4	5	20°	Level	100,000	9,579	0.0958	3.22E-10	**1.79E-09**
298	100 ft	4	5	20°	Descending	100,000	18,878	0.1888	6.35E-10	
299	100 ft	4	5	30°	Level	100,000	10,129	0.1013	1.58E-10	
300	100 ft	4	5	30°	Descending	100,000	43,395	0.4340	6.75E-10	

Table B-4: TCV Rates and Collision Risk Probabilities with 150 ft Position Accuracy

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
301	150 ft	0	1	20°	Level	100,000	493	0.0049	1.66E-11	**2.86E-10**
302	150 ft	0	1	20°	Descending	100,000	318	0.0032	1.07E-11	
303	150 ft	0	1	30°	Level	100,000	10,119	0.1012	1.57E-10	
304	150 ft	0	1	30°	Descending	100,000	6,534	0.0653	1.02E-10	
305	150 ft	0	2	20°	Level	100,000	2,069	0.0207	6.95E-11	**7.67E-10**
306	150 ft	0	2	20°	Descending	100,000	1,591	0.0159	5.35E-11	
307	150 ft	0	2	30°	Level	100,000	21,489	0.2149	3.34E-10	
308	150 ft	0	2	30°	Descending	100,000	19,894	0.1989	3.09E-10	
309	150 ft	0	3	20°	Level	100,000	3,647	0.0365	1.23E-10	**1.02E-09**
310	150 ft	0	3	20°	Descending	100,000	3,203	0.0320	1.08E-10	
311	150 ft	0	3	30°	Level	100,000	22,823	0.2282	3.55E-10	
312	150 ft	0	3	30°	Descending	100,000	27,877	0.2788	4.34E-10	
313	150 ft	0	4	20°	Level	100,000	4,942	0.0494	1.66E-10	**1.17E-09**
314	150 ft	0	4	20°	Descending	100,000	4,853	0.0485	1.63E-10	
315	150 ft	0	4	30°	Level	100,000	21,354	0.2135	3.32E-10	
316	150 ft	0	4	30°	Descending	100,000	32,505	0.3251	5.06E-10	
317	150 ft	0	5	20°	Level	100,000	6,919	0.0692	2.33E-10	**1.39E-09**
318	150 ft	0	5	20°	Descending	100,000	8,407	0.0841	2.83E-10	
319	150 ft	0	5	30°	Level	100,000	18,635	0.1864	2.90E-10	
320	150 ft	0	5	30°	Descending	100,000	37,773	0.3777	5.88E-10	
321	150 ft	1	1	20°	Level	100,000	650	0.0065	2.18E-11	**3.56E-10**
322	150 ft	1	1	20°	Descending	100,000	453	0.0045	1.52E-11	
323	150 ft	1	1	30°	Level	100,000	12,013	0.1201	1.87E-10	
324	150 ft	1	1	30°	Descending	100,000	8,518	0.0852	1.32E-10	
325	150 ft	1	2	20°	Level	100,000	2,697	0.0270	9.07E-11	**8.90E-10**
326	150 ft	1	2	20°	Descending	100,000	2,218	0.0222	7.46E-11	
327	150 ft	1	2	30°	Level	100,000	22,917	0.2292	3.56E-10	
328	150 ft	1	2	30°	Descending	100,000	23,687	0.2369	3.68E-10	
329	150 ft	1	3	20°	Level	100,000	4,480	0.0448	1.51E-10	**1.13E-09**
330	150 ft	1	3	20°	Descending	100,000	4,384	0.0438	1.47E-10	
331	150 ft	1	3	30°	Level	100,000	22,230	0.2223	3.46E-10	
332	150 ft	1	3	30°	Descending	100,000	31,553	0.3155	4.91E-10	
333	150 ft	1	4	20°	Level	100,000	5,959	0.0596	2.00E-10	**1.28E-09**
334	150 ft	1	4	20°	Descending	100,000	6,385	0.0639	2.15E-10	
335	150 ft	1	4	30°	Level	100,000	19,848	0.1985	3.09E-10	
336	150 ft	1	4	30°	Descending	100,000	35,622	0.3562	5.54E-10	
337	150 ft	1	5	20°	Level	100,000	7,799	0.0780	2.62E-10	**1.50E-09**
338	150 ft	1	5	20°	Descending	100,000	10,814	0.1081	3.63E-10	
339	150 ft	1	5	30°	Level	100,000	16,249	0.1625	2.53E-10	
340	150 ft	1	5	30°	Descending	100,000	39,862	0.3986	6.20E-10	
341	150 ft	2	1	20°	Level	100,000	832	0.0083	2.80E-11	**4.35E-10**
342	150 ft	2	1	20°	Descending	100,000	650	0.0065	2.18E-11	
343	150 ft	2	1	30°	Level	100,000	14,046	0.1405	2.18E-10	
344	150 ft	2	1	30°	Descending	100,000	10,734	0.1073	1.67E-10	

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
345	150 ft	2	2	20°	Level	100,000	3,477	0.0348	1.17E-10	**1.01E-09**
346	150 ft	2	2	20°	Descending	100,000	3,144	0.0314	1.06E-10	
347	150 ft	2	2	30°	Level	100,000	22,714	0.2271	3.53E-10	
348	150 ft	2	2	30°	Descending	100,000	27,685	0.2769	4.31E-10	
349	150 ft	2	3	20°	Level	100,000	5,521	0.0552	1.86E-10	**1.25E-09**
350	150 ft	2	3	20°	Descending	100,000	5,908	0.0591	1.99E-10	
351	150 ft	2	3	30°	Level	100,000	20,589	0.2059	3.20E-10	
352	150 ft	2	3	30°	Descending	100,000	35,161	0.3516	5.47E-10	
353	150 ft	2	4	20°	Level	100,000	6,956	0.0696	2.34E-10	**1.38E-09**
354	150 ft	2	4	20°	Descending	100,000	8,128	0.0813	2.73E-10	
355	150 ft	2	4	30°	Level	100,000	17,739	0.1774	2.76E-10	
356	150 ft	2	4	30°	Descending	100,000	38,329	0.3833	5.96E-10	
357	150 ft	2	5	20°	Level	100,000	8,767	0.0877	2.95E-10	**1.61E-09**
358	150 ft	2	5	20°	Descending	100,000	13,465	0.1347	4.53E-10	
359	150 ft	2	5	30°	Level	100,000	13,996	0.1400	2.18E-10	
360	150 ft	2	5	30°	Descending	100,000	41,622	0.4162	6.47E-10	
361	150 ft	3	1	20°	Level	100,000	1,188	0.0119	3.99E-11	**5.19E-10**
362	150 ft	3	1	20°	Descending	100,000	871	0.0087	2.93E-11	
363	150 ft	3	1	30°	Level	100,000	15,827	0.1583	2.46E-10	
364	150 ft	3	1	30°	Descending	100,000	13,093	0.1309	2.04E-10	
365	150 ft	3	2	20°	Level	100,000	4,318	0.0432	1.45E-10	**1.12E-09**
366	150 ft	3	2	20°	Descending	100,000	4,401	0.0440	1.48E-10	
367	150 ft	3	2	30°	Level	100,000	22,084	0.2208	3.43E-10	
368	150 ft	3	2	30°	Descending	100,000	31,314	0.3131	4.87E-10	
369	150 ft	3	3	20°	Level	100,000	6,602	0.0660	2.22E-10	**1.37E-09**
370	150 ft	3	3	20°	Descending	100,000	7,988	0.0799	2.68E-10	
371	150 ft	3	3	30°	Level	100,000	18,652	0.1865	2.90E-10	
372	150 ft	3	3	30°	Descending	100,000	38,074	0.3807	5.92E-10	
373	150 ft	3	4	20°	Level	100,000	7,816	0.0782	2.63E-10	**1.49E-09**
374	150 ft	3	4	20°	Descending	100,000	10,425	0.1043	3.50E-10	
375	150 ft	3	4	30°	Level	100,000	15,788	0.1579	2.46E-10	
376	150 ft	3	4	30°	Descending	100,000	40,757	0.4076	6.34E-10	
377	150 ft	3	5	20°	Level	100,000	9,163	0.0916	3.08E-10	**1.70E-09**
378	150 ft	3	5	20°	Descending	100,000	16,145	0.1615	5.43E-10	
379	150 ft	3	5	30°	Level	100,000	11,916	0.1192	1.85E-10	
380	150 ft	3	5	30°	Descending	100,000	42,487	0.4249	6.61E-10	
381	150 ft	4	1	20°	Level	100,000	1,637	0.0164	5.50E-11	**6.20E-10**
382	150 ft	4	1	20°	Descending	100,000	1,336	0.0134	4.49E-11	
383	150 ft	4	1	30°	Level	100,000	17,166	0.1717	2.67E-10	
384	150 ft	4	1	30°	Descending	100,000	16,285	0.1629	2.53E-10	
385	150 ft	4	2	20°	Level	100,000	5,353	0.0535	1.80E-10	**1.24E-09**
386	150 ft	4	2	20°	Descending	100,000	5,873	0.0587	1.97E-10	
387	150 ft	4	2	30°	Level	100,000	20,787	0.2079	3.23E-10	
388	150 ft	4	2	30°	Descending	100,000	34,510	0.3451	5.37E-10	

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
389	150 ft	4	3	20°	Level	100,000	7,387	0.0739	2.48E-10	**1.47E-09**
390	150 ft	4	3	20°	Descending	100,000	10,036	0.1004	3.37E-10	
391	150 ft	4	3	30°	Level	100,000	16,833	0.1683	2.62E-10	
392	150 ft	4	3	30°	Descending	100,000	40,096	0.4010	6.24E-10	
393	150 ft	4	4	20°	Level	100,000	8,411	0.0841	2.83E-10	**1.59E-09**
394	150 ft	4	4	20°	Descending	100,000	12,637	0.1264	4.25E-10	
395	150 ft	4	4	30°	Level	100,000	13,729	0.1373	2.14E-10	
396	150 ft	4	4	30°	Descending	100,000	42,725	0.4273	6.65E-10	
397	150 ft	4	5	20°	Level	100,000	9,520	0.0952	3.20E-10	**1.79E-09**
398	150 ft	4	5	20°	Descending	100,000	19,098	0.1910	6.42E-10	
399	150 ft	4	5	30°	Level	100,000	10,174	0.1017	1.58E-10	
400	150 ft	4	5	30°	Descending	100,000	43,241	0.4324	6.73E-10	

Table B-5: TCV Rates and Collision Risk Probabilities with 200 ft Position Accuracy

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
401	200 ft	0	1	20°	Level	100,000	316	0.0032	1.06E-11	**1.98E-10**
402	200 ft	0	1	20°	Descending	100,000	276	0.0028	9.28E-12	
403	200 ft	0	1	30°	Level	100,000	7,072	0.0707	1.10E-10	
404	200 ft	0	1	30°	Descending	100,000	4,387	0.0439	6.82E-11	
405	200 ft	0	2	20°	Level	100,000	1,943	0.0194	6.53E-11	**7.37E-10**
406	200 ft	0	2	20°	Descending	100,000	1,488	0.0149	5.00E-11	
407	200 ft	0	2	30°	Level	100,000	20,879	0.2088	3.25E-10	
408	200 ft	0	2	30°	Descending	100,000	19,098	0.1910	2.97E-10	
409	200 ft	0	3	20°	Level	100,000	3,663	0.0366	1.23E-10	**1.02E-09**
410	200 ft	0	3	20°	Descending	100,000	3,302	0.0330	1.11E-10	
411	200 ft	0	3	30°	Level	100,000	22,486	0.2249	3.50E-10	
412	200 ft	0	3	30°	Descending	100,000	27,742	0.2774	4.32E-10	
413	200 ft	0	4	20°	Level	100,000	4,887	0.0489	1.64E-10	**1.15E-09**
414	200 ft	0	4	20°	Descending	100,000	4,706	0.0471	1.58E-10	
415	200 ft	0	4	30°	Level	100,000	21,077	0.2108	3.28E-10	
416	200 ft	0	4	30°	Descending	100,000	32,388	0.3239	5.04E-10	
417	200 ft	0	5	20°	Level	100,000	6,801	0.0680	2.29E-10	**1.38E-09**
418	200 ft	0	5	20°	Descending	100,000	8,499	0.0850	2.86E-10	
419	200 ft	0	5	30°	Level	100,000	18,422	0.1842	2.87E-10	
420	200 ft	0	5	30°	Descending	100,000	37,396	0.3740	5.82E-10	
421	200 ft	1	1	20°	Level	100,000	413	0.0041	1.39E-11	**2.46E-10**
422	200 ft	1	1	20°	Descending	100,000	315	0.0032	1.06E-11	
423	200 ft	1	1	30°	Level	100,000	8,511	0.0851	1.32E-10	
424	200 ft	1	1	30°	Descending	100,000	5,711	0.0571	8.88E-11	
425	200 ft	1	2	20°	Level	100,000	2,624	0.0262	8.82E-11	**8.61E-10**
426	200 ft	1	2	20°	Descending	100,000	2,119	0.0212	7.12E-11	
427	200 ft	1	2	30°	Level	100,000	21,956	0.2196	3.42E-10	
428	200 ft	1	2	30°	Descending	100,000	23,155	0.2316	3.60E-10	
429	200 ft	1	3	20°	Level	100,000	4,575	0.0458	1.54E-10	**1.13E-09**
430	200 ft	1	3	20°	Descending	100,000	4,430	0.0443	1.49E-10	
431	200 ft	1	3	30°	Level	100,000	21,904	0.2190	3.41E-10	
432	200 ft	1	3	30°	Descending	100,000	31,229	0.3123	4.86E-10	
433	200 ft	1	4	20°	Level	100,000	5,866	0.0587	1.97E-10	**1.27E-09**
434	200 ft	1	4	20°	Descending	100,000	6,387	0.0639	2.15E-10	
435	200 ft	1	4	30°	Level	100,000	19,725	0.1973	3.07E-10	
436	200 ft	1	4	30°	Descending	100,000	35,467	0.3547	5.52E-10	
437	200 ft	1	5	20°	Level	100,000	7,803	0.0780	2.62E-10	**1.49E-09**
438	200 ft	1	5	20°	Descending	100,000	10,854	0.1085	3.65E-10	
439	200 ft	1	5	30°	Level	100,000	16,376	0.1638	2.55E-10	
440	200 ft	1	5	30°	Descending	100,000	39,419	0.3942	6.13E-10	
441	200 ft	2	1	20°	Level	100,000	574	0.0057	1.93E-11	**3.10E-10**
442	200 ft	2	1	20°	Descending	100,000	442	0.0044	1.49E-11	
443	200 ft	2	1	30°	Level	100,000	10,313	0.1031	1.60E-10	
444	200 ft	2	1	30°	Descending	100,000	7,402	0.0740	1.15E-10	

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
445	200 ft	2	2	20°	Level	100,000	3,472	0.0347	1.17E-10	**9.85E-10**
446	200 ft	2	2	20°	Descending	100,000	3,100	0.0310	1.04E-10	
447	200 ft	2	2	30°	Level	100,000	22,230	0.2223	3.46E-10	
448	200 ft	2	2	30°	Descending	100,000	26,901	0.2690	4.18E-10	
449	200 ft	2	3	20°	Level	100,000	5,424	0.0542	1.82E-10	**1.25E-09**
450	200 ft	2	3	20°	Descending	100,000	6,074	0.0607	2.04E-10	
451	200 ft	2	3	30°	Level	100,000	20,573	0.2057	3.20E-10	
452	200 ft	2	3	30°	Descending	100,000	34,841	0.3484	5.42E-10	
453	200 ft	2	4	20°	Level	100,000	6,846	0.0685	2.30E-10	**1.37E-09**
454	200 ft	2	4	20°	Descending	100,000	8,177	0.0818	2.75E-10	
455	200 ft	2	4	30°	Level	100,000	17,676	0.1768	2.75E-10	
456	200 ft	2	4	30°	Descending	100,000	38,073	0.3807	5.92E-10	
457	200 ft	2	5	20°	Level	100,000	8,827	0.0883	2.97E-10	**1.60E-09**
458	200 ft	2	5	20°	Descending	100,000	13,199	0.1320	4.44E-10	
459	200 ft	2	5	30°	Level	100,000	13,936	0.1394	2.17E-10	
460	200 ft	2	5	30°	Descending	100,000	41,026	0.4103	6.38E-10	
461	200 ft	3	1	20°	Level	100,000	811	0.0081	2.73E-11	**3.78E-10**
462	200 ft	3	1	20°	Descending	100,000	590	0.0059	1.98E-11	
463	200 ft	3	1	30°	Level	100,000	11,938	0.1194	1.86E-10	
464	200 ft	3	1	30°	Descending	100,000	9,336	0.0934	1.45E-10	
465	200 ft	3	2	20°	Level	100,000	4,402	0.0440	1.48E-10	**1.10E-09**
466	200 ft	3	2	20°	Descending	100,000	4,317	0.0432	1.45E-10	
467	200 ft	3	2	30°	Level	100,000	21,378	0.2138	3.33E-10	
468	200 ft	3	2	30°	Descending	100,000	30,290	0.3029	4.71E-10	
469	200 ft	3	3	20°	Level	100,000	6,492	0.0649	2.18E-10	**1.36E-09**
470	200 ft	3	3	20°	Descending	100,000	7,939	0.0794	2.67E-10	
471	200 ft	3	3	30°	Level	100,000	18,972	0.1897	2.95E-10	
472	200 ft	3	3	30°	Descending	100,000	37,586	0.3759	5.85E-10	
473	200 ft	3	4	20°	Level	100,000	7,646	0.0765	2.57E-10	**1.48E-09**
474	200 ft	3	4	20°	Descending	100,000	10,198	0.1020	3.43E-10	
475	200 ft	3	4	30°	Level	100,000	15,889	0.1589	2.47E-10	
476	200 ft	3	4	30°	Descending	100,000	40,739	0.4074	6.34E-10	
477	200 ft	3	5	20°	Level	100,000	9,225	0.0923	3.10E-10	**1.69E-09**
478	200 ft	3	5	20°	Descending	100,000	16,188	0.1619	5.44E-10	
479	200 ft	3	5	30°	Level	100,000	11,966	0.1197	1.86E-10	
480	200 ft	3	5	30°	Descending	100,000	42,062	0.4206	6.54E-10	
481	200 ft	4	1	20°	Level	100,000	1,117	0.0112	3.75E-11	**4.57E-10**
482	200 ft	4	1	20°	Descending	100,000	816	0.0082	2.74E-11	
483	200 ft	4	1	30°	Level	100,000	13,580	0.1358	2.11E-10	
484	200 ft	4	1	30°	Descending	100,000	11,645	0.1165	1.81E-10	
485	200 ft	4	2	20°	Level	100,000	5,151	0.0515	1.73E-10	**1.21E-09**
486	200 ft	4	2	20°	Descending	100,000	5,677	0.0568	1.91E-10	
487	200 ft	4	2	30°	Level	100,000	20,413	0.2041	3.18E-10	
488	200 ft	4	2	30°	Descending	100,000	33,679	0.3368	5.24E-10	

Scenario Number	Position Measurement Accuracy (σ)	Proc. Time (sec)	Sensor Update Rate (sec)	Deviation Angle	Deviation Vertical Profile	Number of Aircraft Pairs	Number of TCVs	P(TCV| Dθ∩DV)	P(TCV) Deviation Type	Collision Risk per Approach
489	200 ft	4	3	20°	Level	100,000	7,398	0.0740	2.49E-10	**1.47E-09**
490	200 ft	4	3	20°	Descending	100,000	9,980	0.0998	3.35E-10	
491	200 ft	4	3	30°	Level	100,000	16,918	0.1692	2.63E-10	
492	200 ft	4	3	30°	Descending	100,000	40,238	0.4024	6.26E-10	
493	200 ft	4	4	20°	Level	100,000	8,411	0.0841	2.83E-10	**1.58E-09**
494	200 ft	4	4	20°	Descending	100,000	12,522	0.1252	4.21E-10	
495	200 ft	4	4	30°	Level	100,000	13,740	0.1374	2.14E-10	
496	200 ft	4	4	30°	Descending	100,000	42,769	0.4277	6.65E-10	
497	200 ft	4	5	20°	Level	100,000	9,500	0.0950	3.19E-10	**1.80E-09**
498	200 ft	4	5	20°	Descending	100,000	19,168	0.1917	6.44E-10	
499	200 ft	4	5	30°	Level	100,000	10,246	0.1025	1.59E-10	
500	200 ft	4	5	30°	Descending	100,000	43,215	0.4322	6.72E-10	

Appendix C: Acronyms

This appendix includes a list of acronyms associated with this study.

ASAT^{ng}	-	Airspace Simulation and Analysis Tool – Next Generation
ASR	-	Airport Surveillance Radar
CAT II	-	Category II ILS
CSPO	-	Closely Spaced Parallel Operations
ERJ	-	Embraer regional jet
E-Scan	-	Electronic Scan
FAA	-	Federal Aviation Administration
FMA	-	Final Monitor Aid
HUR	-	High Update Rate
ILS	-	Instrument Landing System
MSL	-	Mean Sea Level
MSSR	-	Monopulse Secondary Surveillance Radar
NAS	-	National Airspace System
NM	-	Nautical Miles
NTZ	-	No Transgression Zone
pdfs	-	Probability Density Functions
PRM	-	Precision Runway Monitor
PRM-A	-	Precision Runway Monitor – Alternative
PTL	-	Predictor Target Line
RCLS	-	Runway Centerline Spacing
STARS	-	Standard Terminal Automation Replacement System
TCV	-	Test Criterion Violation