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Safety Study of Closely Spaced Parallel Operations with High Update Rate Surveillance

May 2018

Technical Report

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12. Abstract

The Federal Aviation Administration (FAA) Flight Systems Laboratory (AFS-450) was requested by the NextGen R&D Portfolio Branch (ANG-C22) to conduct a study to analyze the minimum runway spacing requirement for simultaneous independent operations to parallel runways while using high update rate (HUR) surveillance. Collision risk was assessed as a function of HUR surveillance capabilities and runway centerline spacing (RCLS) to simultaneous independent dual and triple straight-in and offset final approach courses for Instrument Landing System (ILS) and Global Positioning System (GPS) equipped Area Navigation (RNAV)/Required Navigation Performance (RNP) aircraft flying with flight director guidance (or autopilot). To identify the benefits of utilizing HUR capabilities, analysis began at the current minimum RCLS requirements for non-HUR Closely Spaced Parallel Operations (CSPO) operations, followed by additional reductions in RCLS down to 2500 ft. Evaluations were conducted utilizing generic CSPO runway configurations and a number of airport specific runway configurations that differed from the generic cases. FAA Order JO 7110.65X, *Air Traffic Control* (paragraphs 5-9-7 and 5-9-8) and FAA Order JO 7210.3AA, *Facility Operation and Administration* (paragraph 10-4-6) contain the current provisions governing air traffic control separation for independent precision approach operations at airports with dual or triple parallel approach configurations.

The results indicate possible reductions to established minimum RCLS requirements for airports with:

- Dual parallel runways with RCLS of 3200 ft or more without localizer offset, referred to as dual straight-in approach
- Dual parallel runways with RCLS of 2500 ft or more and a single localizer offset between 2.5° and 3°, referred to as dual offset approach
- Triple parallel runways with RCLS of 3400 ft or more without localizer offset, referred to as triple straight-in approach
- Triple parallel runways with RCLS of 2500 ft or more with at least one localizer offset to an outside runway between 2.5° and 3°, referred to as triple single offset approach or triple dual offset approach

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Final Monitor Aid (FMA) High Update Rate (HUR) No Transgression Zone (NTZ) Normal Operating Zone (NOZ) Precision Runway Monitor (PRM) Predictor Target Line (PTL) Processing Time (PT) Runway Centerline Spacing (RCLS) Surveillance Sensor Update Rate (SSUR) Test Criterion Violation (TCV)	Uncontrolled
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Executive Summary

The Federal Aviation Administration (FAA) NextGen R&D Portfolio Branch (ANG-C22) requested that the Flight Technologies and Procedures Division (AFS-400) Flight Systems Laboratory (AFS-450) conduct a study to provide an analysis of the possible reductions in required runway centerline spacing of parallel runways based upon the high update rate (HUR) surveillance parameter study. An HUR surveillance system is defined as one with a sensor update rate of less than 4.8 seconds. Collision risk was assessed as a function of HUR surveillance capabilities and runway centerline spacing (RCLS) to simultaneous independent dual and triple straight-in and offset final approach courses for Instrument Landing System (ILS)[1] and area navigation/required navigation performance (RNAV/RNP)[2] aircraft flying with flight director guidance (or autopilot). To identify the benefits of utilizing HUR capabilities, analysis began at the current minimum RCLS requirements for non-HUR closely spaced parallel operations (CSPO), followed by additional reductions in RCLS down to 2500 ft. Evaluations were conducted utilizing generic CSPO runway configurations and a number of airport specific runway configurations that differed from the generic cases.

FAA *Order JO 7110.65X, Air Traffic Control (ATC)* (paragraphs 5-9-7 and 5-9-8) and FAA *Order JO 7210.3AA, Facility Operation and Administration* (paragraph 10-4-6) contain the current provisions governing ATC separation for independent precision approach operations at airports with dual or triple parallel runway configurations. The current minimum RCLS requirements for CSPO are listed below:

- Approaches to dual parallel runways with RCLS of 3400 ft (HUR)[3] and 3600 ft (non-HUR)
- Approaches to triple parallel runways with RCLS of 3900 ft
- Approaches to dual and triple parallel runways with RCLS of 3000 ft with at least one localizer offset to an outside runway between 2.5° and 3°

Analyses were conducted to determine the probability of a midair collision between aircraft conducting dual and triple simultaneous independent closely spaced parallel approaches with HUR surveillance. The results listed below, indicate possible reductions to established minimum RCLS requirements for airports with field elevations up to 2000 ft mean sea level (MSL) utilizing a surveillance sensor update rate (SSUR) of 1 second and a maximum processing time (PT) of 3 seconds for approaches to: [4]

- Dual parallel runways with RCLS of 3200 ft or more without localizer offset, referred to as dual straight-in approach
- Dual parallel runways with RCLS of 2500 ft or more and a single localizer offset between 2.5° and 3°, referred to as dual offset approach
- Triple parallel runways with RCLS of 3400 ft or more without localizer offset, referred to as triple straight-in approach

[1] Localizer Performance with Vertical guidance (LPV) and Ground Based Augmentation System (GBAS) Landing System (GLS) approaches are considered operationally equivalent to ILS approaches in this study.

[2] The term "RNAV/RNP" is utilized in this study to signify RNAV(GPS) and RNAV(RNP) approaches.

[3] RCLS reduction to 3400 ft for locations using HUR is endorsed in *DOT-FAA-AFS-440-21, Safety Study Report for Multilateration/STARS FMA Used as a Precision Runway Monitoring System to Parallel Runways Separated by 3,400 Feet*, Flight Technologies and Procedures Division, Federal Aviation Administration, May 2006 and was incorporated into *FAA Order JO 7110.65W*. However, RCLS reduction to 3400 ft is not explicitly stated in *FAA Order JO 7110.65X* or *FAA Order JO 7210.3AA.*

[4] For analyses performed for RCLS ≤ 3400 ft, normal operating zone (NOZ) remained constant at 700 ft; and for RCLS ≥ 3400 ft, no transgression zone (NTZ) remained constant at 2000 ft.

- Triple parallel runways with RCLS of 2500 ft or more with at least one localizer offset to an outside runway between 2.5° and 3° referred to as triple single offset approach or triple dual offset approach

1 Introduction

This report presents the results of a safety study conducted on simultaneous independent CSPO[5] for approaches utilizing ILS[6] and RNAV/RNP[7] navigation. Evaluations were conducted utilizing generic CSPO runway configurations and a number of airport specific runway configurations that differed from the generic cases.

When visual approaches cannot be conducted, capacity at busy airports has been significantly increased by using simultaneous independent CSPO, which are defined as two parallel runways whose extended RCLS is less than 4300 ft.[8] These approaches are also termed Precision Runway Monitor (PRM) approaches. The distance between parallel runways is one of the main parameters that affects airport capacity by determining whether simultaneous independent (higher throughput) or dependent (lower throughput) parallel operations can be performed in place of single runway approach operations. Initially, CSPO approaches were conducted at airports utilizing short-range airport surveillance radar (ASR) systems. Subsequently, the introduction of HUR surveillance systems[9], use of precise navigation capabilities, improved analysis techniques,[10] offset approaches, and specific air traffic equipment and procedures have contributed to reductions in minimum RCLS requirements for simultaneous independent CSPO. Current HUR and non-HUR (i.e., ASR) surveillance system minimum RCLS requirements are specified in Table 1-1 below.

Table 1-1: Current Minimum RCLS Requirements

Surveillance System	CSPO Runway Configuration	Minimum RCLS for Straight-In Approaches	Minimum RCLS for Offset Approaches
HUR	Dual	3400 ft	3000 ft
HUR	Triple	3900 ft	3000 ft
Non-HUR	Dual	3600 ft	3000 ft
Non-HUR	Triple	3900 ft	3000 ft

[5] For a list of acronyms, refer to Appendix I.

[6] Localizer Performance with Vertical guidance (LPV) and Ground Based Augmentation System (GBAS) Landing System (GLS) approaches are considered operationally equivalent to ILS approaches in this study.

[7] The term "RNAV/RNP" is utilized in this study to signify RNAV(GPS) and RNAV(RNP) approaches.

[8] Air Traffic Organization, *Order JO 7110.65X, Air Traffic Control*. Federal Aviation Administration. October 12, 2017.

[9] Flight Systems Laboratory, *DOT-FAA-AFS-450-56, Safety Study Report on Simultaneous Parallel Instrument Landing System (ILS) and Area Navigation (RNAV) or Required Navigation Performance (RNP) Approaches - Phases 3 and 4*, Flight Technologies and Procedures Division, Federal Aviation Administration, July 2010.

[10] Flight Systems Laboratory, *DOT-FAA-AFS-450-63, Geometrical Models for Aircraft in Terminal Area Risk Analyses*, Flight Technologies and Procedures Division, Federal Aviation Administration, April 2011.

This study identifies potential reductions in RCLS requirements associated with performance-based capabilities using HUR surveillance across the National Airspace System (NAS) by utilizing improved analysis techniques previously applied in non-HUR environments.[11,12] Refer to Appendix E for a list of airports in the NAS that may potentially benefit from this study. Future studies may address other factors such as ILS localizer antenna position distance to runway threshold (also referred to as localizer distance to runway threshold) for simulations flown by ILS, ILS glide slope and RNAV vertical path angles, fleet mix, and runway threshold stagger.

1.1 Background

Standards for dual simultaneous independent approaches to closely spaced parallel runways in the National Airspace System (NAS) are contained in FAA *Order 8260.3D, United States Standard for Terminal Instrument Procedures*[13] and FAA *Order JO 7110.65X, Air Traffic Control*.[14]

A 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 the use of a high-resolution color display as well as automated visual and aural alerting algorithms for each monitored runway known as a Final Monitor Aid (FMA). The monitored zone, the runways, the final approach courses, and an NTZ established equidistant between the extended final approach courses are all displayed on the FMA. Separate monitor controllers, each with transmit/receive and override capability on the local control frequency, to ensure separation between aircraft and to prevent aircraft from penetrating 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 between 2.5° and 3°.

[11] Flight Systems Laboratory, *DOT-FAA-AFS-450-69, Simultaneous Independent Close Parallel Approaches - High Update Radar Not Required,* Flight Technologies and Procedures Division, Federal Aviation Administration, September 2011.

[12] Flight Systems Laboratory, *DOT-FAA-AFS-400-84, Separation Requirements for Simultaneous Offset Independent Dual Instrument Approaches - High Update Rate Surveillance Not Required*, Flight Technologies and Procedures Division, Federal Aviation Administration, July 2014.

[13] Flight Standards Service, *Order 8260.3D, United States Standard for Terminal Instrument Procedures (TERPS),* Federal Aviation Administration, February 16, 2018.

[14] Air Traffic Organization. *Order JO 7110.65X*.

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

- 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 must be capable of depicting the NTZ, an adjustable predictor target line (PTL), and must provide visual (yellow caution/red warning) and aural alerts (caution/warning) when an aircraft is projected to enter, or has entered the NTZ. Final monitor controllers are dedicated to each runway and each is provided a display

Figure 1-1 depicts a simultaneous independent CSPO. The FMA issues a yellow caution when the 10-second PTL crosses into the NTZ and issues a red warning aircraft enters the NTZ.

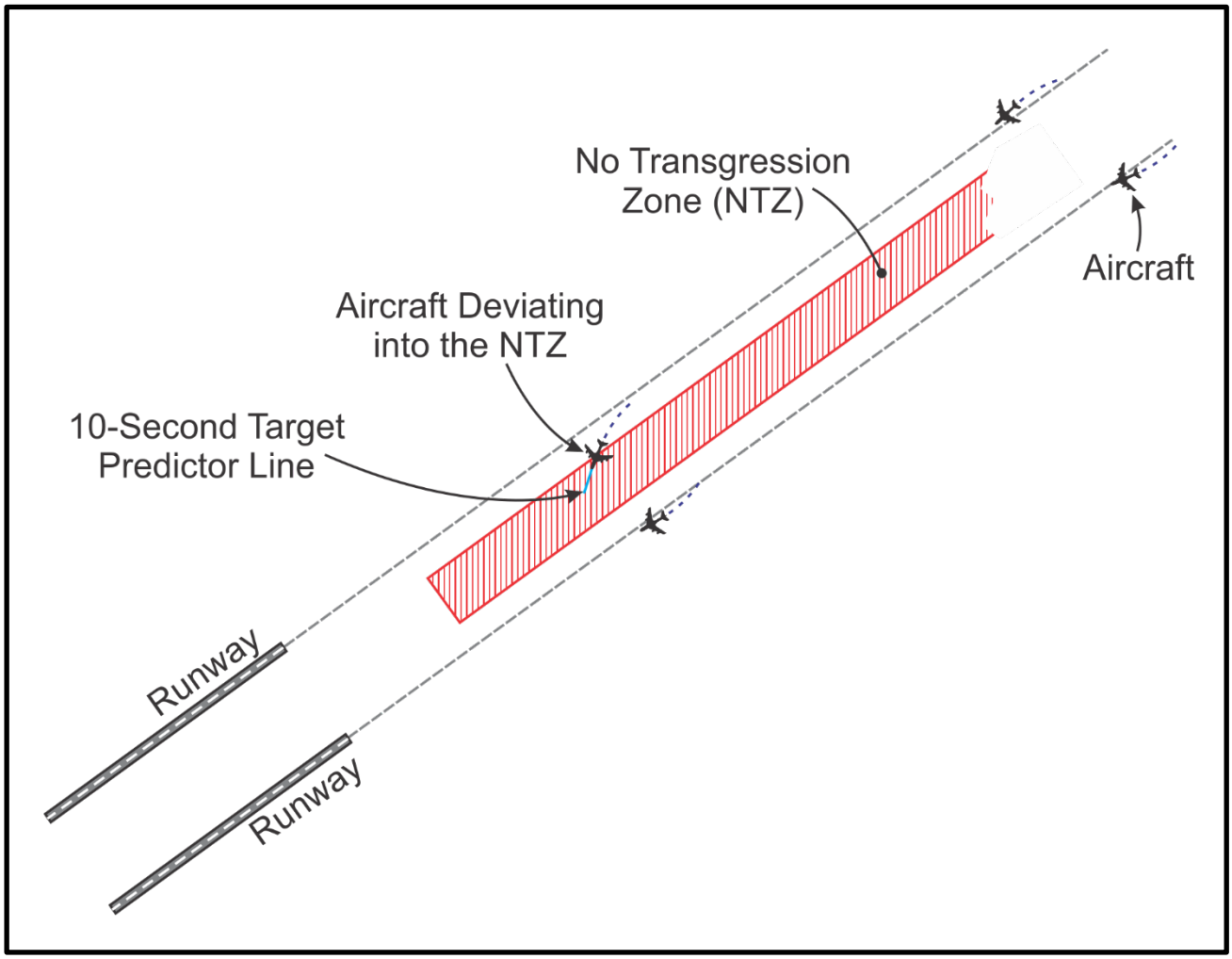

Figure 1-1: Example of CSPO showing NTZ and 10-Second PTL

Despite being operationally effective, the PRM system using the E-Scan radar is no longer in production and is only supported by spare parts from unused systems. 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 collision risk probabilities for various RCLS for simultaneous independent operations to parallel runways while utilizing HUR surveillance capabilities. The project expanded on results obtained in the *Evaluation of High Update Rate Surveillance System Parameters for Closely Spaced Parallel Operations Technical Report*,[15] which evaluated the impact of various HUR surveillance system parameters on the collision risk associated with dual simultaneous independent CSPO. These findings established coefficient values for the alpha-beta-gamma tracker, a value for position measurement accuracy, and boundaries for SSUR and processing time. The system parameters depicted in Figure 1-2 were used in this study to evaluate an HUR surveillance system with a 1-second FMA display update rate, where the display depicts a 10-second PTL.

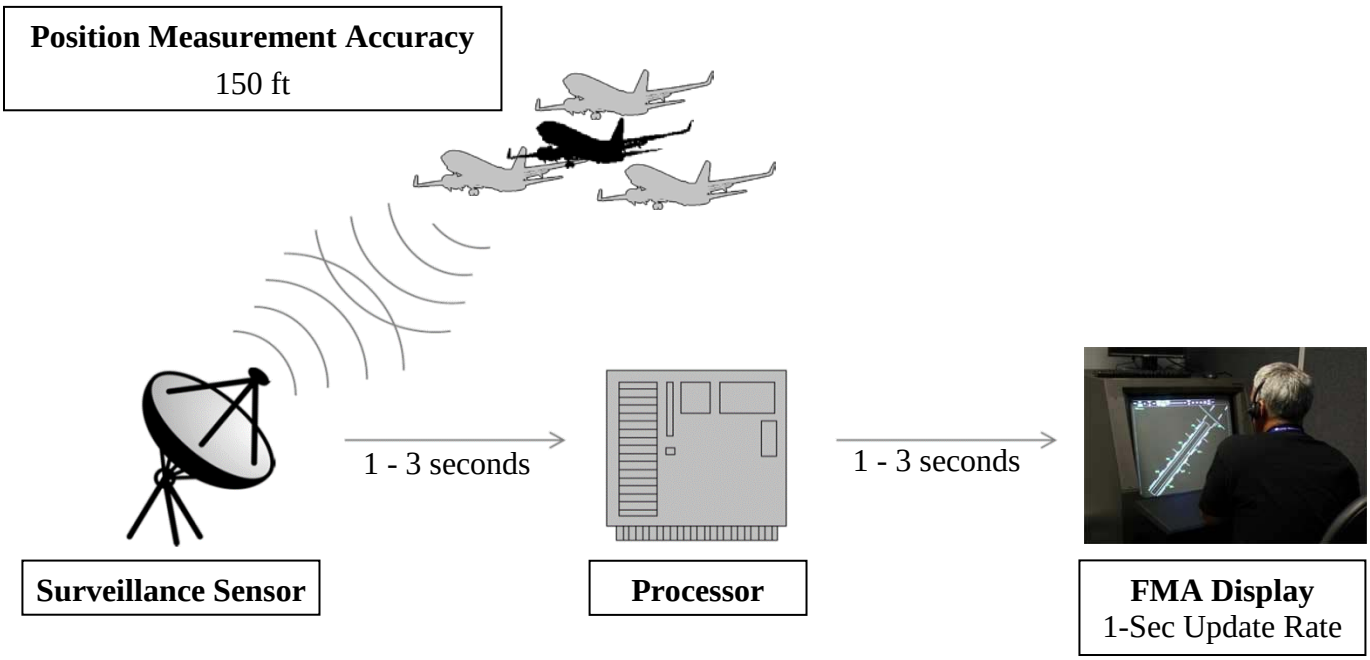

Figure 1-2: HUR Surveillance System Parameters

[15] Flight Systems Laboratory, *DOT/FAA/AFS400/2017/R/20, Evaluation of High Update Rate Surveillance System Parameters for Closely Spaced Parallel Operations*, Flight Technologies and Procedures Division, Federal Aviation Administration, June 2017.

This report presents results for both straight-in and offset final approach courses for dual and triple simultaneous independent CSPO. To identify the benefits of utilizing HUR capabilities, analysis began at the current minimum RCLS requirement for non-HUR CSPO approaches, followed by additional reductions in RCLS down to 2500 ft. The current CSPO minimum RCLS requirements are as follows and identified in Figure 1-3:

- Approaches to dual parallel runways with an RCLS of 3400 ft (HUR) and 3600 ft (non-HUR)[16]
- Approaches to triple parallel runways with an RCLS of 3900 ft
- Approaches to dual and triple parallel runways with an RCLS of 3000 ft with at least one offset to an outside runway between 2.5° and 3°

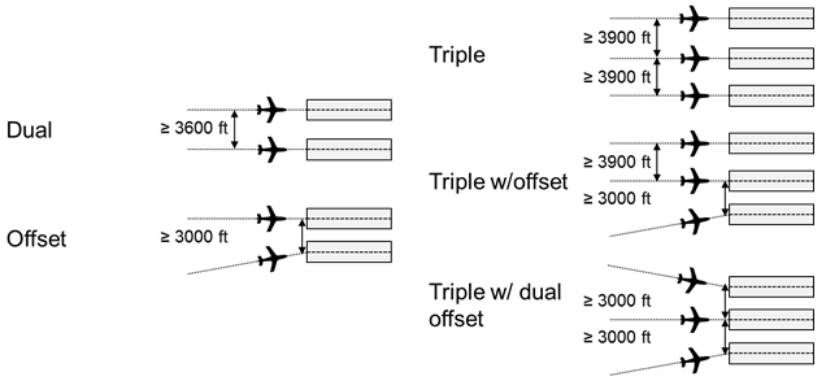

Figure 1-3: Current Minimum RCLS Requirements for CSPO

[16] Flight Systems Laboratory, *DOT-FAA-AFS-450-69.*

2 Objectives and Scope

The objective for this study is to attain the probability of collision for both straight-in and offset final approach courses for dual and triple simultaneous independent CSPO with HUR surveillance capabilities at varying RCLS values between 3900 ft and 2500 ft to identify configurations for potential reduction in RCLS separation standards. The scope of this report is limited to collision risk and did not address wake turbulence avoidance, Traffic Collision Avoidance System (TCAS),[17] radar separation standards, or controlled flight into terrain.

[17] TCAS was not evaluated in this study. The design of TCAS is not conducive for use during closely spaced parallel operations. TCAS in traffic advisory (TA) only mode, issues a caution to the pilot without a resolution. A TA does not provide adequate information for the pilot to evade another aircraft; or make a maneuver contrary to an air traffic control climb or descend breakout clearance. The use of TCAS in resolution advisory (RA) mode provides maneuvering information to the pilot; however, it can be assumed that during a closely spaced approach the system may issue an excessive amount of nuisance alerts.

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 fast-time simulation tool for aviation related safety assessments. In a real-time simulation, only a small amount of variables can be simulated; therefore, fast-time simulation is preferred. A fast-time simulation must be carefully constructed in order to instill confidence in the probability of collision. ASAT^{ng} uses high fidelity models of all components of an aviation scenario to ascertain the probability. 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 scenarios. ASAT^{ng} also uses official FAA databases of navigation and surveillance facilities, runways, fixes, etc. Additionally, a conservative aircraft fleet mix was used for the generic cases, and fleet mixes consistent with recent data were used for the specific airports evaluated in this study. Further details on the fleet mixes are included in Appendix C.

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 a sweeping 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 with greater fluctuations. Unnecessary NTZ penetrations will occur due to the greater fluctuations of the PTL sweeping motion. When these penetrations occur, a controller response is required resulting in an unnecessary breakout of the evading aircraft. This is referred to as a nuisance breakout (NBO). While an NBO produces an increase level of safety, it should be disregarded since the NTZ was triggered prematurely by an overly sensitive PTL. 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. Values of the coefficients utilized in this

evaluation were 0.35, 0.25, and 0.05. These values were derived in a previous study[18] using combinations of sensor accuracies, sensor update rates, and processing times.

3.2 Test Design and Scenarios

A principal safety concern in simultaneous independent CSPO is the risk of collision due to an aircraft deviation, where one aircraft unexpectedly turns toward another aircraft on the parallel final approach course, putting the non-deviating aircraft at risk. These aircraft deviations are sometimes referred to as blunders.

During triple operations, an aircraft deviating from an outboard approach toward the center approach will cause the controller to issue an evasion command that could potentially put the center evading aircraft at a risk for collision with the aircraft on the opposite outboard approach. This is known as a "cascading deviation." Cascading deviations were not accounted for in this study. The distance between runways is considered large enough for the final monitor controllers to have adequate time to issue proper evading commands.

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 (typically a turn and a climb) 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.

Probability density functions (pdfs) for controller and pilot response times developed in previous human-in-the-loop studies[19,20] were incorporated into ASAT^{ng} for this study. These pdfs were used instead of generating an additional human-in-the-loop study. These pdfs were determined to be applicable to this research for the following reasons: a) similar runway configurations[21], b) the incorporated pdfs were generated utilizing a 4.8 seconds short-range radar, and current CSPO minimums with RCLS and NTZ/NOZ larger than used in this study, c) the previous configuration assumes longer controller response times than would be expected using an HUR radar; therefore, the use of longer response times ensures a conservative approach[22], and d) smaller runway spacing may shorten pilot response times due to heightened situational awareness of the proximity to other aircraft.

[18] Flight Systems Laboratory, *DOT/FAA/AFS400/2017/R/20.*

[19] Flight Systems Laboratory. *DOT-FAA-AFS-450-67, Report on Pilot Response Times from the March 2010 Human in the Loop Data Collection Effort.* Flight Technologies and Procedures Division, Federal Aviation Administration. June 2011.

[20] Flight Systems Laboratory. *DOT-FAA-AFS-450-68, Controller Response Times from the August and December 2010 Human in the Loop Data Collection Effort.* Flight Technologies and Procedures Division, Federal Aviation Administration, August 2011.

[21] Safety Risk Management Panel's (SRMP) Project Plan CSPO-001, "Simultaneous Independent Dual Straight-In ILS Approaches with Runway Centerlines at 3,000 Feet Using a 4.8 Second Surveillance Update Rate."

[22] Additionally, to compensate for controller learning effect, two seconds were added to minimum and maximum controller response times.

As ASAT^{ng} runs a scenario, it pairs flights together and samples deviation angles and response times from these pdfs, and then simulates the flight until the minimum distance between the two targets is achieved. This distance is then recorded in an output file and used to determine a test criterion violation (TCV). For this study, generic dual and triple runway configurations were designed for evaluation. ILS or RNAV/RNP aircraft with flight director guidance were simulated in scenarios utilizing various RCLS and NTZ widths, surveillance sensor update rates, processing times, and when applicable, ILS localizer antenna distance to runway thresholds. In addition, specific CSPO runway configurations at several airports were evaluated that differed from the generic cases.

3.2.1 Test Design and Scenarios – Generic Airport (KGEN) Configuration

Parameters were set and evaluated as follows:

- Runway lengths were modeled at 7500 ft and 10,000 ft with localizer antennas set at a distance of 1000 ft from the departure end of the runway
- ILS glide slope angles were set at 3°
- Runway field elevations were set at 2000 ft MSL
- Aircraft fleet mix was set at 20% heavy aircraft, 55% large aircraft, and 25% small aircraft. Position measurement accuracy, the difference between the aircraft's actual position and detected position, was set at 150 ft (1σ). The 150 ft value was specified by the Surveillance and Broadcast Services Program Office to accommodate the requirements of ADS-B, wide area multilateration, and Airport Surface Detection Equipment, Model X (ASDE-X)/Precision Runway Monitor-Alternative (PRM-A) multilateration
- Surveillance Sensor Update Rate (SSUR), the time between updates of target position information from the sensor to the processor, was varied at values of 1, 2, and 3 seconds. These values encompass HUR surveillance sensor update rates available in the NAS, which typically range from 1.0 to 2.4 seconds
- Processing time (PT), 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, was varied at values of 1, 2, and 3 seconds
- Level and descending course deviations were varied at values ranging from 15° to 35°. These values were determined from deviation data taken by MITRE Center for Advanced Aviation System Development[23] at 12 airports during fiscal years 2008 through 2012, during SIPIA 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

[23] Massimini, S.V., G.C. McNeil, N. Tene, *MP090245, Frequency and Severity of Deviations during Simultaneous Independent Approaches to Parallel Runways – A 2009 Update*, The MITRE Corporation Center for Advanced Aviation System Development, September 2009.

Scenarios were modeled utilizing the above parameters. Table 3-1 describes the simultaneous independent straight-in and offset approach operations to dual and triple parallel runways analyzed in this study.

Table 3-1: Scenario Matrix for Generic Cases

Number of Scenarios	Procedure	Expanded procedure	Diagram	Deviation	ILS/RNP	Level Deviation Angle	Descending Deviation Angle	SSUR (sec)	PT (sec)
108	Dual Straight-In	Aligned 10000 ft Runways		L-R R-L	II, IR, RI, RR	20°, 30°	20°, 30°	1,2,3	1,2,3
108	Dual Straight-In	Aligned 7500 ft Runways		L-R R-L	II, IR, RI, RR	20°, 30°	20°, 30°	1,2,3	1,2,3
72	Dual Straight-In	Aligned 10000 ft & 7500 ft Runways		L-R R-L	II	20°, 30°	20°, 30°	1,2,3	1,2,3
72	Dual Straight-In	Staggered 10000 ft Runways		L-R R-L	II	20°, 30°	20°, 30°	1,2,3	1,2,3
72	Dual Straight-In	Staggered 7500 ft Runways		L-R R-L	II	20°, 30°	20°, 30°	1,2,3	1,2,3
72	Dual Straight-In	Staggered 10000 ft & 7500 ft Runways		L-R R-L	II	20°, 30°	20°, 30°	1,2,3	1,2,3
72	Dual Straight-In	Staggered 10000 ft & 7500 ft Runways		L-R R-L	II	20°, 30°	20°, 30°	1,2,3	1,2,3
288	Dual Offset	Aligned 10000 ft Runways		L-R R-L	II, IR, RI, RR	20°, 30°	20°, 30°	1,2,3	1,2,3
108	Triple Straight-In	Aligned 10000 ft Runways		L-R L-C C-R	II	20°, 30°	20°, 30°	1,2,3	1,2,3
216	Triple with One Offset	Aligned 10000 ft Runways		L-R/R-L L-C/C-L C-R/R-C	II	20°, 30°	20°, 30°	1,2,3	1,2,3
108	Triple with Two Offsets	Aligned 10000 ft Runways		L-R L-C C-R	II	20°, 30°	20°, 30°	1,2,3	1,2,3

Table 3-2 denotes the RCLS and NTZ widths evaluated in the study for dual straight-in (DS), dual offset (DO), triple straight-in (TS), triple offset (TO) or triple two-offset (TTO) approaches. Evaluations were conducted for RCLS values between 2500 ft and 3700 ft, NTZ widths between 1100 ft and 2000 ft with each NTZ equidistant between the runway centerlines, and a field elevation of 2000 ft MSL.

Table 3-2: RCLS/NTZ Evaluation Matrix

RCLS (ft) / NTZ (ft)	2500	2600	2700	2800	2900	3000	3100	3200	3300	3400	3500	3600	3700
1100	DO, TO, TTO												
1200		DO, TO											
1300			DO, TO										
1400				DO, TO									
1500					DO, TO								
1600						DO, DS							
1700							DS						
1800								DS, TS					
1900									DS, TS				
2000										DS, TS	TS	TS	TS

All aircraft were simulated using Category II (CAT II) Instrument Landing System (ILS) or RNAV/RNP approaches with flight director at a glide slope of 3° with lateral and vertical distributions as defined in Appendix F. The aircraft release positions were distributed uniformly between 16 and 3 nautical miles (NM) from their respective thresholds. Each pair was released at risk as defined in Appendix A. 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 TCV, which is considered a collision if the centers of gravity of the two aircraft also pass within 80 ft vertically of each other. A TCV will occur without timely action from both the controller and the pilot of the endangered aircraft if the previous two conditions were to occur. The TCV volume is depicted in Figure 3-1.

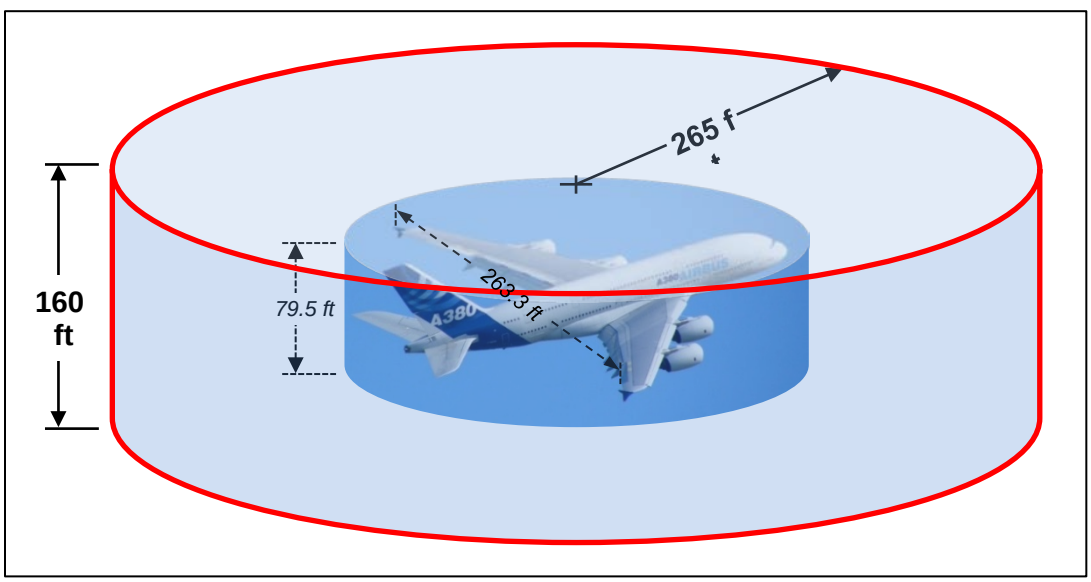

Figure 3-1: TCV Volume

The fleet mix utilized 20% heavy aircraft, 55% large aircraft, and 25% small aircraft. For this study, heavy aircraft are defined as aircraft capable of takeoff weights of more than 255,000 pounds whether or not they are operating at this weight during a particular phase of flight. Large aircraft are defined as having maximum takeoff weight (MTOW) of more than about 100,000 pounds, and up to 255,000 pounds; and small aircraft are defined as aircraft with an MTOW of less than 100,000 lbs. Half of the heavy aircraft were represented by the Airbus A330 and the other half by the Boeing 747-400 (B747) to represent the MTOW extremes in the heavy category. The large aircraft were all represented by the Boeing 737-800 (B737) and the small aircraft were all represented by an Embraer regional jet. Each aircraft type in the mix had different approach speeds and dynamics. The fleet mix is a significant driver for the conditional risk of a case, as heavy aircraft tend to respond more slowly in the evasion maneuver and small aircraft tend to respond more quickly. Please refer Appendix C for more information on the effect of fleet mix on collision risk.

Level and descending aircraft deviations were assumed to occur with equal probability. There were two controller response time distributions used in this study, one for 20° course deviations and one for 30° course deviations (also commonly referred to as 20° and 30° deviations). The 20° deviations and 30° deviations were sampled from bounded uniform distributions with ranges of deviations 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.[24] Both 20° and 30° deviations were fitted to a Johnson SB distribution.

3.2.2 Test Design and Scenarios – Specific Airport Configuration

Airports with dual and triple runway configurations with RCLS distances addressed in this study include: Detroit Metropolitan Wayne County Airport (KDTW), Raleigh-Durham International Airport (KRDU), Memphis International Airport (KMEM), Minneapolis-St. Paul International Airport (KMSP), Chicago O'Hare International Airport (KORD), Portland International Airport (KPDX), Salt Lake City International Airport (KSLC), John F. Kennedy International Airport (KJFK), Dallas Love Field Airport (KDAL), St. Louis Lambert International Airport (KSTL), Denver International Airport (KDEN), Seattle-Tacoma International Airport (KSEA), Phoenix Sky Harbor International Airport (KPHX), John Glenn Columbus International Airport (KCMH), and Philadelphia International Airport (KPHL). Of these, all of the runway configurations fall within the bounds of the generic cases except those at KDTW, KORD, KJFK, KDEN, and KSEA. Additional scenarios were created and evaluated at these five airports due to the uniqueness of their configurations. Parameters were set and evaluated as described in the generic airport configuration above with the following exceptions:

- Runways were modeled using the current displaced thresholds for each runway
- Localizers were modeled at their current antenna locations and beam widths at threshold
- ILS glide slope angles were set to current operational values. In some circumstances, the angles were subsequently modified to values within the ranges of 2.5° and 3.2° for additional evaluation
- Actual runway field elevations were used in place of the 2000 ft MSL values used in the generic cases

[24] Flight Systems Laboratory, *DOT-FAA-AFS-450-68.*

- Fleet mixes that were consistent with recent data were used at select airports
- Analysis was limited to ILS operations. RNAV/RNP operations were not evaluated for these airports

Table 3-3 denotes the RCLS and NTZ widths evaluated in the study for dual straight-in (DS), dual offset (DO), dual two offset (DTO), and triple straight-in (TS) approaches.

Table 3-3: Scenario Matrix for Each RCLS/NTZ

RCLS (ft) / NTZ (ft)	2500	2599	3000	3100	5800
1100	DO (KSEA) DTO (KSEA)				
1200		DO (KDEN) DTO (KDEN)			
1600			TS (KDTW) DS (KJFK)		
1700				DS (KORD)	
2000					TS (KDTW)

3.3 Simulation Assumptions

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

- Surveillance source not specified (i.e., single sensor or fusion[25] [as long as specific fusion mode collision risk values do not exceed single sensor values])
- Aircraft were established on the final approach course pursuant to all other criteria contained in FAA *Order JO 7110.65X*[26] and *FAA Order JO 7210.3AA*[27]
- Aircraft did not slow until within 2 NM prior to the final approach fix
- Aircraft were flown using CAT II ILS with flight director (i.e., flight director and/or autopilot required)
- Aircraft deviations were distributed uniformly along the final approach course
- Vertical guidance was utilized
- Dual communications requirements were in place which included a different local controller tower frequency and secondary PRM frequency for each runway; on each runway, the local controller transmitted on both frequencies and the monitor controller overrode both frequencies[28]
- Pilots and controllers were trained to conduct PRM operations
- An attention all Users Page (AAUP) and PRM approach plate were utilized by the flight crews
- Published missed approaches diverge by at least 45°

[25] Air Traffic Organization, *Notice JO 7110.745, Air Traffic Control*, Federal Aviation Administration, December 22, 2017.
[26] Air Traffic Organization, *Order JO 7110.65X*.
[27] Air Traffic Organization, *Order JO 7210.3AA*.
[28] Air Traffic Organization, *Order JO 7110.65X*.

- NTZ/NOZ
  - For RCLS ≤ 3400 ft, NOZ remained constant at 700 ft
  - For RCLS ≥ 3400 ft, NTZ remained constant at 2000 ft
- Airport elevation was 2000 ft MSL unless noted otherwise
- The temperature profile was based on the International Standard Atmosphere with winds at zero knots
- The vertical navigation errors due to the effects of temperature variance were not addressed (i.e., Baro-VNAV)
- FMA display update rate was 1 second
- Position measurement accuracy was set at 150 ft (1σ)
- 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 unless noted otherwise
- Acceptable percentages of nuisance breakouts are assumed, refer to Appendix D for additional information
- Evading aircraft performed a maneuver which included a turn and a climb; it was assumed that sufficient airspace was available to conduct the breakout maneuver

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
- RCLS
- NTZ width
- NOZ width
- Course deviations
- ILS glide slope angles (the RNAV/RNP aircraft utilized the same CRM vertical deviation distributions used for the ILS approaches)
- Runway lengths
- Localizer distance to runway threshold
- ATC monitoring and surveillance equipment
  - Surveillance sensor update rate
  - Processing time

3.5 Dependent Variables

- TCV rate

4 Data Analysis

4.1 Collision Risk

4.1.1 Collision Risk – Generic Airport Configuration

The analysis methodology used to determine collision risk is described in Appendix A. Course deviation pdfs of 20° and 30° have been created from data collected during actual simultaneous independent parallel instrument approaches (SIPIA) during instrument flight conditions. 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 figure below depicts the collision risk associated with the four deviation types. The Air Traffic Organization (ATO) Safety Management System Manual[29] establishes the suitable level of risk for extremely improbable catastrophic events.

Figure 4-1 through Figure 4-14 depict the collision risk associated with various RCLS and NTZ values with respect to surveillance sensor update rate, processing time, and flight guidance (i.e., ILS or RNAV/RNP). Additional figures and tables providing more details of the analysis are included in Appendix B and Appendix G. One hundred thousand aircraft pairs were simulated for each scenario.

[29] Air Traffic Organization, *Safety Management System Manual, Air Traffic Control*, Table 3.5, Federal Aviation Administration, July 2017. An extremely improbable catastrophic event is defined as occurring less than one per billion.

Figure 4-1 depicts collision risk associated with generic dual straight-in ILS and RNAV/RNP approaches to parallel 7500 ft runways with aligned thresholds, an RCLS of 3100 ft, and an NTZ of 1700 ft. The figure shows how collision risk varies for an SSUR and PT at 1, 2, and 3 seconds.

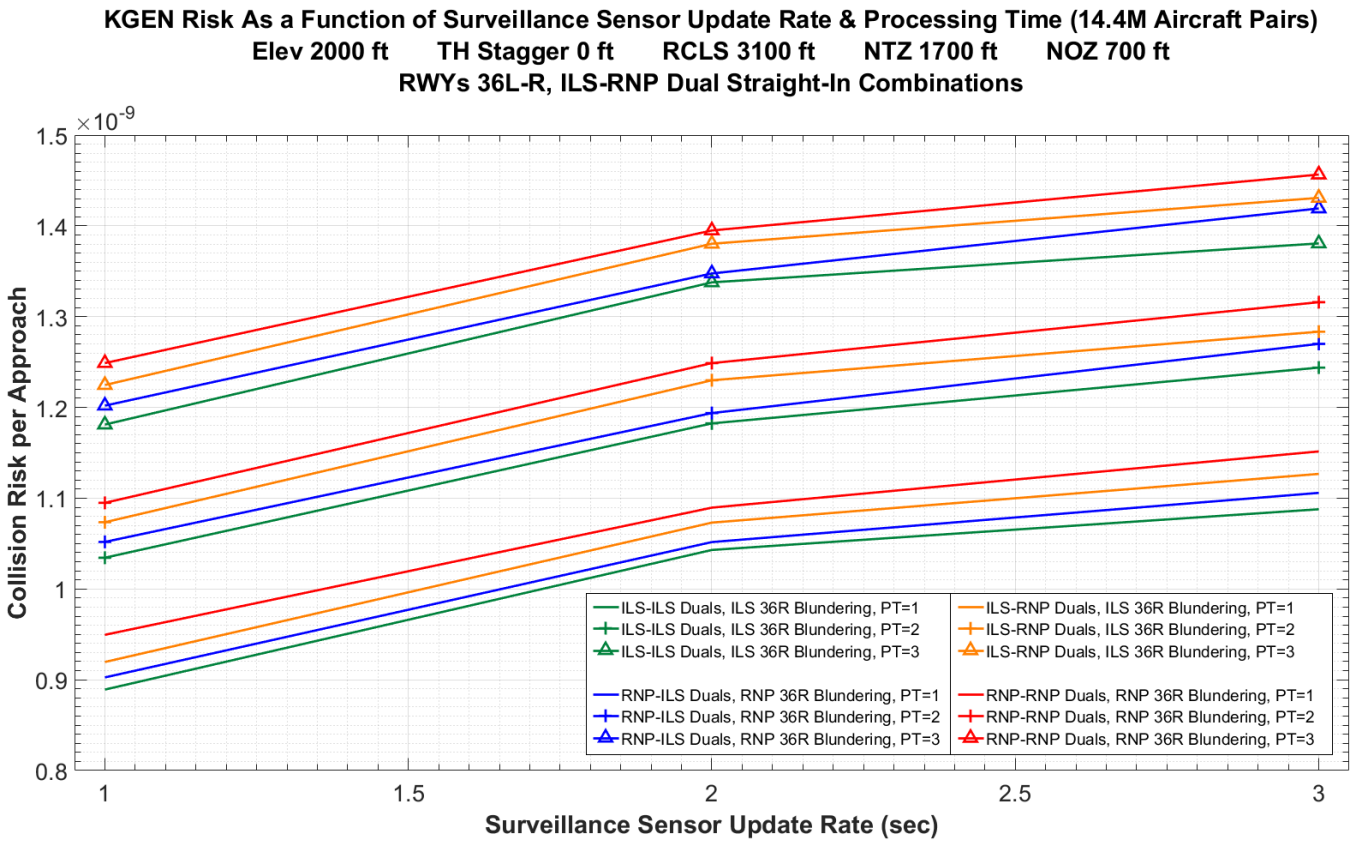

Figure 4-1: Dual Straight-In Approaches with 7,500 ft Runways

Figure 4-2 depicts collision risk associated with various generic dual straight-in ILS approaches to parallel runways with an RCLS of 3100 ft and an NTZ of 1700 ft. Initial results for a site-specific scenario indicated that localizer distance to runway threshold would influence collision risk. Seven cases were developed to determine the impact. Cases varied by utilizing aligned runway thresholds or runway threshold staggers of 2500 ft and runway lengths of 7500 ft or 10,000 ft. The ILS localizer antenna was placed 1000 ft beyond the departure end of the runway. Results for aligned thresholds yielded lower collision risk values than staggered thresholds and the shorter runway pairs yielded lower values than longer runway pairs.

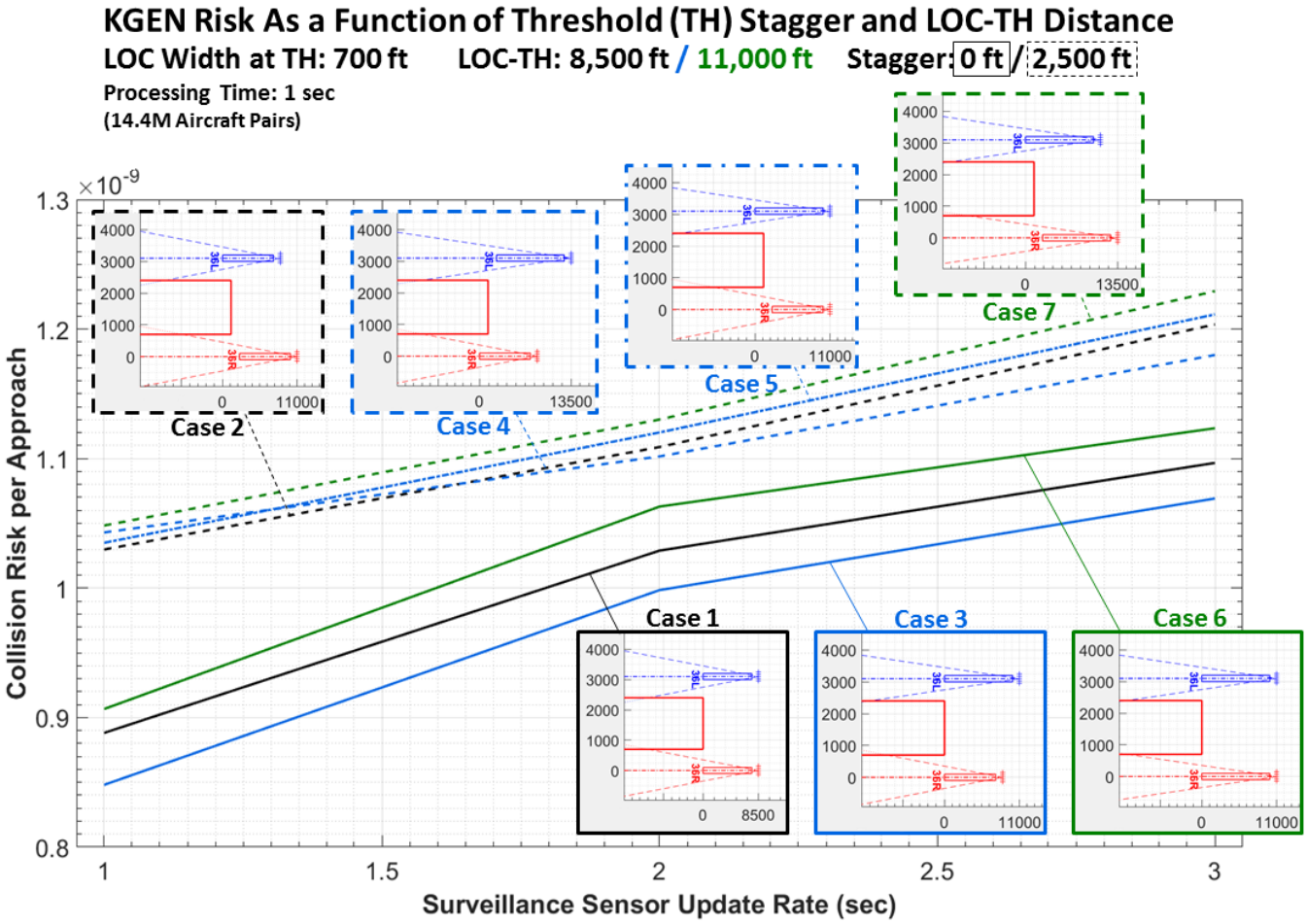

Figure 4-2: Various Configurations for Generic (KGEN) Dual Straight-In Approaches

Figure 4-3 depicts collision risk associated with a generic dual offset (i.e., dual one-offset or dual single-offset) approach with aligned thresholds, an RCLS of 2500 ft, and an NTZ of 1100 ft. The bold black lines represent the cumulative collision risk for 7500 ft runway lengths and the normal black lines represent the cumulative collision risk for 10,000 ft runway lengths. Varying the runway lengths has a miniscule impact on the cumulative collision risk.

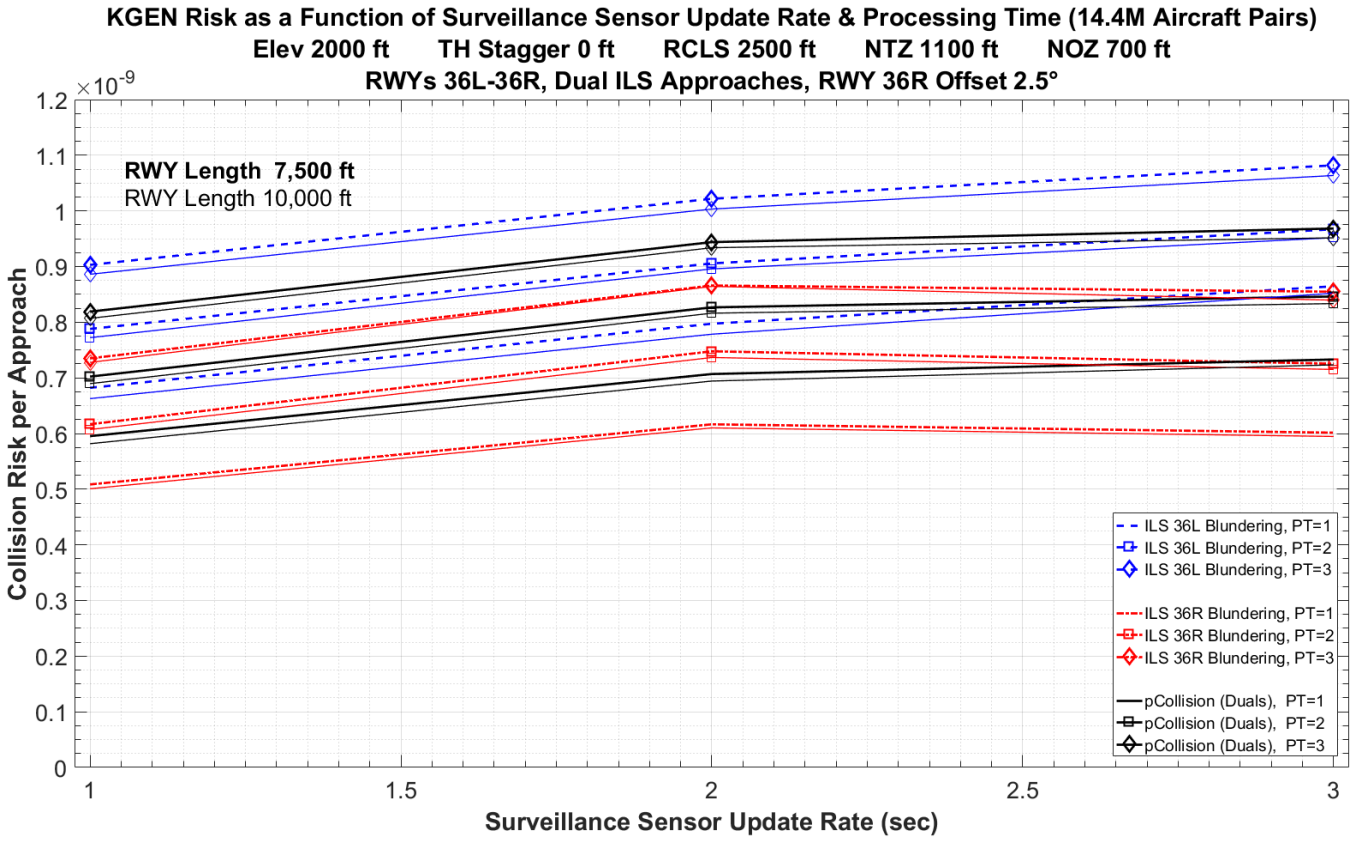

Figure 4-3: Dual Offset Approaches with 7500 ft and 10,000 ft Runways

Figure 4-4 depicts collision risk associated with a generic triple straight-in approach to parallel 10,000 ft runways at multiple RCLS. As anticipated, the collision risk is lower for wider RCLS. For RCLS values from 3200 ft to 3400 ft, the NTZ increases from 1800 ft to 2000 ft. For RCLS values 3400 ft to 3700 ft, the NTZ remains constant at 2000 ft.

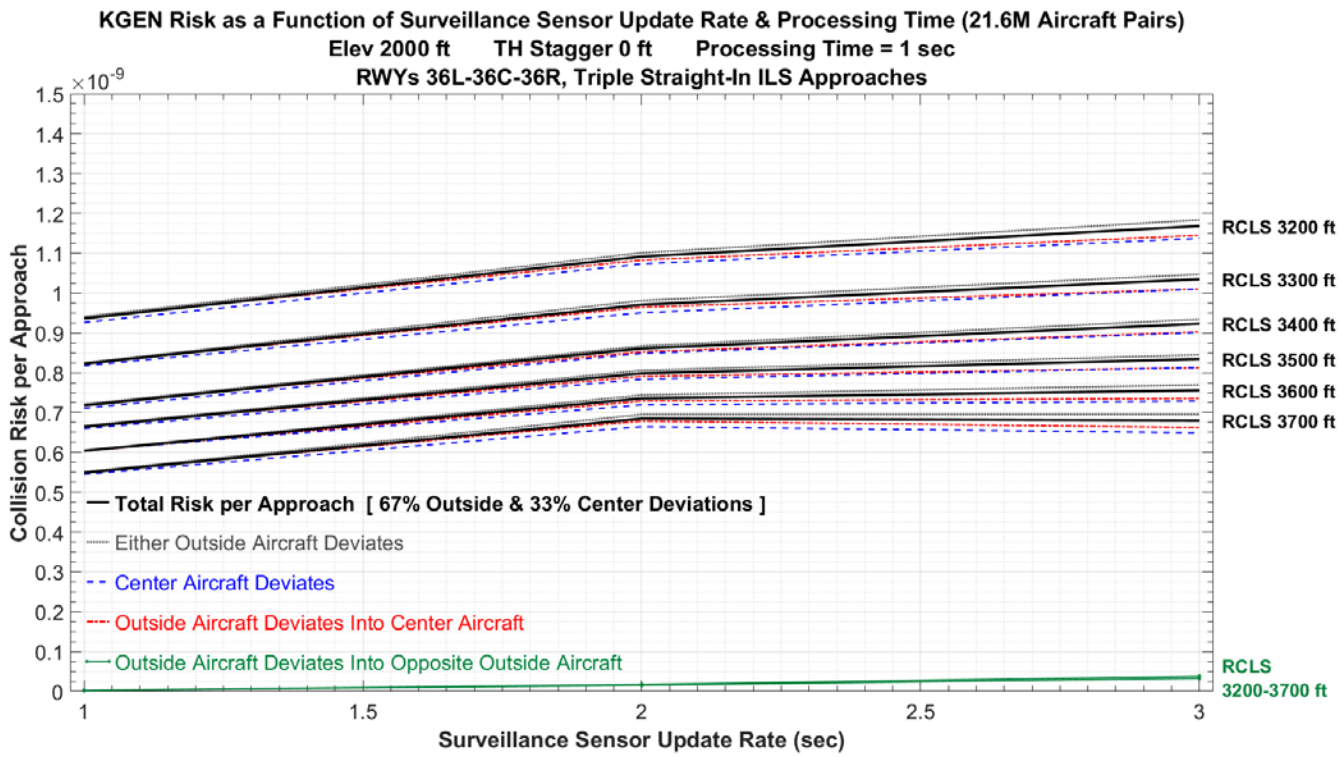

Figure 4-4: Triple Straight-In Approaches with 10,000 ft Runways

Figure 4-5 depicts collision risk associated with a generic triple offset (i.e., triple one-offset or triple single-offset) approach to parallel 10,000 ft runways. It portrays the collision risk associated with the six types of deviations[30] encountered during a triple offset approach. The figure contains three elements: top, middle, and bottom. The top element shows the risk associated with an aircraft deviating from the center approach (ILS 2) to the outboard offset approach (ILS 3) or the outboard offset approach (ILS 3) deviating toward the center approach (ILS 2). The middle element shows the risk associated with a deviation from the center approach (ILS 2) to the outboard straight-in approach (ILS 1) or the outboard straight-in (ILS 1) deviating toward the center approach (ILS 2). The bottom element shows the risk associated with a deviation from the outboard straight-in approach (ILS 1) deviating toward the outboard offset approach (ILS 3) and the outboard offset approach (ILS 3) to the outboard straight-in approach (ILS 1). Collision risk associated with the bottom element (outboard approaches) is a small value when considered in the overall risk of the triple's operation due to the significant (5800 ft) spacing between the runways.

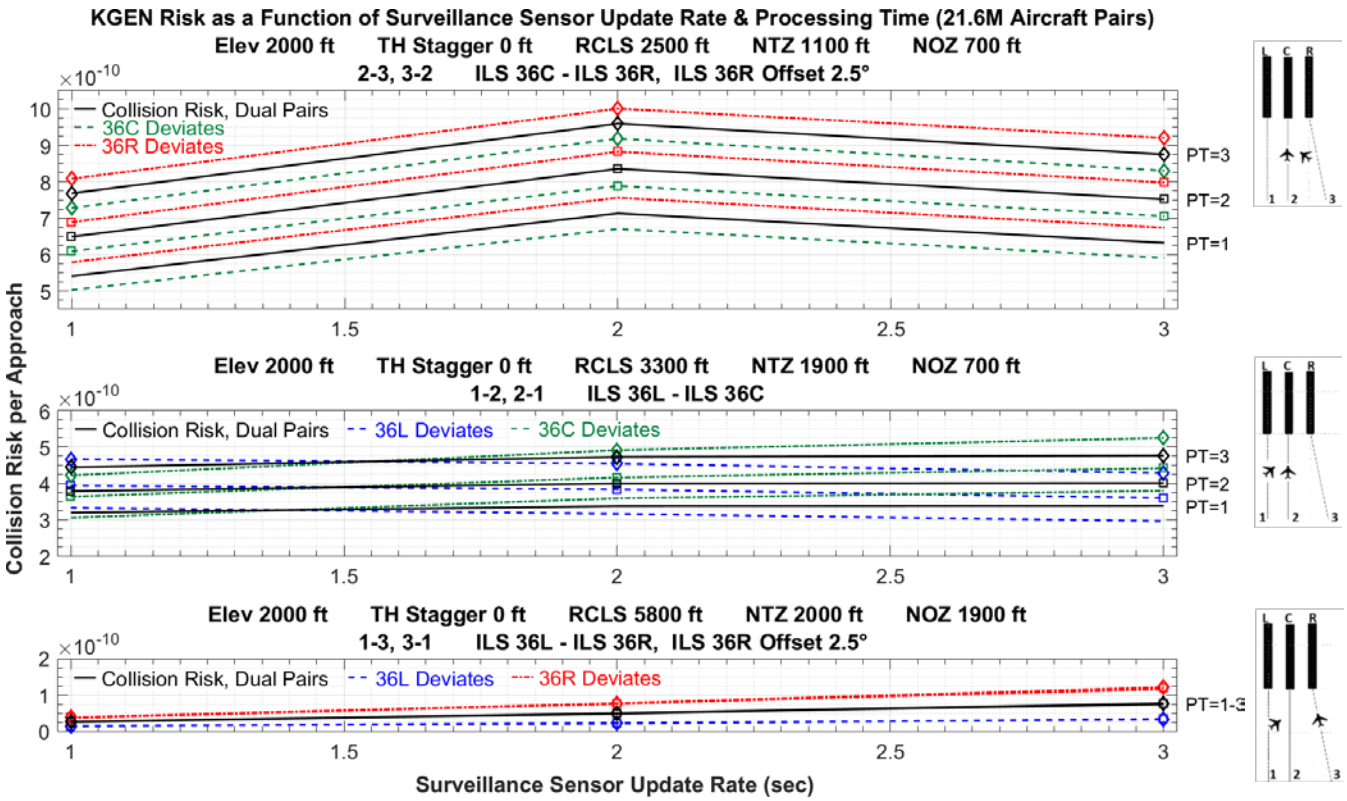

Figure 4-5: Triple Single-Offset Approaches with 10,000 ft Runways

[30] Air Traffic Organization, *Safety Management System Manual, Air Traffic Control*, Table 3.5, Federal Aviation Administration, July 2017.

[30] The six deviation types consist of course deviations on approach from ILS 1 to ILS 2, ILS 2 to ILS 3, ILS 1 to ILS 3, and their reciprocals.

Figure 4-6 depicts collision risk associated with a generic triple dual-offset (a.k.a., triple two-offset) approach to parallel 10,000 ft runways, with an RCLS of 2500 ft. The solid black line represents the cumulative collision risk of the triple's operation where the localizers on both outboard runways are offset by 2.5°. As in the previous figure, where the spacing between outboard runways is 5800 ft, the collision risk for a deviation from an outboard approach (ILS 1) toward the opposite outboard approach (ILS 3) with 5000 ft spacing contributes a small amount to the overall collision risk.

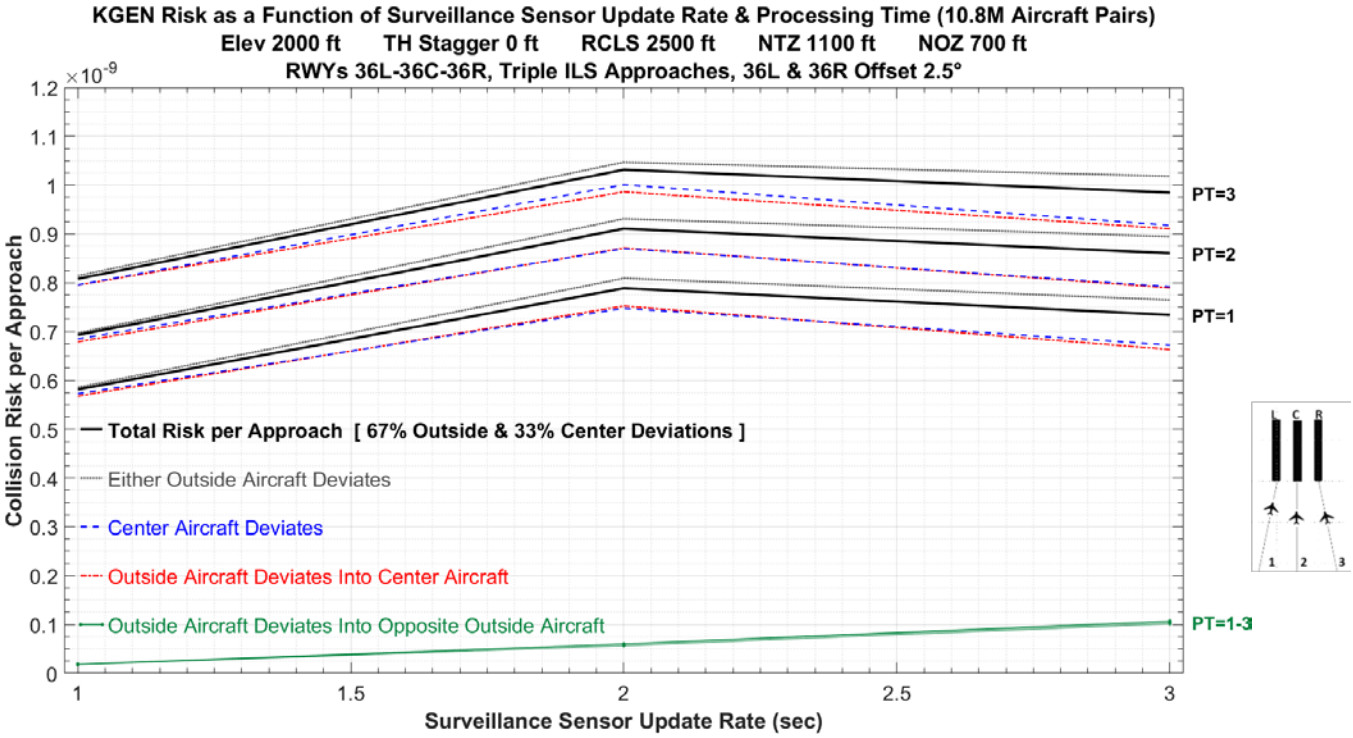

Figure 4-6: Triple with Dual-Offset Approaches with 10,000 ft Runways

The collision risk analysis performed on generic approaches found that possible reductions may be achieved for configurations as depicted in Figure 4-7.

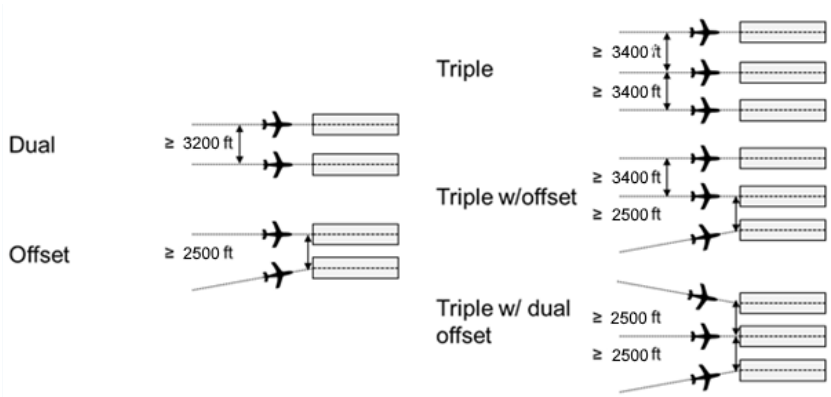

Figure 4-7: Potential Minimum RCLS Requirements for CSPO

4.1.2 Collision Risk – Specific Airport Configuration

Airports with unique runway configurations outside the bounds of generic cases included KDTW, KORD, KJFK, KDEN, and KSEA. Factors contributing to the determination of airports being outside the bounds of the generic cases include significant runway stagger, placement of ILS localizer antennas, and airport elevation. Increased runway threshold stagger had an adverse impact on collision risk for several runway configurations. Future investigation beyond the scope of this study should be considered to determine the impact of runway threshold stagger, ILS localizer distance to runway threshold, and ILS glide slope angles on collision risk; and the possibility of further reduction in the minimum acceptable RCLS requirements for simultaneous independent CSPO.

4.1.2.1 Collision Risk – KDTW

The runway configuration at KDTW is unique because of significant runway stagger and the separation between the approach runways (21L-22L-22R). In the analysis, consideration was given to the utilization of all three runways; however, because of the considerable separation of runways 21L and 22L (i.e., 5800 ft), the risk of a collision is considered negligible between aircraft approaching these runways. This is also true for runways 21L and 22R (i.e., 8800 ft). This same logic applies to the reciprocal runways (4L-4R-3R). Current CSPO approaches to runways 22L and 22R utilize an offset localizer; however, due to signal interference from taxiing aircraft, straight-in approaches were evaluated in this study. When modeling the scenarios at KDTW, a fleet mix that is consistent with recent data was used. Additional scenario modifications were created that varied the difference in ILS glide slope angles between runway pairs. These modifications effectively mitigated collision risk values as the difference in ILS glide slope angles between runway pairs increased. Evading aircraft performed a turn and a climb maneuver in all simulations. Evading by climbing without a turn would likely change the collision risk. Figure 4-8 displays the collision risk associated with changes in the ILS glide slope angles.

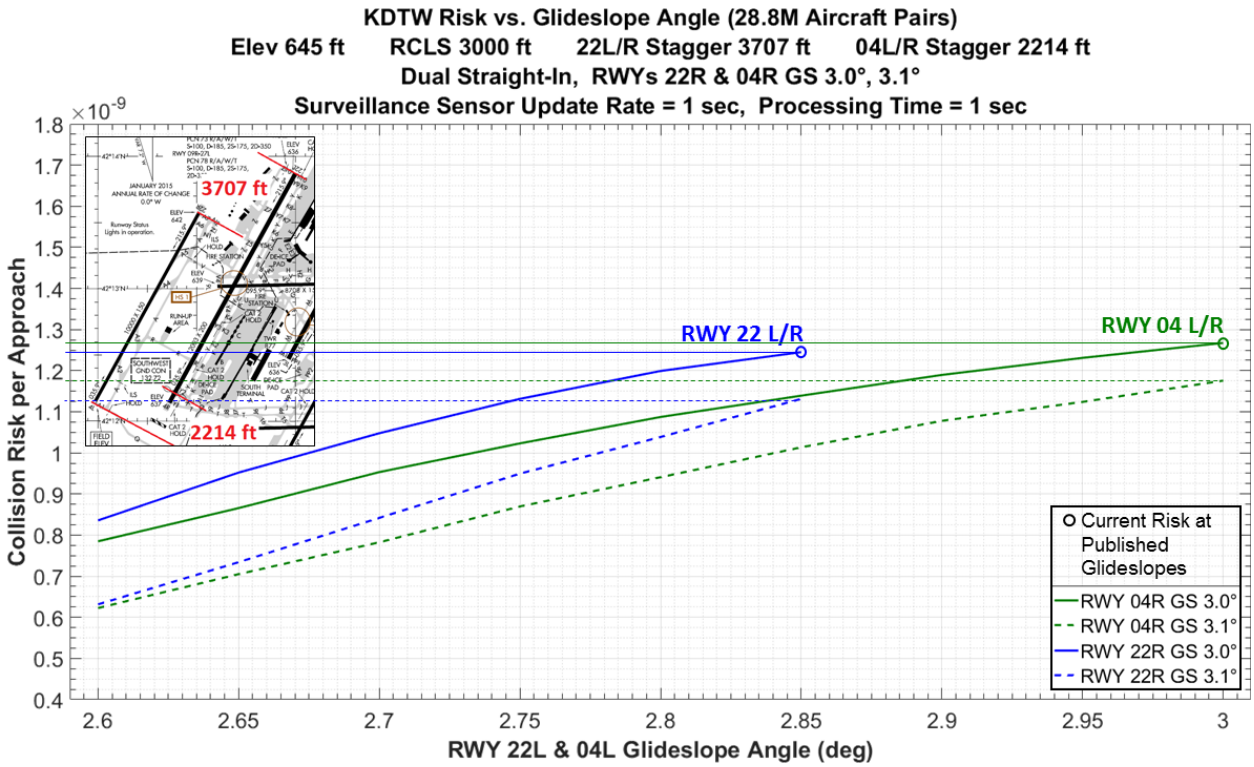

Figure 4-8: Triple Straight-In ILS Approaches at KDTW

4.1.2.2 Collision Risk – KORD

The configuration at KORD consists of runways that vary in length, runway 10R is 7500 ft and runway 10C is 10,801 ft. Their reciprocal runway lengths are also 7500 ft for runway 28L and 10,801 ft for runway 28C. The runways feature a stagger of 990 ft when approaching runways 10C and 10R, and a stagger of 2312 ft when making an approach toward runways 28C and 28R. Although KGEN scenarios were similar to the configuration at KORD (refer to KGEN case 5), specific scenarios were thought to provide more benefit due to the inconsistent localizer (LOC) to threshold (TH) distances at KORD. Refer to Table E-1 in Appendix E for KORD LOC-TH distances. KGEN case 5 scenarios were modeled with a 2500 ft stagger and a consistent LOC-TH distance of 1000 ft from the departure end of runway. The KORD analysis used site-specific placement of the localizer antennas. It was found that with the LOC placement and stagger differences, KORD yielded a lower collision risk. Figure 4-9 displays the collision risk associated with a dual straight-in approach to runways 10C-10R and runways 28L-28C.

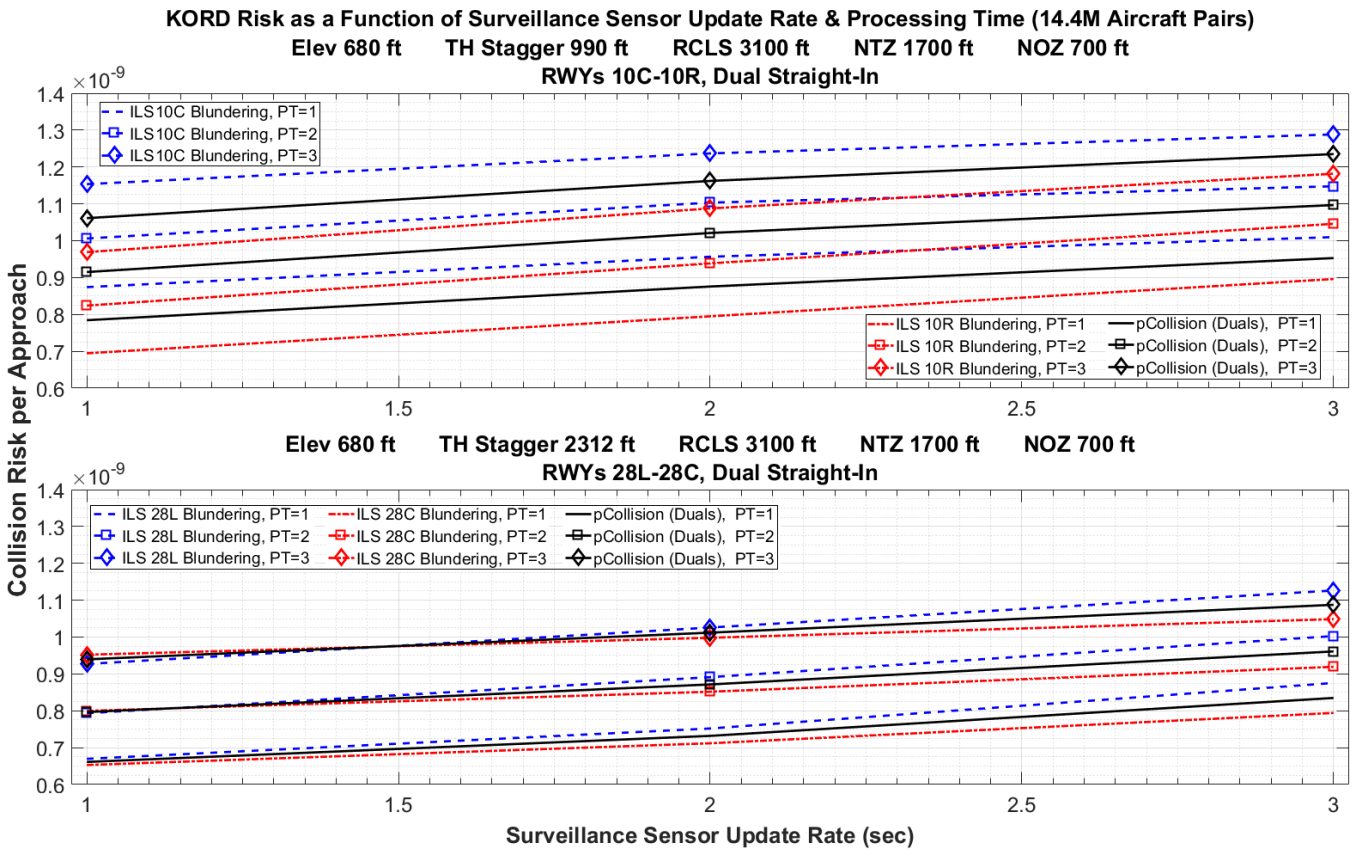

Figure 4-9: Dual Straight-In ILS Approaches at KORD (RWYs 10C-10R and 28L-28C)

4.1.2.3 Collision Risk – KJFK

Like KDTW, the runways utilized for CSPO at KJFK have an RCLS of 3000 ft (4L-4R and 22L-22R); however, with its unique configuration of a short localizer distance to threshold due to a seawall obstruction and the shortened runways caused by a displaced threshold (Appendix E), KJFK's collision probability is somewhat lower for approaches to runways 22L and 22R. The localizer distance to threshold appears to play a much larger role than originally anticipated in the collision risk analysis. This assumption should be studied more in-depth in future Flight Systems Laboratory work. Figure 4-10 displays the collision risk associated with dual straight-in approaches to runways 4L-4R and 22L-22R.

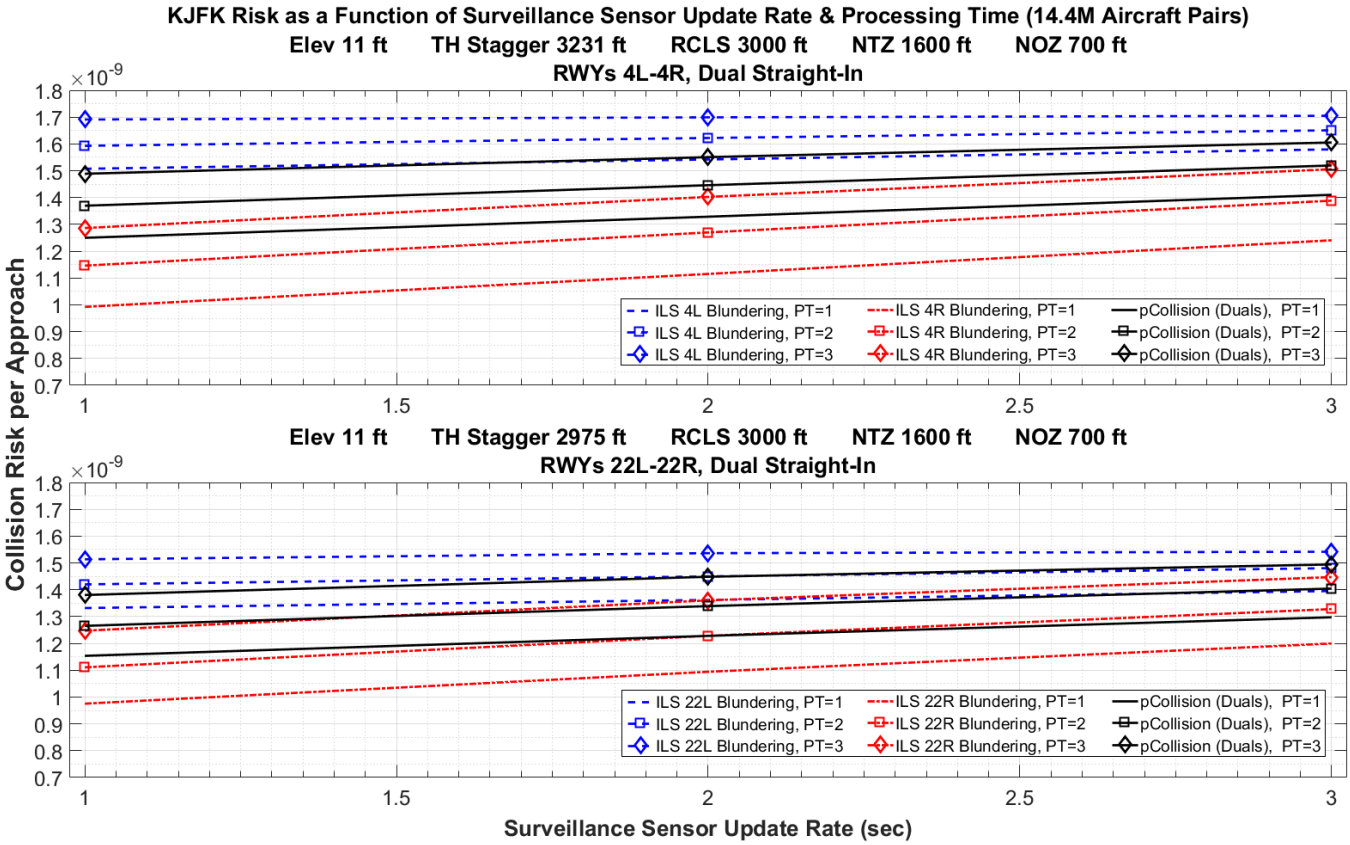

Figure 4-10: Dual Straight-In ILS Approaches at KJFK (RWYs 4L-4R and 22L-22R)

4.1.2.4 Collision Risk – KDEN

The runway configurations for CSPO at KDEN with RCLS of 2599 ft are unique due to the airport's elevation of 5430 ft and long runway lengths of 12,000 ft (16R/34L) and 16,000 ft (16L/34R). Straight-in approaches yielded an elevated risk compared to offset approaches. By incorporating a 2.5° offset approach, collision risk values were effectively lowered. Figure 4-11 displays the collision risk associated with dual straight-in and dual offset approaches to runways 34L and 34R. The risk is significantly reduced with offset approaches when compared to a straight-in approach; with the lowest probability of collision attained with a 2.5° offset approach to runway 34R.

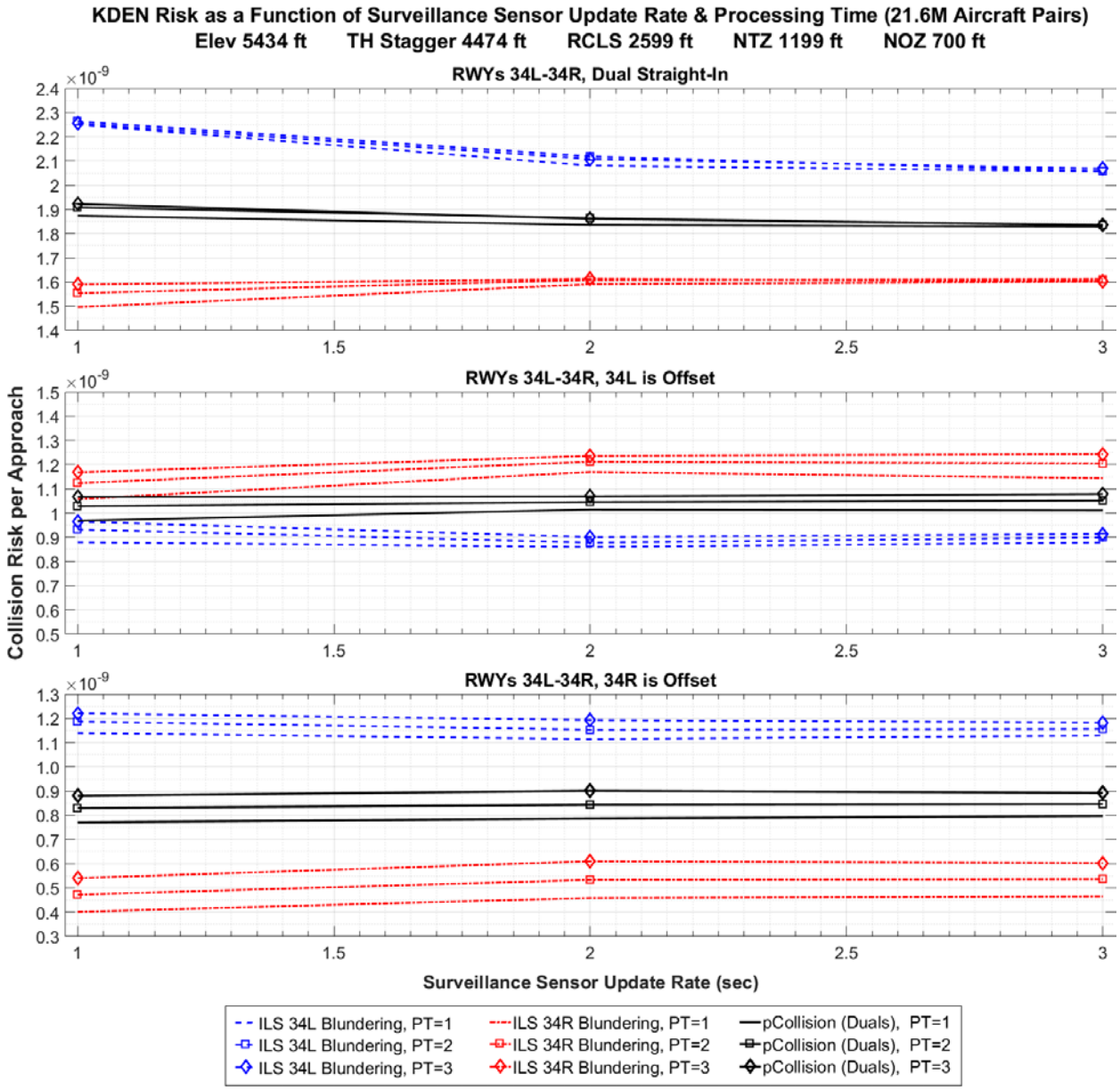

Figure 4-11: Dual Straight-In and Offset ILS Approaches at KDEN (RWY 34L-34R)

Figure 4-12 displays the collision risk associated with dual straight-in and dual offset approaches to runways 16L and 16R. The risk is significantly reduced with offset approaches when compared to a straight-in approach; with the lowest probability of collision attained with a 2.5° offset approach to runway 16R.

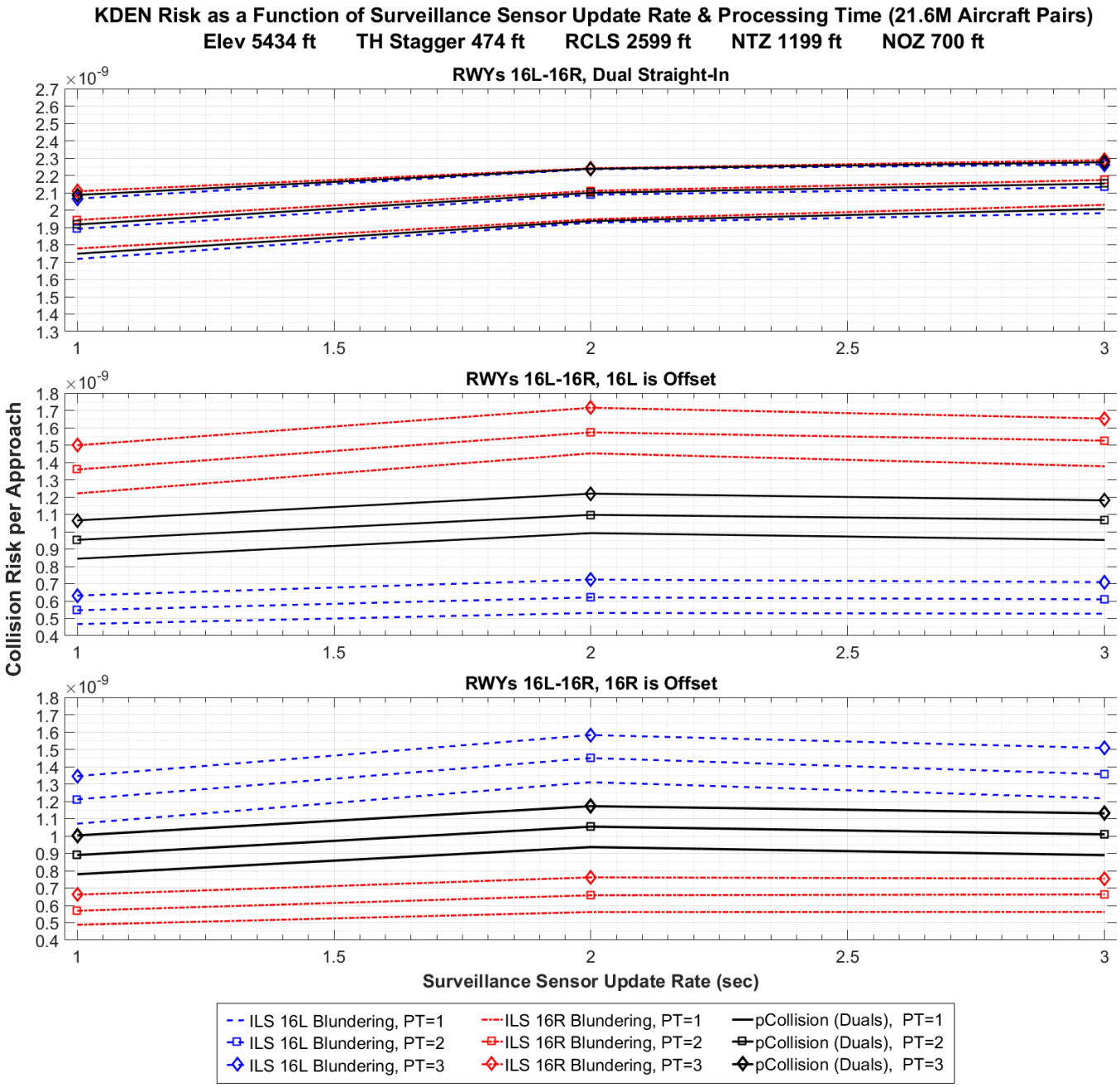

Figure 4-12: Dual Straight-In and Offset ILS Approaches at KDEN (RWY 16L-16R)

4.1.2.5 Collision Risk – KSEA

The configuration for runways 16L and 16R at KSEA is a good example of a generic airport with runways separated by 2500 ft due to its limited stagger of 25 ft. The configuration of the reciprocal runways (34L and 34R) has a significant stagger of 3400 ft. Straight-in approaches yielded a higher risk compared to offset approaches. Scenarios were created that explored either approach having a 2.5° localizer offset, or both approaches utilizing a 2.5° localizer offset. These individual modifications effectively mitigated collision risk values. When performing an approach to runways 16L and 16R with one offset, the probability of collision is radically reduced compared to a straight-in approach. The insignificant stagger between runways 16L and 16R creates a virtually aligned threshold situation. If using the probability of collision to determine whether 16L or 16R should be offset, no preference should be made due to an insignificant difference in the probability. The risk can be further reduced by introducing two offsets between 2.5° and 3° to runways 16L and 16R. Figure 4-13 displays the collision risk associated with dual straight-in, dual single-offset, and dual two-offset approaches to runways 16L and 16R.

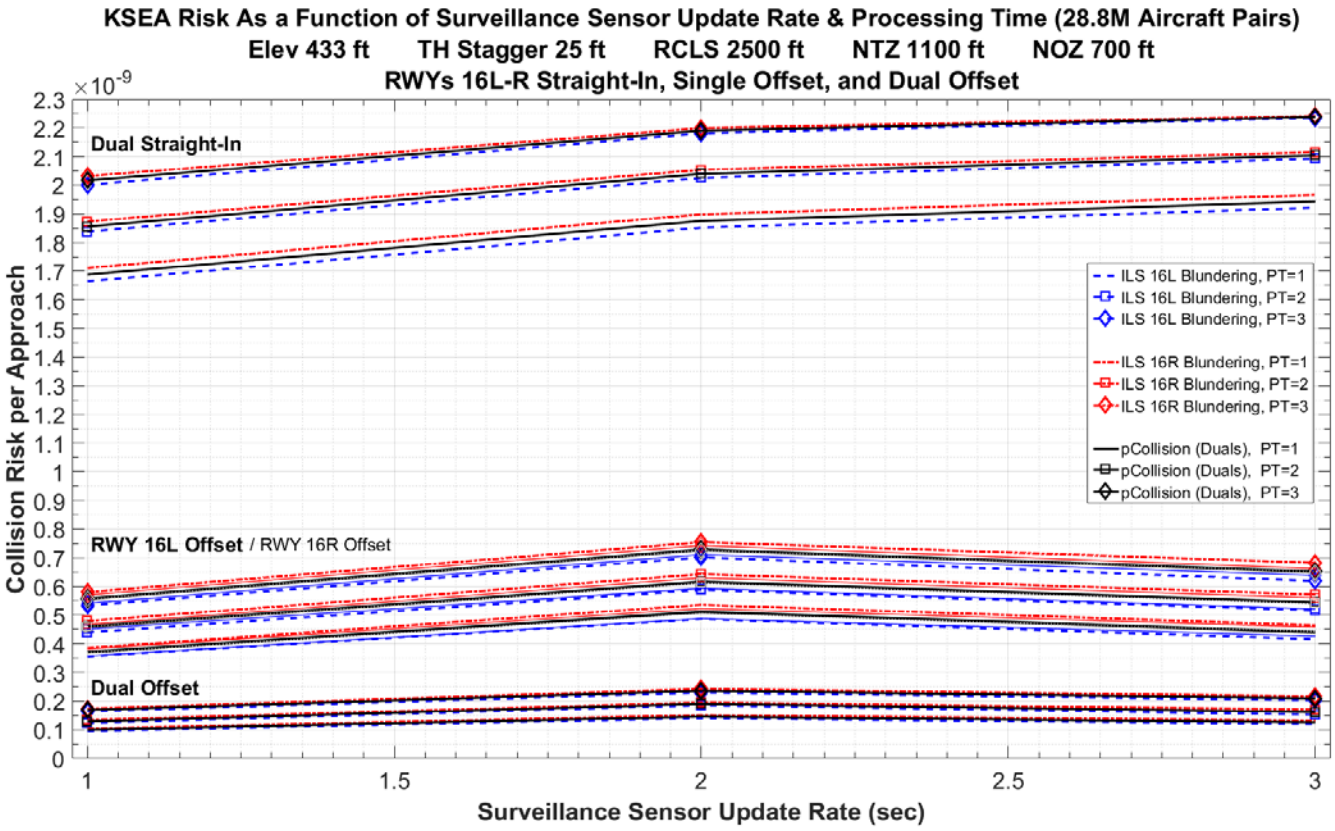

Figure 4-13: Dual Straight-In and Offset ILS Approaches at KSEA (RWY 16L-16R)

Much like KDEN, the approaches to runways 34L and 34R at KSEA feature a very large stagger (3400 ft). Due to the large stagger and the correlating localizer distances to threshold, results show a larger disparity in collision probability depending on which approaching aircraft (i.e., the one on 34L or 34R) deviates. Unlike approaches to runways 16L and 16R, the difference in risk between either side being offset for approaches to 34L or 34R is significant. Figure 4-14 displays the collision risk associated with dual straight-in, dual single-offset, and dual two-offset approaches to runways 34L and 34R. As with the approaches to runways 16L and 16R, the probability of collision is greatly reduced by utilizing an offset on both approaches.

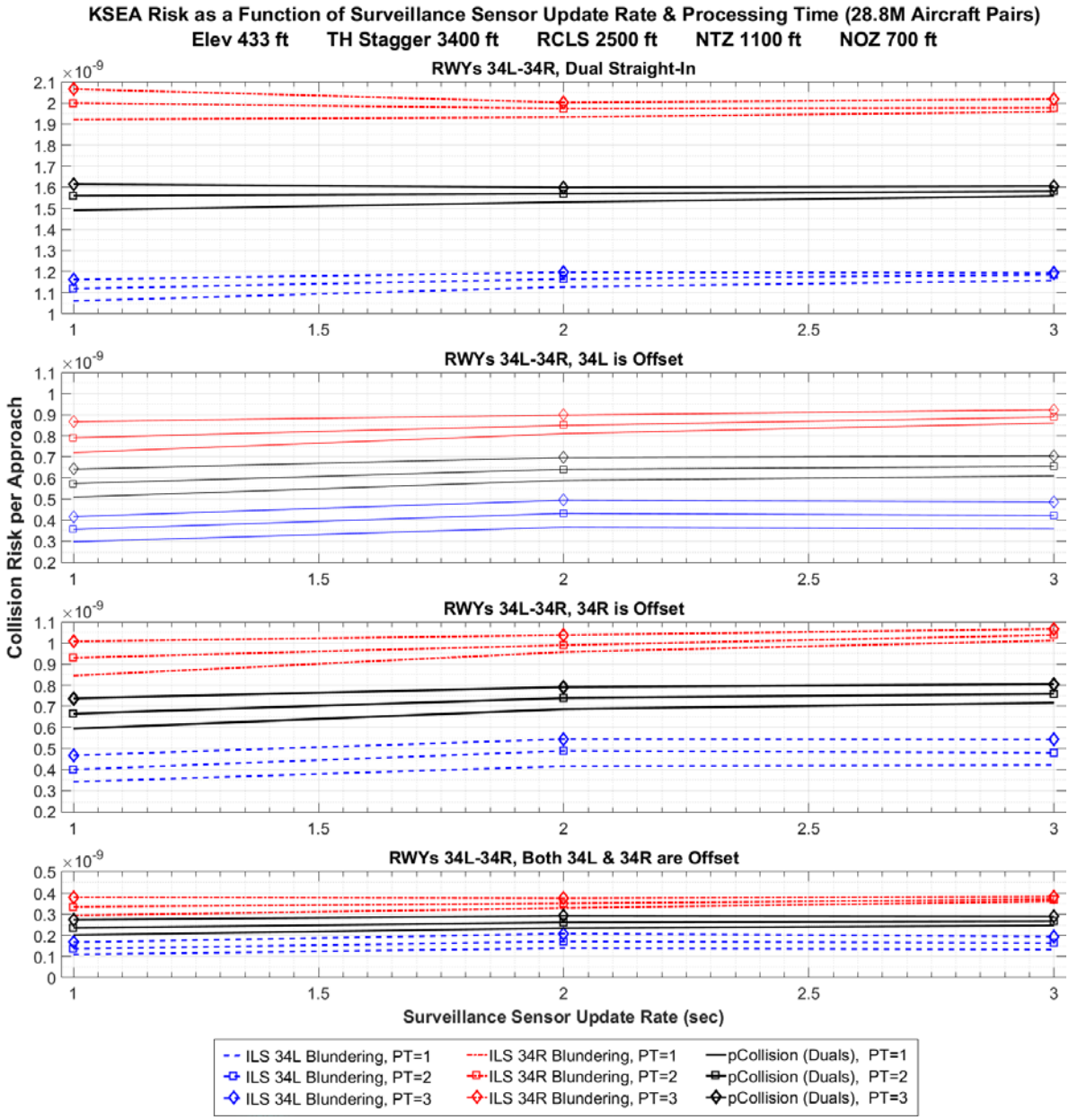

Figure 4-14: Dual Straight-In and Offset ILS Approaches at KSEA (RWY 34L-34R)

5 Conclusions

This report presents the results of an analysis identifying collision risk for generic airports with both straight-in and offset final approaches for dual and triple simultaneous independent CSPO with HUR surveillance capabilities utilizing CAT II ILS with flight director guidance and RNAV/RNP aircraft flying with flight director guidance. Site-specific airport runway configurations were also evaluated using CAT II ILS with flight director guidance.

For generic airport scenarios utilizing CAT II ILS approaches with aligned runway thresholds, the results indicate possible reductions to established runway centerline spacing for airports with field elevations up to 2000 ft MSL with an SSUR of 1 second and a maximum PT as follows:[31]

- Dual parallel runways with RCLS of 3100 ft or more with a PT of 1 second[32]
- Dual parallel runways with RCLS of 2500 ft or more and a single localizer offset of at least 2.5° with a PT of 3 seconds (refer to Figure G-10 and Figure G-11)
- Triple parallel runways with RCLS of 3400 ft or more with a PT of 3 seconds (refer to Figure G-12)
- Triple parallel runways with RCLS of 2500 ft or more with at least one localizer offset to an outside runway of at least 2.5° with a PT of 3 seconds (refer to Figure G-13 and Figure G-14)

Additional generic airport scenarios utilizing CAT II ILS and RNAV/RNP at 3200 RCLS evaluated how runway length and runway threshold stagger impact overall collision risk. The results for straight-in approaches indicate possible reductions to established runway centerline spacing for airports with field elevations up to 2000 ft MSL with an SSUR of 1 second and a maximum PT as follows:

- Dual parallel runways with RCLS of 3200 ft or more in:
  - All cases with aligned runway thresholds (refer to cases 1, 3, and 6 as depicted in Figure G-8) with a PT of 2 seconds[33]
  - All cases with a runway threshold stagger of 2500 ft (refer to cases 2, 4, 5, and 7 as depicted in Figure G-9) with a PT of 1 second

Appendix H summarizes the current RCLS minimum requirements as well as the possible benefits that could be achieved as indicated by the analysis performed during this study with the use of an HUR surveillance system.

[31] For analyses performed for RCLS ≤ 3400 ft, normal operating zone (NOZ) remained constant at 700 ft; and for RCLS ≥ 3400 ft, no transgression zone (NTZ) remained constant at 2000 ft.

[32] Generic cases (refer to cases 1 through 7 as depicted in Figure 4-2 and Figures G-1 through G-7) were evaluated at an RCLS of 3100 ft utilizing CAT II ILS approaches using flight director guidance. Case 1 was also evaluated utilizing RNAV/RNP with flight director guidance (as depicted in Figure 4-1) for an SSUR of 1 second and a PT of 1 second.

[33] The collision risk for generic cases 1 and 6 with an SSUR of 1 second and a PT of 3 seconds for ILS approaches are lower than for RNAV/RNP approaches with an SSUR of 1 second and a PT of 3 seconds.

Analysis of specific CSPO runway configurations at KDTW, KORD, KJFK, KDEN, and KSEA indicated that runway threshold stagger, ILS localizer distance to runway threshold, and ILS glide slope angles can significantly affect collision risk.

For KDTW, the analysis mitigated the collision risk between the two closest runways, in both directions, by varying the current ILS glide slope angle values from 2.85° for runway 22L and 3.00° for runways 22R, 4L, and 4R, to:

- 22L ≤ 2.85°; 22R = 3.20°
- 04L ≤ 2.85°; 04R = 3.20°

For KORD, the analysis found that the collision risk for straight-in approaches maintained a relatively consistent linear nature as SSUR and processing time increase. When compared to KGEN case 5 (Figure G-5, Appendix G), it can be seen that though the configurations are similar, the collision risk to KORD runways 28L and 28C or their reciprocals is much lower. The mitigating factor is assumed to be the distance between the localizer antenna and the threshold (LOC-TH).

For KJFK, the configuration was unique because of a short LOC-TH due to a seawall obstruction and a shortened runway caused by a displaced threshold on runway 22R. Approaches to runways 22L and 22R yielded a collision probability lower than the reciprocal runways that share a more typical LOC-TH distance.

For KDEN and KSEA, the collision risk between the CSPO runways for straight-in approaches was reduced by utilizing a single localizer offset of at least 2.5°. The collision risk was further mitigated by utilizing dual localizer offsets of at least 2.5°.

Further investigation of the effects of attributes such as runway threshold stagger, ILS LOC-TH, ILS glide slope angles, and fleet mix variability on collision risk is suggested to determine if additional reduction in the minimum acceptable RCLS requirements for simultaneous independent CSPO are possible.

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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. 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 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:

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

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}.[34] 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 approach. 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°, 20°, and 30° by 10° increments as indicated in Table A-1.[35] 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:

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

[34] Flight Systems Laboratory, *DOT-FAA-AFS-400-83, Reduction of Diagonal Separation from 1.5 Nautical Miles to 1.0 Nautical Mile for Parallel Dependent Approaches*, Flight Technologies and Procedures Division, Federal Aviation Administration, February 2014.

[35] Massimini, Tene, *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:

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

Appendix B: Conditional TCV Rates and Aggregate Collision Risk Probabilities

This appendix includes the results of the analysis for generic scenarios examined in this study. Collision risk probabilities for HUR surveillance system parameters are summarized in Table B-1 through Table B-13. Each table consists of appropriate combinations of surveillance sensor update rates and processing times for ILS approaches to parallel 10,000 ft runways with aligned thresholds. The ILS localizer distance to runway threshold remained constant at 1000 ft from departure end of runway. For scenarios performed with RCLS ≤ 3400 ft, the NOZ remained constant at 700 ft. For scenarios performed with RCLS ≥ 3400 ft, the NTZ remained constant at 2000 ft. Collision risk associated with dual straight-in approaches are depicted in Table B-1 through Table B-4, dual offset approaches in Table B-5, triple straight-in approaches in Table B-6 through Table B-11, and triple offset approaches (single and dual) in Table B-12 and Table B-13.

Table B-1: Collision Risk for Dual Straight-In ILS Approaches with 3000 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	1.03E-09	1.20E-09	1.25E-09
2	1.18E-09	1.36E-09	1.41E-09
3	1.35E-09	1.50E-09	1.56E-09

Table B-2: Collision Risk for Dual Straight-In ILS Approaches with 3100 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	9.07E-10	1.06E-09	1.12E-09
2	1.06E-09	1.21E-09	1.28E-09
3	1.21E-09	1.37E-09	1.42E-09

Table B-3: Collision Risk for Dual Straight-In ILS Approaches with 3200 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	7.02E-10	8.35E-10	9.00E-10
2	8.46E-10	9.84E-10	1.06E-09
3	9.83E-10	1.14E-09	1.21E-09

Table B-4: Collision Risk for Dual Straight-In ILS Approaches with 3300 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	6.05E-10	7.33E-10	7.84E-10
2	7.35E-10	8.63E-10	9.30E-10
3	8.62E-10	1.01E-09	1.08E-09

Table B-5: Collision Risk for Dual Offset ILS Approaches with 2500 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	5.82E-10	6.94E-10	7.23E-10
2	6.90E-10	8.16E-10	8.33E-10
3	8.07E-10	9.34E-10	9.52E-10

Table B-6: Collision Risk for Triple Straight-In ILS Approaches with 3200 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	9.36E-10	1.09E-09	1.17E-09
2	1.08E-09	1.25E-09	1.32E-09
3	1.23E-09	1.38E-09	1.45E-09

Table B-7: Collision Risk for Triple Straight-In ILS Approaches with 3300 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	8.23E-10	9.71E-10	1.03E-09
2	9.60E-10	1.11E-09	1.18E-09
3	1.10E-09	1.25E-09	1.32E-09

Table B-8: Collision Risk for Triple Straight-In ILS Approaches with 3400 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	7.18E-10	8.61E-10	9.23E-10
2	8.55E-10	9.95E-10	1.06E-09
3	9.80E-10	1.14E-09	1.20E-09

Table B-9: Collision Risk for Triple Straight-In ILS Approaches with 3500 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	6.64E-10	7.99E-10	8.34E-10
2	7.79E-10	9.27E-10	9.67E-10
3	9.11E-10	1.06E-09	1.10E-09

Table B-10: Collision Risk for Triple Straight-In ILS Approaches with 3600 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	6.04E-10	7.36E-10	7.56E-10
2	7.15E-10	8.60E-10	8.80E-10
3	8.31E-10	9.78E-10	1.00E-09

Table B-11: Collision Risk for Triple Straight-In ILS Approaches with 3700 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	5.49E-10	6.85E-10	6.80E-10
2	6.51E-10	7.99E-10	7.92E-10
3	7.66E-10	9.18E-10	9.15E-10

Table B 12: Collision Risk for Triple Single Offset ILS Approaches with 3300 ft and 2500 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	5.91E-10	7.34E-10	6.97E-10
2	7.03E-10	8.57E-10	8.20E-10
3	8.27E-10	9.89E-10	9.53E-10

Table B-13: Collision Risk for Triple Dual Offset ILS Approaches with 2500 ft RCLS

Processing Time (sec)	Surveillance Sensor Update Rate (sec)		
	1	2	3
1	5.81E-10	7.89E-10	7.34E-10
2	6.93E-10	9.11E-10	8.60E-10
3	8.08E-10	1.03E-09	9.85E-10

Appendix C: Aircraft Fleet Mix

This appendix describes the impact of aircraft fleet mix on collision risk. The ratio of heavy, large, and small aircraft in an approach operation is a factor that contributes to collision risk calculations. This study utilized a conservative fleet mix of 20% heavy aircraft, 55% large aircraft, and 25% small aircraft for generic cases. Prior studies applied different fleet mixes and often used a ratio of 20% heavy aircraft, 40% large aircraft, and 40% small aircraft. For this study, heavy aircraft are defined as aircraft capable of takeoff weights of more than 255,000 pounds whether or not they are operating at this weight during a particular phase of flight. Large aircraft are defined as having a maximum takeoff weight (MTOW) of more than about 100,000 pounds, and up to 255,000 pounds. Small aircraft are defined as aircraft with an MTOW of less than 100,000 lbs. Half of the heavy aircraft were represented by the Airbus A330 and the other half by the Boeing 747-400 (B747) to represent the MTOW extremes in the heavy category. The large aircraft were all represented by the Boeing 737-800 (B737) and the small aircraft were all represented by an Embraer regional jet. Each aircraft type in the mix had different approach speeds and dynamics. The fleet mix is a significant driver for the overall success or failure of a case, as heavy aircraft tend to respond more slowly in the evasion maneuver and small aircraft tend to respond more quickly. Table C-1 shows how variations in fleet mix affect the overall collision risk of an operation using a 20% heavy, 40% large, and 40% small ratio as a baseline indicator.

Table C-1: Fleet Mix Collision Risk Relative to Baseline Case

Heavy (%)	Large (%)	Small (%)	Comparative Risk Values
100	0	0	14.8% higher risk than baseline
35	64	1	9.8% higher risk than baseline
0	100	0	8.1% higher risk than baseline
30	50	20	5.0% higher risk than baseline
0	80	20	3.5% higher risk than baseline
20	55	25	3.5% higher risk than baseline
5	65	30	1.1% higher risk than baseline
30	30	40	0.9% higher risk than baseline
20	40	40	baseline
20	35	45	1.3% lower risk than baseline
0	60	40	1.4% lower risk than baseline
10	40	50	2.6% lower risk than baseline
0	0	100	10.6% lower risk than baseline

Table C-2 shows the aircraft fleet mix during one-year period from July 1, 2016 – June 30, 2017 for specific airports associated with this study. This study utilized a fleet mix of 20% heavy aircraft, 55% large aircraft, and 25% small aircraft for generic airports. A recalculation of collision risk utilizing the KJFK or KSFO fleet mixes indicated below, would yield slightly higher risk values; while utilizing the fleet mixes at any of the other airports would yield slightly lower values.

Table C-2: Airport Aircraft Fleet Mix (July 1, 2016 - June 30, 2017)

Airport	Heavy	Large	Small	Total
KCMH	0.3	35.8	63.9	100.0
KDAL	0.2	64.7	35.1	100.0
KDEN	3.5	66.8	29.7	100.0
KDTW	9.2	40.4	50.4	100.0
KJFK	31.6	47.8	20.6	100.0
KMSP	8.8	49.0	42.2	100.0
KORD	11.0	40.9	48.1	100.0
KPDX	5.6	48.8	45.6	100.0
KPHL	9.8	34.6	55.6	100.0
KPHX	5.8	67.6	26.6	100.0
KRDU	4.1	31.5	64.4	100.0
KSEA	9.7	59.9	30.4	100.0
KSFO	21.2	63.5	15.4	100.0
Average	**9.3**	**50.1**	**40.6**	**100.0**
Std Dev	**8.6**	**13.1**	**15.8**	**0.0**

Appendix D: Nuisance Breakouts

This appendix describes nuisance breakouts and their impact on collision risk and airport operations. The final monitor aid system is an alerting algorithm used by the final monitor controller that alerts the controller to predicted penetrations of the NTZ, called FMA caution alerts, or actual penetrations of the NTZ, called FMA warnings. Typically, aircraft positions are predicted 10 seconds into the future, making the alerting algorithm sensitive to approach geometries and groundspeed. Nuisance breakouts (NBO) occur when an aircraft flies close enough to the NTZ to trigger a caution even though the aircraft is not actually on a ground track that would enter the NTZ. This is commonly referred to as a nuisance alert in the FMA system. In this case, the monitor controller will attempt to return the aircraft to its final approach course. At the same time, the monitor controller for the adjacent approach, seeing an aircraft likely to enter the NTZ, may choose to breakout his aircraft as a precautionary measure. This will decrease the arrival rate and require additional ATC services to re-sequence the aircraft.

A number of NBOs can be expected to occur in any Closely Spaced Parallel Operation. An aircraft can be aligned on the final approach course, yet be close to the NTZ due to total system error (TSE) to cause an NBO. The probability density functions (pdf) of controller and pilot response times collected in previous human-in-the-loop experiments are typically used in fast-time simulations to estimate the rate of NBOs. For ILS approaches, the estimated rate of generating a nuisance alert is proportional to the length of the final approach course. Since aircraft on longer ILS finals have a higher probability of encountering nuisance alerts, the length of final is a limiting factor when considering the resultant capacity gained by operating SIPIA to closely spaced parallel runways. The acceptable percentage of nuisance breakouts is determined by each facility. Operational experience at Minneapolis revealed an NBO rate between 3% and 4% reduced capacity and SIPIA operations were terminated.

The Air Traffic Simulation, Incorporated (ATSI) NTZ Incursion Analysis Tool (NIAT) utilizes the following parameters to estimate the rate of NBOs:

- runway spacing
- NTZ width
- approach offset
- navigation system
- distance between the localizer (LOC) antenna and the threshold (TH)
- course width of GPS landing system (GLS) and localizer performance with vertical guidance (LPV)
- length of final
- Flight technical error (FTE) model
    - CAT I ILS hand flown using raw data
    - CAT II ILS hand flown using a flight director
    - CAT II ILS using an autopilot

For example, a 20 NM final and 10,000 feet LOC to TH distance results in a probability of an incursion between 6.8% and 18.6%, depending on the approach type. The approach design must take into account the resultant NBO rate when determining the length of final.

Table D-1 shows the NBO rate (i.e., likelihood of NTZ penetration) of aircraft on an RNAV/RNP parallel approach with a runway separation of 3600 ft and an NTZ width of 2000 ft. The NOZ, the distance from NTZ to approach centerline is 800 ft. An NBO rate of 0.006 for an RNAV/RNP value of 0.1 NM indicates nuisance breakouts will occur at a rate of approximately 0.6%.

Table D-1: NBO Rate for RCLS 3600 ft and NTZ 2000 ft for RNAV/RNP Approach

RNAV/RNP (NM)	Final Length					
	6.67 NM	**10.00 NM**	**13.33 NM**	**16.67 NM**	**20.00 NM**	**23.33 NM**
0.1	0.006	0.006	0.006	0.006	0.006	0.006
0.3	0.200	0.200	0.200	0.200	0.200	0.200
0.5	0.307	0.307	0.307	0.307	0.307	0.307

Table D-2 shows the NBO rate (i.e., likelihood of NTZ penetration) of aircraft on an ILS straight-in approach with a runway separation of 3600 ft and an NTZ width of 2000 ft. The NOZ, the distance from NTZ to approach centerline is 800 ft. An NBO rate of 0.022 for CAT II flight director with a 10 NM final, 700 ft LOC width at TH, and 10,000 ft LOC to TH distance indicates nuisance breakouts will occur at a rate of approximately 2.2%.

Table D-2: NBO Rate for RCLS 3600 ft and NTZ 2000 ft for ILS Approach

FTE Models	LOC to TH (ft)	Final Length					
		6.67 NM	10.00 NM	13.33 NM	16.67 NM	20.00 NM	23.33 NM
CAT I	8000	0.052	0.137	0.186	0.186	0.248	0.248
CAT II FD		0.012	0.039	0.070	0.093	0.125	0.166
CAT II AP		0.002	0.011	0.037	0.068	0.092	0.092
CAT I	8500	0.052	0.137	0.186	0.186	0.248	0.248
CAT II FD		0.009	0.029	0.070	0.093	0.125	0.166
CAT II AP		0.001	0.011	0.028	0.068	0.068	0.092
CAT I	9000	0.037	0.100	0.186	0.186	0.248	0.248
CAT II FD		0.006	0.029	0.070	0.093	0.125	0.125
CAT II AP		0.001	0.008	0.028	0.051	0.068	0.092
CAT I	9500	0.037	0.100	0.137	0.186	0.248	0.248
CAT II FD		0.006	0.022	0.053	0.093	0.093	0.125
CAT II AP		0.001	0.008	0.021	0.051	0.068	0.092
CAT I	10000	0.026	0.100	0.137	0.186	0.186	0.248
CAT II FD		0.005	0.022	0.053	0.070	0.093	0.125
CAT II AP		0.001	0.006	0.015	0.038	0.068	0.068
CAT I	11000	0.026	0.072	0.137	0.186	0.186	0.248
CAT II FD		0.003	0.022	0.039	0.070	0.093	0.125
CAT II AP		0.000	0.005	0.011	0.028	0.051	0.068
CAT I	12000	0.019	0.072	0.137	0.186	0.186	0.186
CAT II FD		0.002	0.016	0.029	0.070	0.093	0.093
CAT II AP		0.000	0.003	0.011	0.021	0.038	0.068
CAT I	13000	0.019	0.052	0.137	0.137	0.186	0.186
CAT II FD		0.002	0.016	0.029	0.053	0.070	0.093
CAT II AP		0.000	0.002	0.008	0.021	0.038	0.051

Table D-3 shows the NBO rate (i.e., likelihood of NTZ penetration) of aircraft on an ILS straight-in approach with a runway separation of 3000 ft and an NTZ width of 1600 ft. The NOZ, the distance from NTZ to approach centerline is 700 ft. An NBO rate of 0.029 for CAT II flight director with a 10 NM final, 700 ft LOC width at TH, and 10,000 ft LOC to TH distance indicates nuisance breakouts will occur at a rate of approximately 2.9%.

Table D-3: NBO Rate for RCLS 3000 ft and NTZ 1600 ft for ILS Approach

FTE Models	LOC to TH (ft)	Final Length					
		6.67 NM	10.00 NM	13.33 NM	16.67 NM	20.00 NM	23.33 NM
CAT I	8000	0.072	0.137	0.186	0.248	0.248	0.323
CAT II FD		0.016	0.053	0.093	0.125	0.166	0.222
CAT II AP		0.005	0.021	0.051	0.068	0.092	0.124
CAT I	8500	0.072	0.137	0.186	0.248	0.248	0.248
CAT II FD		0.016	0.053	0.093	0.125	0.125	0.166
CAT II AP		0.003	0.015	0.051	0.068	0.092	0.124
CAT I	9000	0.052	0.137	0.186	0.186	0.248	0.248
CAT II FD		0.016	0.053	0.070	0.093	0.125	0.166
CAT II AP		0.002	0.015	0.038	0.068	0.092	0.092
CAT I	9500	0.052	0.137	0.186	0.186	0.248	0.248
CAT II FD		0.012	0.039	0.070	0.093	0.125	0.166
CAT II AP		0.002	0.011	0.028	0.068	0.092	0.092
CAT I	10000	0.052	0.137	0.186	0.186	0.248	0.248
CAT II FD		0.009	0.029	0.070	0.093	0.125	0.166
CAT II AP		0.001	0.011	0.028	0.051	0.068	0.092
CAT I	11000	0.037	0.100	0.137	0.186	0.248	0.248
CAT II FD		0.006	0.029	0.070	0.093	0.093	0.125
CAT II AP		0.001	0.008	0.021	0.051	0.068	0.092
CAT I	12000	0.026	0.100	0.137	0.186	0.186	0.248
CAT II FD		0.005	0.022	0.053	0.070	0.093	0.125
CAT II AP		0.001	0.006	0.015	0.037	0.051	0.068
CAT I	13000	0.026	0.100	0.137	0.186	0.186	0.248
CAT II FD		0.005	0.022	0.053	0.070	0.093	0.125
CAT II AP		0.001	0.006	0.015	0.028	0.051	0.068

Appendix E: Potential Dual and Triple Runway Candidates with HUR Surveillance

This appendix lists airports and associated dual and triple straight-in approach information for runway pairs with RCLS less than 3600 ft and triples with RCLS less than 3900 ft, down to an RCLS of 2500 ft. Currently, Closely Spaced Parallel Operations are not authorized in a non-HUR environment at these RCLS distances. The benefits achieved via the use of HUR surveillance referenced in this study, provide the opportunity to utilize these configurations for dual and triple CSPO straight-in or offset approaches.

Table E-1 shows the relationship between the various runways lengths and the localizer (LOC) distances to threshold (TH).

Table E-1: Dual Runways – Potential Airports with RCLS < 3600 ft down to 2500 ft

RCLS (ft)	Airport	Runway A (ft)	Runway B (ft)	Runway C (ft)	Runway D (ft)	Runway A LOC-TH (ft)	Runway B LOC-TH (ft)	Runway C LOC-TH (ft)	Runway D LOC-TH (ft)
3564	KPHX	07L/10300	25R/10300	08/10591	26/11489	11624	N/A	11602	12503
3502	KCMH	10L/8000	28R/8000	10R/10113	28L/10113	9010	9019	11131	11131
3500	KRDU	05L/10000	23R/10000	5R/7500	23L/7500	11478	11002	8519	8509
3400	KMEM	18C/11120	36C/11120	18R/9320	36L/9320	12772	11722	10191	10379
3380	KMSP	12L/8200	30R/8000	12R/10000	30L/10000	8626	9210	10837	11249
3100	KORD	10C/10801	28C/10801	10R/7500	28L/7500	13310	11813	9653	8513
3099	KPDX	10L/8535	28R/9290	10R/11000	28L/11000	9545	10300	12320	12667
3060	KSLC*	16L/12002	34R/12002	17/9597	35/9272	13036	13105	10731	4434
3000	KDTW	04L/10000	22R/10000	04R/11494	22L/12003	11010	11010	12525	13021
3000	KJFK	04L/11619	22R/8655	04R/8400	22L/8400	12224	5474	9427	8873
2975	KDAL	13L/7352	31R/7752	13R/8310	31L/8800	8521	8101	9095	10115
2968	KPHL	08/5000	26/5000	09R/12000	27L/10087	N/A	3767	13010	11155
2800	KSTL	11/9001	29/9001	12R/10552	30L/10818	10850	10050	11652	11822
2599	KDEN	16L/12000	34R/12000	16R/16000	34L/16000	13019	13020	17009	17009
2500	KSEA	16L/11901	34R/11901	16R/8500	34L/8500	12908	12367	9513	9510

*Note: Runways at KSLC are not parallel and are offset 5°

Table E-2 identifies the runways and associated RCLS available for triple parallel operations for KDTW.

Table E-2: Triple Runways – Potential Airports with RCLS < 3900 ft down to 2500 ft

RCLS	Airport	Runway A	RCLS A-B	Runway B	RCLS B-C	Runway C
3800 & 3000	KDTW	03L/21R	3800	04R/22L	3000	04L/22R
5800 & 3000	KDTW	03R/21L	5800	04R/22L	3000	04L/22R

Appendix F: Error Distributions

This appendix describes the impact of the components of TSE on the overall collision risk associated with approach operations analyzed in this study. Total system error is the difference between the true position and the desired position of the aircraft. The TSE is equal to the vector sum of the navigation system error (NSE), flight technical error (FTE), and path definition error (PDE).

Collision risk for simultaneous independent CSPO was assessed for ILS and RNAV/RNP approaches. ASAT^{ng} fast-time simulations were configured and conducted to examine approaches utilizing CAT II ILS with flight director guidance and GPS-equipped RNAV/RNP aircraft flying with flight director guidance. RNAV aircraft that rely on distance measuring equipment (DME) and inertial reference unit (IRU) for DME/DME or DME/DME/IRU navigation were not considered for this study.

Tracking performance for the ILS aircraft was based on International Civil Aviation Organization (ICAO) collision risk model (CRM) distributions for both the lateral and vertical deviations from glide path. For the RNAV/RNP aircraft considered in this study, the initial lateral deviation of the aircraft was based on an NSE defined by a Gaussian (normal) distribution with zero mean and 50-meter standard deviation, the FTE distribution with zero mean and 50-meter standard deviation, and the PDE a 20-meter standard deviation. The RNAV/RNP aircraft utilized the same CRM vertical deviation distributions that were used for the ILS approaches.

Table F-1 shows a comparison of the cumulative lateral deviation distribution percentages bounded within a given standard deviation. The CRM distribution (for ILS aircraft) has a more compact distribution near the mean than the Gaussian distribution (for RNAV/RNP aircraft). The opposite is true at the edges of the distributions, where the CRM distribution (for ILS aircraft) flattens out and has much thicker tails than the Gaussian distribution (for RNAV/RNP aircraft). Restated, the CRM distribution (for ILS aircraft) is the tighter distribution at lower standard deviations and the Gaussian distribution (for RNAV/RNP aircraft) becomes the tighter distribution at approximately 1.7 standard deviation and beyond.

Table F-1: Lateral Distribution Cumulative Probabilities (CRM vs Gaussian)

Standard Deviation	Normal Distribution	CRM at 1200 meters	CRM at 4200 meters	CRM at 7800 meters
0.4	31.08%	39.66%	40.64%	41.10%
1.0	68.27%	75.14%	75.20%	75.08%
1.4	83.85%	86.48%	86.24%	86.00%
1.6	89.04%	90.08%	89.75%	89.50%
1.8	92.81%	92.68%	92.37%	92.15%
2.0	95.45%	94.62%	94.31%	94.11%
2.4	98.36%	97.08%	96.84%	96.74%
3.0	99.73%	98.84%	98.72%	98.71%
3.4	99.93%	99.37%	99.31%	99.35%

Table F-2 displays the displacement in meters of one standard deviation laterally and vertically for the ILS and RNAV/RNP approaches used in this study. For ILS, LPV, and GLS approaches, the lateral displacement increases as a function of range from runway threshold. For RNAV/RNP approaches, the lateral displacement remains constant.

Table F-2: Standard Deviations of Aircraft Displacement during Approach[36]

Category	Range (meters)	Lateral Displacement (meters)	Vertical Displacement (meters)		
			2.5° Glide Path	3.0° Glide Path	3.5° Glide Path
CAT II ILS Flight Director	1200	11.4	4.5	5.3	6.1
	4200	23.7	7.7	9.2	10.8
	7800	41.9	16.9	20.3	23.7
RNAV/RNP Flight Director	1200	74.1	4.5	5.3	6.1
	4200	74.1	7.7	9.2	10.8
	7800	74.1	16.9	20.3	23.7

*Note: Root-sum-squaring the NSE, FTE, and PDE values translates to a lateral 1σ TSE displacement of 0.04 NM (i.e., 74.1 meters) for flight director-guided RNAV/RNP approaches.

[36] *ICAO Manual on the Use of the Collision Risk Model (CRM) for ILS Operations,* International Civil Aviation Organization, 1980.

Appendix G: Supplemental Graphs

Below is supplemental information that includes KGEN graphs addressing various runway lengths and stagger scenarios. ILS localizer distance to runway threshold remained constant at 1000 ft from departure end of runway. Figure G-1 through Figure G-7 are dual straight-in approaches with constant RCLS of 3100 ft and NTZ of 1700 ft. Figure G-8 and Figure G-9 are dual straight-in approaches with constant RCLS of 3200 ft and NTZ of 1800 ft. Figure G-10 and Figure G-11 are dual offset approaches with constant RCLS of 2500 ft and NTZ of 1100 ft. Figure G-12 through Figure G-14 are triple straight-in and triple offset operations with varying RCLS and NTZ widths depending on the type of approach.

Figure G-1 depicts collision risk associated with case 1. Case 1 represents a generic dual straight-in approach scenario with two 7500 ft runways with aligned thresholds.

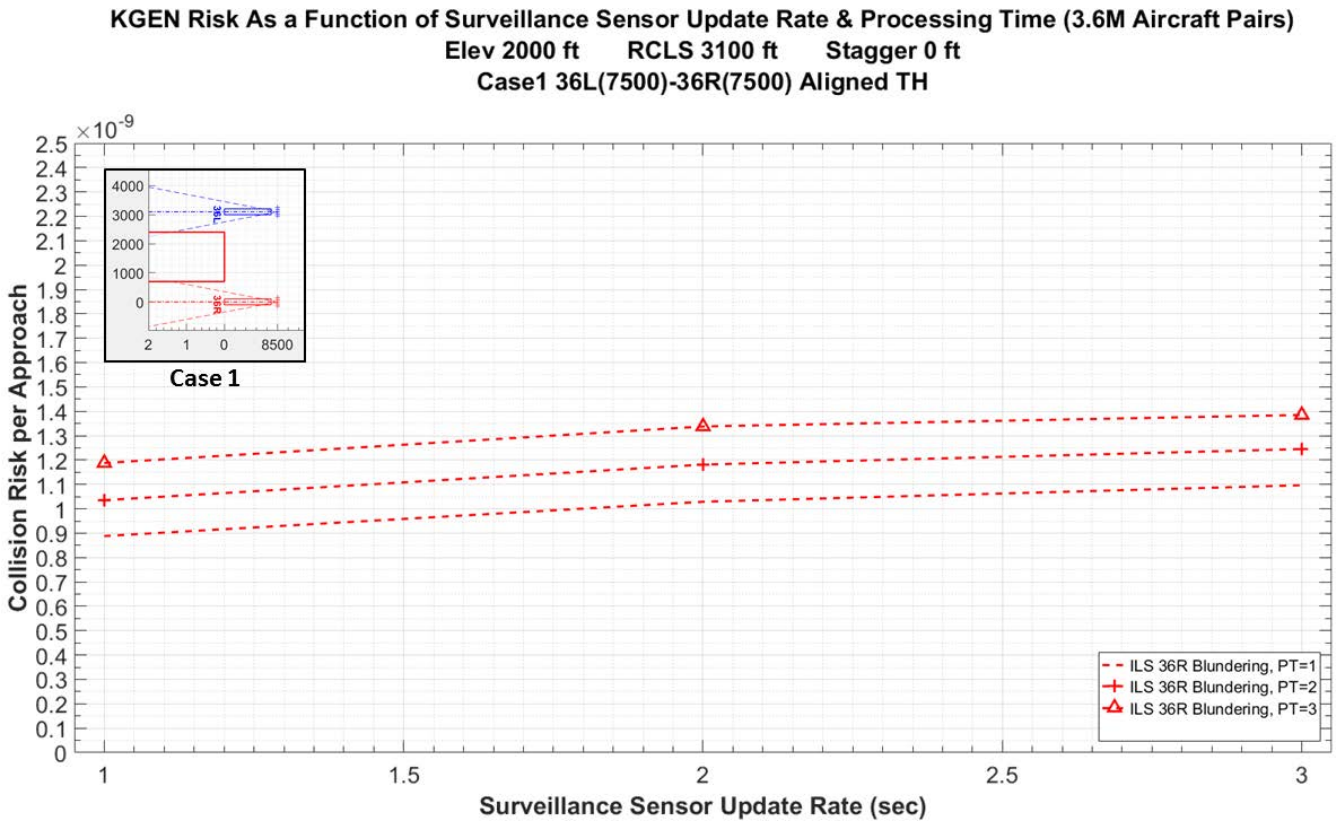

Figure G-1: Dual Straight-In with 7500 ft Runways and No Stagger

Figure G-2 depicts collision risk associated with case 2. Case 2 represents a generic dual straight-in approach scenario with two 7500 ft runways featuring a stagger of 2500 ft with the left runway positioned closer to the approaching aircraft.

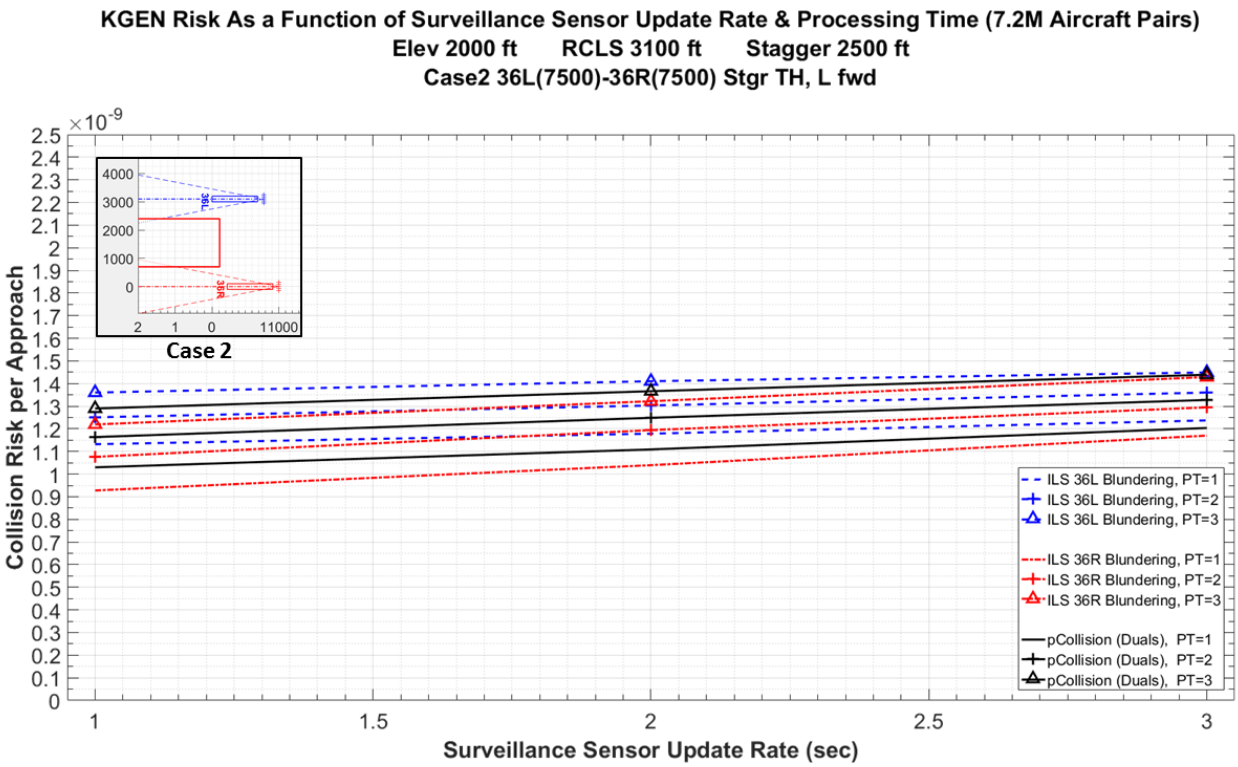

Figure G-2: Dual Straight-In with 7500 ft Runways and 2500 ft Stagger

Figure G-3 depicts collision risk associated with case 3. Case 3 represents a generic dual straight-in approach scenario with a 10,000 ft runway and a 7500 ft runway. The thresholds are aligned.

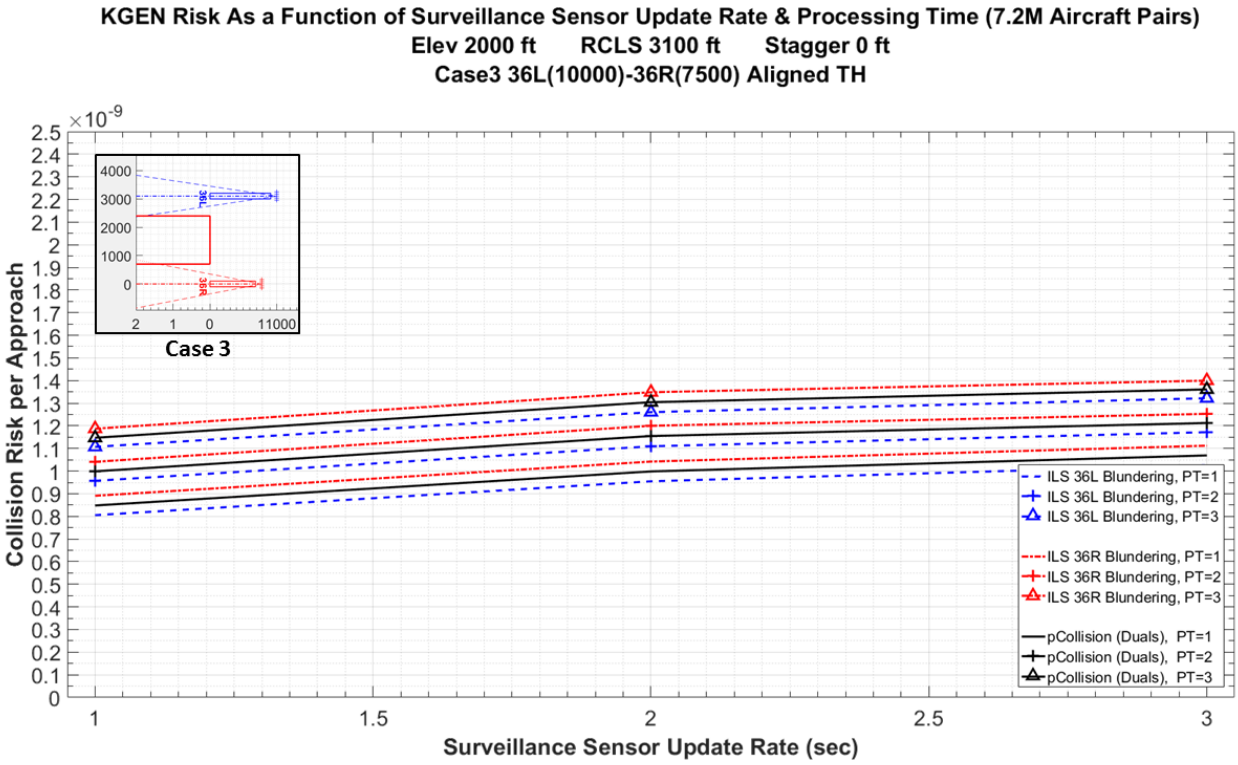

Figure G-3: Dual Straight-In with 10,000 ft/7500 ft Runways and No Stagger

Figure G-4 depicts collision risk associated with case 4. Case 4 represents a generic dual straight-in approach scenario with a 10,000 ft runway and a 7500 ft runway. There is a 2500 ft stagger between the thresholds, with the shorter (7500 ft) runway closer to the approaching aircraft.

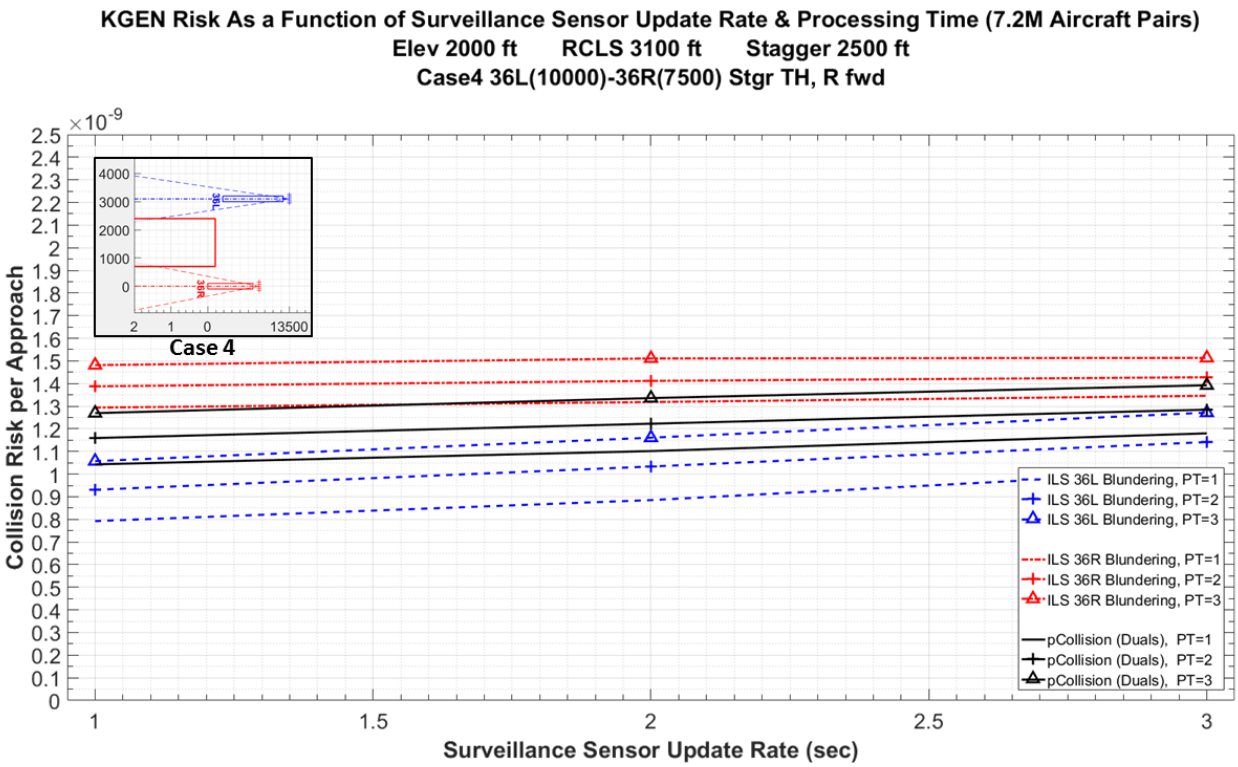

Figure G-4: Dual Straight-In with 10,000 ft/7500 ft Runways and 2500 ft Right Stagger

Figure G-5 depicts collision risk associated with case 5. Case 5 represents a generic dual straight-in approach scenario with a 10,000 ft runway and a 7500 ft runway. There is a 2500 ft stagger between the thresholds, with the longer (10,000 ft) runway closer to the approaching aircraft.

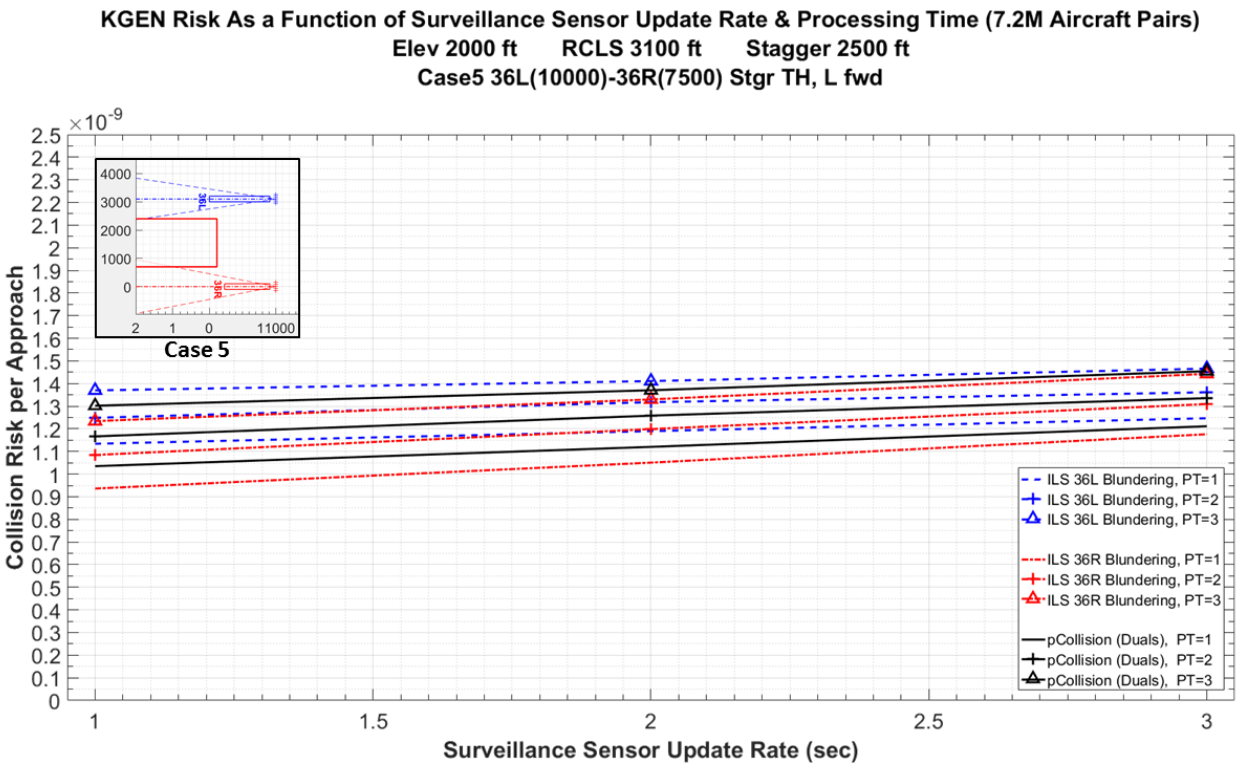

Figure G-5: Dual Straight-In with 10,000 ft/7500 ft Runways and 2500 ft Left Stagger

Figure G-6 depicts collision risk associated with case 6. Case 6 represents a generic dual straight-in approach scenario with 10,000 ft runways. The thresholds are aligned.

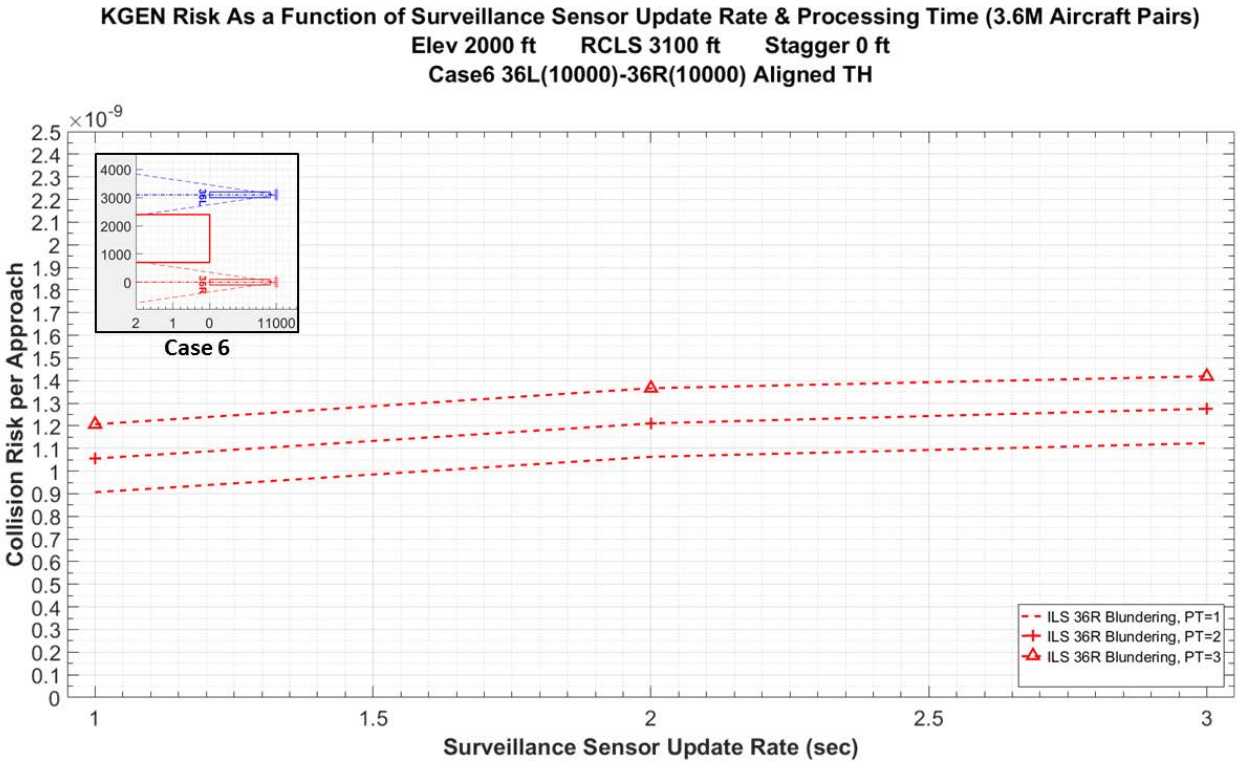

Figure G-6: Dual Straight-In with 10,000 ft Runways and No Stagger

Figure G-7 depicts collision risk associated with case 7. Case 7 represents a generic dual straight-in approach scenario with 10,000 ft runways. There is a 2500 ft stagger between the thresholds. The left runway is closer to the approaching aircraft.

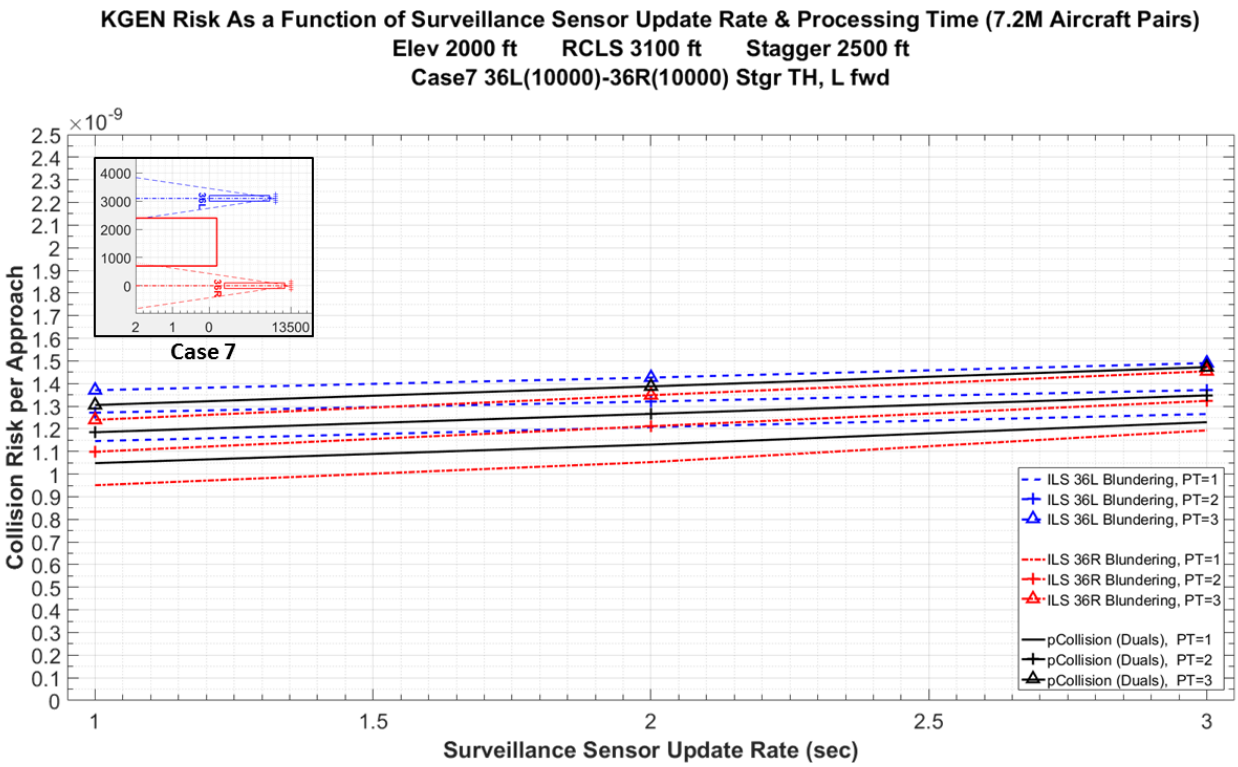

Figure G-7: Dual Straight-In with 10,000 ft Runways and 2500 ft Stagger

Figure G-8 depicts collision risk associated with generic dual straight-in approaches for cases 1, 3, and 6 with RCLS of 3200 ft and NTZ of 1800 ft. This figure displays the overall risk associated with these cases when performing either an ILS or RNAV/RNP approach.

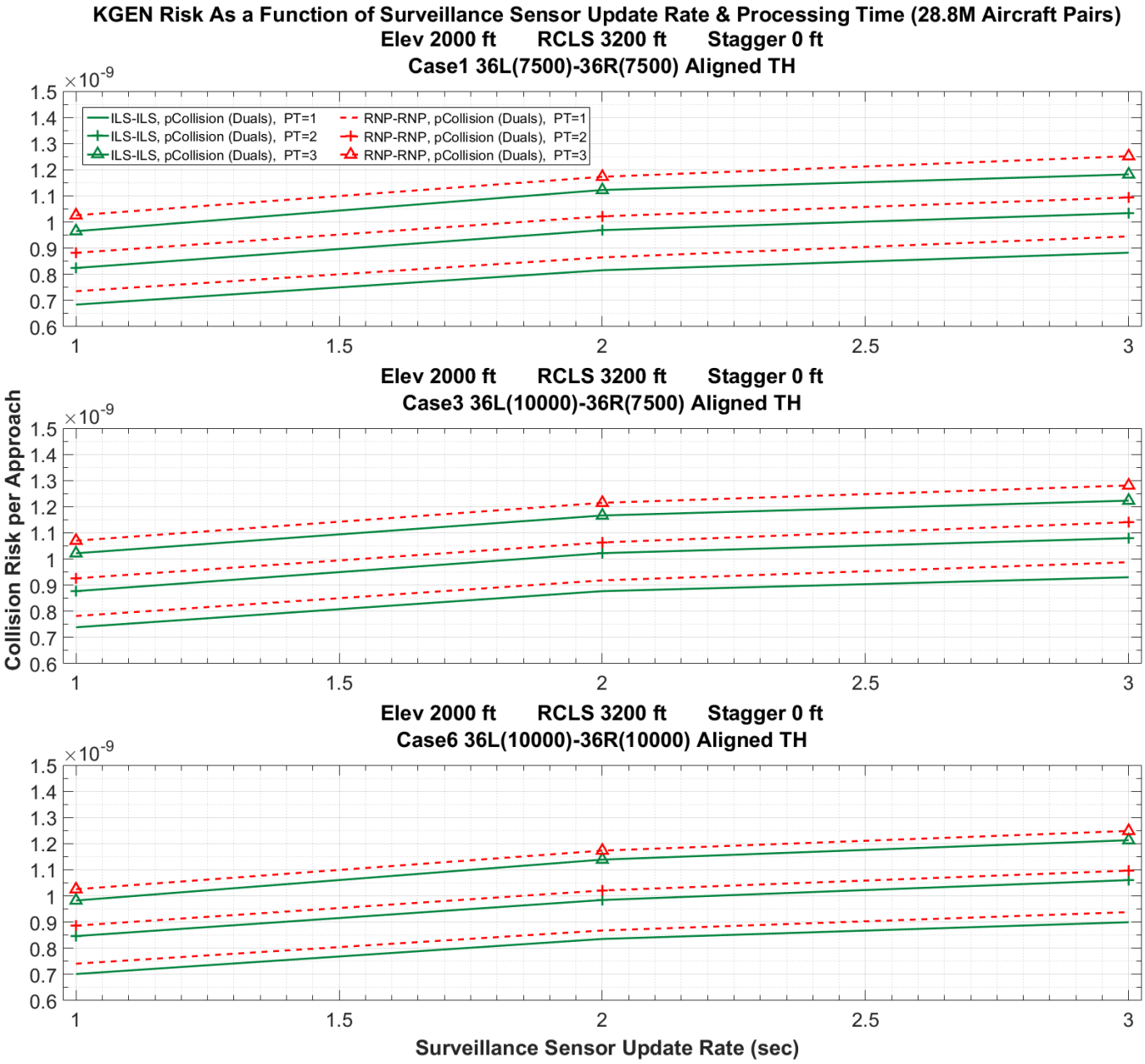

Figure G-8: Dual Straight-In with 10,000 ft/7500 ft Runways and No Stagger

Figure G-9 depicts collision risk associated with generic dual straight-in approaches for cases 2, 4, 5, and 7 with RCLS of 3200 ft and NTZ of 1800 ft. This figure displays the overall risk associated with these cases when preforming either an ILS or RNAV/RNP approach.

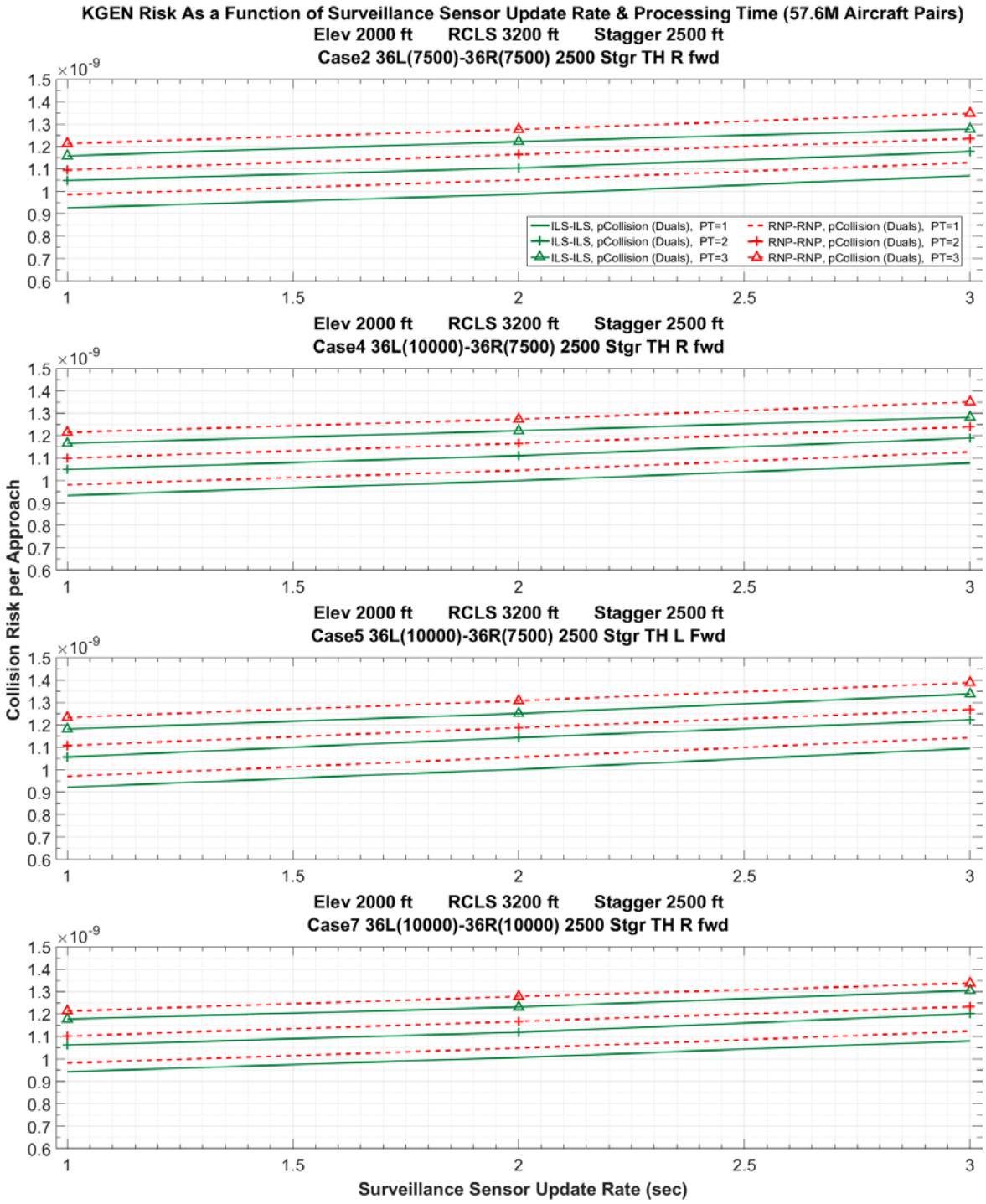

Figure G-9: Dual Straight-In with 10,000 ft/7500 ft Runways and 2500 ft Stagger

Figure G-10 depicts collision risk associated with a generic dual offset approach with runway lengths of 7500 ft.

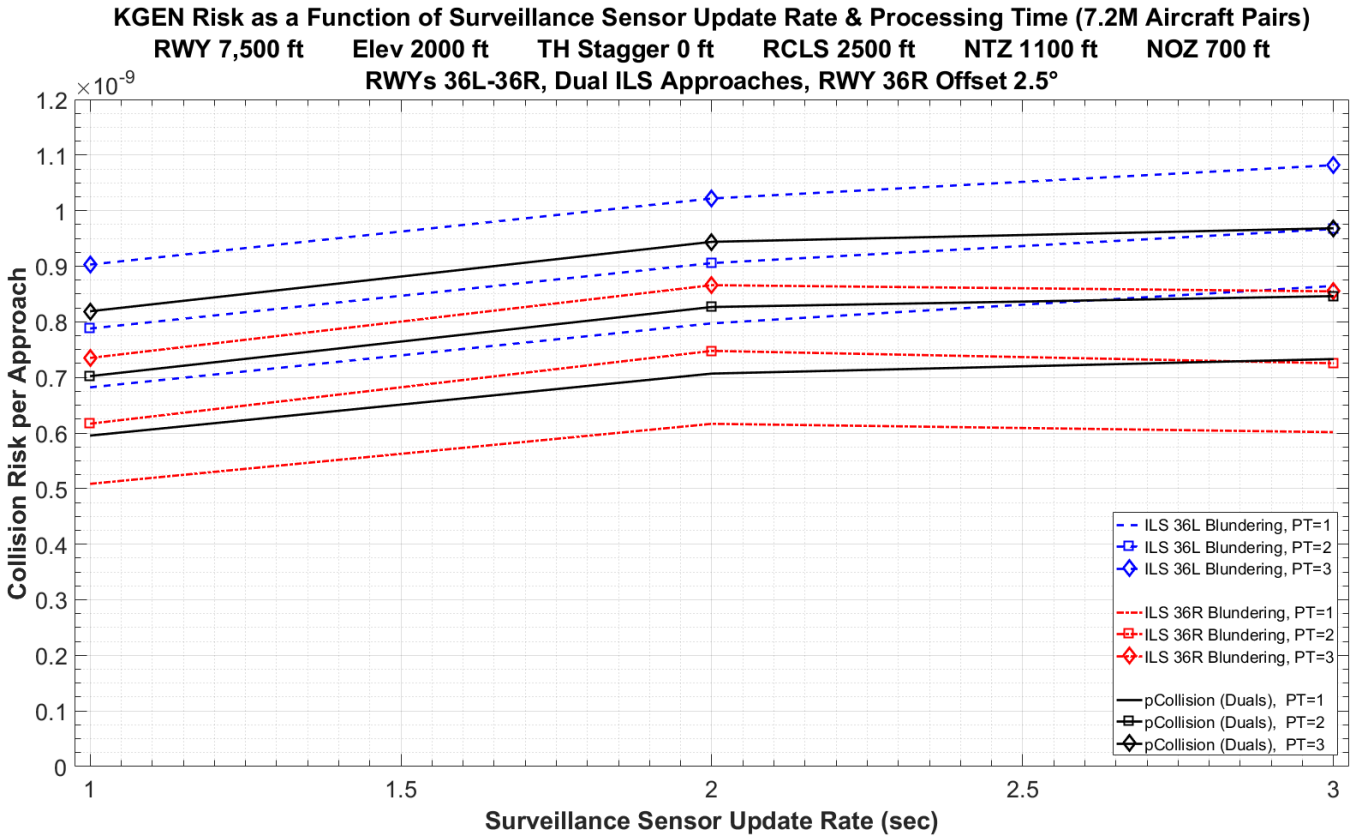

Figure G-10: Dual Offset with 7500 ft Runways

Figure G-11 depicts collision risk associated with a generic dual offset approach with runway lengths of 10,000 ft.

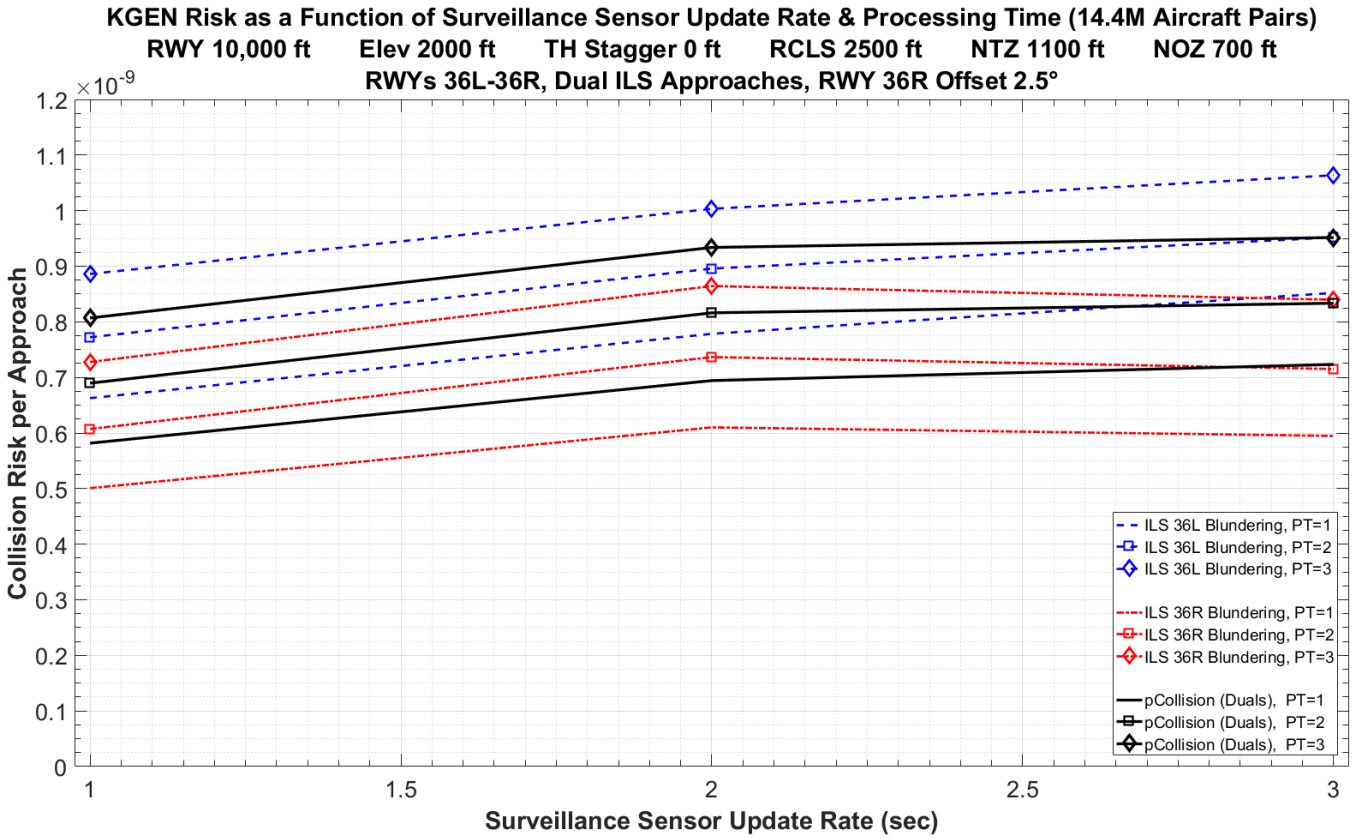

Figure G-11: Dual Offset with 10,000 ft Runways

Runway length in these scenarios do not play a significant factor in determining overall risk associated with this type of configuration.

Figure G-12 depicts collision risk associated with a generic straight-in approach to a triple runway configuration. The solid black line depicts the overall collision risk. For collision risk associated with individual deviations, refer to the figure's legend.

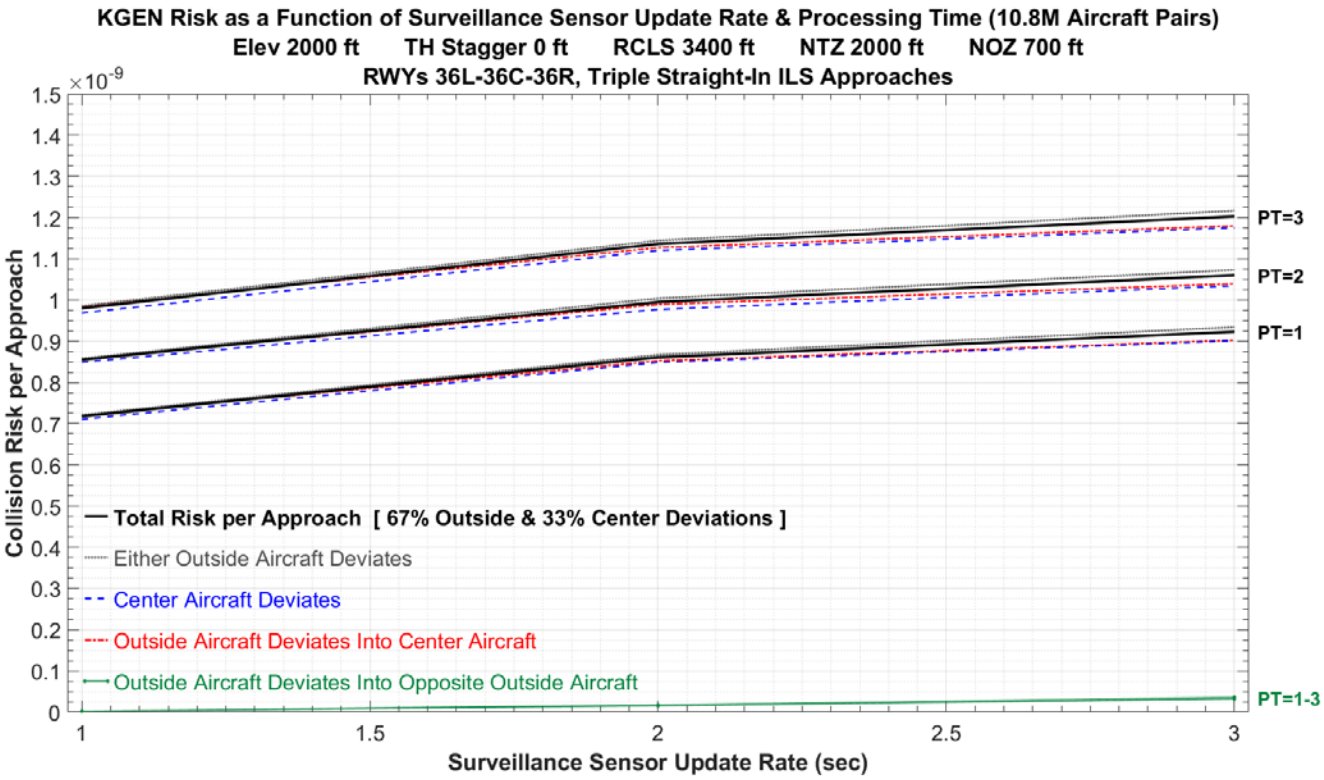

Figure G-12: Triple Straight-In with 10,000 ft Runways

Figure G-13 depicts collision risk associated with a generic one offset approach to a triple runway configuration.

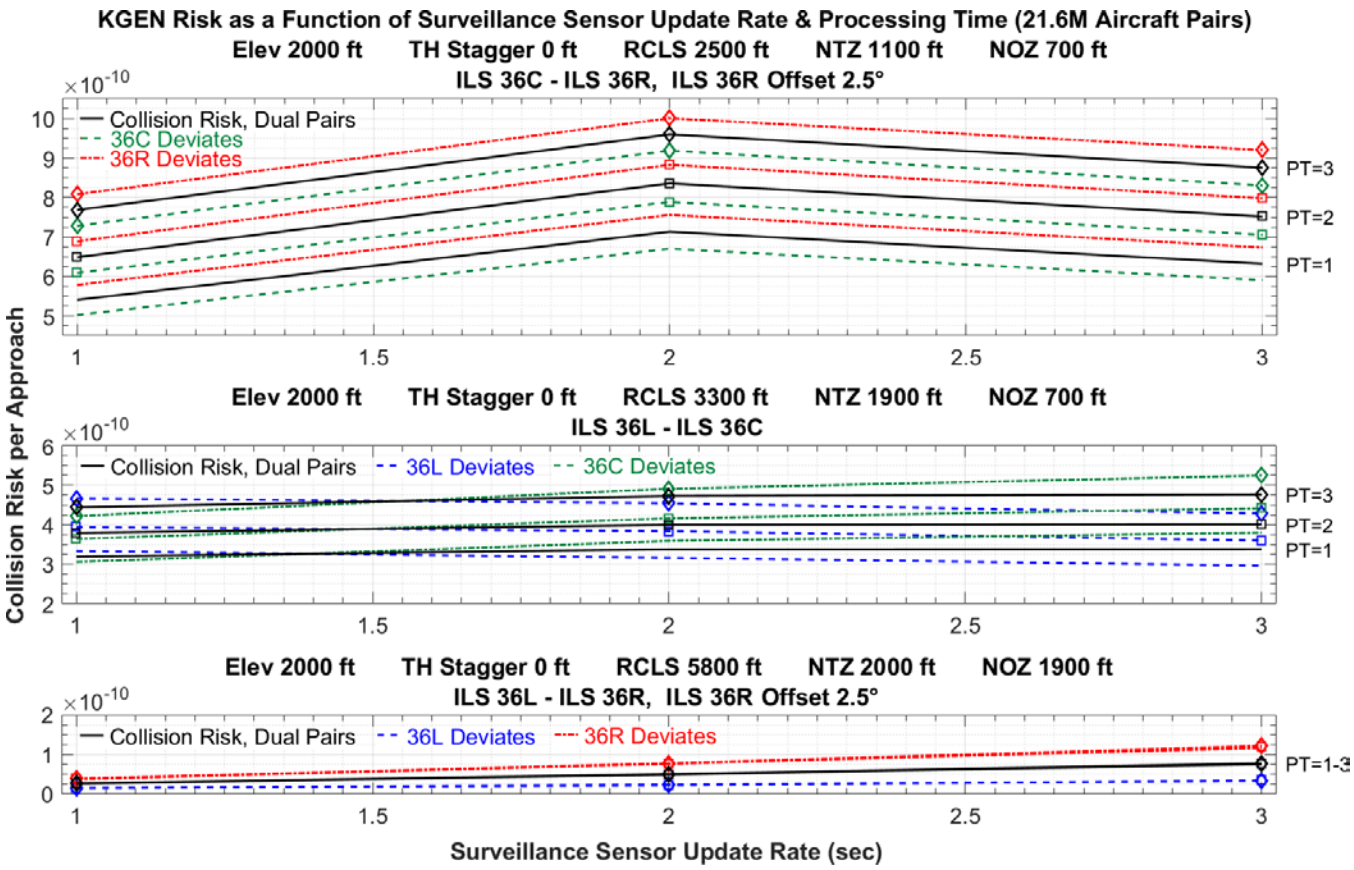

Figure G-13: Triple with One Offset with 10,000 ft Runways

Figure G-14 depicts collision risk associated with a generic two offset approach to a triple runway configuration. For each 1-second increment in processing time (1, 2, and 3 seconds), the collision risk increases by approximately 1×10^{-10}.

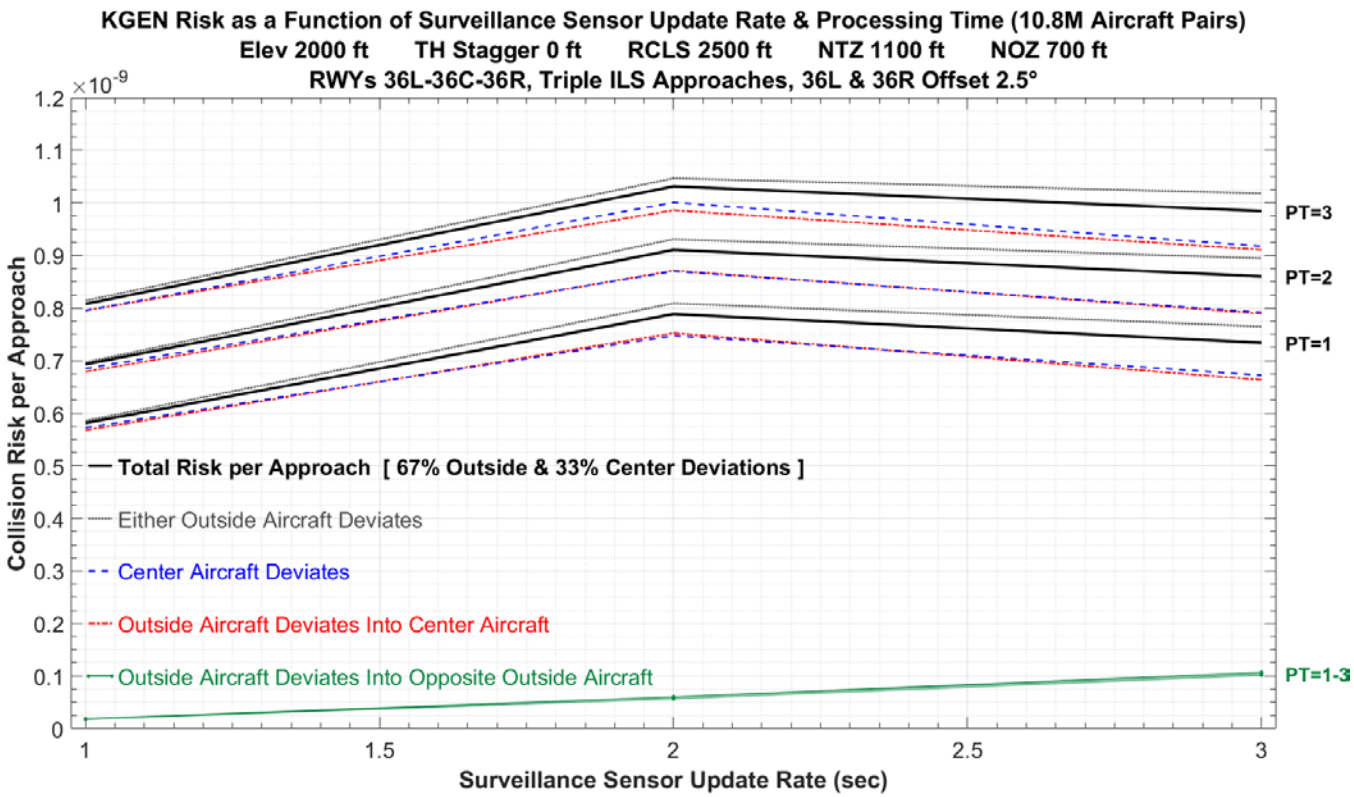

Figure G-14: Triple with Two Offsets with 10,000 ft Runways

Appendix H: Current and Potential Minimums

FAA *Order JO 7110.65X, Air Traffic Control (ATC)* (paragraphs 5-9-7 and 5-9-8) and FAA *Order JO 7210.3AA, Facility Operation and Administration* (paragraph 10-4-6) contain the current provisions governing ATC separation for independent precision approach operations at airports with dual or triple parallel runway configurations. The current minimum RCLS requirements for CSPO are listed below and identified in Figure H-1:

- Approaches to dual parallel runways with RCLS of 3400 ft (HUR)[37] and 3600 ft (non-HUR)
- Approaches to triple parallel runways with RCLS of 3900 ft
- Approaches to dual and triple parallel runways with RCLS of 3000 ft with at least one localizer offset to an outside runway between 2.5° and 3°

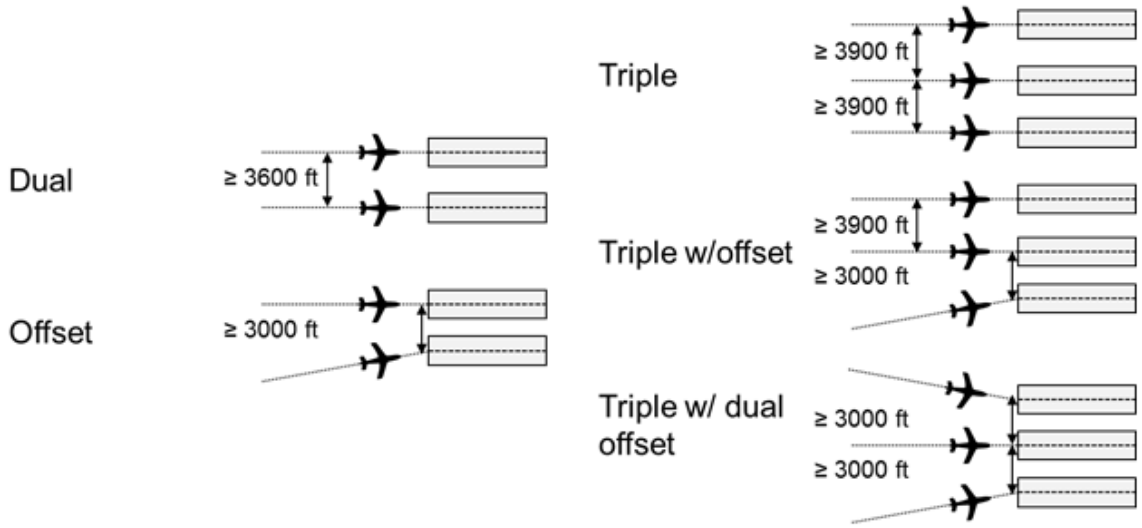

Figure H-1 Current Minimum RCLS Requirements for CSPO

[37] RCLS reduction to 3400 ft for locations using HUR is endorsed in *DOT-FAA-AFS-440-21, Safety Study Report for Multilateration/STARS FMA Used as a Precision Runway Monitoring System to Parallel Runways Separated by 3,400 Feet*, Flight Technologies and Procedures Division, Federal Aviation Administration, May 2006 and was incorporated into *FAA Order JO 7110.65W*. However, RCLS reduction to 3400 ft is not explicitly stated in *FAA Order JO 7110.65X* or *FAA Order JO 7210.3AA*.

Analyses were conducted to determine the probability of a midair collision between aircraft conducting dual and triple simultaneous independent closely spaced parallel approaches with HUR surveillance. The results listed below and identified in Figure H-2, indicate potential benefit for airports with field elevations up to 2000 ft mean sea level (MSL) utilizing a surveillance sensor update rate (SSUR) of 1 second and a maximum processing time (PT) of 3 seconds for approaches to:[38]

- Dual parallel runways with RCLS of 3200 ft or more without localizer offset, referred to as dual straight-in approach
- Dual parallel runways with RCLS of 2500 ft or more and a single localizer offset between 2.5° and 3°, referred to as dual offset approach
- Triple parallel runways with RCLS of 3400 ft or more without localizer offset, referred to as triple straight-in approach
- Triple parallel runways with RCLS of 2500 ft or more with at least one localizer offset to an outside runway between 2.5° and 3° referred to as triple single offset approach or triple dual offset approach

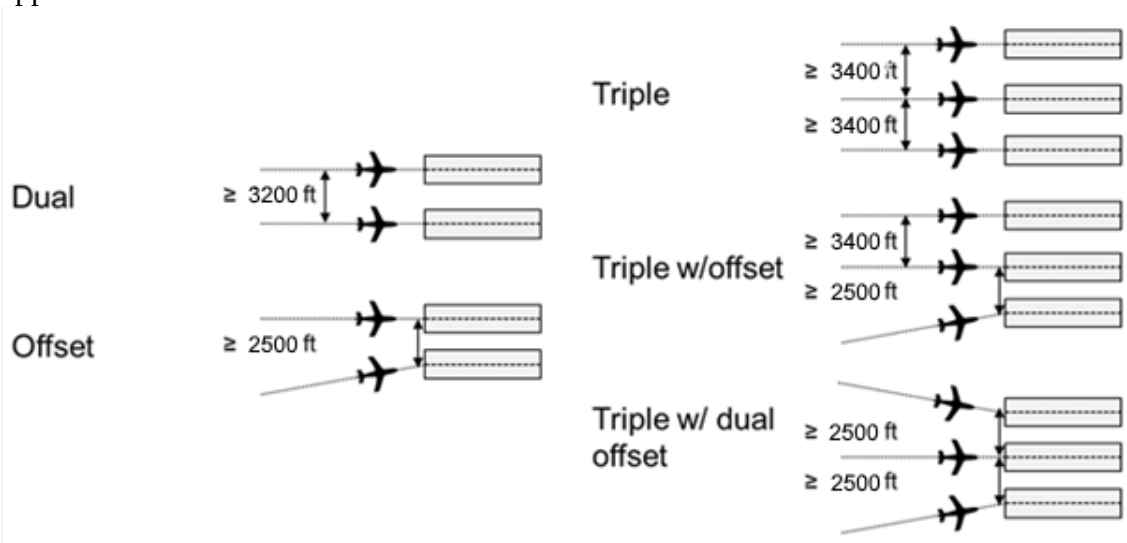

Figure H-2: Potential Minimum RCLS Requirements for CSPO

[38] For analyses performed for RCLS ≤ 3400 ft, normal operating zone (NOZ) remained constant at 700 ft; and for RCLS ≥ 3400 ft, no transgression zone (NTZ) remained constant at 2000 ft.

Appendix I: Acronyms

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

ADS-B	-	Automatic Dependent Surveillance – Broadcast
ASAT^{ng}	-	Airspace Simulation and Analysis Tool – Next Generation
ASDE-X	-	Airport Surface Detection Equipment, Model X
ATSI	-	Air Traffic Simulation, Incorporated
ASR	-	Airport Surveillance Radar
ATC	-	Air Traffic Control
ATO	-	Air Traffic Organization
CAT II	-	Category II ILS
CRM	-	Collision Risk Model
CSPO	-	Closely Spaced Parallel Operations
DME	-	Distance Measuring Equipment
E-Scan	-	Electronic Scan
FAA	-	Federal Aviation Administration
FMA	-	Final Monitor Aid
FSL	-	Flight Systems Laboratory
FTE	-	Flight Technical Error
GBAS	-	Ground-Based Augmentations System
GLS	-	GBAS Landing System
GPS	-	Global Positioning System
HUR	-	High Update Rate
ICAO	-	International Civil Aviation Organization
ILS	-	Instrument Landing System
IRU	-	Inertial Reference Unit
LOC	-	Localizer
LPV	-	Localizer Performance with Vertical Guidance
MSL	-	Mean Sea Level
MSSR	-	Monopulse Secondary Surveillance Radar
MTOW	-	Maximum Takeoff Weight
NAS	-	National Airspace System

NBO	-	Nuisance Breakout
NIAT	-	NTZ Incursion Analysis Tool
NM	-	Nautical Miles
NOZ	-	Normal Operating Zone
NSE	-	Navigation System Error
NTZ	-	No Transgression Zone
pdfs	-	Probability Density Functions
PDE	-	Path Definition Error
PRM	-	Precision Runway Monitor
PRM-A	-	Precision Runway Monitor – Alternative
PT	-	Processing Time
PTL	-	Predictor Target Line
RCLS	-	Runway Centerline Spacing
RA	-	TCAS Resolution Advisory
RNAV	-	Area Navigation
RNP	-	Required Navigation Performance
RWY	-	Runway
SIPIA	-	Simultaneous Independent Parallel Instrument Approaches
SRMP	-	Safety Risk Management Panel
SSUR	-	Surveillance Sensor Update Rate
STARS	-	Standard Terminal Automation Replacement System
TA	-	TCAS Traffic Advisory
TCAS	-	Traffic Collision Avoidance System
TCV	-	Test Criterion Violation
TERPS	-	Terminal Instrument Procedures
TH	-	Threshold
TSE	-	Total System Error